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RESEARCH ARTICLE

Dual Band (S-X) Ground Station Antenna for Low Earth Orbit (LEO) Satellite Tracking Application

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ABSTRACT Design and realization of a dual band, dual polarized composite monopulse tracking feed, covering S- (2.0-2.3 GHz) and X-band (7.8-8.5 GHz) is reported in this article. X-band feed is a five element monopulse feed, comprising a corrugated horn acting as the main or Sum element surrounded by four circular septum polarizers serving as tracking elements. S-band feed is a four element monopulse feed consisting of square dielectric array arranged in 2 × 2 configurations. Illumination efficiency of the proposed composite feed, positioned in the same Cassegrain plane, is above 90 % for both the bands. S/X composite feed is systematically designed, fabricated and experimentally characterized revealing excellent correspondence with the simulated result. The realized composite feed is installed in 7.5m antenna system at NRSC Hyderabad, ISRO, India and currently fully operational. Expected / targeted G/T of 32 dB/K is achieved with the realized antenna system. The proposed feed is highly efficient, compact, simple and cost-effective, uses generic design style and perfectly suitable as ground station reflector feed antenna, meeting stringent industry specification.

INDEX TERMS Monopulse feed, dual band, corrugated horn, circular septum polarizer, cassegrain, secondary pattern.

I. INTRODUCTION

Modern ground station system often involves multiple frequency reception using a single antenna aperture. As fabrication cost of the big antenna aperture is huge, it is prudent to use diversity techniques in terms of frequency and polarization. Dual band reception system for Cassegrain reflector can be achieved by the use of frequency selective surfaces, such as, dichroic sub reflector [1]. Fabrication of dichroic subreflector is difficult and need high precision expensive facilities. Horn antenna with broadband characteristics obtained from optimized smooth wall profile [2] is also capable of receiving multiple frequencies. However, with this kind of smooth wall profiled horn, it is difficult to achieve stringent specification in terms of G/T and cross polarization performance in both the bands. Composite feed in this case can be very sensible choice where feed for both the bands are kept in a common cassegrain plane without affecting performance in other band.

In this article, design and practical realization of a composite dual band, dual polarized monopulse feed is reported. Several such attempts, mostly for single band operation, have been carried out in search of optimum feed for monopulse tracking [3]–[7].Out of various available monopulse feed configurations, four element [5], five element [6], [7], multimode feed [8] are interchangeably used depending on application, system specification and cost effectiveness.

Herein, dual band composite S/X-feed is realized using simple, fabrication-friendly and cost effective configuration without affecting the system performance. Proposed composite feed is positioned in a common cassegrain plane. Schematic of the proposed feed is shown in Fig. 1. X-band

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TABLE 1. Comparison between existing dual/single –band feed with proposed dual-band, dual-polarized composite feed.

[Ref]	Single band/ Dual Band	Polarization	Monopulse feed	Techniques used	Gain(dBi) Efficiency(%)
[1]	Dual Band Around 1.75GHz/ (4–4.3 GHz)	Single	No	Axially corrugated chokes horn Radially Corrugated waveguide Coaxially placed dual band	37.68/45.48 69.81/74.8
[2]	Dual band S band(3.38-3.92 GHz) Ka band(24.9-40GHz)	Single	No	Ka -band ADE Reflector, Horn antenna and Dipole antenna Coaxially placed dual band	13.7/32.1 42/47
[3]	Single band 14.5- 15.35 GHz	Dual	No	Dielectric rods with step transition Offset reflector antenna, OMT	45.5 47
[4]	Dual Band Downlink (3.4 – 4.2 GHz) Uplink (6.3-6.8 GHz)	Single	Yes (down link)	Single dielectric rod for uplink 2x2 Array for downlink	49.3/56 56/61.5
[5]	Dual Band S band (2-3 GHz) X band (10.4 – 10.6 GHz)	Single	No	Coaxial waveguide configuration One-ring Choke	28.5 /38.4 69/73
[6]	Single band at 5.6GHz	Dual	No	Dielectric rod	- -
[7]	Single band S band (2.025 – 2.3 GHz)	Dual	Yes	Five horn feed Horn antenna Open end waveguide ADE	37.6 50
[8]	Single band W band (93GHz)	Single	Yes	Multimode feed horn Pyramidal horn	40 53
[9]	Dual Band C band (6.2 – 7 GHz) Ku band (10 – 15 GHz)	Single	No	Choke Horn Circular dipole	Gain not mentioned 50%
Present work	**Dual band S-band (2.0-2.3GHz) X-band(7.7-8.5 GHz)**	**Dual**	**Yes**	**Composite feed in Cassegrain plane; X-band five element with corrugated horn; S-band 2x2 dielectric rod Array**	**55.1/43.1 78/69**

