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Design and characterization of a circularly polarized microstrip-line-fed slot array antenna for S-band applications

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ABSTRACT

A 2×2 slot array antenna fed by microstrip line for circular polarization operated in the S band frequency range is designed in this paper. Single cross slot with single port feed as well as dual port feed is taken into consideration for realizing circular polarization and combining these two processes, the slot array is designed with single feed for circular polarization. The antennas are designed on a Teflon glass fiber substrate of thickness 0.8 mm. The slot array dimension is 120×142×1.636 mm^3. Smith chart of single cross slot antenna with single feed as well as dual feed has a dip at 2.69 and 2.53 GHz respectively indicate the capability of realizing circular polarization in the S band frequency range. The return loss of the slot array antenna is -58 dB shows good input impedance matching of the antenna. A dip in the smith chart of the slot array shows circular polarization near 2.4 GHz ensuring wireless applications as well. Axial ratio is found to be less than 1 dB in the resonance frequency. The impedance bandwidth percentage of the slot array antenna is 12.24%. The simulation is done by using keysight advanced design system (ADS) software.

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1. INTRODUCTION

Circular polarization is the greatest option for antenna design engineers if they want a communication to be independent of signal misalignment between sending and receiving, adverse weather, and user terminal mobility. Because multi-path loss is reduced by circularly polarized (CP) antennas, they are also more desired and beneficial for radio and wireless communications as well as multiple-input multiple-output (MIMO) systems [1]–[4]. Furthermore, they have beneficial applications for 5G cellular applications [5]. Numerous studies have focused on the purpose of circular polarization [6]–[9]. Due to the advantages of its planar construction, such as its simplicity, compactness, cost effectiveness, and planar feeding mechanism, slot array antennas are an appealing choice for circular polarization [10], [11]. Additionally, it benefits from the versatility of polarization and ease of antenna orientation [12].

Achieving circular polarization is possible in several ways. Circular polarization can be achieved using a series-fed end fire array. A radial line slot array antenna can be a good approach to create circular polarization, but it needs a hybrid feed network connected to the power divider to achieve 90° phase changes. Cutting edges of a microstrip patch can create two orthogonal degenerate modes, which can achieve circular polarization with only a single feed without the need for a phase shifter but have a bandwidth percentage of only 5.1% [13]–[15]. In [16], three feeds are used to obtain CP, but it also necessitates a 120° phase shift between them. Although CP may be accomplished for microstrip patch antennas without a phase shifter by using triple feed [17]. In slot antennas, there is also the option of using four ports to reach CP [18]. In a four-slot system with orthogonal alignment and individual feed, stimulating two of the slots with a 90° phase shift while isolating the other two allows for the realization of CP.

Popular array antennas for CP include those fed by microstrip line, among many other feeding methods [19]–[21]. Additionally, typical shapes for CP include C-shaped feed lines, W-shaped feed lines, and L-shaped feed lines. Although switching from a L to a V-shaped fed line can increase impedance bandwidth by up to 9.1%, an L-shaped feed is preferred because it can produce two orthogonal modes with a 90° phase shift with the right feed length sizing, making it simpler to realize CP [22]–[25]. Even yet, multiple feed facilitates CP implementation more readily than single feed. In comparison to using numerous feeds to acquire circular polarization, generating an orthogonal feed to an antenna with a single feed simplifies the structure [26], [27].

This article designs and simulates a slot array antenna for a circular polarization application in the S band frequency range. Two methods are used to feed each individual slot in the array: an L-shaped microstrip line and a microstrip to slot feeding mechanism from a single feed point. As a result, this structure only assures a single port feed rather than several ports, which is often the case when feeding an array. The structure exhibits good CP radiation at the 2.4 GHz frequency and also outperforms earlier work in terms of impedance bandwidth percentage as well as impedance matching.

In this article, a cross slot antenna fed by microstrip line with single feed as well as dual feed to realize circular polarization is demonstrated. Then a single feed slot array antenna fed by microstrip line to achieve circular polarization in the S band applications is presented with simulated results which is done using ADS software. The design of the single slot and slot array is described in section 2. Section 3 shows the simulated results and discussion followed by conclusion in section 4.

