Date of receiving: 07/07/2023 Date of revisions: 05 June 2024 Accepted: 05 August 2024

Ku band Diplexer Antenna for Data Relay Satellite Uplink in ITU-R

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ABSTRACT

This work describes a substrate-integrated waveguide (SIW)based Ku band diplexer antenna (DA) for data relay satellite (DRS) low and medium data rate uplink. Designing diplexers that operate at closely spaced frequencies is difficult. The DA's bandwidth (BW) in the proposed design ranges from 12.6 to 15.2 GHz. According to the ITU-R standard, one of the DA's ports operates between 12.75 and 13.25 GHz, while the other operates between 14.5 and 14.75 GHz. The proposed antenna achieves both high gain and wide BW concurrently, which is challenging to do in DA.The radiation caused by the coupling between the proximity modes is excited using a back-to-back triangular SIW and square slots. This SIW DA radiates with 25 dB port isolation and linear polarisation at broad frequencies. It is small, and the slot-loading effect reduces the antenna size. It is suitable for DRS's low and medium data rate uplink multiplexing applications since both ports obtain a wide BW of 20.14 percent at frequencies between 12.6 and 15.2 GHz and a gain of 4.5 dBi.The smaller ECC (less than 0.4) ensures mutual coupling between ports and improves performance and data transmission.

Keywords: Diplexing antenna; Substrate-integrated waveguide; Ku band; Data relay satellite

NOMENCLATURE

BW : Bandwidth
CP : Circularly polarized
DA : Diplexer antennas
ϵ_r :Relative permittivity
dBi : Decibels relative to isotropic
DR : Data relay
GHz : Gigahertz[1]
ITU-R : International Telecommunication Union Radio communication Sector
LHCP : Left hand circularly polarized
RHCP : Right hand circularly polarized
SD : Self-diplexing
SIW : Substrate integrated waveguide
$\tan\delta$: Loss tangent
VNA : Vector network analyser
VSWR :Voltage standing wave ratio

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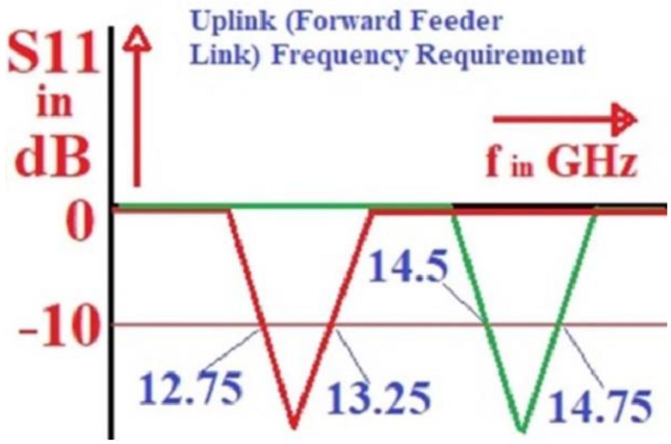
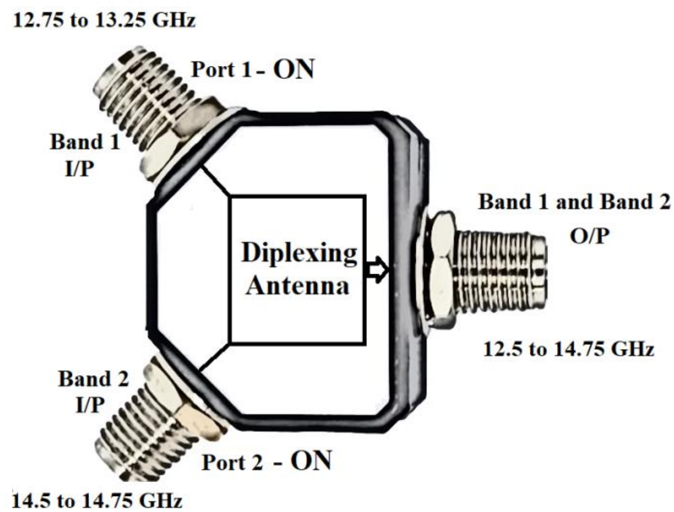
1. INTRODUCTION