operation is realized using five element feed with corrugated horn as main element and four circular septum polarizers (CSP) acting as tracking elements. Corrugated horn is used as main element as it offers superior performance in terms of low cross polarization and symmetric beam, thanks to its linear aperture field [9], [10]. Use of electrically coupled CSP [11] allows access of dual polarized signal in the form of coaxial output making the feed a compact one eliminating waveguide joints and bulky extra elements. S-band feed consists of an array of dielectric rods fed by CSP arranged in 2 × 2 square configurations. As aperture of dielectric rod extends towards axial direction instead of horizontal direction, it is very much suitable for this kind of composite feed application. Proposed S-X dual band composite feed and associated system components, like polarizer, waveguide components and circular to square transition (CST) are designed and/or co-designed using CHAMP [12] and Ansys HFSS [13] followed by fabrication, realization, extensive measurements and installation in 7.5m antenna at National Remote sensing centre, Jodhpur, India. This realized antenna system yields excellent measured G/T results matching with the estimated value. Specifications of the proposed S-X band feed along with achieved results are presented in Table-2.

Proposed feed is very compact, simple, easy to fabricate and an optimum one for S–X dual band operation. It provides high illumination efficiency (more than 90 %) when integrated with 7.5m reflector enabling antenna system to achieve high G/T ratio (32 dB/deg K and 18 dB/deg K for X and S band respectively). This feed also provides a low cross-polarization response (better than 25dB). Various figure of single/dual-band feed with tracking and not tracking characteristics are compared with that of the existing design and presented in TABLE 1 [14]–[22].

The novelty of design and new technical contribution is summarized below:

- Most of the previous design of dual band feed is not highly efficient as the proposed dual band feed. The Table -1 clearly depicts that the efficiency of the proposed feed is much higher than the previously reported monopusle dual-band feed.
- Design approach of the proposed dual-band feed is distinctly different compared to the previously designed dual-band feeds. Most of the previous design of dual band feed employs coaxial waveguide techniques and are not equipped with monopulse tracking with both dual-band, dual-polarized functionality.

TABLE 2. Specification of S-X band feed.

Parameter	Specification	Achieved value
Gain	21.5 dB	21.05 dB
Cross polarization (X-band)	25 dB	30 dB
X-polarization (S-band)	20 dB	25 dB
Null depth	30 dB	> 30 dB
G/T (X-band)	31.5 dB/deg K	32 dB/deg K
G/T (S-band)	17 dB/deg K	18 dB/deg K

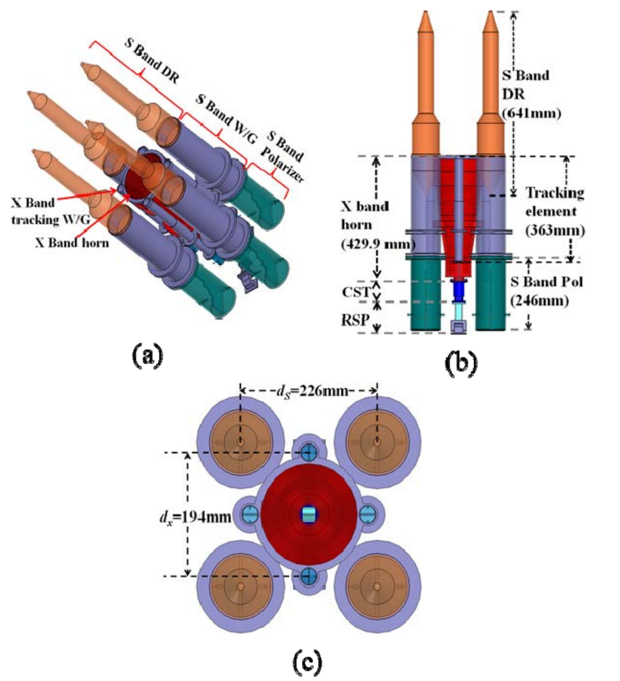

FIGURE 1. X- S band assembly; (a) 3d view; (b) side view and (c) top view.

- Use of electrically coupled circular septum polarizer with coaxial output in both S and X-band makes this feed very compact in nature. Thus the realized feed, to the best of author's knowledge, is simplest and compact yet most effective dual-band composite feed reported in open article.
- Moreover, proposed design concepts are generic and can be easily extended for any other dual band feed as per user's requirement and applications. In TABLE-3, dimensions are mentioned in terms of λ so that it can be used as generic design guideline in other frequencies also.

