Investigations on Efficient Feeds for Offset Parabolic Reflector Antenna with Wide Cross-Polar Bandwidth

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1. Abstract

In the global scenario, the communication satellites are increasingly closely spaced and employ frequency reuse to double the communication capacity. This puts the stringent requirement on the antenna systems to have very low cross-polarization and low sidelobe level. Offset reflectors have high gain, low sidelobe level, higher efficiency, and no spurious radiation. While the offset parabolic reflector has considerable advantages as compared to the front-fed parabolic reflector antenna, it generates very high cross-polarization due to its structural asymmetry when used with a linearly polarized primary feed. Also, it squints the main beam when used with circular polarization. Existing solutions to overcome this problem will increase the complexity and bulk of the system.

In this thesis, the research work is mainly focused on the investigation on improving the cross-polarization bandwidth in an offset parabolic antenna using conjugate matched feed horn. Here, the high cross-polarization is introduced by the offset geometry. The higher level of cross-polarization in the far-field pattern results in loss of energy in unwanted polarization, which reduces the overall efficiency of the antenna system. In remote sensing application, measurement errors will occur because of higher cross-polarization. In communication, where the concept of frequency reuse is employed, it results in interference with the orthogonal polarized co-polar signal, thus lower the capacity of the channel. Also, in mono pulse tracking radars, the peak of the cross-polarized field component will be along the boresight. this results in boresight uncertainty which enforces limitations upon the accuracy of radar tracking.

Considering these unwanted effects of high cross-polarization, it requires to establish the appropriate method or technique to reduce the undesirable cross-polarized field in the asymmetry plane of the offset parabolic reflector antenna over a wide bandwidth. In the present thesis, a wideband multimode feed has been employed to reduce the effect of high cross-polarization over a wide band making use of the conjugate matching technique. In order to design such a multimode feed, the knowledge of the focal region field of offset reflector is necessary, the focal region field has been thoroughly formulated at the beginning of the thesis. The concept of matched multimode feed and higher-order modes required to suppress high cross-polarization field is thoroughly described. The design of matched feed using symmetric arrays of post discontinuity placed 120 degrees apart across the diameter of the horn is presented. The novel wideband conjugate matched feed horn has been designed and fabricated in a smooth cylindrical structure. The detailed designs of these matched feed structures have been presented in the thesis.

2. A brief description of the state of the art of the research topic

Very high-gain and wideband antennas are required for long-distance radio communications (radio-relay links and satellite links), radio altimeter, radio-astronomy, high-resolution radars, etc. Reflector systems are probably the most widely used high-gain and wideband antennas. They can easily achieve gains of above 30 dB for microwave and higher frequencies. The simplest parabolic reflector as illustrated in Figure 1(a), which consists of a rotational symmetrical reflector with feed at the focal point of the parabolic reflector. It has many advantages like the antenna system is simple to design, higher gain and very less cross-polarization. Lower cross-polarization results from cancellation of field component which is

180 degree out of phase with respect to the field component of the adjacent quadrant. The feed placed at the focus will obstruct the field reflected from the reflector which reduces gain, increases side lobe level, also mutual reaction between feed and reflector will take place. Because of the feed in the reflected path, this antenna system cannot be used for the very sensitive application. Very large feed or Array of feed also may not be used because of similar reasons.

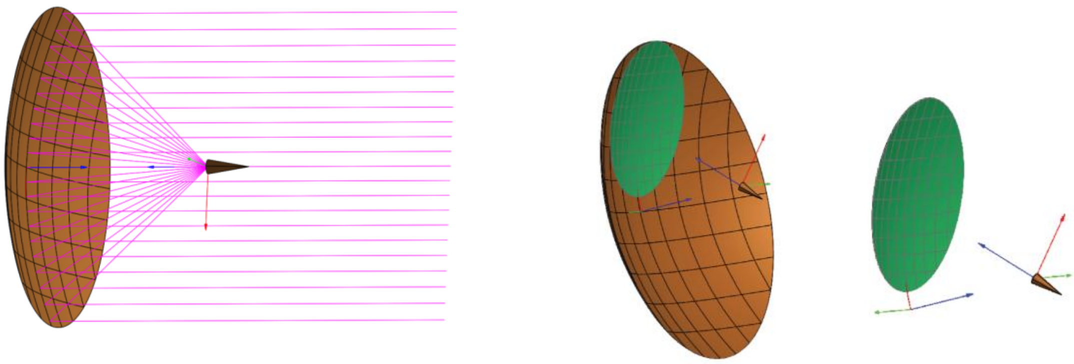

Fig.1 (a) Rotationally symmetrical front fed parabolic reflector antenna without strut and support (b) Generation of Offset reflector parabola from parent parabola

Many application demands use of an array of feed like

- Generation of contour beam to cover the particular geographical area without transmitting to the nearby region.
- The requirement of multiple beams
- Mono pulse radar application

In these applications we cannot use a symmetrical front fed reflector, instead, we are using the offset configuration (Fig. 1(b)) which uses only a portion of the reflector with primary feed tilted to the center of offset portion. This system has many advantages compared to symmetrical reflector such as

- It prevents aperture blockage from the feed.
- The absence of feed blockage in an offset parabolic reflector antenna ensures high illumination efficiency as compared to the symmetric parabolic reflector antenna.
- The reflector imposes much less of a reaction upon the primary feed than the symmetric reflector. This allows the primary feed voltage standing wave ratio to be essentially independent of the reflector.

- Low sidelobe level
- Allows uses of large feed structures and an array of the antenna.

In spite of these advantages, such reflector antennas suffer from two limitations

- When used with linearly polarized primary feed it generates very high cross-polarization. This due to the asymmetry of the offset configuration. In the plane of asymmetry, the cross-polarization is considerably high as compared to that in the plane of symmetry
- When used with circular polarization, the antenna main beam will be squinted away from the axis.