In satellite transmission systems, antenna[1-2]is a very important part. They allow stations on Earth and satellites in space to send and receive signals. Compact diplexer antennas (DA) have recently received a lot of attention due to the rapid development of satellite communication system requirements. DA is a passive device that uses two ports to broadcast frequency-multiplexed signals. Both ports' signals operate in separate frequency ranges and coexist without interfering with each other. The signal on port 1 will typically occupyone frequency range, while the signal on port 2 willoccupy another. The diplexer in this case iscomprised of band pass filters (ideally a low-pass and a high-pass filter) that connect to suitable ports to pass the frequencies. DA can be categorized into two types based on the duplexing frequencies: (i) in-band diplexers and (ii) out-of-band diplexers. The in-band diplexer resonates at two frequencies inside the same band, while the out-of-band diplexer resonates at two different bands. Out-of-band DAs are comparatively simple to construct because of the large frequency separation and high degree of port isolation. An antenna that diplexes the in-band frequencies, such as DR satellite low and medium data rates, for uplink in the Ku band is crucial. The typical frequency requirement of the ITU-R recommendation of DR satellite low and medium data rates for uplink is shown (Fig.1a), and the functions of duplexing antennas are shown (Fig. 1 b). The challenge of this research is to diplex the two frequency ranges (i) 12.75–13.25 GHz and (ii) 14.5–14.75 GHz with a guard band of 1.2 GHz in the Ku band. Four aspects of prior research work have been reviewed: SIW[3-4] antenna, diplexer antenna, and diplexer antenna based on SIW and Ku band applications. As a planar waveguide, SIW retains most of the advantages of classic waveguides, such as low loss, a high Q factor, and high power capacity. Due to their superior performance, such as high gain, low profile, wide BW, frequency reconfigurability, and low cross polarization, SIW cavity antennas have attracted interest[5-10]. The self-diplexing (SD) antenna eliminates the requirement for a higher-order diplexer network, resulting in a more compact and efficient RF front-end system. Low-cost wireless transceiver applications, on-chip active antennas, retro directive antennas, and other applications greatly benefit from these circuits. A two-port planar SD SIW slot antenna[11] was the subject of investigation, where researchers done the various analysis.



(a)



(b)

Figure 1.(a)Frequency requirement of ITU-R recommendation of DR satellite low and medium data rate for uplink (b) Diplexing Antenna Operation

Two distinct feed lines excite a bowtie-shaped slot with a SIW cavity backing to resonate at two different frequencies in the X-band (8–12 GHz). For radiation at 8.97 GHz and 11.3 GHz, the two HMSIW resonators are placed together in a shared slot. There is around 20 dB of isolation between the two ports, which offer gains of 4.3 and 4.2 dBi at their respective resonance frequencies. Over a frequency range of 2.5–2.7 GHz, a 12 patch dual-polarized antenna array[12] is described. In order to optimize the radiation performance, it has an artificial periodic structure as well as a pair of cavities that are located below the radiating elements. It provides good isolation between its two ports while operating at two different frequencies. In addition, the literature describes a diplexing antennas[13] with double T-stubs loaded apertures. The authors describe a dual-fed, self-diplexing planar inverted 'F' antenna[14] and its related RF front-end. It is demonstrated that co-designing the antenna and front-end may be used to double the operational BW without sacrificing substantial size or performance.

A dual-band, dual-sense circularly polarized (CP) antenna[15] array with SD aperture sharingis used for transmitting and receiving applications in X-band satellite communication systems. The antenna can receive and transmit left-handed CP (LHCP) signals in the low band while receiving and sending right-handed CP (RHCP) signals in the high band. SIW technology, which works as a bridge between planar and non-planar technology, is an excellent choice for the creation of microwave diplexers. Due to this, SIWdiplexer antennas[16-19] take advantage of the high gain, high power capacity, low cross polarization, and high selectivity, of planar diplexer antennas. Certain SIW-based triplexing[20] and quadruplexing[21-22] antennas have also been reported in the literature. Recently, there has been a lot of interest in antenna research and applications for usage in the Ku band, as well as an increasing number of antenna systems to provide various services[23-26].

Satellite communication systems use a variety of DAs. Some of these antennas are SIW cavity-backed slot antennas intended for wideband, S-band, and C-band use. These include DA with high port isolation, polarized antennas, low-profile Ku-Band antennas, and double-layer Ku/K dual-band antennas. These antennas are intended to provide a wide BW, multi-band operation, high efficiency, and low profile designs. However, designing DAs for closely spaced frequencies is challenging. The proposed DA provides useful gain for Ku band DA while also providing a wide BW. Moreover, this antenna is specifically developed for data relay satellite uplink in ITU-R.

In this work, a compact, wide BW, SIW DA is proposed to multiplex the low and medium data rates for uplink in DR satellites. It is made up of square slots with orthogonal feed lines and a back-to-back triangular SIW. This structure closes the distance between the two modes, allowing them to merge. The orthogonal feed with square slots improves the transmission zeros, leading to higher port isolation, and the coupling of two modes creates ultra-BW. This proposed antenna is unique because it has (i) mode-based design method for dual-band and self-back-to-back triangular SIW, (ii) leading diagonal square slots, (iii) operation of both ports in the same band, (iv) wide band in all port operating conditions, and (v) diplexing the low and medium data rates for DR satellite uplink. Better performance in many antenna parameters like gain, return loss, VSWR, current distribution, power matching, polarization etc. are the advantages of the proposed DA.