2. ANTENNA CONFIGURATION

This section describes a single slot antenna with single feed as well as dual feed followed by the slot array antenna design. At first, a single slot antenna is designed with a single feed and then designed and analyzed the same slot antenna by dual feed technique to acquire circular polarization. Finally, the proposed slot array antenna is designed and analysed to obtain CP.

2.1. Single cross-slot antenna design

Single feed single cross slot antenna has a substrate layer with a cross shape slot cut in the ground layer. Signals are provided by microstrip lines on the top layer of the substrate. The microstrip line is arranged in such a way that signals can flow through both arms of the slot. The microstrip line extends a quarter-wavelength over one arm of the slot with a right-angle bend that extends a quarter-wavelength beyond the second arm of the slot. The substrate layer is made of Teflon glass fiber with a relative dielectric constant of 2.15 and thickness of 0.8 mm. Microstrip line width is of 2.6 mm. Figure 1 shows the single feed single cross slot antenna configuration with cross-sectional view, where microstrip line is placed on top of substrate layer.

As depicted in Figure 2, for dual feed single element antenna, the slot layer is in between the two layer of substrates made of Teflon glass fiber with a relative dielectric constant of ϵ_r = 2.15. Both substrate layers have a 0.8 mm height. Microstrip line is placed on top of upper substrate layer and another microstrip line beneath the lower substrate layer as shown in the figure. The two port is fed with 90^0 phase shift between one another as well as placed in such a way that it seems orthogonal to each other. Both microstrip line is 2.4 mm wide and has a height of 0.018 mm.

2.2. Slot array design

For designing slot array, the slot layer is placed in between two substrate layer. Four cross slots are arranged in a 2×2 manner in the slot layer as shown in Figure 3. A T-shaped microstrip line is placed beneath substrate 2. Input port also connected to this microstrip line. Two other microstrip lines of same dimension are placed on top of upper substrate (substrate 1) layer. These microstrip lines gives feed configuration to slot #1 and slot #2 in a manner that previously shown dual feed single cross slot antenna have. The top layer microstrip lines are extended in a L-shape way that other two cross slots i.e., slot #3 and slot #4 are fed in an orthogonal manner like single feed single cross slot antenna. These two types of microstrip lines are electronically connected by a 0.2 mm slot line which is placed along center of the antenna in the slot layer. The microstrip line that is beneath substrate 2 has a half wavelength as it passes the slot line before dividing into two lines and has a quarter wavelength up to slot line from the feed point. This alignment gives T-shaped microstrip line a quarter wavelength longer length than other two microstrip lines. The design parameters of the proposed slot array antenna is described in details in Table 1.