Several remedial measures to reduce the depolarization effect of such antenna which has been reported in the literature are as follows:

- Use of the polarization selective grid [1]. Such a solution may add complexity and increase system cost.
- Use of conventional dielectric lens in front of the horn [2]. The presence of dielectric increases the noise temperature as well as reduces the system gain
- Use of large focal-length-to-diameter ratio (F/D) with a small offset angle helps in solving such a problem [3]. But, large F/D results in a bulky and heavy structure which is not feasible for spaceborne application.
- Use of higher-order modes in addition to the fundamental mode in proper phase and amplitude as proposed by Rudge and Adatia [4]. This technique is widely used nowadays for the design of feed as a multi-mode horn or antenna array. Such feeds are called matched feed.

As discussed in the previous section, by using the conjugate matching cross-polarization can be reduced with the help of multimode horns. This concept has been known to the research community from a long time but the design techniques of such kind of feeds have not been taken comprehensively in literature. The matched feed design is quite complex but still, it is an active research area as manifest from recent and earlier publications.

- The first numerical and experimental data were published by Chu and Turrin [5]. They have investigated Variation of maximum cross-polarization in case of linearly polarized feed and beam squinting for circularly polarized feed as a function of F/D ratio, offset angle and half subtended angle.

- The detailed analysis of polarization losses of offset paraboloid antennas has been published by Jacob Dijk et al [6].
- Jacobsen [7] has suggested the techniques to design low cross-polarized feeds for the offset reflectors. Two separate feeds, one based on mode-matching technique and the other based on Huygens‟ source technique have been reported.
- Lier and Skyttemyr [8] proposed a single offset reflector antenna illuminated by a phase-correcting lens horn, which provides a secondary radiation pattern with high efficiency and low cross-polarization
- The concept of matched feed to suppress undesired cross-polarization is first proposed by Rudge and Adatia[4].
- Bahadoori and Samii used a tri-mode cylindrical matched feed [9] to feed the gravitationally balanced back-to-back reflector antenna. The bandwidth for Cross polarization reduction reported here was about 3 %.
- Sharma and Pujara et al. [10] discussed the cross-polar performance of a rectangular, matched-feed fed offset reflector with experimental results for mono pulse radar
- Pour and Shafai has done an analytical study of cross-polar suppression in offset reflector using the dual-mode cylindrical feed in the inter-cardinal plane and asymmetry planes[11]. Also, a ring choke exited feed also proposed by the same author[12]
- Sharma and Pujara et al. developed a corrugated cylindrical matched feed which uses fundamental mode HE11 and higher-order mode HE21[13]
- Dey, Chakrabarty, et al, proposed a broadband feed having symmetrical cascaded discontinuities created using the intersection of three off-centered junctions of circular waveguide placed symmetrically with an angular spacing of 120 deg. The author has reported cross-polar bandwidth of around 9 % in asymmetry plane.[14].
- Jana and Bhattacharjee[15] proposed a matched feed having an aperture formed by an intersection of circular and rectangular waveguides. The cross-polar suppression of 7 dB over a bandwidth of about 7% has been reported by the author.

Many satellite applications require a cross-polarization bandwidth of more than 10%. From this extensive literature survey, it has been observed that very few attempts have been made which achieve bandwidth in excess of 10% in asymmetry plane of offset reflector. This motivates us to do further investigation on to widen the cross-polar bandwidth of an offset reflector with novel feed structure using the conjugate matching technique.

3. Definition of the problem

The prime objective of this research is to develop a practical solution to overcome the cross-polarization bandwidth limitation of a single offset parabolic reflector having F/D <1.

For clarity, the problem undertaken as stated below:

"***To investigate and design a linearly polarized cylindrical multimodal horn feed for an offset reflector antenna with low F/D, to reduce the high cross-polarization in an asymmetrical plane for wide bandwidth with acceptable Return Loss***"

4. Objective and scope of work

Following objectives are taken as reference for developing the multimode feed.

1) To develop a program for analytical calculation of secondary pattern of offset parabola for multimode feed excitation and compare the analytical pattern (from Matlab) with simulated pattern (from Grasp's Ticra).
2) To achieve cross-polarization suppression bandwidth of 10% which is below 7 dB to the peak cross-polarization of Gaussian feed.
3) To design a multimode feed which satisfies previous objectives for different reflector configuration having
    a. F/D between 0.5 to 1, with low offset angle, more specifically F/D=0.8 and offset angle = 36 deg.
    b. F/D=0.5, with moderate offset angle, more specifically F/D=0.5 and offset angle = 55 deg.
    c. F/D=0.4, with very high offset angle, more specifically F/D=0.4 and offset angle = 90 deg.

5. Original contributions by the thesis

1. Detail simplified formulation to find out focal region field of offset parabolic reflector has been done. Based on this field power required for higher-order more is predicted and is validated using simulation.

2. Effect of an array of pin discontinuity with a parametric study on a number of parameters has been carried out.

3. A novel cylindrical primary multi-mode feed for offset reflector with F/D = 0.8 and Offset angle = 35 have been designed, fabricated and tested by the author. The feed can provide at least 7 dB cross-polarization suppression in the asymmetrical plane for 16% bandwidth in comparison to conventional Gaussian feed as a primary feed. Earlier works on similar configuration report maximum cross-polarization bandwidth of 10%.

4. The concept of the feed proposed earlier by the author has been extended using similar kind of discontinuity in cylindrical feed to generate higher-order modes for offset reflector configuration with F/D = 0.5 and Offset angle = 55. The proposed feed can provide at least 7 dB cross-polarization suppression in the asymmetrical plane for more than 15% bandwidth in comparison to conventional Gaussian feed as a primary feed. In Literature Earlier similar configuration reports maximum cross-polarization bandwidth of 8%. A patent has been filed based on proposed feed.