2. DESIGN OF DIAGONAL SIW SQUARE CAVITY DIPLEXER ANTENNA

The DA has gained interest in many multi-communication systems. This section describes the diagonal SIW square cavity DA in detail, with the required reflection analysis and radiation characteristics. Due to its diplexing characteristics, DA reduces the requirement for additional antennas and improves the compactness and efficiency of the overall RF front end. In the designed SIW structure, holes are placed at the corner of the cavity, called a diagonal SIW antenna. The folded SIW at four corners forms walls, and this antenna has a square slot cut at leading diagonals. The cavity formation reduces the antenna size and provides good reflection coefficients. The designed SIW DA with a diagonal rectangular slot is etched on the top (Fig. 2).

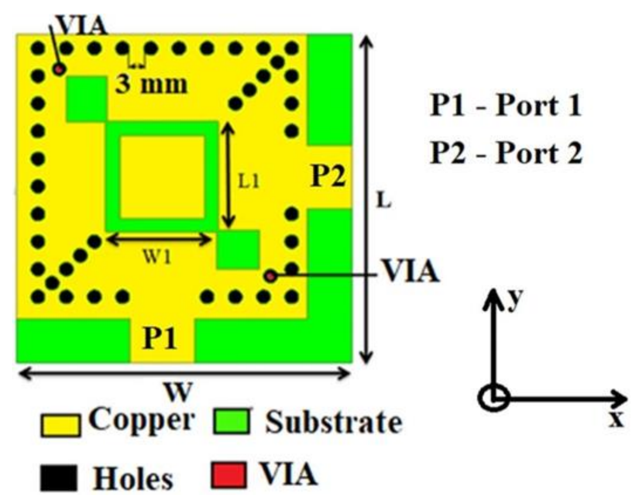


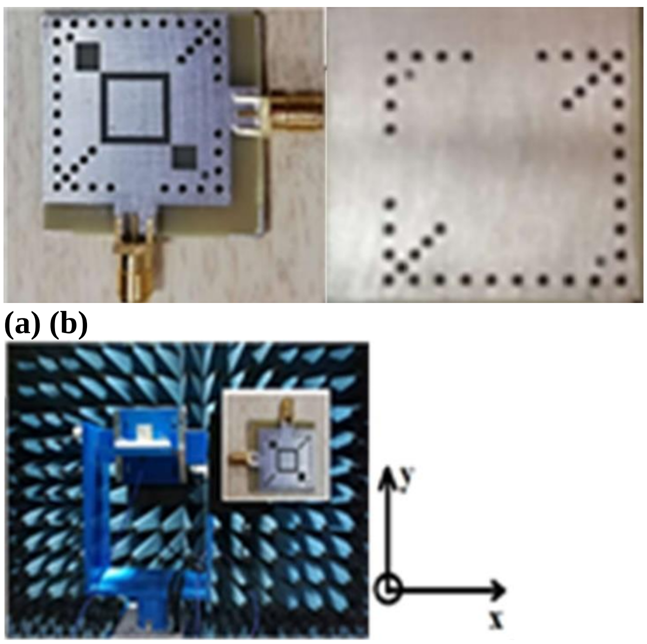
Figure 2. Geometry of the proposed SIW based diplexing antenna

From the direction of the electric fields on the port, the mode of excitation is identified.The TE10 mode, for instance, denotes the direction of the electric field that is resonating in the first mode when one port is excited. Similarly, in dual port excitation, directions of electric fields are excited in two modes. A $h =$

$1.6\ mm$ thick FR4 substrate$\varepsilon_r = 4.4$and $\tan\delta = 0.02$and the Ansoft's HFSS full-wave simulator are used for analysis. The size parameters of the diagonal SIW square cavity DA are given in Table 1.In addition to having the high isolation between the ports, two different feed lines in resonant modes provide high gain.The DA has a diagonal SIW square cavity slot on the top of the patch, and the corner cavity is extended through via holes.

Table1 Design parameter of proposed DA

h (mm)	L (mm)	W (mm)	L1 (mm)	W1 (mm)	P (mm)	D (mm)
1.6	35	35	11.78	11.78	3	2

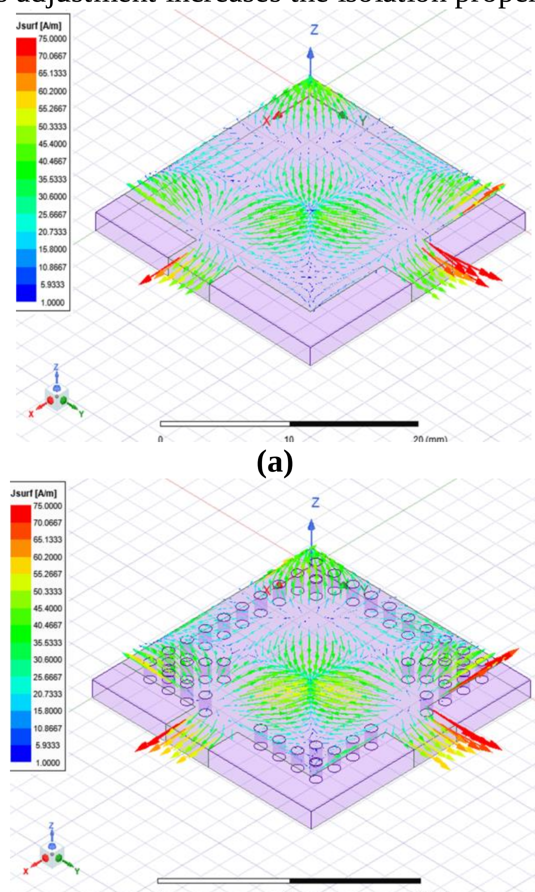


(a) (b)

