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Wideband Gap Coupled Sectoral Antenna for Communication Systems

Abhishek Kandwal*, Jai V. Chauhan, and Sunil K. Khah

Abstract—This paper presents the design of a novel wideband gap coupled sectoral antenna for communication systems. The circular patch is placed in the aperture of four sectoral rings. The antenna parameters are optimized using various simulations to attain good return loss and corresponding resonant frequency. The antenna operates in X-band at 10.35 GHz showing wideband characteristics along with high directivity and reduced side lobe level to a good extent. The antenna has also been studied using fuzzy inference system (FIS). The return loss and analogous frequency obtained from simulated results and fuzzy system are compared and in good agreement. Design is extended to an array of nine elements mutually coupled to the active fed patch. The antenna is fabricated, and the simulated results are found to be in good agreement with experimentally measured ones. A bandwidth of 900 MHz at resonant frequency of 10.35 GHz with a directivity of 7.0 dBi and reduced side lobe level of −18.9 dB is therefore obtained.

1. INTRODUCTION

Microstrip antennas (MSAs) have many attractive features such as low profile, light weight, ease of manufacture, conformability to curved surfaces, low production cost, and compatibility with integrated circuit technology. These attractive features have recently increased the application of MSAs and stimulated greater effort to investigate their performances. MSAs have been used in various configurations such as square, rectangle, circle, triangle, trapezoid, ellipse, etc. The development of small-integrated antennas plays a significant role in the progress of the rapidly expanding military and commercial communications applications. Wideband wireless connection promises to make interactive voice, data, and video services available anytime and anywhere [1–13]. In microstrip antenna (MSA) designs, it is very important to determine the resonant frequencies of the antenna accurately as these MSAs have narrow bandwidths and can only operate effectively in the vicinity of the resonant frequency. So, a technique to compute the resonant frequency accurately is helpful in antenna designs. Several techniques are available in the literature to calculate the resonant frequency of microstrip antenna (rectangular, circular, etc.), as these are the most popular and convenient shapes [14–19]. These techniques can be broadly classified into two categories viz. analytical and numerical techniques. The analytical techniques offer both simplicity and physical ease, but depend on several assumptions and approximations that are valid only for thin substrates. The numerical techniques provide accurate results but usually require considerable computational time and costs. Models based on different algorithms are used in calculating resonating frequency of different microstrip antennas. Applications of genetic algorithms for optimization problems are widely known. Their advantages and disadvantages in comparison with classical numerical methods are also known. The performance of the genetic algorithm is determined by the investigation and utilization of relationships throughout the run. This balance

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* Corresponding author: Abhishek Kandwal (kandwal_abhishek@rediffmail.com).
The authors are with the Electromagnetic Analysis Lab, Department of Physics and Materials Science, Jaypee University of Information Technology, Waknaghat, Solan, HP 173234, India.

between the utilization of the whole solution space and the detailed searching of some parts can be modified to change the genetic algorithm operators (i.e., election, crossover and mutation). Fuzzy logic can be used for dynamically computing appropriate genetic algorithm control parameters using the experience and knowledge of the operators. This adaptive change of the selected parameters is taking place by the way of Fuzzy Inference System on the basis of genetic algorithm feedback [4]. Genetic algorithm feedback is realized by means of specially designed characteristics. The FIS is designed on the basis of genetic algorithm expert knowledge. The Matlab Fuzzy Logic Toolbox was used for FIS development. Fuzzy inference systems are the most essential modeling tool based on the fuzzy set theory [20–24].

In our proposed antenna design, we used aperture sharing technique to obtain better antenna characteristics. An array of 3×3 circular patches was placed in the aperture of 3×3 array of sectoral rings. We also used fuzzy inference system or fuzzy logic approach to calculate the resonant frequency and corresponding return loss. The data obtained using FIS model are compared with the results obtained through HFSS simulation software and in good agreement with each other. Further the antenna design is extended to an array of nine elements mutually coupled to each other. The results are therefore compared using simulation software and experimentally tested.

2. ANTENNA DESIGN AND FUZZY APPROACH (FIS)

The results of the proposed antenna design of a novel gap coupled sectoral antenna are presented in this section. Impedance bandwidth is specified as the frequency bandwidth in which the return loss is greater than 10 dB. Different design parameters are calculated and discussed. Simulation softwares such as CST studio suite and HFSS are therefore used. For experimental verification, prototype is designed and tested using vector network analyzer (VNA).

