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High Gain and Wide Bandwidth Array Antenna for Sector Beam Pattern Synthesis

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Abstract—This paper presents a novel design structure of a series fed array antenna for desired shaped beam pattern synthesis. The desired beam shape is obtained by varying the width of patch elements. A uniform array is designed for the desired frequency, and then the proportionate values of the widths are calculated using amplitude coefficients obtained from the Woodward Lawson array synthesis method, while keeping excitation phase and inter element spacing constant. The proposed antenna is designed and simulated in HFSS. A prototype is fabricated on FR-4 epoxy dielectric material and tested at 12.5 GHz. The overall antenna has a compact size of 112 mm×34 mm×0.8 mm. The array structure exhibits impedance bandwidth of 1.8 GHz and fractional bandwidth of 15.2%, from 11 GHz to 12.8 GHz frequency range with return loss of −29.6 dB and high gain of 14.7 dB. The series fed configuration results in a VSWR of 1.38 and considerably low side lobe level of −21 dB. There is a fine similarity between simulation and fabrication measurement parameter values such as return loss, VSWR, gain, and bandwidth.

1. INTRODUCTION

For the past two decades, the concept of beam pattern has been extended to satellite communications and millimeter-wave applications. This area has received great extended attention in past and recent research [1, 2]. However, shaped beams generation using variation in patch dimensions of array antenna has not been reported so far. Most of the past research work reported the element patterns as identical [3–6]. Uniform excitation of array radiates in broad side with many side lobes. Nonuniform excitations offer reasonable directivity with approved side lobe level [7]. The convenient feature of a simple rectangular patch antenna allows us to change its gain by changing its width at the desired frequency. Hence, amplitude tapering of microstrip patch array antenna elements can be achieved by changing their width [8, 9]. However, most researchers have concentrated on gain enhancement and reduction of side lobe level, but not on beam shaping [10, 11]. Therefore, it is proposed to synthesize amplitude excitations for the shaped radiation pattern generation from a compact patch antenna array by unequal widths of the array elements.

Due to various advantages of patch antennas, they are used widely in modern communication engineering [12, 13]. Microstrip patch antennas mainly have two types of feeding, namely series-fed and corporate-fed techniques. Corporate-fed one suffers from small radiation efficiency due to various losses. Additional internal elements such as power dividers limit the main side lobe level, which is undesirable in beam shaping [14]. A series fed configuration is very simple to realize in microstrip patch arrays [15, 16]. In this configuration, all the patch elements are connected in series using transmission lines. For practical fabrication purpose, this configuration possesses a simple and compact feed network with lower feed line loss, while possessing compatibility with performance methods such as slots [17, 18].

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Fourier Transform and Woodward-Lawson methods are the two most popular array synthesis methods for shaped beams generation. Woodward method offers array design procedure with low side lobe level [19]. This paper presents a systematic approach to modify patch widths of a series-fed array antenna using amplitude coefficients calculated from Woodward-Lawson array synthesis method for desired beam shape. The proposed antennas possess good beam efficiency. Beam efficiency is the ratio of radiated power within main beam to the total power or ratio of gain and directivity or expressed as a function of centre-to-edge amplitude ratio [20]. The main beam is narrow with high gain and low side lobes, the antenna array offers appreciable beam efficiency.

2. ARRAY ANTENNA DESIGN

The overall procedure for the design, simulation, fabrication, and testing process is presented as a flowchart in Figure 1.

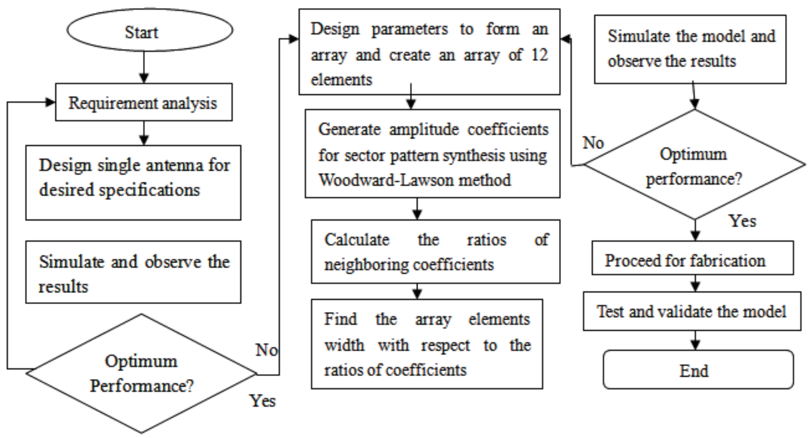


Figure 1. Flow chart describing the methodology.