(c)

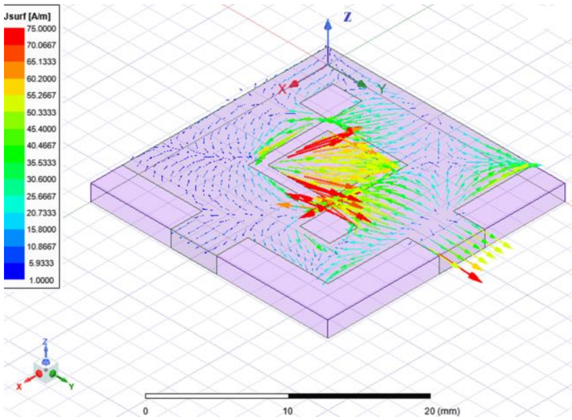
Figure3. Designed fabricated prototype antenna (a) top view and (b) bottom view (c) measurement setup of antenna parameters in Anechoic chamber

This overall structure reduces the antenna size and provides improved radiation characteristics. A patch is connected to the feed for excitation, and the holes act as the electric sidewalls or fences of SIW, and they are also used to increase the electric path and BW of the antenna. The holes couple the energy from the feeding network, and the smooth transition between the substrate and the dielectric 'via' further enhances the BW of the antenna and the isolation between the ports above 20 dB. The overall view of the designed antenna and the fabricated prototype of the designed antenna are shown (Fig. 3). The SIW and diagonal slots help to increase isolation between the two ports. The proposed design consists of four main steps: (i) microstrip patch; (ii) SIW inclusion in patch; (iii) diagonal slot inclusion in patch; and (iv) a combination of all three steps. The current distributions of all steps are shown (Fig. 4) to demonstrate the isolation effectiveness of the proposed antenna design. Inserting the SIW fence (step 2) into a plain microstrip patch improves the current length, as seen (Fig. 4b). Additional slots in the microstrip patch's diagonals (step 3) enhance the current distribution closer to the antenna's centre, as seen (Fig. 4 c). In step 4, both SIW walls and diagonal slots lengthen the currents while also changing their phase, as shown (Fig. 4d). The current phase's adjustment increases the isolation properties.

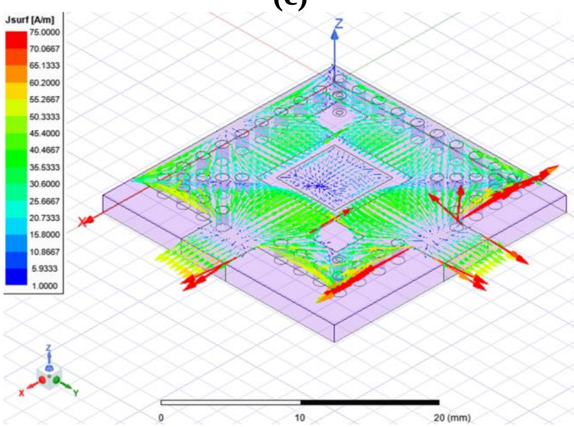


(a)

(b)



(c)



(d)

Figure 4. Current distributions of development steps of proposed antenna design (a) Step-1; Antenna without SIW and slots (b) Step-2; Antenna with SIW (c) Step-3; Antenna with slots (d) Step-4; Antenna with SIW and slots (proposed)

The improvement in isolation can be seen (Fig.5), which displays the isolation of each step and how the proposed antenna design performs better. High isolation ensures that the signals from one port do not significantly affect the signals on another port, which is particularly important in applications like DA, where multiple signals are transmitted and received simultaneously.

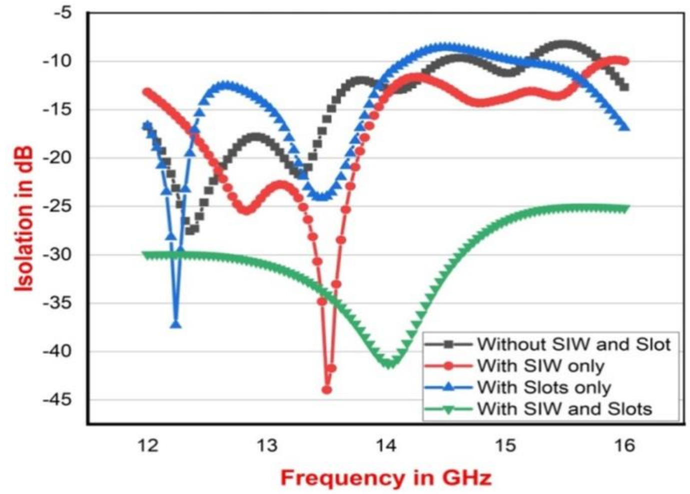


Figure5.Isolation parameter of development steps (step1 to step 4) of proposed antenna design

An isolation value of less than -20 dB is generally considered a satisfactory standard. The proposed antenna achieved this at the required frequency (12.6 GHz to 15.2 GHz). The SIW structure in the proposed DA confines electromagnetic waves, which helps reduce unwanted coupling between ports.