2.1. Geometry of Antenna

The geometry of the proposed antenna consists of a gap coupled sectoral antenna with a circular patch placed in the aperture of the four sectoral rings as shown in Figure 1. The antenna consists of a finite ground plane with a dielectric substrate. The dimensions of the ground plane and substrate are ($116\,\text{mm} \times 116\,\text{mm}$). The substrate used is Rogers/Duroid RT 5880 with a dielectric constant of 2.2, loss tangent of 0.0009 and thickness/height $(h) = 1.59\,\text{mm}$. The circular patch is of radius $(r) = 3\,\text{mm}$. The circular ring of inner radius $(r_1) = 5\,\text{mm}$ and outer radius $(r_2) = 15\,\text{mm}$ is divided into four sectors by cutting notches. The horizontal gap and vertical gap between the four ring sectors is same $(g) = 4\,\text{mm}$. The antenna is fed coaxially at a distance of (5, 5) at an angle of 45 deg. from the center of the antenna structure. Only one of the sectors is fed coaxially and rest of the patches act as parasitic patches coupled mutually to the active patch with an element spacing of 1 mm. Figure 2 shows the prototype of the antenna designed.

Figure 1(c) shows the equivalent circuit diagram of single element antenna. In the circuit diagram, ΔL represents the inductance introduced because of notches and ΔC the introduced capacitance because of notches. As a central circular patch is parasitically coupled with our main patch (ring), there will be a modification in the equivalent circuit and that is represented in Figure 1(d). If we compare Figure 1(c) with Figure 1(d), we observe a capacitance C_g which is introduced because of gap coupling.

In Figure 1(c),

R_1 represents resistance because of ring patch,

L_1 represents inductance because of ring patch,

C_1 represents capacitance because of ring patch.

In Figure 1(d),

R_2 represents resistance because of central circular patch,

L_2 represents inductance because of central circular patch,

C_2 represents capacitance because of central circular patch.