A single element antenna for the desired frequency is shown in Figure 2(a). The width of the radiating patch is calculated as below.

2.1. Single Antenna Design

$$W = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}} \tag{1}$$

where f_r = resonant frequency, μ_0 = permittivity of free space, ε_0 = dielectric constant of free space. Effective dielectric constant is calculated by Equation (2).

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\sqrt{1+\frac{12h}{W}} \tag{2}$$

where ε_r = dielectric constant of the substrate, h = thickness of the substrate, and W = width of the patch

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} \tag{3}$$

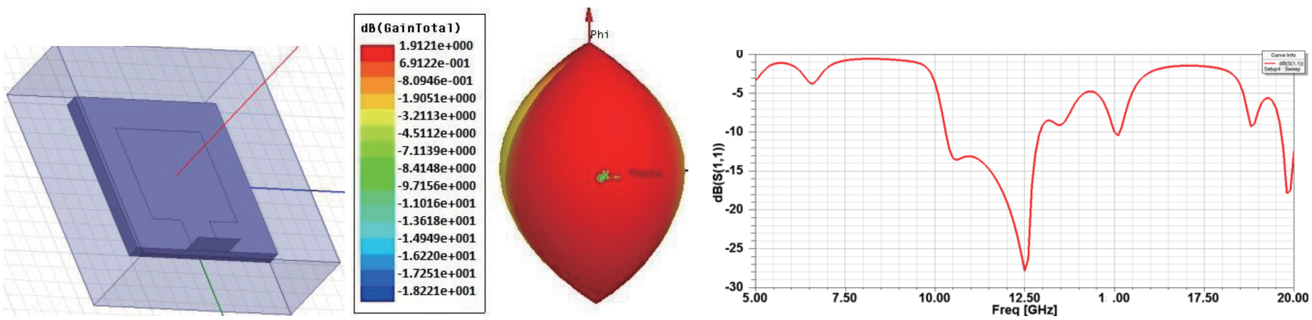
Here c = velocity of light in space. But the effective length of the antenna is longer than physical length due to fringing effect. It differs from the physical length by ΔL.

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)\left(\dfrac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\dfrac{W}{h}+0.8\right)} \tag{4}$$

The overall length of the patch is given by

$$L_{eff} = L + 2\Delta L \tag{5}$$

The antenna possesses a unidirectional radiation pattern along the Z-axis. Figures 2(b) and 2(c) show results of antenna simulation. The antenna has an impedance bandwidth of 300 MHz from 11.9 GHz to 12.2 GHz, and gain varies from 6.4 dB to 6.9 dB over the frequency range. It can be confirmed that the antenna has a unidirectional radiation pattern with good performance.



(a) (b) (c)

Figure 2. (a) Single antenna 3D view. (b) Radiation pattern of single antenna. (c) Return loss plot of antenna.

2.2. Full Array Design

To generate differently shaped patterns, array factor is expressed with amplitude variation at several sample points required for the desired shape. From Woodward-Lawson method, the array factor for a uniform linear array is expressed as below.

$$A(\theta) = \sum b_n \frac{\sin \dfrac{N}{2} kd(\cos\theta - \cos\theta_m)}{N \sin\left[\left(\dfrac{1}{2}\right) kd\left(\cos\theta - \cos\theta_m\right)\right]} \tag{6}$$

where N represents the total number of array elements, and m represents a specific element number.

$K{=}2\pi/\lambda$, the wave number. Here, b_n represents the amplitude coefficient for each array element. These values for the desired beam shape represented by $A(\theta)$ are found using Woodward Lawson array synthesis method. Table 1 below shows the calculated amplitude coefficients for an array of 12 elements to generate a sector pattern.

Table 1. Excitation amplitude coefficients computed from Woodward method.