5. The proposed concept to reduce cross-polarization has been further investigated for the extreme case of offset configuration having critical F/D of 0.4 and highest possible offset angle of 90 deg. Using the proposed feed -7dB cross-polarization suppression bandwidth for more than 16% compared to the of cross-polarization due to Gaussian feed as primary feed have been reported by the author. Maximum reported cross-polar bandwidth for similar offset configuration was only 3% in the literature. A patent has been filed and published on proposed feed**.**

6. The methodology of Research, Results / Comparisons

6.1. Primary and secondary pattern generation and validation

The methodology adopted for the research work is as shown in Figure 2. First of all, for a given reflector configuration the basic parameter is calculated depending on the application requirement. generally, the diameter of the reflector (D), the required focal length to diameter ratio (F/D) and offset angle are given. Based on these three parameters all other physical parameters of offset reflector are calculated. Matlab program for obtaining all other parameters like subtended angle, clearance, etc, have been prepared by the researcher.

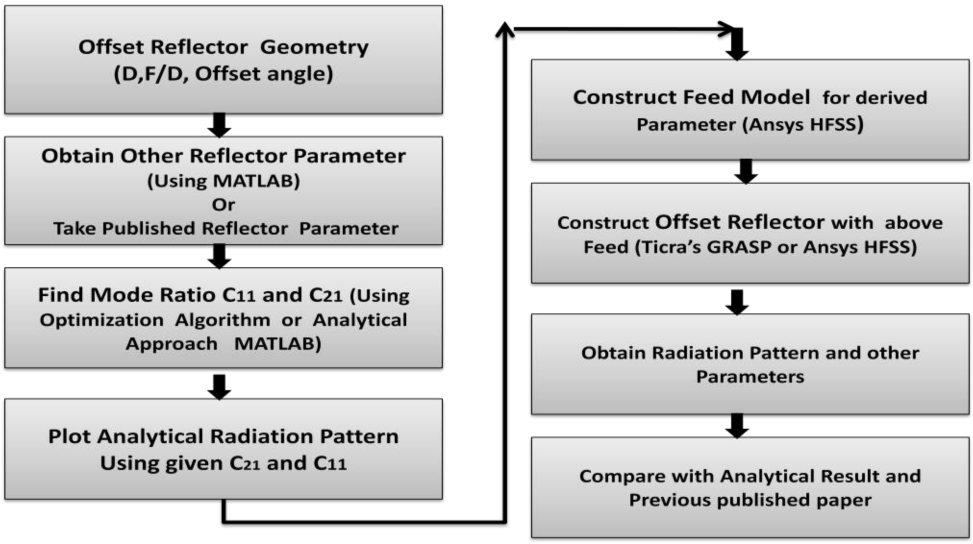

Figure 2. Flow for the research methodology adopted for investigating the cross-polarization reduction of offset parabolic reflector

For the given primary parameter (D, F/D and offset angle). the power required to cancel cross-polarized feed has been formulated and validated. For obtaining this a detail formulation on focal region field have been discussed and power required in higher-order mode, TE21 in addition to TE11 mode have been presented.

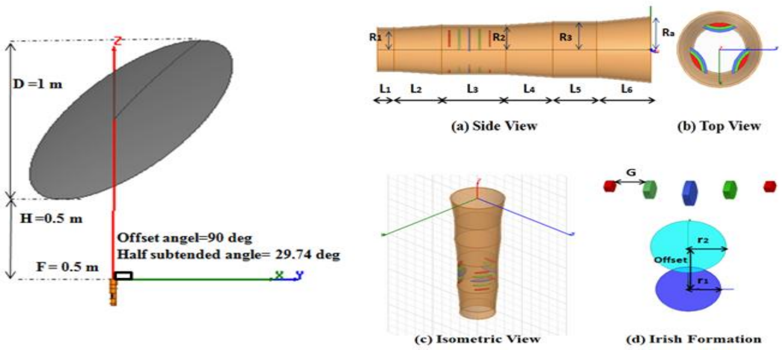

Figure 3(a). Simulated offset reflector configuration with offset angle 90 deg and F/D of 0.5 with diameter 1meter at 10GHz.(b) Different views of designed simulated feed and formation of Irish discontinuity.

Once required power in higher-order is obtained, analytical radiation pattern for the feed with given higher-order mode can be obtained easily. The field from primary feed has been given as an input to the reflector and analytical secondary radiation pattern has been generated by using the approach shown in Figure 4. Here Ludwig's third definition is used to calculate co polar and cross-polar field component.

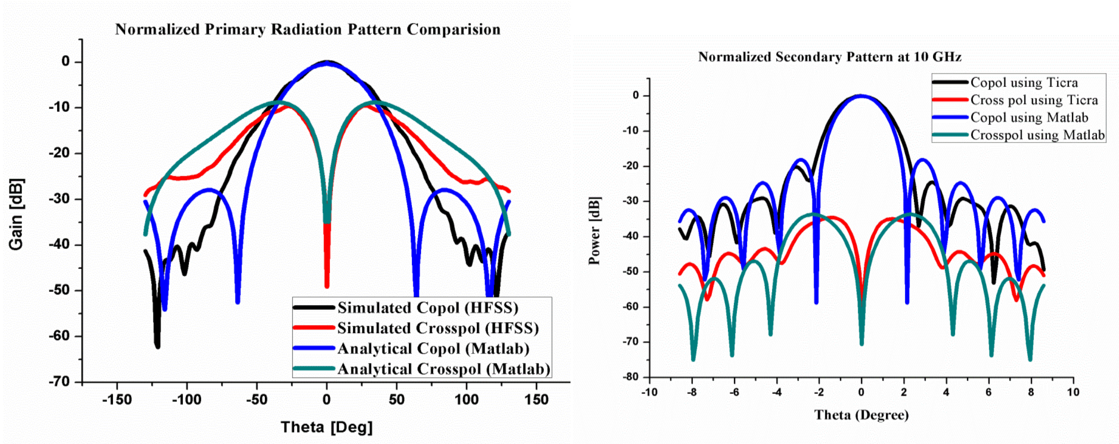

Figure 4.(a) Comparision of primary feed radiation pattern using an analytical method with the primary pattern of simulated feed. (b) Comparison of secondary radiation pattern using an analytical method with Secondary pattern of simulated offset reflector with simulated feed as an input.