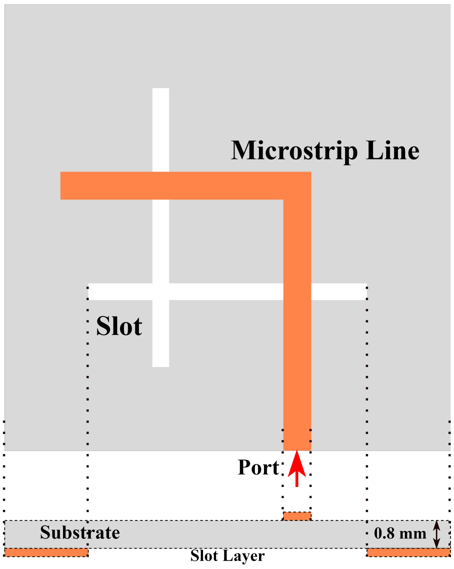

Figure 1. Geometry of single feed single cross-slot antenna

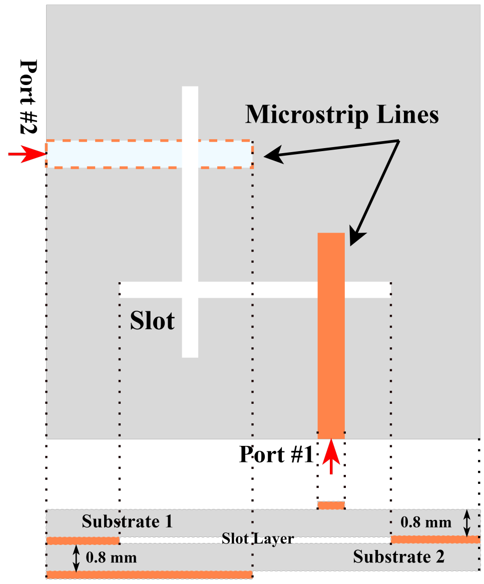

Figure 2. Geometry of dual feed single cross-slot antenna

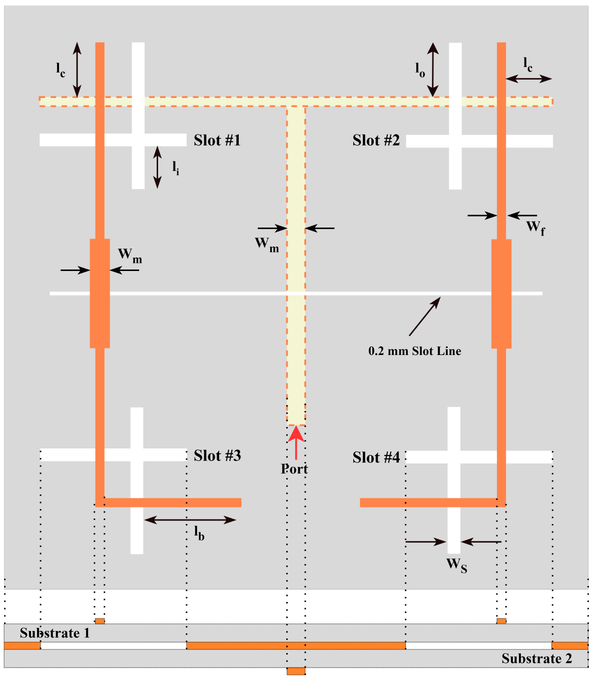

Figure 3. Proposed slot array antenna configuration

Table 1. Design parameters of the slot array antenna

Parameter	Value	Parameter	Value
Microstrip line length, l_c	12.3 mm	Slot line width	0.2 mm
Outer slot length, l_o	16 mm	Slot width, W_S	1.3 mm
Inner slot length, l_i	17 mm	Microstrip line thickness	0.018 mm
Perpendicularly bent patch length, l_b	23.3 mm	Input impedance	50 Ω
Microstrip line width, W_m	2.4 mm	Substrate thickness	0.8 mm
Microstrip line width, W_f	0.8 mm	Relative dielectric constant, ϵ_r	2.15

2.3. Antenna working principle

When the microstrip line of single feed single slot antenna as shown in Figure 1 is excited with an input signal, the bend in microstrip line makes it possible to achieve a 90° phase shift among slot arms signal, thus realizing circular polarization. And when two microstrip lines of dual feed single cross slot antenna as shown in Figure 2 are excited with equal amplitude and a 90° phase difference between them, the slot arms get excited with equal amplitude and a 90° phase shift. Thus, circular polarization is realized for dual feed single antenna. Input impedance for both input signal is 50Ω.

The slot array antenna is made by taking consideration of these two techniques. A 0.2 mm slot line in the slot layer connects the microstrip line on either side of the substrates electronically. Input signal is fed at port of the microstrip line beneath substrate 2 as shown in Figure 3.

As the signal propagates, slot #1 and slot #2 are fed by dual feed antenna manner to achieve a 90° phase shift among slot arms, where slot #3 and slot #4 are fed by single feed manner and varying length of the bend in microstrip line can make the slot arms to produce two orthogonal degenerative modes. Thus, circular polarization is realized by the four slots of the proposed slot array antenna. In Figure 4, operation principle of the proposed slot arrray antenna is depicted, where dotted circle indicates the microstrip-slot branch and circle indicates slot-microstrip branch which are parallel and series power divider respectively. The parallel divider split the signal in phase and series divider divides the signal into two equal amplitude out of phase signal [28]. Due to the fact that they are microstrip-slot branches, the phase signal received by eight slot arms of four cross-like slots has the same amplitude. Slots #1 and #2 are fed by two microstrip lines, one coming from the top of the upper substrate and the other from the bottom of the lower substrate. Slots #3 and #4 are fed by microstrip lines with an orthogonal bend, allowing both arms of those slots to be fed by signals coming from the slot-microstrip branch.