Element number	Amplitude coefficient	Normalized coefficient	Element number	Amplitude coefficient	Normalized coefficient
1	0.0630	0.21	7	0.2927	1
2	0.0653	0.22	8	0.2391	0.81
3	0.0867	0.29	9	0.1567	0.53
4	0.1567	0.53	10	0.0867	0.29
5	0.2391	0.81	11	0.0653	0.22
6	0.2927	1	12	0.0630	0.21

The relation between the patch width and patch impedance is given by

$$R_{in} = \frac{1}{2G_e} \tag{7}$$

where

$$G_e = 0.00836\frac{W}{\lambda_0} \tag{8}$$

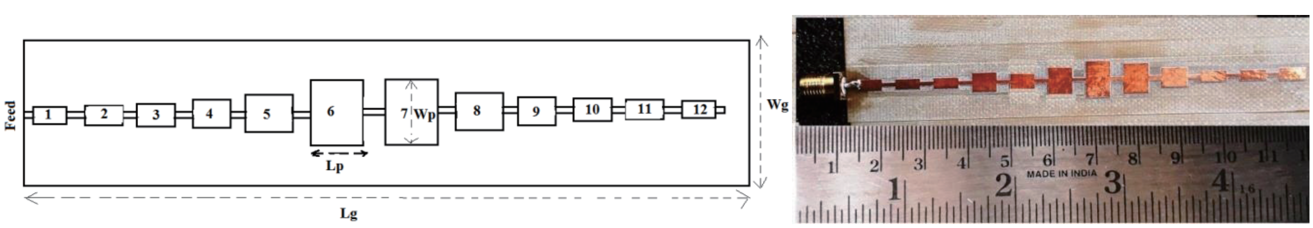
Here, G_e = conductance, W = patch width and λ_0 = free space wave length.

It can be concluded that impedance (R_{in}) and patch width (W) are inversely proportional, and the impedance offered by each element of an array antenna can be varied by controlling its width. An array of 12 identical patches with dimensions of 6 mm×7 mm is designed and placed on an FR-4 dielectric substrate of 0.8 mm thickness. All the patch elements have an equal length of 6 mm (L_p). The ground plane length and width are 112 mm×34 mm, and substrate dimensions are also same. The neighboring elements are separated with a uniform spacing of 3.1 mm and connected by a transmission line of width 1 mm. The array is connected to the source using a port with length of 6.1 mm and height of 15.8 mm for simulation. The width (W) of the patch elements is varied in the proportionate ratio of the amplitude coefficients which are found from Woodward-Lawson array synthesis method. They are synthesized such that the ratio of neighboring patches widths is equal to the ratio of neighboring amplitude coefficients. The calculated widths of the corresponding patches are tabulate din Table 2.

Table 2. Width of the patches calculated using amplitude coefficients of Woodward Lawson method.

Patch Number	1	2	3	4	5	6	7	8	9	10	11	12
Patch Width in mm (W_p)	2.62	2.56	2.54	4.60	5.66	7.00	7.00	5.66	4.60	2.54	2.56	2.62
Patch Length in mm (L_p)	6	6	6	6	6	6	6	6	6	6	6	6

The planned array antenna design is as shown in Figure 3(a). All the array patches are numbered from 1 to 12. A microstrip feed is connected to the left most patch. The same structure is fabricated as shown in Figure 3(b) and tested using network analyzer VNA 9 Anristu No. MS2037C).