Such kind of highly efficient monopulse feed in composite configuration, described in this article, with dual-band, dual-polarized functionality for X- and S-band, to the best of the knowledge of the authors, is not available in open literature.

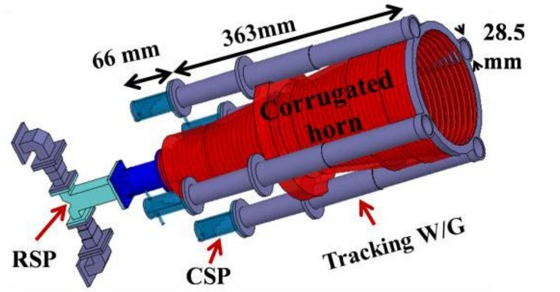

FIGURE 2. X-band feed 3D assembly.

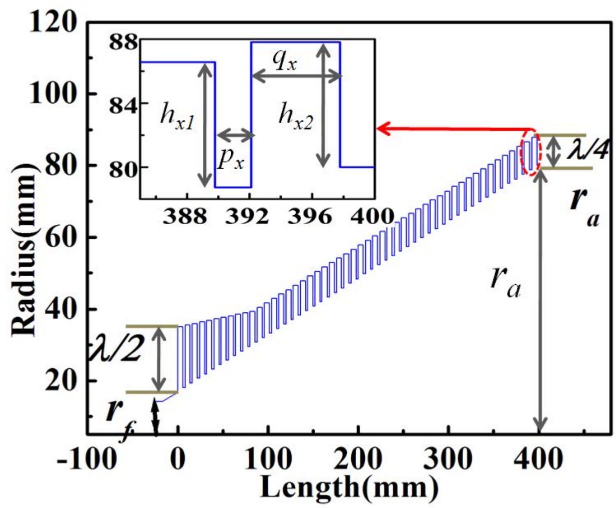

FIGURE 3. Schematic of X-band corrugated horn.

II. DESIGN OF S/X COMPOSITE TRACKING FEED

The design flow involves, i) design of X-band corrugated horn for required specification (explained in Table-1), ii) determining inter-element spacing & aperture of tracking elements or waveguides and iii) design of S-band dielectric rods and polarizers. Radiating elements and waveguide components of X-and S-band feed are initially designed and optimized separately aiming for desired radiation, reflection and transmission characteristics. Later, S-and X-band feeds are integrated resulting in composite S/X feed.

A. X-BAND TRACKING FEED

Fig. 2 shows the schematic of the X-band feed aimed for a 7.5m reflector profile and optics. The design is optimized considering several design objectives, such as, i)low cross-polarized radiation($<$ 25 dB), ii) required gain with taper for maximizing secondary gain. and G/T, iii) low side lobe level (SLL) for Sum pattern(according to ITR recommendation), iv)high null depth ($>$ 30 dB)and v) wide lock angles(+/- 0.2 deg). X-band feed design comprises two parts, i) corrugated horn and ii) tracking waveguides fed with CSP.

i) Design of corrugated horn: Following design steps are adopted for design of corrugated horn:

I) Required gain and taper of the feed radiation pattern are derived from the available profile and optics using GRASP [12]. Here, Gaussian pattern is used to derive optimum gain and taper. Derived optimum gain is 21.2dBi with a taper of -22 dB at 17.10 which is half subtended angle of the sub-reflector.

II) Selection of feed is very much important and corrugated horn is chosen to illuminate the sub-reflector as it provides excellent beam symmetry, minimum cross polarization, low SLL and minimum back lobe level, thanks to its linear aperture fields. Such fields are obtained by producing hybrid modes (HE11), a combination of TE11 (85%) and TM01 (15%) mode [10].

III) Corrugated horn consists of three sections: a) smooth section to improve return loss, b) mode converter to produce hybrid mode and c) corrugations for linear aperture field.

a) Smooth section: Input radius of the smooth section is determined by cut off frequency and its length and waveguide radius is determined by input impedance. Length of the smooth section is 16.54mm (0.45λ) with input radius of 14.25mm (0.39λ) and output radius of 17.89mm (0.49λ).

b&c) Mode converter and corrugated section: Smooth section is followed by a corrugated section. As number of corrugations increases crosspol performance also improves. Here a tradeoff between fabrication complexities and cross-pol performance is made and total 50 corrugations are selected out of which 10 are at mode converter section. Corrugation teeth depth (h1, h2) varies fromλ/2 at mode converter section to λ/4 at the aperture end and determined by equation in [23]. Here linear profile is selected for the corrugations. Optimized schematic diagram of corrugated horn is depicted in figure 3.Corrugation teeth is having dimension of p=2.22mm and q= 5.58 mm. Output aperture of the corrugated horn is determined by the desired gain of the horn. Interior radius of the corrugated horn at the aperture is 80mm while exterior radius is 90mm. Simulated gain of X-band corrugated horn, as shown in figure 8(a), is 21.05 dBi at 8.25 GHz.