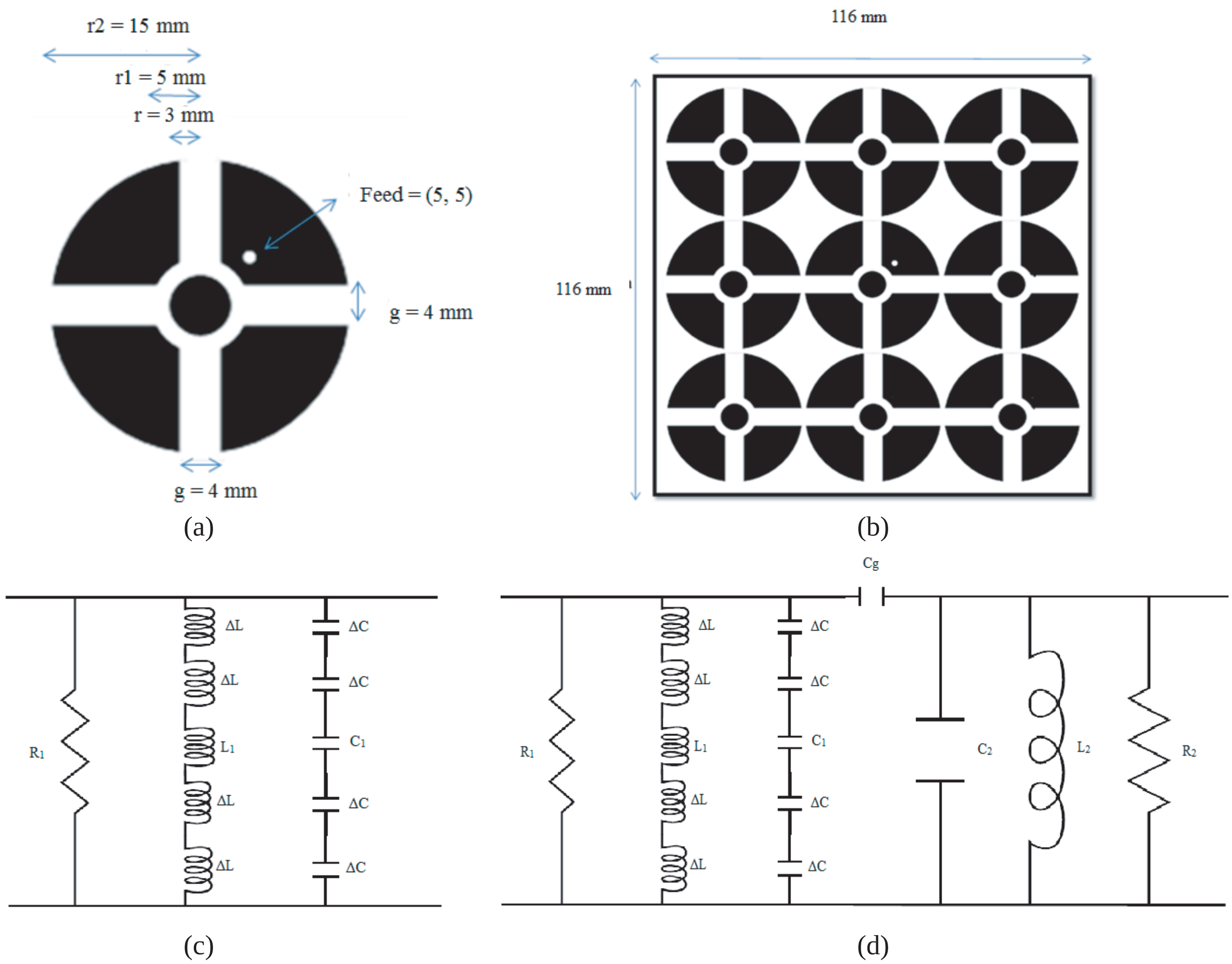


Figure 1. Geometry of proposed microstrip antenna. (a) Single element. (b) Nine element array. (c) Equivalent circuit of ring with notches. (d) Equivalent circuit of whole single element.

Figure 2. Prototype of proposed microstrip antenna.

Figure 1(c) shows the equivalent circuit of a ring with notches. In this, delta L and delta C show the inductance and capacitance introduced because of notches. As the copper is etched because of notches, the effective capacitance of the patch will decrease, and inductance is increased.

For a capacitor, in parallel combination

$$C = C_1 + C_2 + C_3 + \ldots.$$

For series combination

$$1/C = 1/C_1 + 1/C_2 + 1/C_3 + \ldots.$$

So, in series combination effective capacitance is reduced on adding the elements. That is why we add delta L to our circuit and vice versa for inductance.

2.2. Fuzzy Inference System (FIS Approach)

The FIS is a popular computing framework based on the concepts of fuzzy set theory, fuzzy if-then rules, and fuzzy reasoning. It is a very powerful approach for building complex and nonlinear relationship between a set of input and output data. FIS is used in calculating the physical dimensions of patch and the feed location for a given resonant frequency, an input resistance, a bandwidth, and a dielectric substrate material. Fuzzy Inference System is used for the controlling of parameters. The input values are crisp numbers and must be determined for applying FIS to control the parameters. The input values are obtained through numerical or simulated calculations. With crisp inputs and outputs, a fuzzy inference system implements a mapping from its input space to its output space. Basically a fuzzy inference system is composed of functional blocks in which, a rule base containing a number of fuzzy if-then rules, a database which defines the membership functions of the fuzzy sets used in the fuzzy rules, a decision-making unit which performs the inference operations on the rules, a fuzzification interface which transforms the crisp inputs into degrees of match with linguistic values, a defuzzification interface which transform the fuzzy results of the inference into a crisp output.

In the present study, FIS model is used to optimize different antenna parameters so as to obtain the lowest return loss in X-band. The Mamdani fuzzy interface system [19, 20] is used for optimization purpose. The inputs to the FIS system are feed position, gap between the sectors and radius of the circular patch. The input parameter values are the crisp numbers obtained from a data set generated from simulations carried out for the proposed antenna using CST Studio Suite. The feed point location is 5 mm, and the radius of the circular patch is varied from 1 mm to 4 mm with a step height of 0.5 mm respectively. The gap between the sectors is varied from 1 mm to 4 mm. The output of the FIS model represents the return loss and operating frequency parameters of the proposed antenna. The return loss ranges from 0 to 40 dB and frequency lies in the X-band.

The results obtained from the fuzzy model are compared with the simulated results from Ansoft HFSS software and are shown in Table 1 (for test data). From the results, it is clear that outcomes for frequency and return loss are in good agreement with each other with a marginal difference. Also the

Table 1. Results with HFSS and FIS model.