According to Figure 4, the structure radiates in a circular pattern. Each of the four slots has the ability to radiate with circular polarization. However, there is a difficulty with two slots radiating in right right-handed manner while the other two are left-handed. Together, they cancel each other out as they spread. Two meander lines are introduced into the design to address this issue as depicted in Figure 5, changing the phases of slots #1 and #4 and ensuring that all slots radiate in an identical circular pattern.

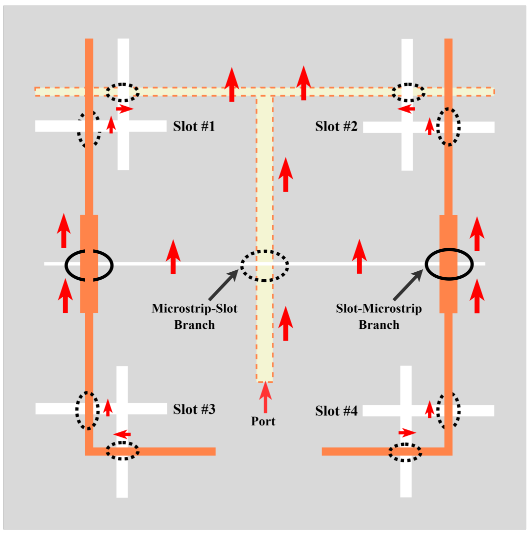

Figure 4. Operation principle of the proposed slot array antenna

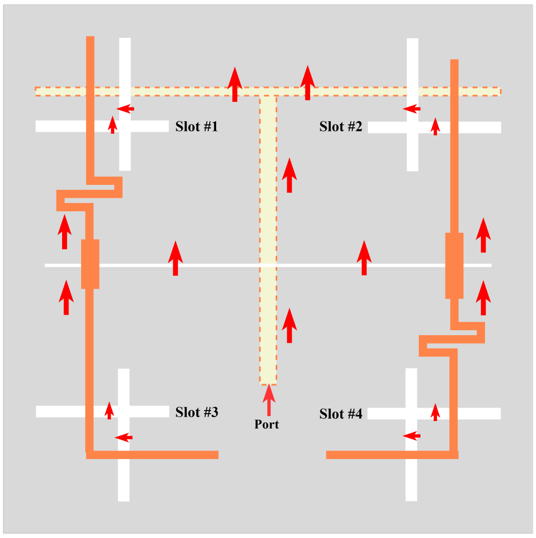

Figure 5. Operation principle of the proposed slot array antenna with meandered line

3. SIMULATED RESULT ANALYSIS

This section shows the simulated results of the single element antenna followed by slot array antenna with parametric analysis of the slot array antenna. Single slot antenna with single feed as well as dual feed is capable of exhibiting CP is shown in the following subsection. The realization of CP by single slot antenna is demonstrated by smith chart mainly. In section 3.2., the slot array antennas CP realization is confirmed by axial ratio plot after a parametric analysis is done.

3.1. Single element result analysis

Figures 6 and 7 shows the simulated return loss and voltage standing wave ratio (VSWR) of the single cross slot antenna for both single feed as well as dual feed respectively. From the figures, it can be seen that single feed single element antenna has a return loss of -42.19 dB at a resonance frequency of 2.47 GHz and a -10 dB return loss over the frequency range of 2.34 to 2.83 GHz making the antenna suitable for S-band applications. And dual feed single cross-slot antenna has an impedance bandwidth percentage of 27.76% and -46.71 dB return loss at a resonance frequency of 2.74 GHz.