This feed is having dual polarization capability achieved by using rectangular septum polarizer (RSP) with stepped septum inside. Return loss of RHCP & LHCP ports and isolation between the two are measured at septum polarizer output and results are shown in figure 4. The measured results show good resemblance with simulated results. Difference elements are brought close to each other by making perturbation on the corrugated horn (as depicted in the fabricated structure in figure 7) to reduce inter-element spacing which produces unwanted notch/nonlinearity in the secondary Difference pattern due to closely spaced grating lobes in primary pattern.

B. DESIGN OF TRACKING ELEMENTS

Four tracking elements in the form of flared waveguides are used. Input diameter of the waveguide is determined by the cut off frequency and waveguides are flared a bit to increase the Difference gain. Input and output diameter of 25.5mm and 28.5mm and wall thickness 1.5mm, fed by CSP, are deployed as tracking elements. Spacing between the tracking elements are optimized to 184 mm Here, electrical coupling is used in design of CSP as it provides higher bandwidth, ease in design and unlike the end launched magnetically coupled circular polarizer [24], does not require any matching structure. As RHCP and LHCP signals are available at coaxial SMA output, this configuration is very compact in nature. Septum bifurcates the circular polarizer in two half circular parts from which RHCP and LHCP signals are collected via coaxial SMA probe with a cap on its top [11].Measured S11 and S21 results of the proposed tracking element (i.e tracking waveguides attached with CSP) are shown in figure 6(a) and 6(b) revealing a good match with the simulated results. Simulated Difference array gain, as shown in figure 8(b), is 10.1 dBi. Error signal, for both the polarization, is generated by feeding two tracking elements to a 180^0 hybrids.

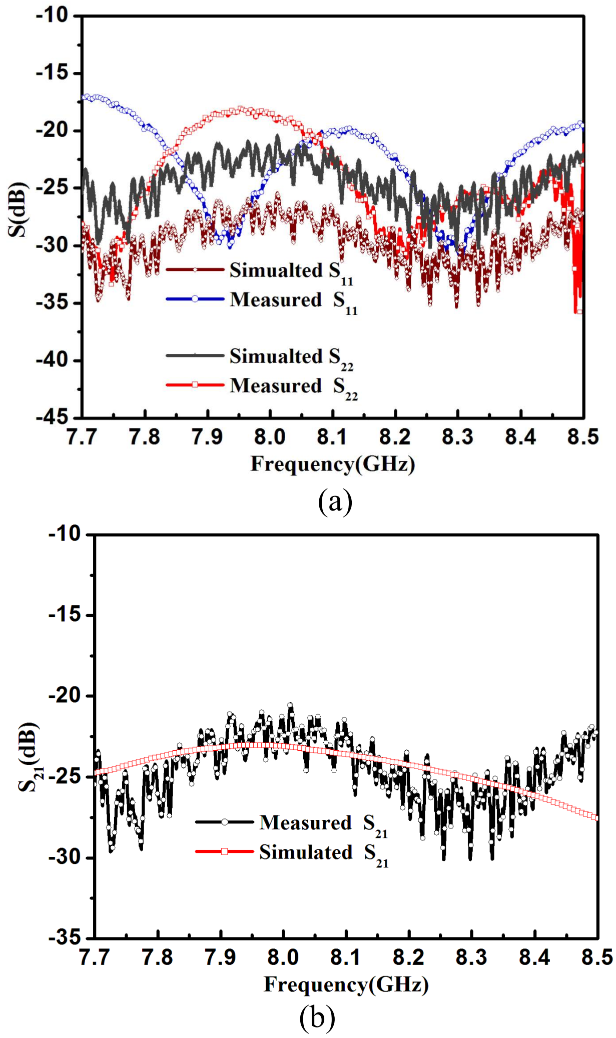

FIGURE 4. (a) Simulated and measured (a) reflection coefficient (S11 and S22), (b) isolation (S21) of X band horn attached with polarizer.