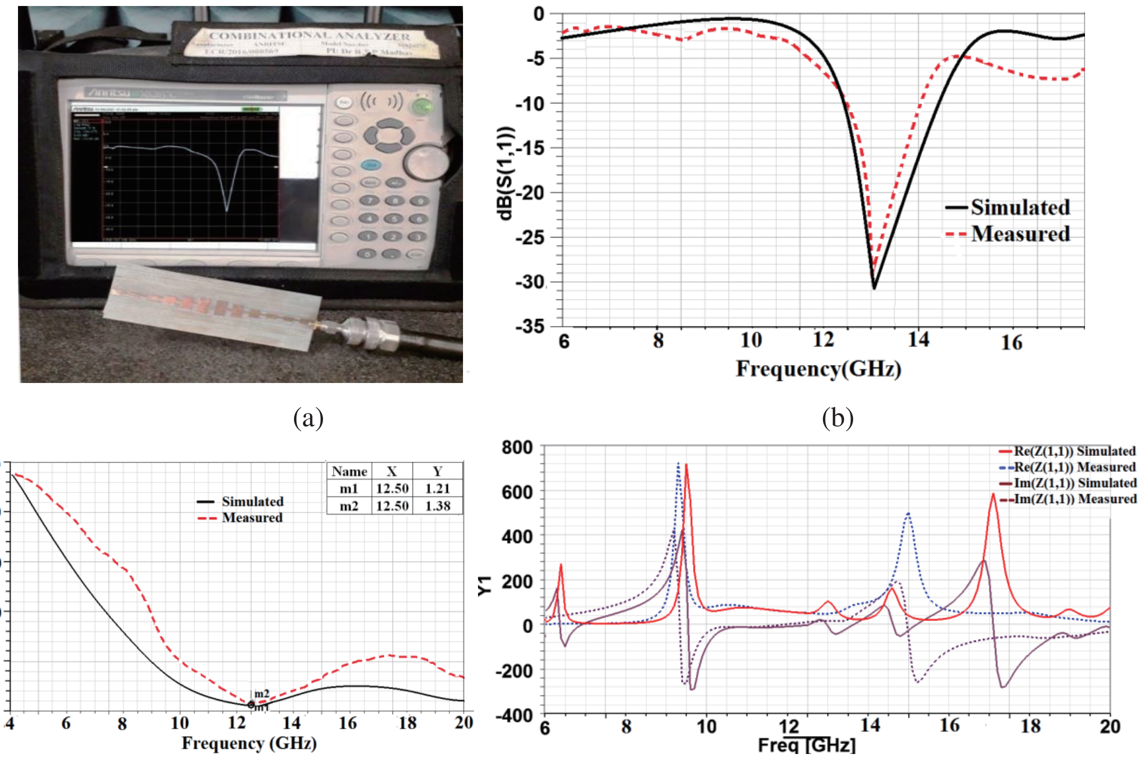


(a) (b)

Figure 3. Proposed antenna array. (a) Design simulation. (b) Fabricated structure.

3. SIMULATION AND EXPERIMENTAL RESULTS

The return loss of antenna fabricated as above is measured in lab and shown in Figure 4(a). The return losses of simulated and fabricated arrays are plotted in Figure 4(b) for comparison. VSWR values for both the arrays are shown in Figure 4(c). The return loss and VSWR of simulated array are −31.32 dB and 1.28, respectively. The simulated array exhibits an impedance bandwidth of 1.9 GHz from 11 GHz to 12.8 GHz frequency range for $|S_{11}| < 10$ dB. The bandwidth of the fabricated array can be observed from the return loss plot as 1.8 GHz over the same frequency range. The fabricated array exhibits a return loss of −29.6 dB and VSWR of 1.38. Compared with simulated values, it can be observed that both have similar values with good agreement.

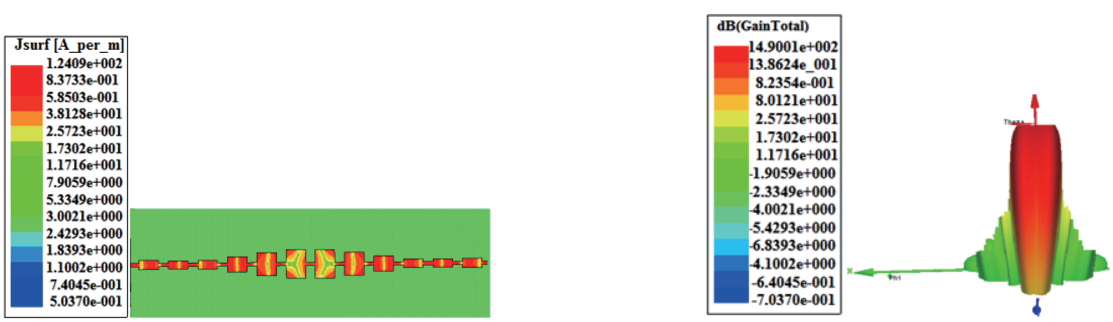


(a) (b)

(c) (d)

Figure 4. (a) Return loss simulation measurement. (b) Return loss simulation and measurement plot. (c) VSWR measurement. (d) Input impedance simulated and measured.