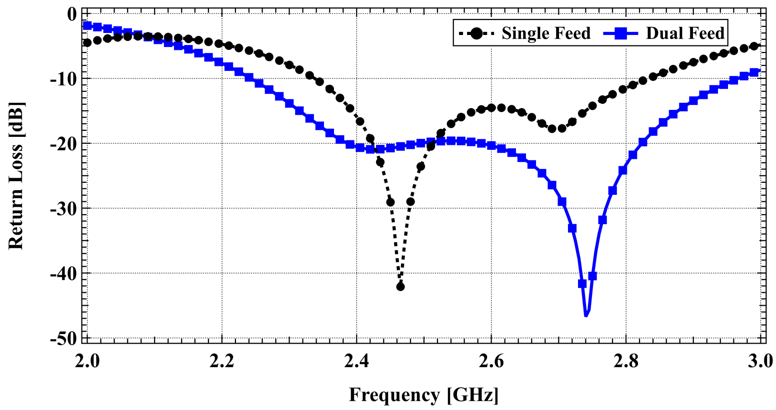

Figure 6. Return loss of single cross-slot antenna

The VSWR$<$ 2 range for single feed and dual feed cross slot antennas are 2.33 to 2.84 GHz and 2.34 to 2.97 GHz respectively. A dip on both Smith charts near one as shown in Figures 8 and 9 indicates the realization of achieving circular polarization by both single slot elements. As a dip in the Smith chart means two orthogonal degenerative modes in two near frequencies which is an indication of circular polarization [29].

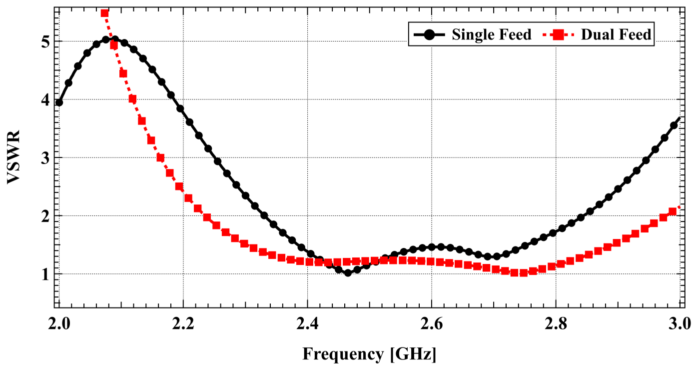

Figure 7. VSWR of single cross-slot antenna

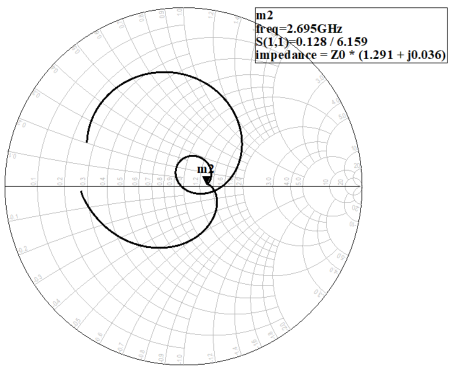

Figure 8. Simulated input impedance of single feed single cross-slot antenna

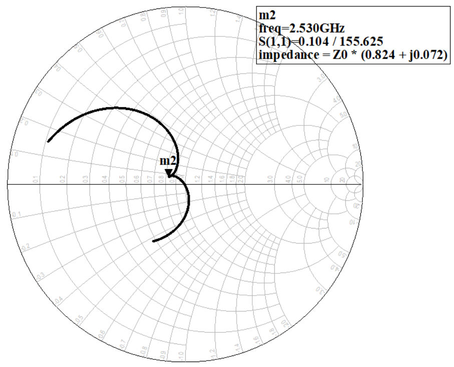

Figure 9. Simulated input impedance of dual feed single cross-slot antenna

3.2. Slot array antenna result analysis

For slot array antenna, several parametric analyses have been done using ADS simulator and results are exploited to archive the goal of this proposed design. An optimized dimension for the proposed slot array is obtained by parametric analyses. After analysing parametric studies, the realization of CP is confirmed by the axial ratio versus frequency graph. This section also includes a comparison data with previous work on this manner.