C. S-BAND TRACKING FEED

S-band feed is an array of four dielectric rods arranged in 2×2 configuration. Dielectric rods are fed with CSP to enable

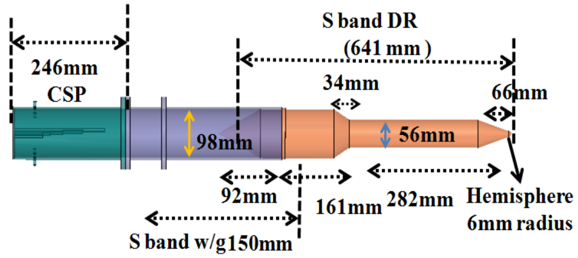

FIGURE 5. S band dielectric rod with dimensions.

TABLE 3. Design parameter for s-band dielectric rod.

Parameter	Input radius(mm)	Output radius(mm)	Length (mm)
conically tapered section inside the waveguide	0	98 (0.74λ)	92 (0.69λ)
1st straight section	98 (0.74λ)	98 (0.74λ)	161 (1.21λ)
tapered section	98 (0.74λ)	56 (0.42λ)	34 (2.04λ)
2nd straight section	56 (0.42λ)	56 (0.74λ)	282 (0.25λ)
final taper section	56 (0.42λ)	6 (0.05λ)	66 (0.50λ)
hemispherical section	6 mm radius		

dual polarization capability. Design of S-band feed involves two parts: i) design of dielectric rod and array and ii) design of CSP.

i) *Design of dielectric rod and array*: Figure 5 shows the schematic diagram of the proposed dielectric rod made of Teflon (εr=2.1. tan δ =0.001) and fed with a waveguide having inner diameter of 98mm and wall thickness 4mm. As shown in Fig. 1, 4-such identical elements, suitably placed in a 2×2 square array configuration with inter-element spacing of 216 mm, comprises the proposed S-band tracking feed. Hybrid modes of the dielectric rods, similar to that of corrugated horn, can produce radiation pattern with symmetrical beam and low cross polarization. Each dielectric rod consists of six cascaded sections with dimension detailed in Table 3. Simulated gain of a single dielectric rod antenna is 16.1 dBi with excellent pattern symmetry and low cross polarization ($>$ 30 dB). Sum and Difference pattern of the proposed S-band dielectric-rod array is shown in figure 9(a) and (b). As revealed from the plots, the realized array yields a symmetric pattern with maximum gain of 21 and 18 dBi for Sum and Difference pattern with very good null depth($>$30 dB) and tracking slope.

ii) Design of CSP: S-band dielectric rods are fed with CSP which separates incoming dual polarized signal into RHCP & LHCP in two half circular parts and channelize them into coaxial (TNC) outputs. This results into a very compact, low loss design avoiding multiple waveguide components. Energy available in the half circular parts is collected by coaxial probe (TNC) with a cylindrical cap on the top. Impedance matching at the coaxial output port is achieved by optimization of cap radius, cap height, probe length inside the circular waveguide and probe distance from the end plate. Step dimension and width of the septum are optimized to achieve isolation between two output ports. The optimized geometry of the circular polarizer has step lengths of 47.95, 41.44, 31.79 and 15.41mm. Step heights are given by 8.44, 21.09, 19.28 and 14.72mm. Connector distance from the end plate is 48.88mm. Polarizer length or distance between face and end plate is 236 mm. Simulated return loss is better than17 dB in 2.025 -2.3GHz frequency range. Isolation between RHCP port and LHCP port is better than 16 dB in 2.025 -2.3 GHz frequency. Return loss and isolation measurement is carried out with polarizer attached to dielectric rod (depicted in figure 6(a) and 6(b)), revealing very good agreement with the simulated results.