3. EXPERIMENTAL AND SIMULATION RESULTS

Scattering and radiation performance: The simulation results are analyzed using finite element analysis in ANSYS HFSS (2021R2). The reflection parameters of the designed antenna are measured using an Agilent VNA with frequency coverage of 30 kHz to 20 GHz. The radiation and scattering performances of the designed antenna are tested in the anechoic chamber, as shown (Fig. 3c). The radiation and scattering characteristics of the two ports of this DA are studied separately as well as together. The simulated results of the S11 parameter for two ports are depicted (Fig. 6). The desired frequency range is in the Ku band, between 12 and 17 GHz. S11 coefficients are described, only when port 1 is ‘ON’ and only when port 2 is ‘ON’. The ‘ON’ means that the signal feed is given to a particular port. The status of the ports and their significance are given in Table 2.

Table2 Diplexing antenna (DA) port’s status and its operation

Ports	State		
Port 1	ON	OFF	ON
Port 2	ON	ON	OFF
Operation	Diplexer	--	--

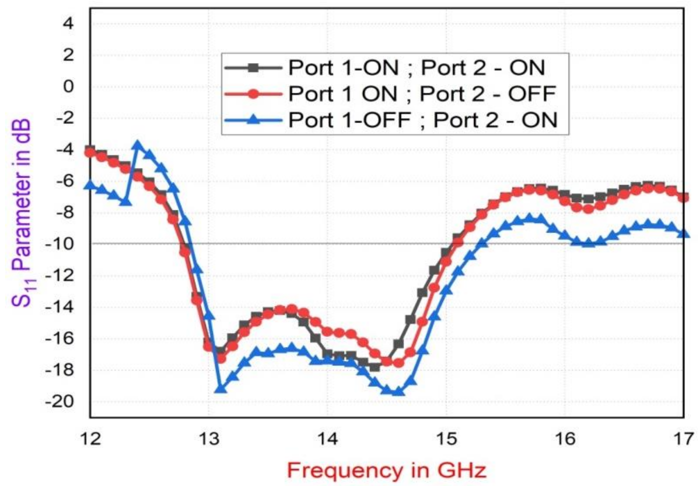


Figure 6. Reflection coefficients of proposed DA corresponding port 'ON'

In addition, the S11 parameter when both ports are 'ON' is shown (Fig. 6). S11 refers to the reflection coefficient, a parameter used to characterize how well a device reflects radio waves. In the case of an antenna, a low S11 value indicates good impedance matching. The designed antenna resonateswith good matching from almost 12.6–15.2 GHz in both ports separately and together, and a wide BW of 20.14 % is achieved (Fig. 6). In addition, S11 performances are well supported by studying the VSWR plot (Fig. 7) in the desired frequency range. The obtained VSWR within the range of 1–1.8 ensures that the designed antenna is well matched to the operating frequency conditions. The gain of the designed DA for an interested frequency range from 12 GHz to 17 GHz is shown (Fig. 8). It refers to the amount of signal a given antenna can radiate or receive in a given direction in a specified frequency range.Slots and SIW, which add more current paths to the antenna element, are the reasons for these improvements. Such paths may alter the overall current distribution, which could improve the antenna's S11 and VSWR.

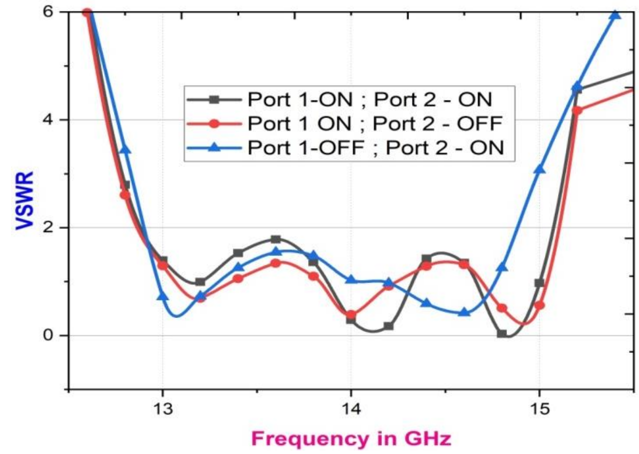


Figure 7. VSWR of proposed diplexing antenna (DA)

The gain of the proposed antenna is computed by comparing the observed power transmitted/received by the proposed DA. The proposed DA has a moderate gain within the required frequency range. The proposed DA operates from 12.6-15.2 GHz with gains ranging from 4.5 to 3.5 dBi. The frequency vs. gain of the proposed DA with port 'ON' conditionsis described (Fig.8). Antenna gain in a particular direction can be increased by gathering more signal energy and confining it in that direction using a larger effective aperture area ofthe proposed DA. DRS typically requires stronger received signals, and the proposed DA with a higher gain ensures sufficient signal strength.