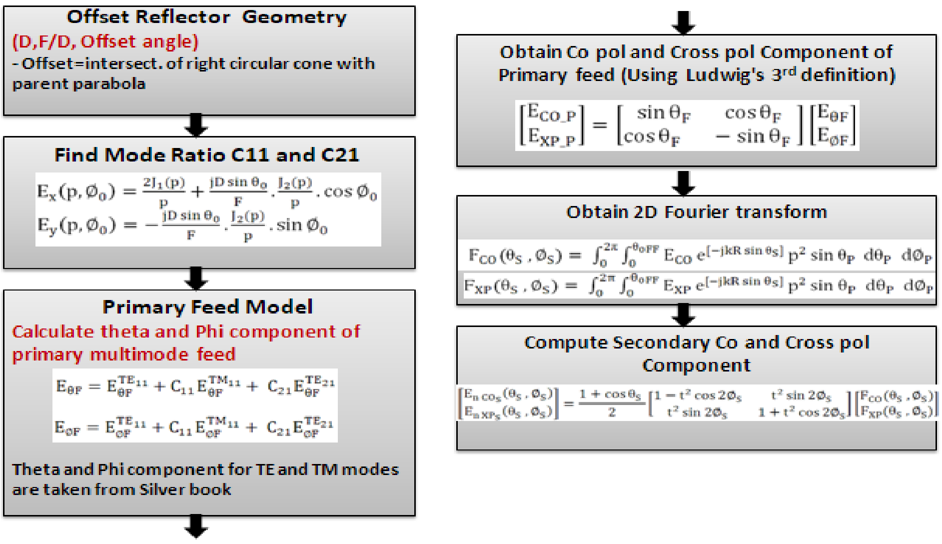

Figure 5. Detail methodology to obtain secondary radiation pattern of offset parabolic reflector

In order to validate the analytical radiation pattern of feed, the feed model has been designed and simulated in commercially available FEM based software, Ansys HFSS to obtain the same parameter as taken in the analytical feed. The output field of this simulated feed is given as an input to the simulated reflector shown in Fig 3. The feed now will illuminate reflector and simulated secondary radiation pattern can be obtained. The comparison of simulated primary and secondary pattern with analytical primary and secondary pattern has been shown in fig 5 and fig 6. The results show a striking similarity between the radiation pattern using an analytical method with the simulated one. This validates the approach used to obtain the secondary pattern for offset reflector antenna configuration.

6.2. Multimode Feeds for different offset reflector configuration:

Different offset reflector configuration has been considered for the research. It was a well-known fact that the magnitude of the cross-polar field component will depend on the F/D ratio and offset angle. For offset reflector having small F/D and large offset angle, the amount of cross-polarization field will be very high. The cross-polarization field will be low for large F/D and small offset angle. Based on these criteria three configurations have been selected for the present study the detail parameters of each configuration is given in Table I.

Table. I Offset reflector Parameter for various Configuration considered in the thesis

Sr no	Parameter	Config I	Config II	Config III
1	Offset Reflector Diameter (D)	1.2 m	1.2 m	4.5 m
2	**F/D = 0.8**	**0.8**	**0.5**	**0.4**
3	**Offset angle**	**35.36 deg**	**53 deg**	**90 deg**
4	Half Subtended angle	31.9 deg	44.42 deg	37.84 deg
5	Clearance	0.012 m	0.024 m	1.35m

For all three configurations, feeds with a similar array of discontinuity is designed which is shown in Figure. This discontinuity will generate required TE_{21} mode. So for each configuration, the height and diameter of discontinuity will be different.

6.2.1. Configuration 1: Offset Reflector with Moderate F/D and Low Offset angle

The parameter for configuration is as described in Table I. The magnitude of Cross-polarized component generated because of the moderate F/D and Low offset angle would be around -25 dB with respect to the peak of co polar field. The required higher-order modes with proper phase and proper amplitude at the aperture of the feed are provided by section L2 and height of the array of pin illustrated in Fig.6. Once the optimized parameter for the feed is obtained using the simulated feed, the actual feed is fabricated using VMC machining and Electrical Discharge Machining (EDM) as depicted in Fig. 7. and Fig. 8. The test setup of the feed is shown in Fig.9. The measured S_{11} [dB] for the feed for this configuration is shown in Fig. 10.

