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Optimum concentric circular array antenna with high gain and side lobe reduction at 5.8 GHz

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Abstract. The significance of high gain directional antennas stems from the need to cope up with the everyday progressing wireless communication systems. Due to low gain of the widely used microstrip antenna, combining multiple antennas in proper geometry increases the gain with good directive property. Over other array forms, this paper uses concentric circular array configuration for its compact structure and inherent symmetry in azimuth. This proposed array is composed of 9 elements on FR-4 substrate, which is designed for WLAN applications at 5.8GHz. Antenna Magus software is used for synthesis, while CST software is used for optimization. The proposed array is designed with optimum inter-element spacing and number of elements achieving a high directional gain of 15.7 dB compared to 14.2 dB of available literature, with a high reduction in side lobe level of -17.6 dB.

1. Introduction

With the developing of wireless communications, it is nowadays required to design directional antennas with high gain and well matched impedance [1,2]. Microstrip patch antenna has been widely used owing to its small size, low profile, lightweight, low cost and easy to conform [3,4]. However, a main drawback of the microstrip patch antenna is the low gain it exhibits [5,6]. The increased gain is achieved by means of simultaneous usage of several antennas [7]. With the arrangement of array elements in a specific configuration, radiation pattern can be scanned electronically in a given direction [8]. In this paper, a resonant frequency of 5.8 GHz is used for WLAN as the 5 GHz frequency band suffers from less interference, supports higher data rate and can carry up to 23 non-overlapping 20 MHz channels and 12 non-overlapping 40 MHz channels compared to a maximum of 3 non-overlapping 20 MHz channels of the 2.4 GHz [9,10]. Among the commonly used arrays, concentric circular array is intended in this paper for its compact structure and inherent symmetry in azimuth, thus, being a highly desirable choice for full peripheral coverage [11].

Many researches have tried to increase the gain with the use of arrays. However, such studies still lack to achieve an optimum array that provides high gain with minimal number of array elements for low cost and small size design. The optimum design proposed in this paper is attained through many stages, starting from the careful selection of single element using an expert synthesis software (Antenna Magus), with low cost substrate (FR-4), selecting proper array geometry, and forming

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minimal number of elements that achieve high gain with reduced side lobe level through optimized inter-element spacing.

2. Design and simulation of single array element

It is often ambiguous to find the best approach for an antenna design. Published literature may be unclear or contradictory and thus provide insufficient information for confident design choices. Therefore, careful selection and design are performed using an expert design system (Antenna Magus) that is thoroughly tested for a wide range of design criteria. Then, a full-wave simulation using Computer Simulation Technology (CST) is performed to optimize the selected element.

2.1. Selection of single element

Modern wireless systems require high gain, low profile, lightweight, and simple structure antennas to ensure reliability, mobility, and high efficiency [12]. Other characteristics are also considered for preferred design, such as patch, planar, inset-fed, integrated, and low cost antennas. To fulfill such characteristics, the expansive antenna database of Antenna Magus is used.

After exploring the antenna database taking into account the above characteristics, from over 300 antennas two candidate antennas are obtained, from which one is then selected. These two antennas are rectangular inset-fed microstrip patch antenna and circular inset-fed linearly polarized patch antenna. The two candidate antennas are then designed using Antenna Magus and simulated using CST, which shows the circular antenna outperforming the rectangular one, as demonstrated in the figures below.

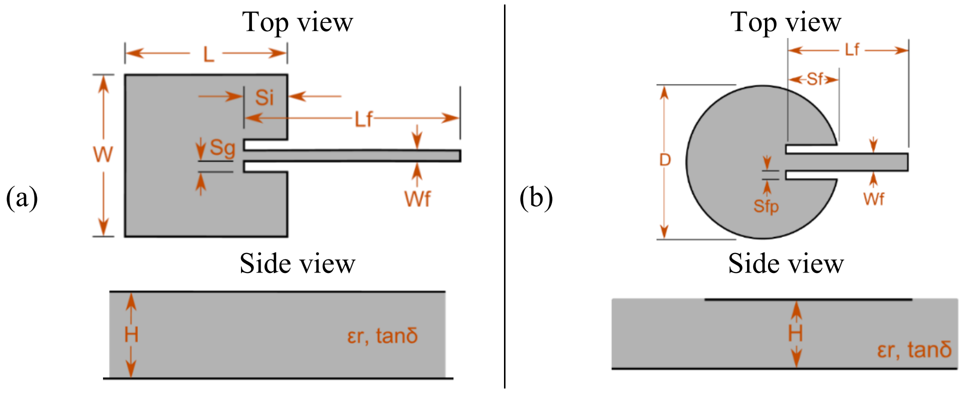


Figure 1. Candidate antenna geometry (a) Rectangular antenna (b) Circular antenna.