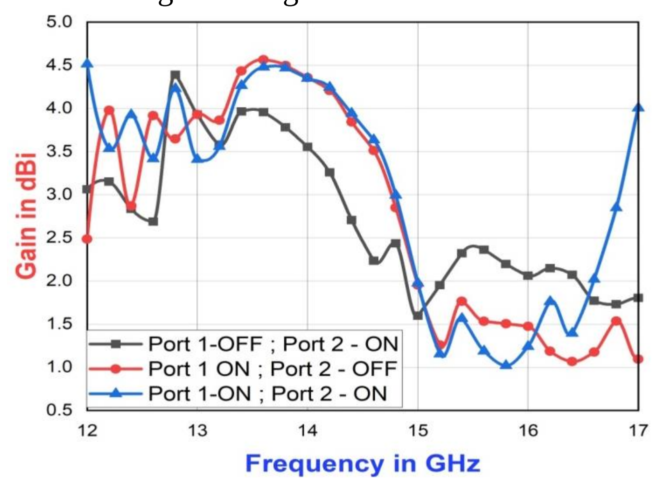


Figure 8. Gain vs frequency of the proposed self-diplexing antenna

The axial ratio is a fundamental parameter used to characterize the polarization purity of an antenna. The axial ratio of the proposed antennais shown (Fig. 9) and the designed DA works well at thespecified operating frequency when ports are excited. Within 12.6–15.2 GHz, the axial ratio is almost steady in the proposed antenna. This is because the plane of the patch, specifically the square patch antenna on a grounded substrate, stimulates currents that primarily flow along the patch's length or width.

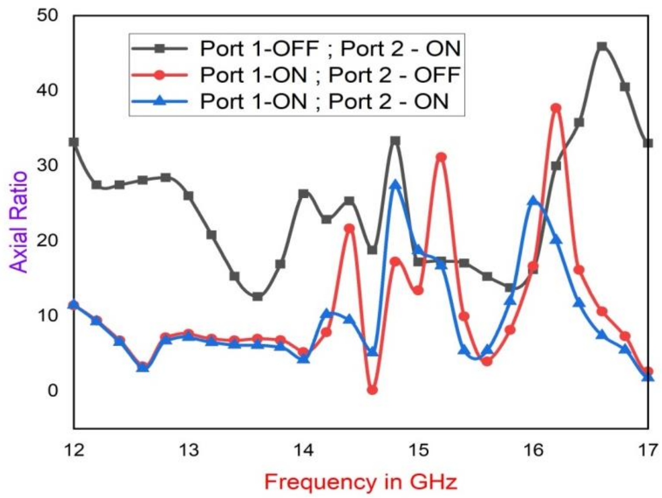
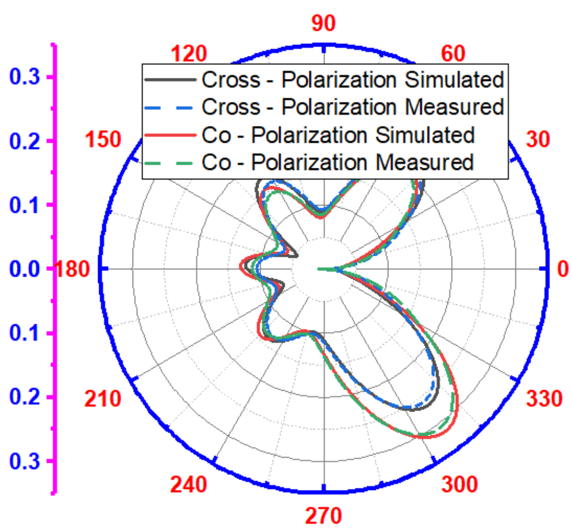
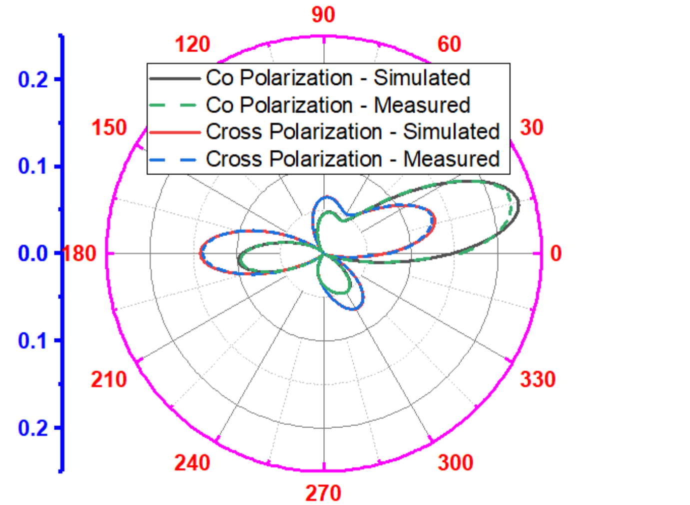


Figure 9. Axial ratio of proposed diplexing antenna

The E-plane (xz-plane) and H-plane (xy-plane) radiation patterns at two frequencies of13 GHzand 14.625 of the proposed DAare shown (Fig. 10). The measured and simulated results agree well with each other in the angular range around the broadside direction. The proposed DA's performance at the two frequencies is consistent with the design objectives in terms of gain, directionality, and minimal interference, as determined from the radiation pattern analysis and the measured pattern closely matches the simulated results.