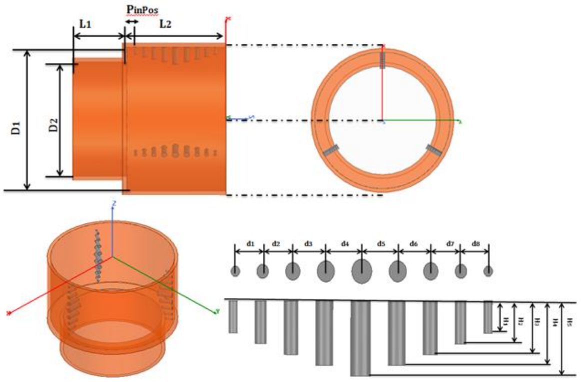

Figure. 6. Simulated primary cylindrical horn with an array of discontinuity in the form of variable hight and variable diameter

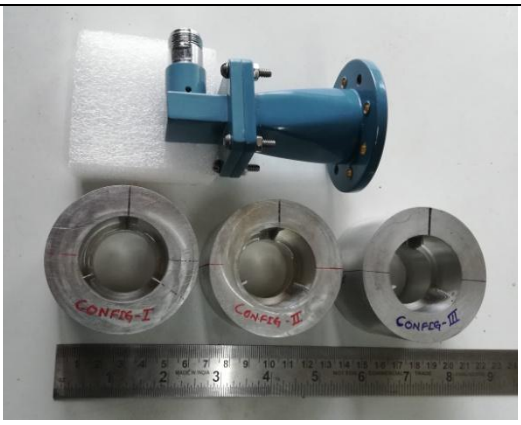

Figure. 7. Fabricated primary cylindrical horns for three different configurations with a waveguide to coaxial adapter and rectangular to circular transition.

Figure. 8. The side view of Fabricated primary cylindrical horn.

Figure. 9. The test set up for fabricated cylindrical horn in the anechoic chamber.

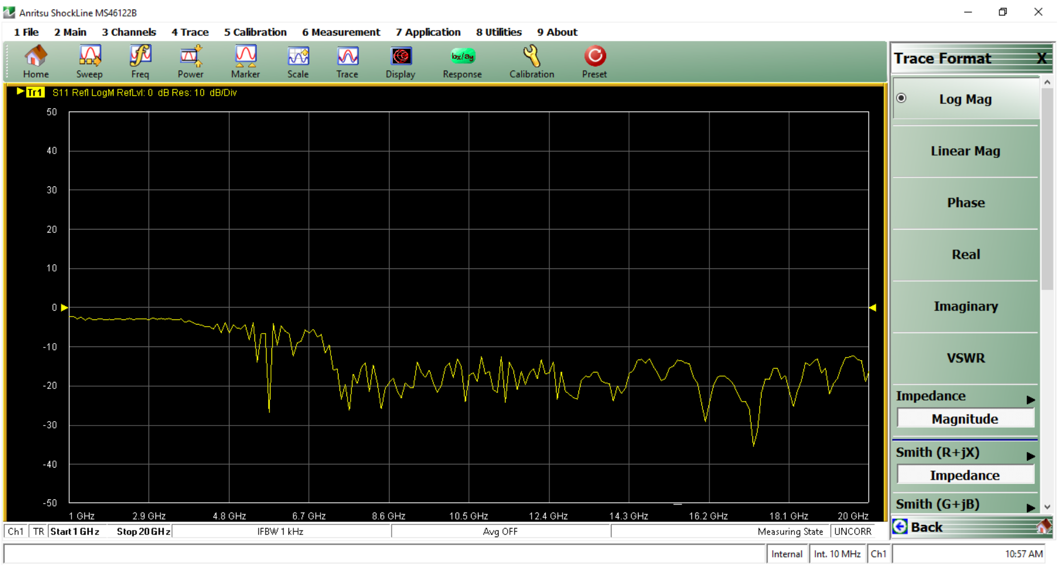

Figure 10. Measured S11 (dB) for the primary feed of configuration I.

The S_{11} shows the wideband characteristic of the horn; it is always 12 dB down as required for the proper impedance match. The radiation field of simulated feed has been used to illuminate the secondary parabolic reflector to obtain secondary radiation pattern. The secondary pattern for the simulated feed compared to conventional Gaussian feed is displayed in Fig.11(a). It can be observed that compared to conventional feed there is better suppression of cross-polarization component when proposed feed is used. For Comparision, the suppression of 7 dB down to the peak of cross-polarization due to Gaussian feed has been taken as a reference The complete cross-polarization suppression bandwidth over the frequency range of 9.4 GHz to 11 GHz is as shown in Fig.11(b) The simulated cross-polarization suppression over more than 1500 MHz can be observed. The cross-polarization suppression bandwidth over 16% with respect to center frequency is obtained. Also over a frequency band, 9.7 GHz to 10.2 GHz the suppression of more than 15 dB is obtained. So this feed may be used for a critical application like a radiometer where very high cross-polarization suppression over small bandwidth is required.

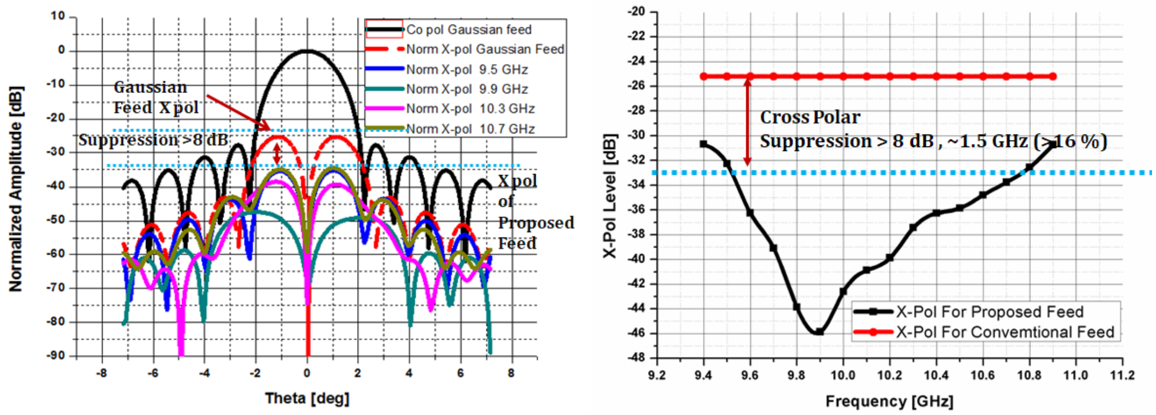

Figure 11(a).comparison of the far-field radiation pattern of offset reflector with proposed feed for config. I as primary feed and conventional feed (Gaussian Feed) as a primary feed. Figure 11(b) Comparision of cross-polarization suppression bandwidth of conventional and proposed feed for config. I

6.2.2. Configuration2: Offset Reflector with Low F/D and High Offset angle

The design parameter for reflector configuration has been given in Table I. This configuration will produce higher cross-polar component compared to the previous configuration. The maximum cross-polar field magnitude would be 18dB down to the peak of co polar magnitude. To reduce this high cross-polar field generated, the power required in higher-order modes would be large with proper phase at the aperture of primary feed.