Table 1. Antenna physical parameters (a) Rectangular antenna (b) Circular antenna.

	(a)			(b)		
	Description	Value		Description	Value (50Ω)	Value (75Ω)
L	Patch length	11.94 mm	D	Patch diameter	14.57 mm	14.2667 mm
W	Patch width	15.88 mm	H	Substrate height	1.2 mm	1.2 mm
W_f	Feed line width	2.859 mm	ε_r	Relative permittivity	4.3	4.3
L_f	Feed line length	14.30 mm	W_f	Feed line width	2.334 mm	1.097 mm
H	Substrate height	1.47 mm	L_f	Feed line length	14.30 mm	14.70 mm
ε_r	Relative permittivity	4.3	S_f	Feed inset	6.216 mm	6.057 mm
tanδ	Loss tangent of the substrate medium.	0	S_{fp}	Spacing between patch and feed line.	249.3 μm	249.3 μm
S_i	Feed inset from edge of patch.	4.151 mm	tanδ	Loss tangent of the substrate medium.	0	0
S_g	Spacing between feed line and patch.	299.1 μm				

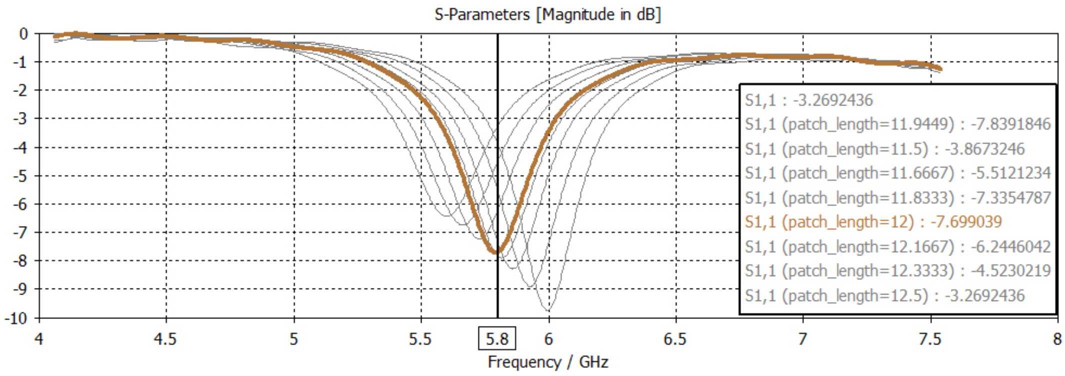


Figure 2. Return loss of rectangular patch antenna.

As Figure 2 shows, the return loss for rectangular antenna is about -7.7 dB, indicating low performance, while for circular antenna it is about -10.3 dB as shown in Figure 3, which indicates a better performance than the rectangular one, since return loss should not exceed -10 dB. Besides, the voltage standing wave ratio (VSWR) for rectangular antenna is about 2.4 that is above the good match level, while it is 1.9 for the circular antenna, which indicates good antenna match. Thus, among the two candidate antennas, the circular antenna is the one selected.

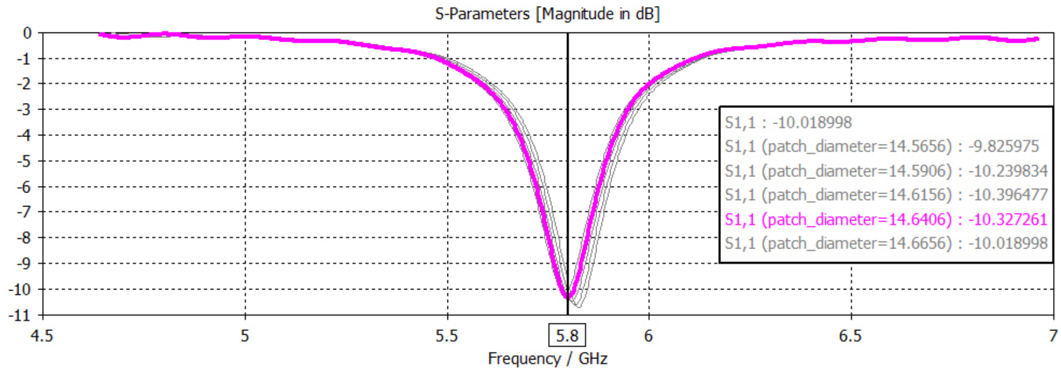


Figure 3. Return loss of circular patch antenna.