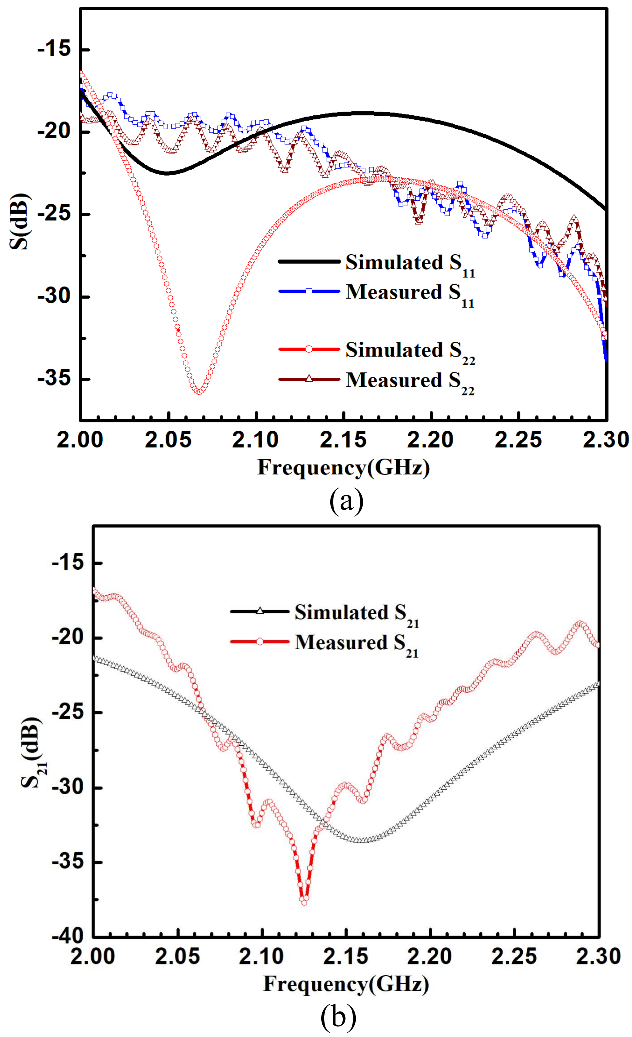

FIGURE 6. Simulated and measured (a) reflection coefficient (S11 and S22) (b) isolation (S21) of S band dielectric attached with polarizer.

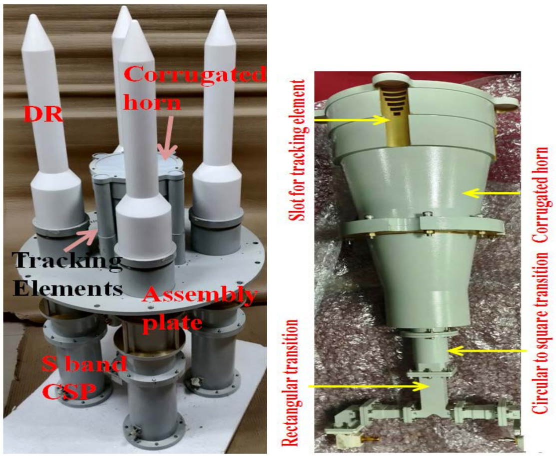

FIGURE 7. Fabricated structure of S/X band feed.

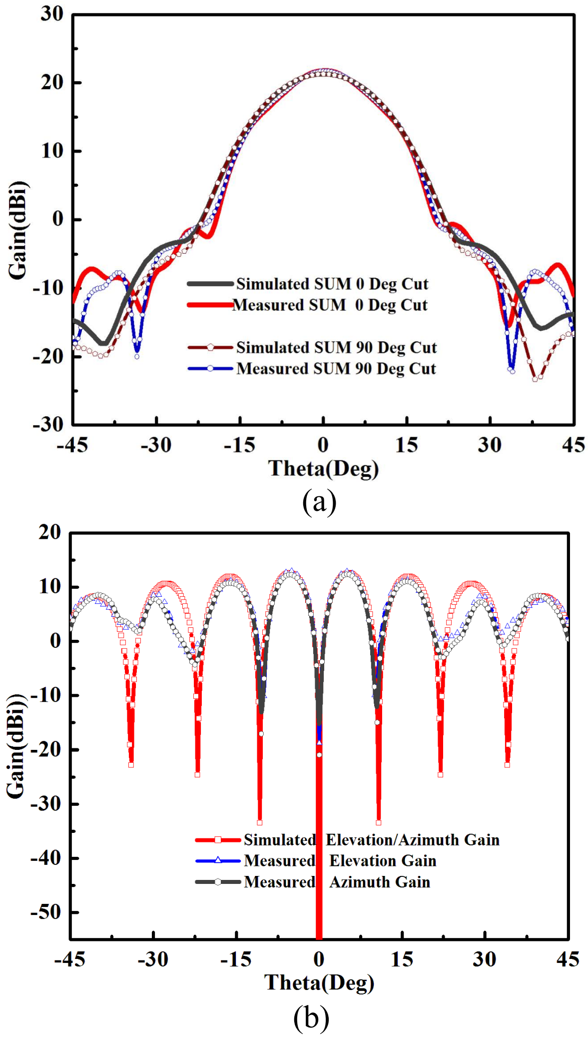

FIGURE 8. Simulated and measured (a) X band Sum primary pattern; (b) X band Difference primary pattern.