3.2.1. Microstrip line length variation

Figures 10 and 11 shows the variation of return losses when extended bent microstrip line length l_b on slot #3 and slot #4 and microstrip line length l_c on slot #1 and slot #2 is varied. As the length l_b increases, resonance frequency decreases by several KHz. But for different values of l_c, return loss is varied while impedance bandwidth as well as resonant frequency remains the same. With the increment of length l_c, return loss decreases by several values at the resonance frequency of 2.43 GHz. For both cases, the impedance bandwidth percentage is about 10.74%. For l_b = 23.3 mm and l_c = 12.3 mm, the best return losses are achieved.

3.2.2. Slot length and width variation

When slot length is varied while keeping other dimensions in their previously analyzed best values, return loss characteristics varies. For different values of l_i, return loss values, impedance bandwidth as well as resonance frequency vary to a great extent. With length decrement, resonance frequency, and impedance bandwidth decreases and the antenna losses its circular polarization capability. Further, with length increment, though impedance bandwidth increases, the antenna return loss decreases at great extent. For l_i = 17 mm, the return loss is -34.89 dB as shown in Figure 12. From Figure 13, it can be seen that, as the slot length l_o increases, impedance bandwidth changes a little where return loss and resonance frequency decrease. Also with a longer slot length the antenna losses its circular polarization capability.

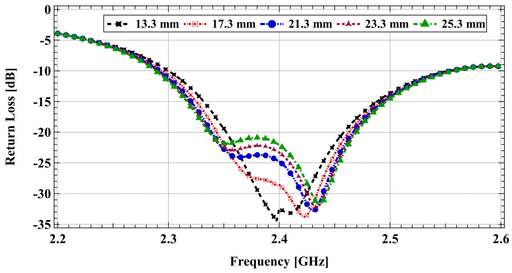

Figure 10. Return loss of the proposed slot array antenna for different l_b, when l_c = 12.3 mm, l_o = 16 mm, l_i = 17 mm, and W_S = 0.7 mm

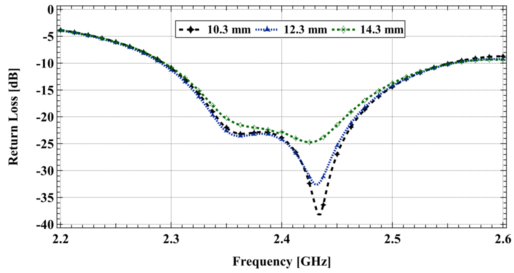

Figure 11. Return loss of the proposed slot array antenna for different l_c, when l_b = 23.3 mm, l_o = 16 mm, l_i = 17 mm, and W_S = 0.7 mm

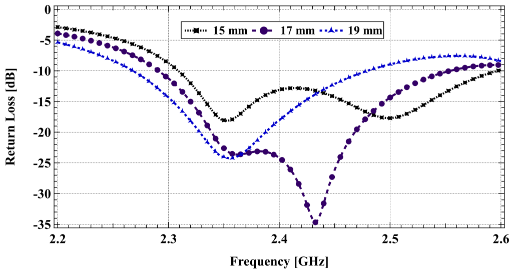

Figure 12. Return loss of the proposed slot array antenna for different l_i, when l_b = 23.3 mm, l_c = 12.3 mm, l_o = 16 mm, and W_S = 0.7 mm

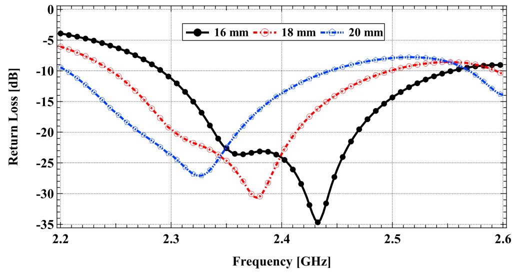

Figure 13. Return loss of the proposed slot array antenna for different l_o, when l_b = 23.3 mm, l_c = 12.3 mm, l_i = 17 mm, and W_S = 0.7 mm

Figure 14 shows return losses with respect to frequency for several slot widths when l_b = 23.3 mm, l_o = 16 mm, l_i = 17 mm, and l_c = 12.3 mm. It can be seen from the plot that, Impedance bandwidth and resonance frequency remains almost the same for different slot width. As the slot width decreases below 0.7 mm, return loss decreases, and with the increment of slot width return loss increases. But above slot width 1.3 mm, return loss again starts to decay to a large extent. For slot width S_W = 1.3 mm, the return loss at 2.45 GHz is -54.13 dB.