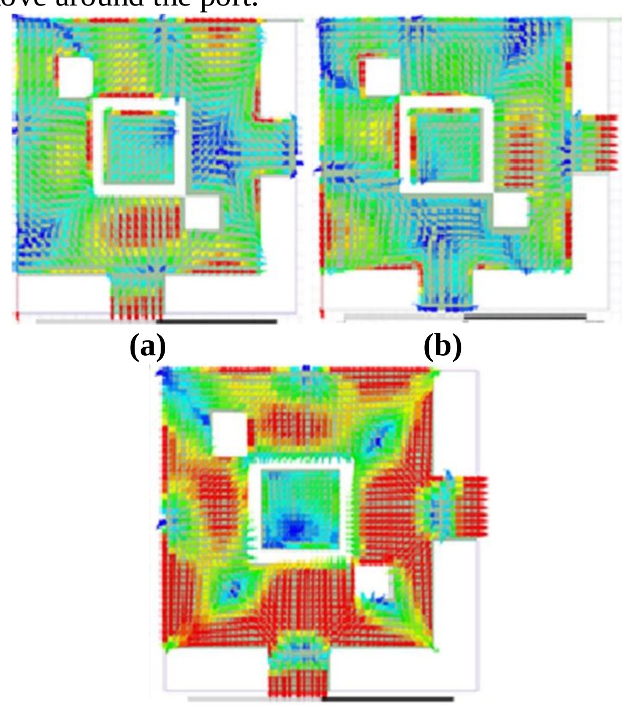
(a)



(b)

Figure 10. E Plane and H Plane radiation pattern, Co polarization and cross polarization pattern (both simulated and measured) of proposed DA (a) at 13 GHz (b) 14.625 GHz

Current Distribution Analysis: The electric field distribution is changed based on the port conditions. The electrons on the patch surface get excited and move around the port.



(a) **(b)**

(c)

Figure11. Current distributions of proposed antenna (a) Port 1 feed (13GHz) 'ON'(b) Port 2 feed(14.62GHz) 'ON' (c) Port 1 feed (13GHz) 'ON' and port 2 feed (14.62GHz) 'ON.

Some imbalanced surface impedance is present along with the patch, which can weaken the current along the y-direction. When port 2 is 'ON', the EM waves incident around port 2's surface and other surfaces havean imbalanced impedance. The red colour indicates a strong electric field, and the blue color indicates a weak electric field. When port 1 is turned on, EM waves collide with port 1's surface. When both ports receive feeds, the current distribution near the ports increases (Fig. 11).In addition, the current distributions are symmetrical with their orthogonal ports. The proposed DA shows the overall radiation performance (Fig. 12) in terms of peak directivity, beam area, incident power, accepted power, radiated power, and radiation efficiency.

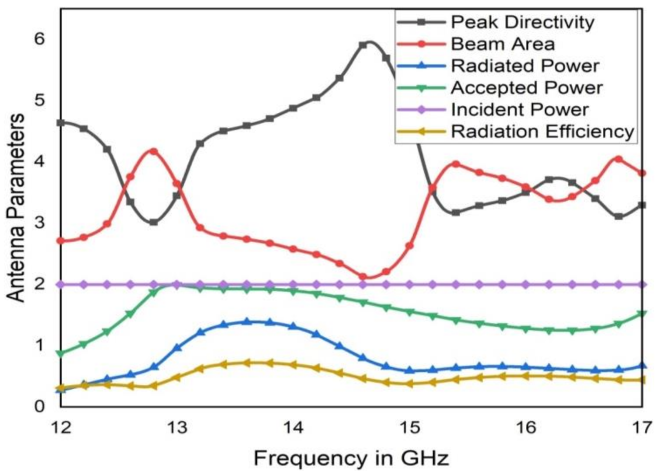


Figure 12. Performance of other antenna parameters

Each parameter's results reveal that the proposed DA has good radiation characteristics and is capable of performing the necessary purpose. The results of the proposed DA's simulated reflection coefficient are displayed (Fig. 13).A smaller discrepancy between simulated and measured scattering coefficients ensures that the developed DA can be used in practice. Table III shows the comparison of the proposed DA with other reported works found[11-13, 15-18]. This comparison mainly focuses on size, frequency, BW, gain, radiation efficiency, and isolation.The antenna[11] has a lower profile than the proposed DA. At the same time, the frequencies are well separated. Despite the fact that isolations are high[12-13], they are relatively larger in size. The proposed DA has a low profile, is restricted to the Ku band, and sticks to the ITU recommendation with moderate isolation.