III. MEASURED RADIATION PATTERN

Fabricated assembly of the X-band feed integrated with S-band is shown in figure 7. This composite feed is tested in Compact Test Range Facility (CATF) to characterize the radiation pattern for both Sum and Difference pattern at both the bands. In Sum RHCP and Sum LHCP, X-band signals are available at RSP ports with identical patterns. Measured Sum pattern for 0^0 and 90^0 cut are compared with the simulated pattern in figure 8(a) revealing a good agreement. Tracking elements outputs are available at four CSP. Outputs of two tracking elements are fed to an 180^0 hybrid to generate error signal (AZ/EL). Thus, four 180^0 hybrids are used for RHCP and LHCP. Measured Difference AZ and EL pattern are shown in figure 8(b). Measured pattern is compared with the simulated pattern with very good match. For S-band feed outputs from four elements are fed to MPC. Outputs of MPCs are Sum and two Difference (AZ and EL) signals. Measured Sum pattern for horizontal and vertical cut (or 0^0 and 90^0) are shown in figure 9(a). It is compared with the simulated pattern. S-band Sum pattern shows excellent resemblance with the simulated pattern. Since RHCP and LHCP patterns are identical, for brevity, only RHCP pattern is presented. Measured AZ and EL Difference pattern are shown in figure 9(b). Simulated Difference pattern shows good agreement with measured Difference pattern. S-band feed and X-band are simulated in standalone situation and in presence of each other. It is seen than mutual effect is minimal (less than 0.15 dB). It can be noted that measured X-band pattern shown in Fig. 8 is taken in presence of S-band feed.

IV. SIMULATED SECONDARY PATTERN AND REALIZATION

Secondary pattern is simulated from the measured primary pattern as input with the help of software module TICRA. Sum and Difference secondary patterns are simulated for both X-band and S-band with measured primary pattern and available profile &optics. As shown in figure 10(a), maximum achieved gain for X-band Sum pattern is 55.1 dBi with SLL minimum 16 dB down meeting ITR-565 recommended limits [25]. In this simulation blockage due to sub reflector and supporting structure are considered. Further, Sum signal encounters losses due to the surface inaccuracy of the main reflector, radiating element loss, radome loss and waveguide loss which cumulatively reduce the net gain to 54.2 dB. Simulated X-band Difference gain is 43.2 dBi. It can be seen that there is no non-linearity in the Difference pattern and pattern meets null depth & slope requirement. Simulated S-band secondary Sum pattern as depicted in figure 10(b), is having maximum gain of 43.1 dBi with desired SLL suppression. Simulated Difference peak gain is 36.3 dBi. Estimated G/T for X- and S-band is 32.3 dB/deg K and18 dB/ deg K respectively. As depicted in figure 11, realized dual band (S-X) feed is installed in 7.5m Cassegrain reflector antenna system at NRSC, Jodhpur. G/T measurement is carried out for both X -S-band using extra- terrestrial sources like Sun and Moon using Y factor method. The measured results yield a G/T value of 32 dB/deg K and 17.9 dB/ deg K for X-and S- band which closely matches the estimated value.