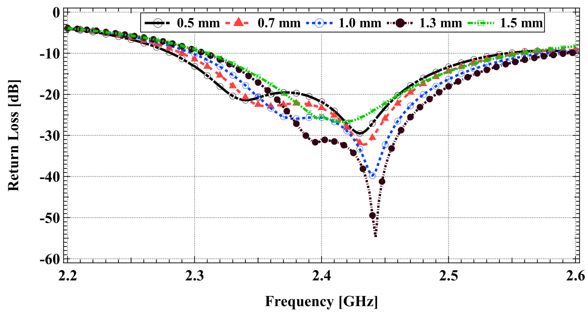

Figure 14. Return loss of the proposed slot array antenna for different W_S, when l_b = 23.3 mm, l_c = 12.3 mm, l_i = 17 mm, and l_o = 16 mm

Figure 15 shows the return loss of the proposed slot array antenna after analyzing different parameters of the antenna. It can be seen from the figure that the return loss at resonance frequency 2.45 GHz is -58.017 GHz over a -10 dB range of 2.3 to 2.6 GHz denoting an impedance bandwidth percentage of 12.14%. This return loss value is the optimized value for the slot array.

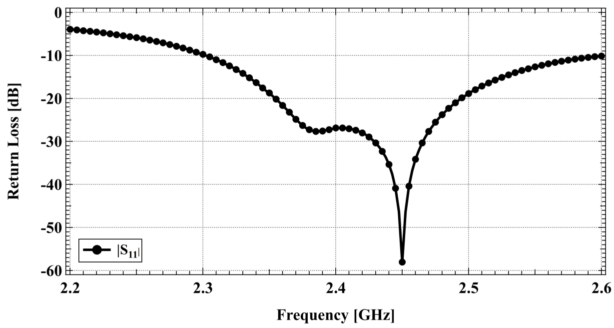

Figure 15. Optimized return loss of the proposed slot array antenna

3.3. Slot array antenna CP analysis

Figure 16 shows the simulated input impedance on the Smith chart of the proposed slot array antenna. A dip on the Smith chart near one, at 2.4 GHz indicates that the proposed slot array antenna is capable of producing two orthogonal resonance modes enabling the antenna to radiate in a circularly polarized way.

As it has been described in section 2.3., two slots get excited orthogonally with phase shift and the other two slots get excited in such a way they can produce degenerative orthogonal mode in near frequency producing circular polarization. The dip in the figure exhibits the phenomena of producing degenerative orthogonal modes. Thus the slot array antenna is a circularly polarized antenna. Table 2 shows the overall parametric analysis values of the slot array antenna.

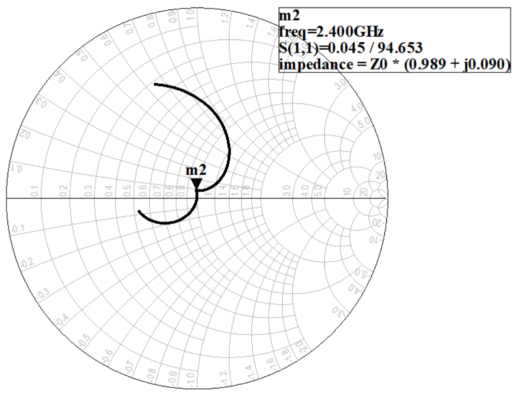

Figure 16. Simulated input impedance of the proposed slot array antenna

Table 2. Performance analysis of different parameters of the proposed slot array antenna