The two candidate antennas are simulated using the default standard input impedance of 50 Ω. It is then found that the circular antenna with the other standard impedance of 75 Ω is outperforming, where the return loss is about -13.3 dB compared to about -10.3 dB of that with 50 Ω, as illustrated in Figure 4. In addition, the VSWR is decreased to about 1.6 with 75-ohm circular antenna.

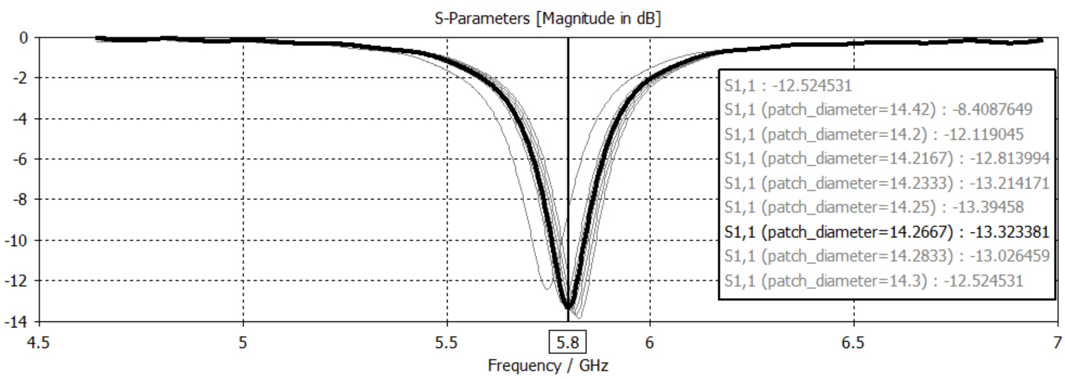


Figure 4. Return loss of circular patch antenna with 75 Ω.

2.1.1. Selected antenna element. The 75-ohm circular inset-fed linearly polarized patch antenna is finally the one selected to be used for circular array, as this selection shows reduced return loss of -13.3 dB and VSWR of 1.6, indicating better performance over the rectangular antenna and the circular one with 50 Ω. The selected antenna is then optimized to resonate at 5.8 GHz.

The geometry of the selected antenna element is as shown in Figure 1(b), where the patch shape is circular that is placed on a rectangular FR-4 substrate with input impedance 75 Ω operating at 5.8 GHz. The FR-4 substrate is used for its low cost in order to achieve a low cost array antenna.

3. Design and simulation of antenna array

Usually the radiation pattern of a single antenna element is relatively wide, and each element provides low directivity (gain). In many applications, it is necessary to design antennas with very directive characteristics (very high gains) to meet the demands of long distance communication. This can be achieved by forming an array of radiating elements in an electrical and geometrical configuration. Five controlling parameters shape the overall pattern of an antenna array that is composed of identical elements. These elements include the geometrical configuration of the overall array, spacing between elements, excitation amplitude and phase of each element, and relative pattern of the individual elements [8].

3.1. Optimum number of array elements

In this paper, it is aimed to achieve a high gain that is beyond 15 dB while maintaining a minimum number of array elements to fulfill a low cost design.

As Table 2 depicts, circular array is designed with different number of elements to reach the desired gain, which is achieved by a number of eight elements. A central element is added to increase the steering capability of the array.

Table 2. Comparison between arrays.

No. of Elements	Directivity (dBi)	Gain (dB)
1	6.8	5.7
2	9.4	8
4	13.3	11.8
(4 + 1)[a]	13.7	12.6
8[b]	16.2	14.8
8[c]	16.3	15.2
(8 + 1)[a]	16.7	15.4
(8 + 1)[d]	17.2	15.7

[a] With central element.
[b] Partially uniform.
[c] Fully uniform.
[d] Non-uniform.