S. No.	Radius (r) mm	Feed (f) mm	Gap (g) mm	Simulated (HFSS)		FIS Model	
				Freq. (GHz)	RL (dB)	Freq. (GHz)	RL (dB)
1.	1	5, 5	4	10.518	20.51	10.6	20.5
2.	2	5, 5	4	10.509	20.87	10.6	20.5
3.	3	5, 5	4	10.350	22.91	10.4	23.8
4.	4	5, 5	4	10.194	28.32	10.1	28.5
5.	3	6.11, 6.11	4	9.825	8.18	9.97	8.31
6.	3	8.33, 8.33	4	13.011	11.03	13.2	12.7
7.	3	10, 10	4	13.74	33.85	13.6	33.5
8.	3	5, 5	3.75	10.374	29.78	10.4	31.6
9.	3	5, 5	3.625	10.32	40.369	10.4	36.6
10.	3	5, 5	3.5	10.284	38.98	10.4	39.4

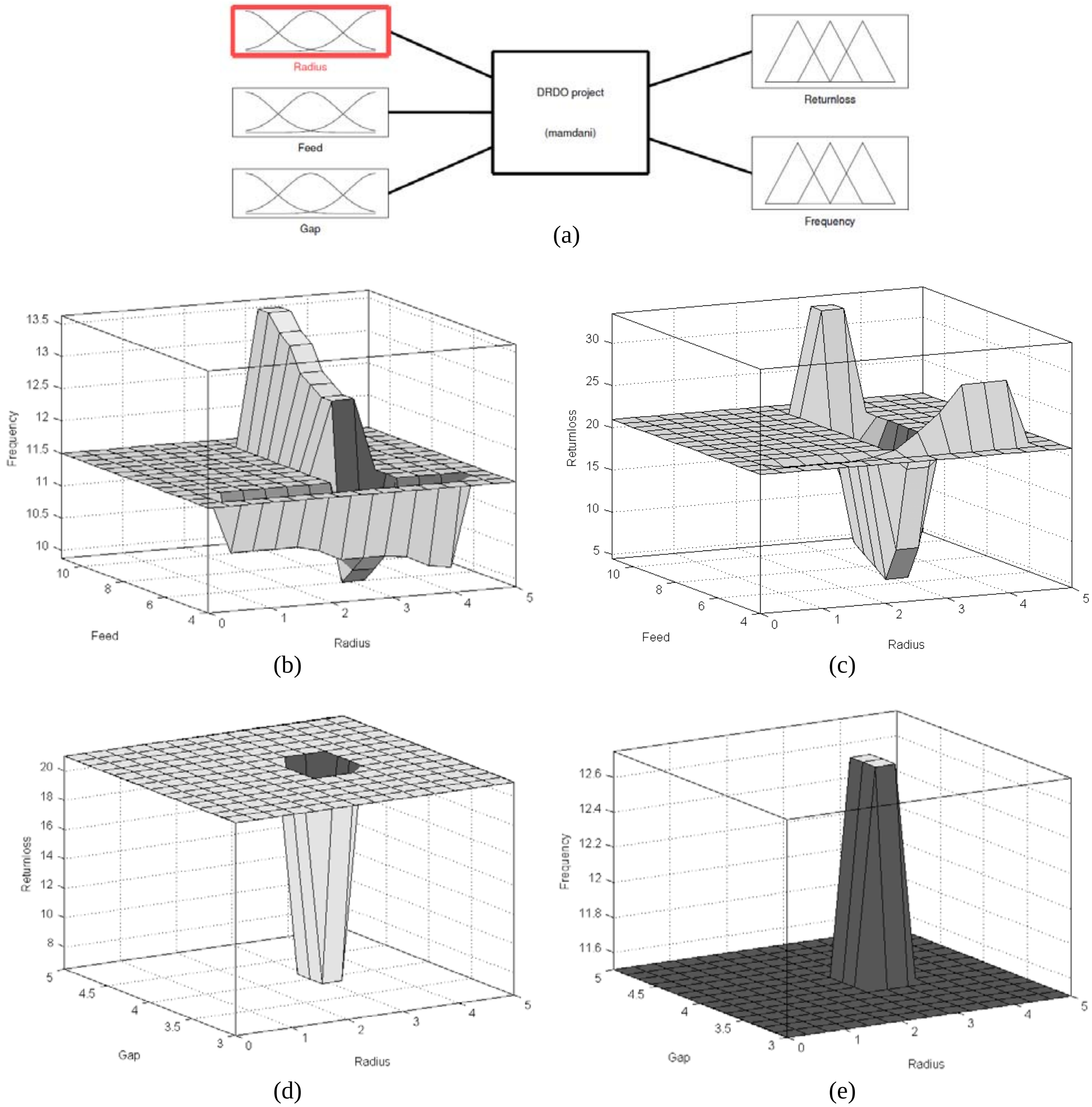


Figure 3. Surface plots for the variation of feed location, gap and radius with frequency and return loss. (a) Mamdani FIS model. (b) Frequency, feed, radius. (c) Return loss, feed, radius. (d) Return loss, gap, radius. (e) Frequency, gap, radius.

results obtained for other variations such as gap and radius with frequency and return loss are in good agreement.