To meet this requirement the feed was simulated in Ansys's HFSS which is similar to Fig. 6. The feed is optimized to provide required power in higher-order mode (TE_{21}) in addition to fundamental TE_{11} mode and proper phase at the aperture for the wide bandwidth. The Power can be varied by changing the diameter and height of the array of the pin. After getting required performance with simulated feed, the prototype of the proposed feed has been fabricated(Fig 7). The radiation pattern and its S_{11} for this feed are measured as shown in Fig.12. The secondary radiation pattern with the proposed cylindrical horn as a primary feed to the given offset reflector is illustrated in Fig. 13(a). This feed can provide a conjugate match about 1500 MHz.This is approximately over 16% bandwidth with respect to the center frequency.at 9.8 GHz peak, cross-polar suppression of 24 dB has been observed from Fig. 13(b)

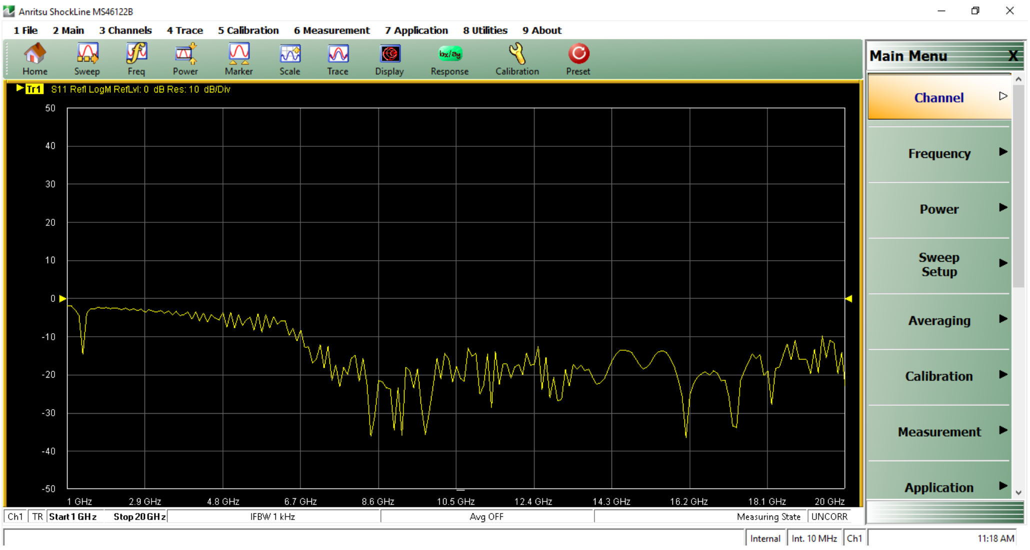

Figure 12. Measured S11 (dB) for the primary feed of configuration II.

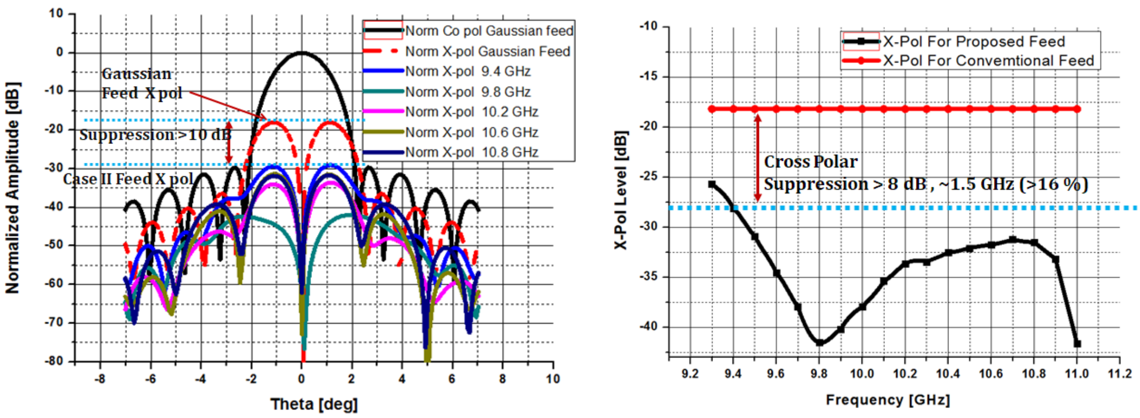

Figure 13(a) comparison of the far-field radiation pattern of offset reflector with proposed feed for config. II as a primary feed with conventional feed as a primary feed. 13(b) Comparision of cross-polarization suppression bandwidth of conventional and proposed feed for config. II

6.2.3. Configuration-III: Offset reflector for extreme case having critical Low F/D and very high offset angle

The offset parabolic reflectors parameters are as given in Table I. This configuration is an extreme case as it is employing critically low F/D of 0.4, and very high offset angle 90 deg. Because of large offset angle, the cross-polarized field generated due to asymmetry would be very high which is of order 15 dB down to the peak of co polar component. Very high power conversion form fundamental mode TE_{11} to higher-order mode TE_{21} is required to suppress the cross-polar field. The prototype of the horn is fabricated with optimized parameter(Fig 7). The Measured return loss parameter is as depicted in Fig. 14. For the complete band it is below 12 dB.