From Table 2, it can be seen that the non-uniformly spaced eight-element array with central element is achieving the highest value of gain with good directive property, as the higher the number of array elements the higher the gain, and thus the array directivity. Thus, this number of elements is deemed to be the optimum number for a low cost design fulfilling the intended gain.

3.2. Optimum inter-element spacing

Inter-element spacing between array elements should be designed carefully, as a spacing below half wavelength of the operating frequency will increase mutual coupling, while a spacing greater than one wavelength will exhibit grating lobes which degrade the array performance [13].

Figure 5 portrays the partially uniform eight-element array with different inter-element spacing, where the array with a spacing of 0.6λ is shown to be more directional with minimised side lobes.

As the inter-element spacing increases the array starts to exihibt greater side lobes. Similarly, as the inter-element spacing decreases below 0.5λ, the array starts to face high mutual coupling between array elements, since higher proximity between array elements causes higher signal interaction.

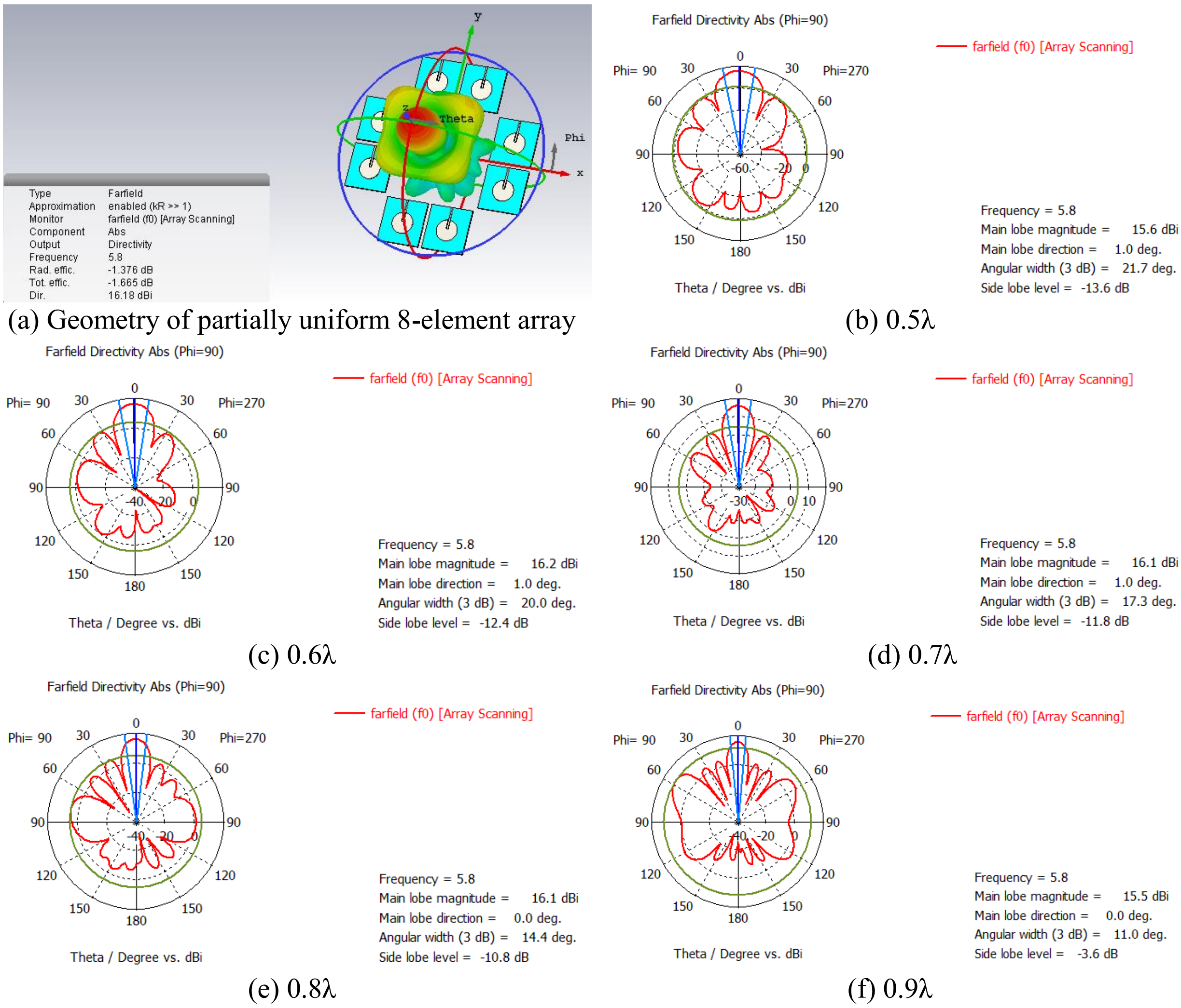


Figure 5. Polar plot of eight-element circular array with different inter-element spacing.