The surface plots for the variation of frequency and return loss with feed location, gap and radius are shown in Figure 3.

3. SIMULATIONS AND MEASUREMENTS

In this section, the wide-band gap coupled sectoral antenna is studied in detail. The antenna is simulated and verified by measurement results. Parameters such as return loss, input impedance, impedance bandwidth for the cases are measured and calculated. The simulated radiation pattern is also presented

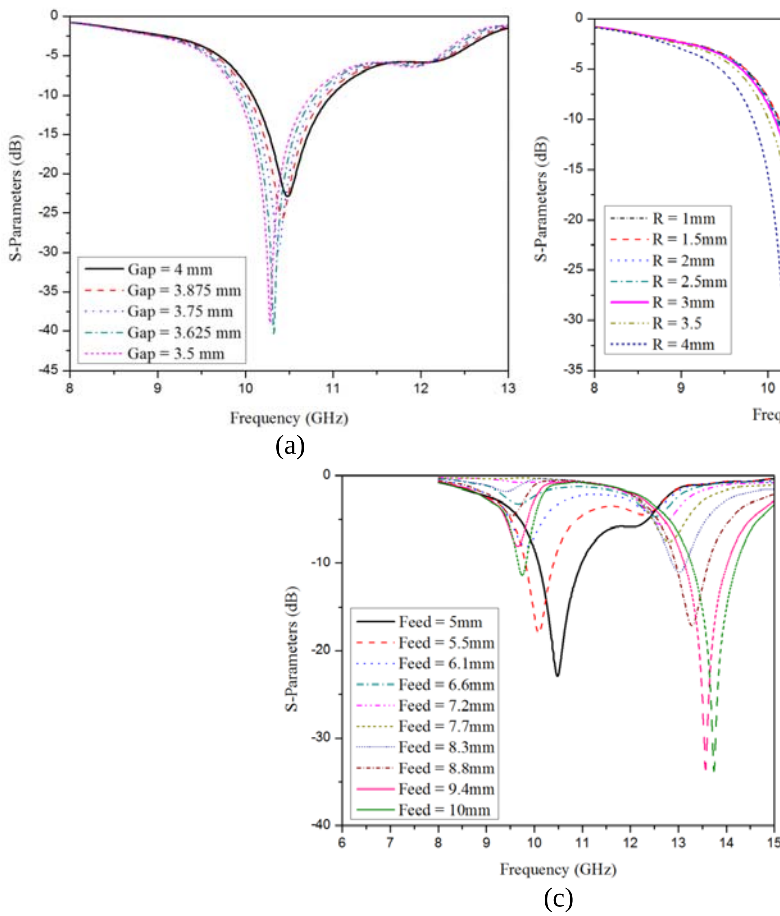


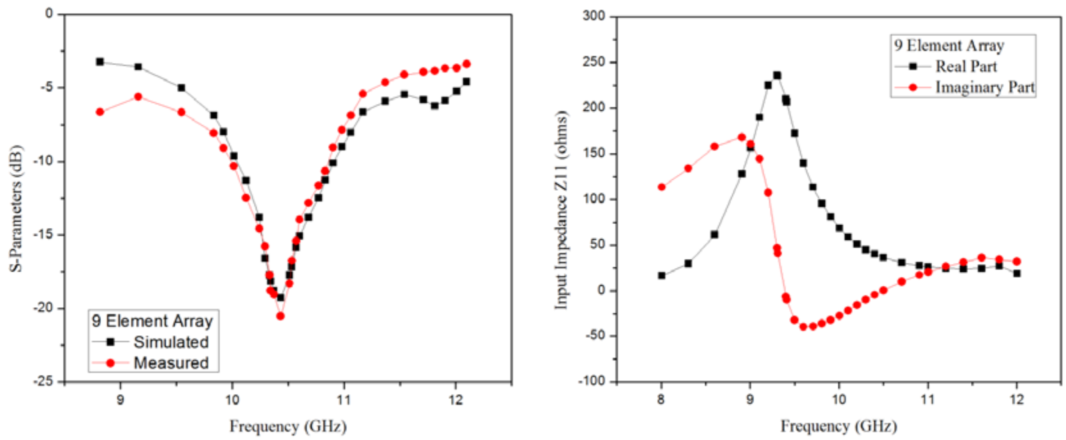
Figure 4. Variation of S-parameters with frequency for: (a) gap variation, (b) radius variation, (c) feed location variation.

for the proposed antenna structure. Simulations are done using HFSS simulation software and vector network analyzer (VNA) has been used for experimental measurement.