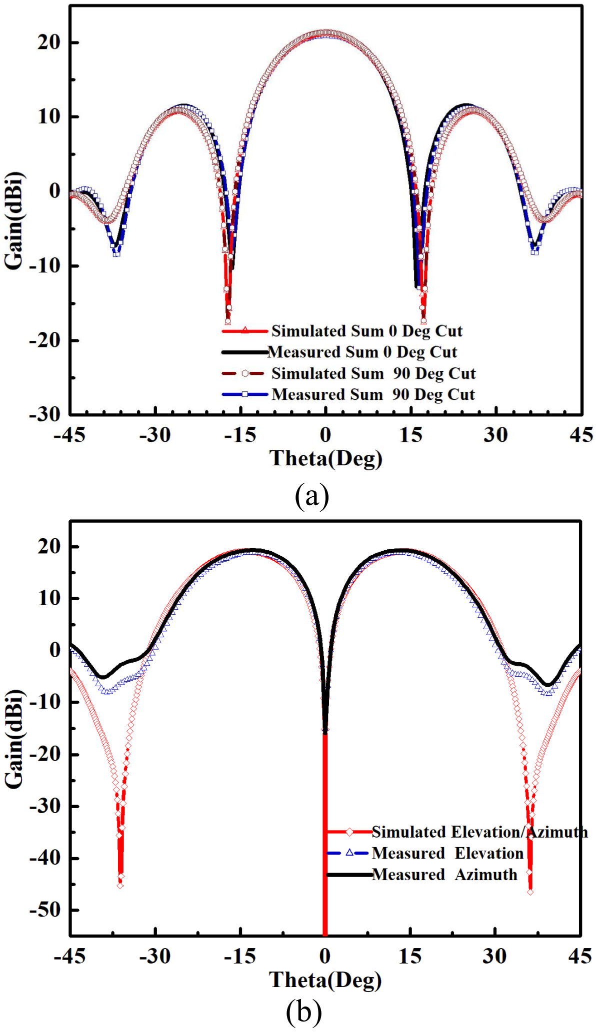

FIGURE 9. **Simulated and measured (a) S band Sum primary pattern; (b) S band difference primary pattern.**

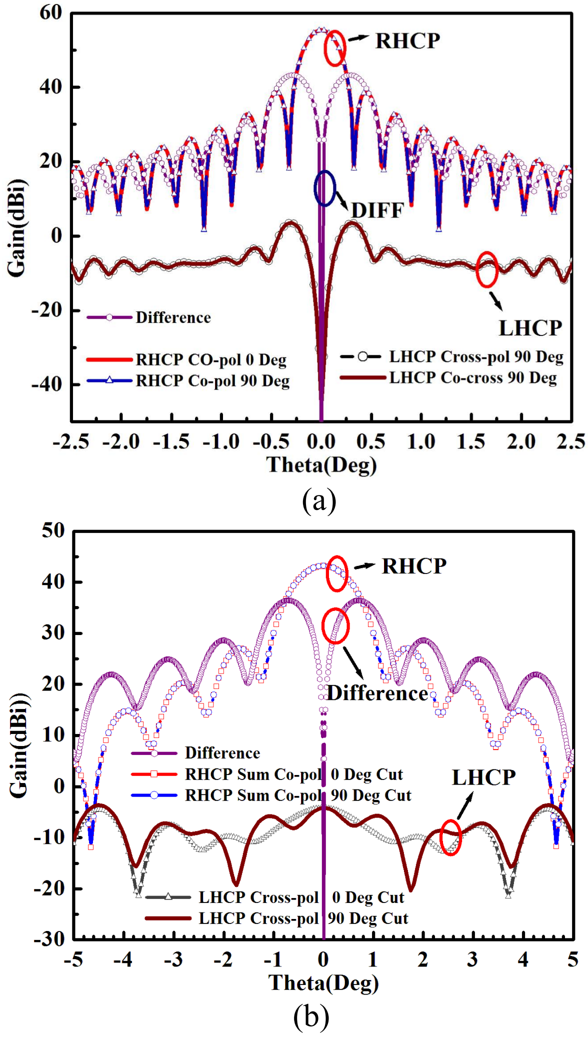

FIGURE 10. **Secondary Sum and Difference (a) X band; (b) S band.**

The main advantage of the proposed dual band feed is summarized below.

Efficiency: The proposed feed is highly efficient in both the bands. The efficiency of the feed is 78 % in X-band and 69 % in S-band.

Simplicity and cost-effectiveness: In the proposed feed simple design approach is followed as composite feed is realized with five-element X-band feed and square array of dielectric rod located in same cassegrain plane. Due to this, the realized feed is very cost-effective yet meeting the desired stringent specifications. Complex structures like coaxial feed, dichroic sub-reflector, which is used for many dual band solution, are not approached here.

Compactness: The propose feed is very compact in nature and does not use bulky waveguide components.

Dual-polarization characteristics: The proposed dual-band feed is also equipped with dual polarization reception/transmission ability, supporting frequency reuse scheme.

Generic design style: Generic design approach makes the feed scalable to other frequency band.

FIGURE 11. **Installed composite feed in the reflector.**

V. CONCLUSION

Design and realization of a composite X-and S-band feed, mounted in the same Cassegrain plane is reported in this article. X-band feed is a corrugated horn surrounded by four circular waveguides fed with CSP. S-band feed is an array of four dielectric rods arranged in 2 × 2 square configurations. Secondary pattern is simulated from achieved primary pattern and available profile & optics. Simulated secondary Sum gains for X- and S-band feed are 55.1 dB and 43.1 dB respectively. Obtained results are verified by G/T measurement from terrestrial sources. S/X band feed is realized, installed and currently operational in 7.5m reflector antenna at NRSC, Jodhpur, ISRO, India

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