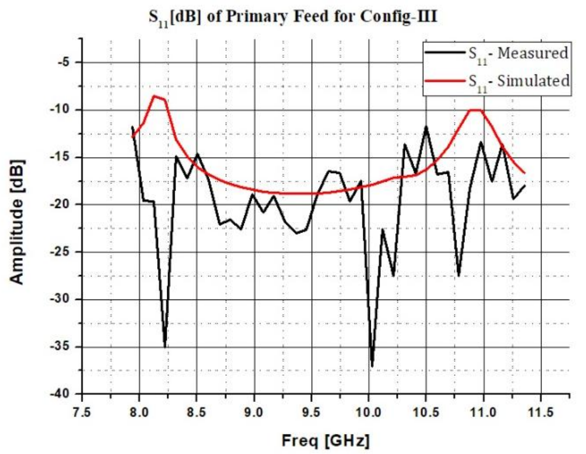

Figure 14. Measured S11 (dB) for the primary feed of configuration III.

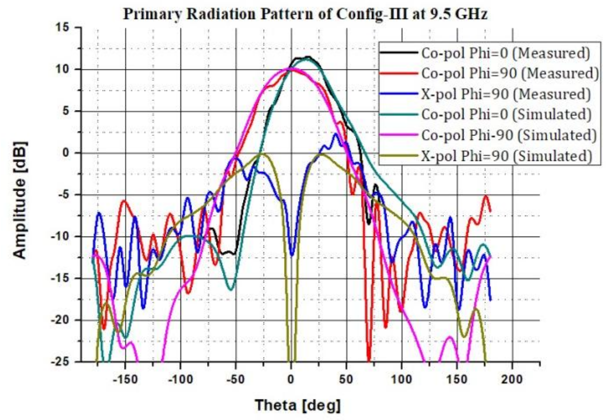

Figure 15. Comparision of simulated and measured primary radiation pattern of configuration III at 9.5 GHz.

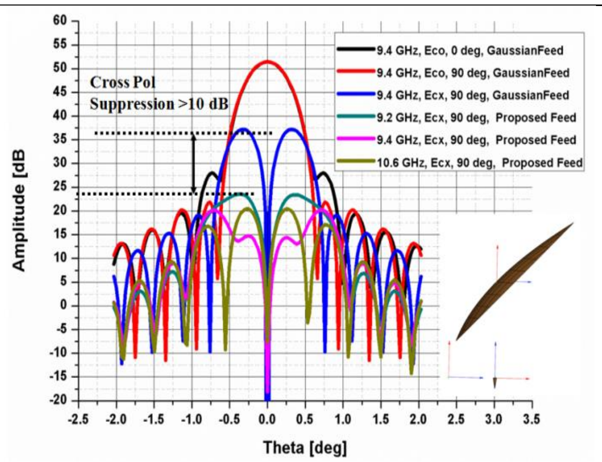

Figure 16. comparison of the far-field radiation pattern of offset reflector with proposed feed for config. III as a primary feed with conventional feed as a primary feed.

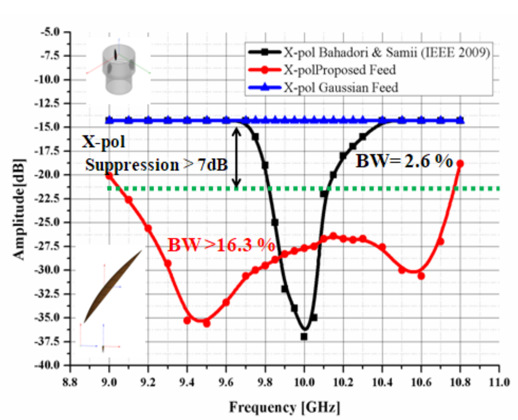

Figure 17. Comparision of cross-polarization suppression bandwidth of conventional and proposed feed for config. II

The comparisons of measured and simulated primary pattern for the given configuration is illustrated in Fig.15. this shows an identical simulated and measured pattern. The secondary radiation pattern for proposed feed is as shown in Fig 16. the feed provides more than 16% cross-polarized suppression bandwidth with reference to the center frequency. (Fig 17). For the same configuration, the cross-polarization suppression bandwidth achieved by Bahadoori and Samii[9] is also displayed in Fig 17. The primary feed is compact and provides a significant reduction in cross-polarization compared to the feed in published literature. This feed can be used for back to back spinning reflector as discussed by Samii [9]. The comparison of the secondary pattern with measured feed radiation pattern at the input of reflector is shown in Fig 18. This shows a close similarity between measured and simulated pattern.