Figure 6 illustrates a nine-element array, where (a) is fully uniform with an optimum uniform spacing of 0.7λ, while (b) is non-uniformly spaced showing the optimum non-uniform configuration. The non-unform array is outperforming, as the directivity is 17.2 dBi compared to 16.7 dBi of the uniform one, and the side lobe level is -17.6 dB compared to -11 dB, respectively.

As compared to the nine-element rectangular array, the circular array outperforms the rectangular array as demonstrated in Figure 6 (c), where the directivity is 17.2 dBi for the circular compared to 15.6 dBi for the rectangular array. In addition, the side lobe level for the circular is -17.6 dB while it is -13.5 dB for the rectangular array.

The optimum inter-element spacing for non-uniform eight-element circular array is about 0.6λ, while it is 0.7λ for uniform eight-element circular array with central element. For non-uniform eight-element circular array with central element, the average inter-element spaing is about 0.71λ. Since geometrical configuration is a controlling parameter that shapes the overall pattern of an antenna array, good directional pattern and gain are achieved through non-uniform geometry manipulation.

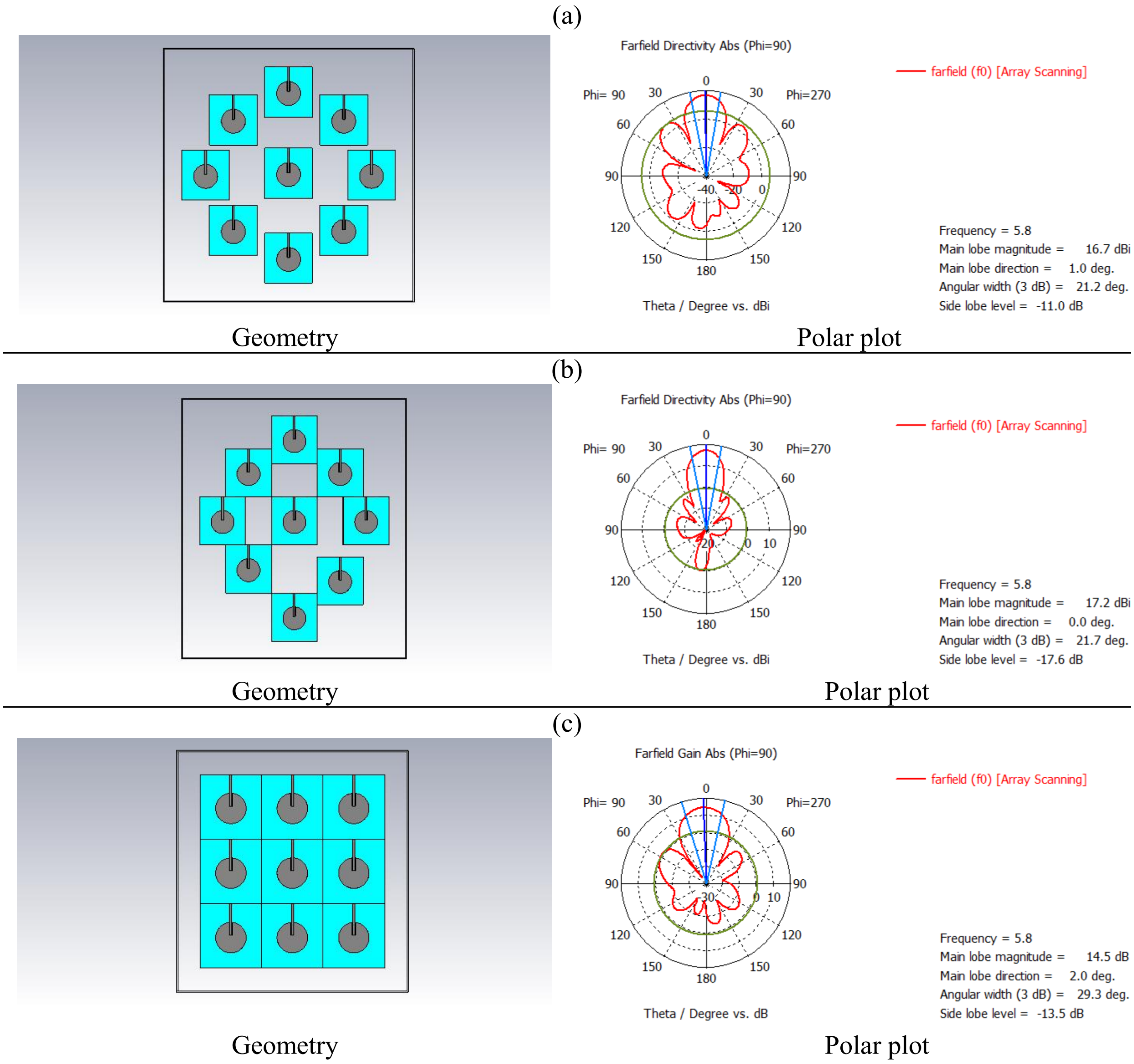


Figure 6. 9-element array (a) Uniform 8-element circular with central element (b) Non-uniform 8-element circular with central element (c) 9-element rectangular array.

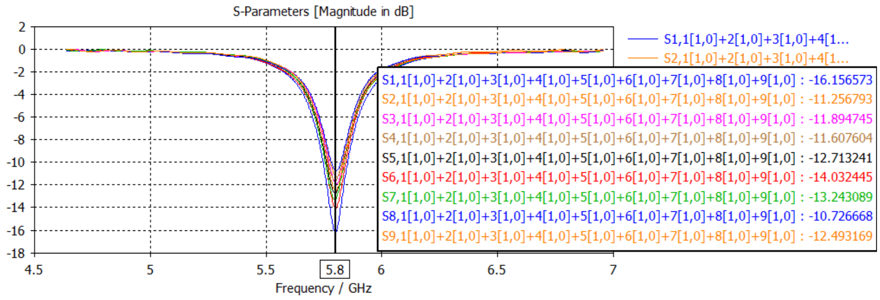