Parameter	Value	Return Loss	f_c	Impedance BW
l_b	21.3 mm	-33.10 dB	2.43 GHz	10.74%
	23.3 mm	-32.89 dB	2.44 GHz	10.96%
	25.3 mm	-32.00 dB	2.45 GHz	11.18%
l_c	10.3 mm	-37.70 dB	2.44 GHz	10.60%
	12.3 mm	-32.89 dB	2.44 GHz	10.60%
	14.3 mm	-24.92 dB	2.44 GHz	10.60%
l_i	15.0 mm	-18.01 dB	2.34 GHz	11.81%
	17.0 mm	-34.50 dB	2.43 GHz	10.96%
	19.0 mm	-24.00 dB	2.35 GHz	08.84%
l_o	16.0 mm	-34.50 dB	2.43 GHz	10.96%
	18.0 mm	-30.97 dB	2.38 GHz	10.52%
	20.0 mm	-27.00 dB	2.32 GHz	09.70%
w_s	0.7 mm	-32.00 dB	2.43 GHz	11.35%
	1.3 mm	-54.18 dB	2.45 GHz	12.24%
	1.5 mm	-26.12 dB	2.42 GHz	10.26%

Following the addition of a meander line to the structure, Figure 17 shows the simulated axial ratio of the suggested slot array. The graph demonstrates that the antenna produces radiation in CP mode at 2.4 GHz, which is its resonance frequency. The antenna's capacity to radiate circularly polarized energy is indicated by the axial ratio, which is around 0.87 dB at resonance frequency 2.4 GHz. Additionally, the plot reveals that the 3 dB axial ratio bandwidth (ARBW) is 1.67%.

The simulated three-dimensional radiation pattern of the slot array antenna is depicted in Figure 18. Normally, a slot in the ground plane will suppress the radiation's back lobe, but because this slot is acting as an antenna, it radiates in both directions, as shown by the pattern. As demonstrated in Table 3, when compared to certain other slot antenna designs that have already been created, this structure performs better in terms of impedance bandwidth, impedance matching, and axial ratio bandwidth (ARBW). The table makes it quite evident that this antenna has an ARBW of 1.67%, which is higher than some of the earlier work. Regarding impedance matching, this antenna has a broad range of bandwidth. The proposed slot array antenna is also very easy to design. Additionally, this antenna makes achieving the required result easier by having only a single-port feed, in contrast to conventional CP antennas which would require several ports.

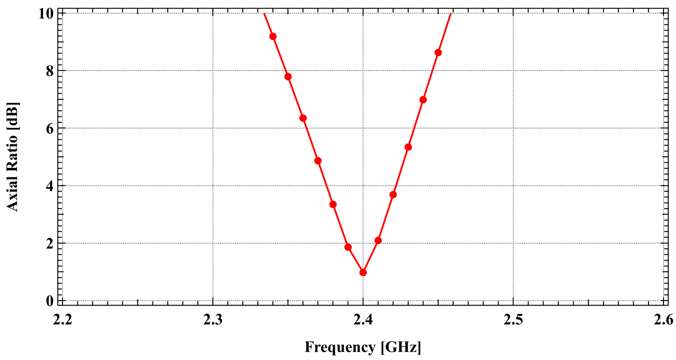

Figure 17. Axial ratio of the proposed design

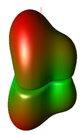

Figure 18. Simulated 3D radiation pattern of the slot array antenna

Table 3. Performance comparison of the proposed slot array antenna with other works

Reference	Phase shifter	No of port	Return Loss	ARBW	Impedance BW
[2]	No	Single-port	-32 dB	1.4%	$> 1\%$
[13]	Yes	Multi-port	-15 dB	-	-
[18]	Yes	Multi-port	-25 dB	-	8.3%
[24]	No	Single-port	-35 dB	1.5%	-
[This work]	No	Single-port	-54 dB	1.67%	12.24%

4. CONCLUSION

In this paper, a single-slot antenna with single feed and dual feed is designed and simulated to realize circular polarization. They have a return loss of -42.189 and -46.712 dB respectively indicating good impedance matching. Then a slot array antenna for circular polarization for S-band application is presented. Signals are fed into the arms of the slot by microstrip lines. It is evident from the simulated results that the slot array antenna can achieve circular polarization at 2.4 GHz frequency ensuring S-band applications. The simulated results also show that the antenna shows very good impedance matching and impedance bandwidth percentage of -54.13 dB and 12.24% respectively. The antenna has axial ratio less than 1 dB at resonance frequency and has a axial ratio bandwidth of 1.67%.

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