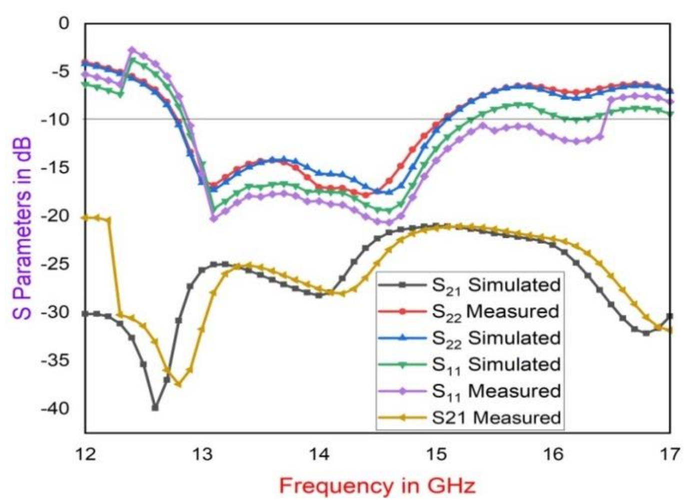


Figure 13.Simulated and measured reflection coefficients

Table3 Performance comparison of proposed DA

Ref.	Size (mm^3)	Frequency (GHz)	BW (GHz)	Gain (dBi)	Rad.Eff. (%)	Isolation (dB)
[11]	18.8×17×0.787	9.0 - 11.2	1.2	4.3	78	27
[12]	120×120×1.6	2.4-2.8	0.4	8.5 to9.1	NR	45
[13]	50×50×1.6	2.5,5.5	3	1.9	87	40
[15]	14.4x14.4x2.7	7.3-8.3	1.0	8	NR	27
[16]	12.5x14x1.5	11-12	1.78	6	NR	14.7
[17]	20.72x0.72x1.58	10.5	1.32	5.95	NR	29

Ref.	Size (mm^3)	Frequency (GHz)	BW (GHz)	Gain (dBi)	Rad.Eff. (%)	Isolation (dB)
[18]	20.7×9.7x1.524	3.6-5.4	1.8	5.34	>90	>32.5
ThisWork	35x35x1.6	12.6-15.2	2.6	4.5	74	25

Mutual coupling between ports in a DA refers to the mutual interaction of signals at several ports. Mutual coupling in a diplexer, which commonly combines or separates signals across many frequency bands, can have an impact on antenna system isolation and performance. To avoid signal interference between ports, restrict mutual coupling. Understanding port interdependence is necessary when measuring mutual coupling with the envelope correlation coefficient (ECC).

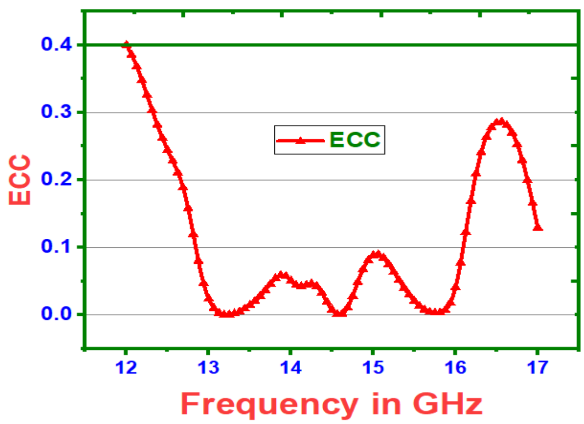


Figure 14.ECC of the proposed diplexer antenna

It is an important metric to measure the performance of multi-frequency and multiport antenna systems, such as those that include diplexers. Lower ECC values (<0.4) recommend improved isolation and diversity performance in diplexer systems. The frequency versus ECC of the proposed DA is shown (Fig. 14), and it is found that mutual coupling is within the stipulated limit in the desired frequency range. By integrating advanced switching mechanisms and exploring new materials and design techniques, researchers can significantly improve the performance and functionality of Ku band diplexer antennas for future data relay satellite applications.

4. CONCLUSION

A Ku band SIW based diplexer antenna (DA) for low and medium data rate data relay satellite (DRS) uplink is presented. It overcomes a diplexer's design constraint of working at closely spaced frequencies. According to the ITU-R guideline, one of the DA's ports operates between 12.75 and 13.25 GHz, while the other operates between 14.5 and 14.75 GHz. The triangular SIW is used inconjunction with square slots to trigger proximity modes and radiation caused by mode coupling. This compact SIW DA radiates with 25 dB port isolation and linear polarization. Its BW in both ports is 20%, making it appropriate for DRS low and medium data rate uplink multiplexing applications. The lower ECC (below 0.4) between the ports results in decreased mutual coupling, which improves the performance and data transmission capabilities of data relay satellites in Ku band applications.

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