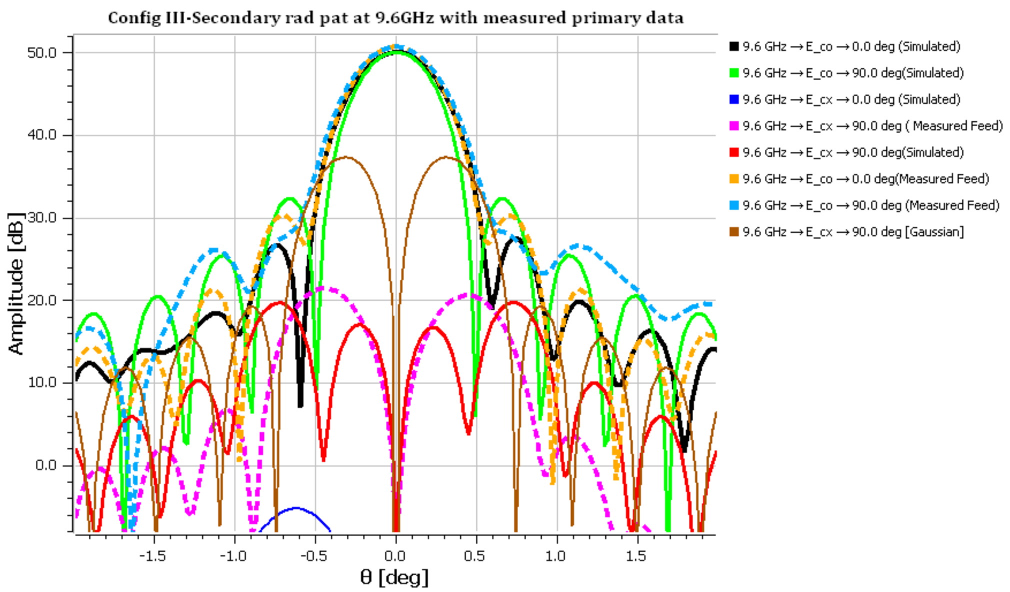

Figure 15. Comparison of simulated and measured secondary radiation pattern of configuration III at 9.5 GHz.

7. Achievements with respect to objectives

- Successfully develop a program for analytical calculation of secondary pattern of offset parabola for multimode feed excitation and compare the analytical pattern (from Matlab) with simulated pattern (from Grasp's Ticra). The program is fairly accurate.
- Three novel cylindrical multimode feed for three offset reflector configuration has been designed

- The first cylindrical waveguide horn using an array of pin discontinuity has been designed, fabricated and tested for F/D=0.8 and offset angle = 36 deg. The cross-polarization suppression bandwidth of more than 15% has been obtained using the proposed horn as a primary feed compared to conventional feed.
- The second cylindrical horn which extends the concept proposed in the earlier feed. This horn has been designed, fabricated and tested for F/D=0.5 and offset angle = 55 deg. When this horn is used as a primary feed for the said reflector, a reduction of at least 7dB of cross-polarization has been obtained for bandwidth more than 15 % compared to conventional feed.
- The third cylindrical horn is designed to validate the proposed concept for the worst case of offset reflector configuration were F/D=0.4, and offset angle = 90 deg. A cross-polarization bandwidth of more than 16% has been obtained using this feed.

In all the cases the wide cross-polar bandwidth has been obtained compared to existing literature.

Table II. Comparisons of Crosspolarization Supresion Bandwidth of Conventional Feed (Gaussian Feed) with Proposed Feed.

Config.	Specification	Xpol due to Gaussian Feed (wrt Peak Co Pol)	Existing (XP Suppression, %BW, BW)	Proposed Feed Cross-pol suppression BW
I	High F/D (0.8) and Low Offset angle (35.36 deg)	-25.38 dB	10% BW (1Ghz)	>15%
II	Low F/D (0.5) and Moderate Offset angle(53 deg)	-18.27 dB	10% BW 1Ghz	>15%
III	Low F/D (0.4) and High Offset angle (90 deg) (Worst Offset angel)	-14.2 dB	3%BW , 250MHz	>15%

8. Conclusions:

In this thesis, a brief investigation on the reduction of Cross polarization generated for various configuration in an offset reflector has been discussed. The concept of conjugate matching is used to design feed horns.

The focal region field of offset parabolic reflector has been simplified and from this formulation power required in higher-order modes for various configuration is derived

The analytical program has been developed to generate analytical radiation pattern for a given configuration of offset reflector and validated by simulation in commercially available software.

Three configurations of offset parabolic reflector horn have been chosen to prove the proposed methodology adopted to suppress cross-polarization in the assymetrical plane of offset reflector. Corresponding to each configuration a primary feed have been designed and optimized. The optimized feed is fabricated based on optimized feed. For all the configuration simulated cross-polarization bandwidth obtained was greater than the bandwidth existed in literature.

9. Publications

UGC Approved Journal

1. Balvant J. Makwana, Dr. Shashi Bhushan Sharma, "A Study on Mode Generation Using Coaxial Probe Discontinuity in Oversized Circular Waveguide With Tapered Short", IJRAR – UGC Approved International Journal of Research and Analytical Reviews (IJRAR), E-ISSN 2348-1269, P- ISSN 2349-5138, Volume.5, Issue 4, Page No pp.731-734, October 2018,doi: http://doi.one/10.1729/Journal.18812

2. Balvant J. Makwana, S. B. Sharma, "Design and Analysis of Simple Dual Band Multimode Conical Horn for C Band " UGC Approved International Journal of Electrical, Electronics, and Computer Science Engineering (IJEECSE) Volume 5, Issue 2 (April 2018), pg 123-127, ISSN-2454-1222.

3. Balvant J. Makwana, S. B. Sharma "Cross-Polarization Reduction for Compact Offset Reflector Antenna Using Conjugate Feed" UGC Approved International Journal of Advance Engineering and Research Development (IJAERD) in Volume- 05, Issue-04 of April 2018, ISSN-2348 6406

International Conferences

1. Balvant J. Makwana, S. B. Sharma, Kush Parikh "The Parametric Analysis of Multimode Feed Horn Antenna to Improve Cross polarization in Single Offset Reflector with High Offset Angle" 12th Annual International Conference - ATMS-2019, Pune, 6 th & 7 th February 2019.

2. Balvant J. Makwana, S. B. Sharma, Kush Parikh "Secondary Pattern Generation and Validation of Single Offset Reflector Antenna with Multi-Mode Feed Horn to Improve Cross Polarization Suppression Bandwidth " 2018 IEEE Indian Conference of Antennas and Propagation (InCap-2018), December 16-19, 2018 at the Hyderabad International Convention Center (HICC)
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