The antenna is tested for return loss and resonant frequency using different variations in the gap between the sectors, feed location and radius of the circular patch. Figure 4(a) shows the variation of S-parameters with the frequency. In this the gap is varied from 4 mm to 3.5 mm. As can be clearly seen from the graph, a bandwidth of 800–900 MHz has been obtained at almost all of the resonant frequencies. A maximum return loss of more than 40 dB has been obtained at resonant frequency. Now, the radius is varied from 1 mm to 4 mm. A maximum return loss of 27 dB has been obtained at the resonant frequency as shown in Figure 4(b). Figure 4(c) shows the variation of S-parameters with frequency when feed location is varied from 5 mm to 10 mm. In X-band, a maximum return loss of 23 dB has been obtained at feed location 5 mm.

Now the antenna is extended to an array of 9 elements. Only one of the elements is excited by keeping rest of the elements mutually coupled to it. The different results obtained for this antenna are shown in Figure 5. Figure 5(a) shows the variation of frequency with return loss. At the resonant frequency, the maximum return loss obtained is 19.2 dB for simulated case. The experimentally measured return loss at the resonant frequency is 20.5 dB. An impedance bandwidth of 890 MHz has been obtained through simulation measurement and a bandwidth of 900 MHz has been obtained through experimental measurement. Both the simulation and experimentally measured results are in good agreement with each other.

Figure 5(b) shows the input impedance variation with frequency. Both the real and imaginary parts are plotted. At the resonant frequency, it is seen that a good impedance matching has been obtained to achieve 50 ohms characteristic impedance.



(a) (b)

Figure 5. (a) Variation of S-parameters with frequency (for 9 element array). (b) Variation of input impedance with frequency (for 9 element array).

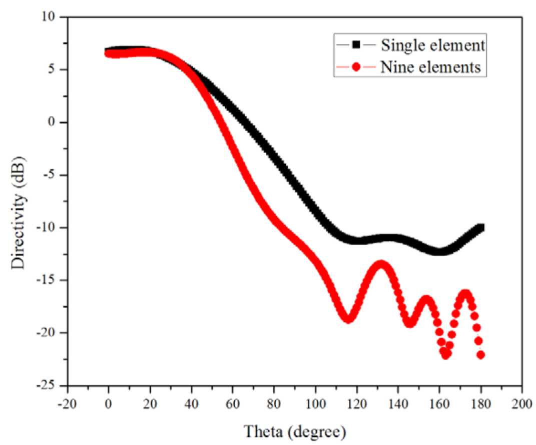


Figure 6. Radiation pattern (directivity plot) at frequency = 10.35 GHz.

The radiation pattern at the resonant frequency of 10.35 GHz is shown in Figure 6. The directivity plot for both the structures, i.e., structure with single element and structure with nine elements has been shown. A directivity of 6.0 dBi in the main lobe direction 11.0 degree has been obtained for single element. Within 3 dB angular width in the direction 89.1 degree, side lobe level of −16.3 dB has been obtained. When the single element is extended to nine elements; the directivity increases to 7.0 dBi in the main lobe direction 10.0 degree. Within 3 dB angular width in the direction 92.0 degree, side lobe level of −18.9 dB has been obtained.

4. CONCLUSION

Design analysis of a gap coupled sectoral antenna for communication systems has been presented for the proposed antenna structure. The proposed antenna with wide bandwidth is optimized using various simulations and MATLAB FIS based on fuzzy decision-making. It has been observed that the gap coupled geometry and optimizing antenna parameters results in good impedance matching with high impedance bandwidth along with high directivity and reduced side lobe level to a good extent. The designed antenna operates in X-band giving a wide impedance bandwidth of about 900 MHz with a directivity of 7.0 dBi and reduced side lobe level of −18.9 dB for application in wireless communications systems.

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