4. Proposed circular array design

From the discussion above, the proposed circular array is the eight-element circular array with central element that is non-uniformly spaced, since this design achieves reduced return loss, provides higher gain, and produces uniform directional radiation pattern as a result of optimum non-uniform arrangement.

As demonstrated by Figure 7, the proposed design shows a return loss of -16 dB, while the mutual coupling is minimized to -27 dB, indicating good performance as mutual coupling is below than -20 dB. The design is optimized to resonate at the frequency of 5.8 GHz.

Compared to available literature [14], the proposed design demonstrates to be outperforming, where the gain is 15.7 dB compared to 14.2 dB of the available literature, considering the same number of elements.

(a)



(b)

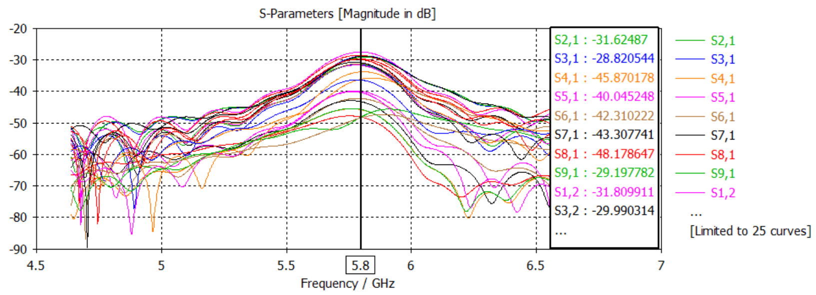


Figure 7. Eight-element circular array with central element (a) Return loss (b) Mutual coupling.

5. Conclusion

In this paper, an eight-element circular array with central element is designed for WLAN applications at 5.8 GHz. The design is optimized to have a minimum number of array elements for low cost design with optimized inter-element spacing in such a way to avoid the exhibition of grating lobes. The proposed design realizes high gain of 15.7 dB with high reduction in side lobe level of -17.6 dB.

Acknowledgement

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