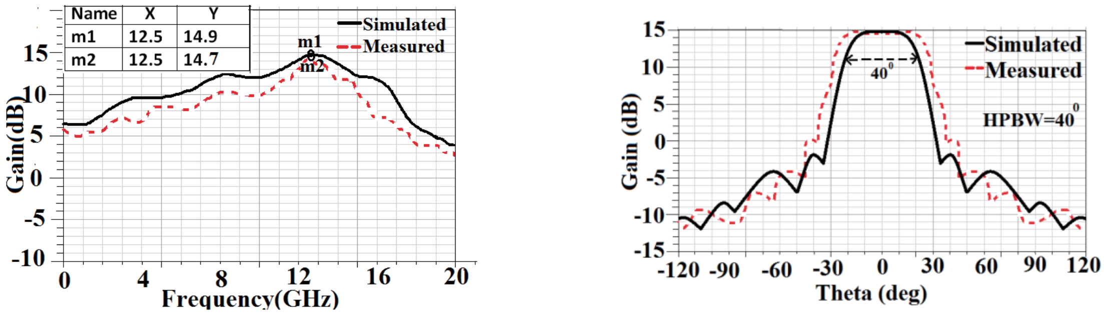
The input impedances of both the arrays are shown in Figure 4(d). The imaginary impedance at 12.5 GHz is zero, and it is concluded that the antenna is resonant at the desired frequency. The surface current distribution and 3D plot of gain for the simulated array are shown in Figures 5(a) and 5(b), respectively. They exhibit a symmetric nature across the array and vertical axis.



(a) (b)

Figure 5. (a) Surface current distribution of simulated array. (b) 3D Gain of simulated array.

The measured gain of fabricated antenna in an echoic chamber at different frequencies is plotted in Figure 6(a). The simulated and measured gain patterns are plotted on one graph and compared in Figure 6(b). A sector pattern in the main beam is achieved. The gain pattern is narrow with half power beam width of 40° at 11.9 dB. It can be noted that the array antenna has good directional



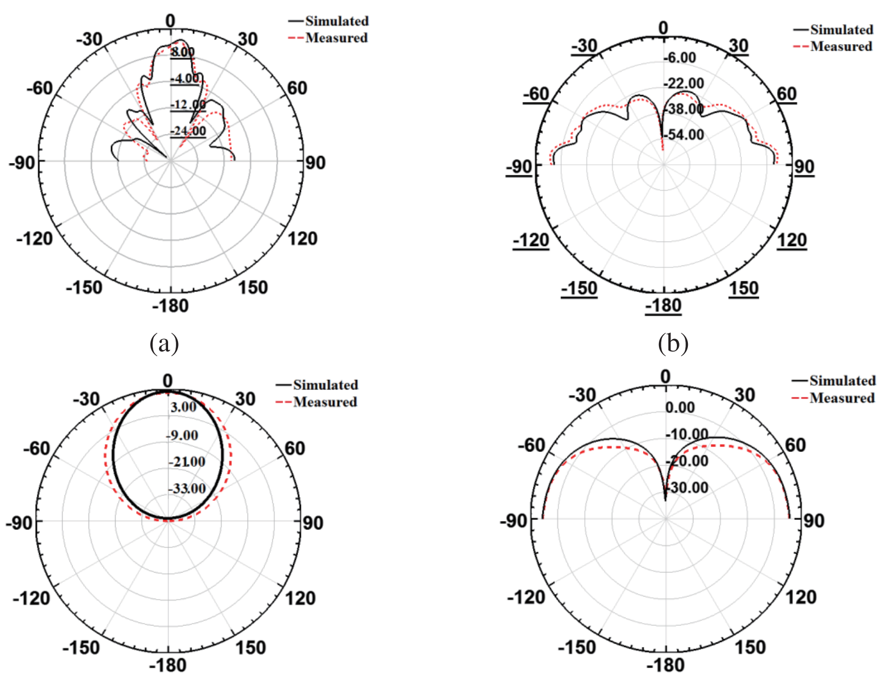
(a) (b)

Figure 6. (a) Frequency-gain plot. (b) Plot of sector shaped gain pattern.

pattern with gain 14.9 dB in the case of simulated array and 14.7 dB in the case of fabricated array. The directivity of the antenna is 15.9 dB. The beam efficiency, which is the ratio of gain and directivity, is 86%. Actual and measured results are slightly different, which may be due to constraints like mutual coupling losses, impedance losses, and other fabrication problems with material properties. The side lobe level is considerably low, -24 dB for the simulated array and -21 dB for the fabricated array.

The co- and cross-polarizations in the XZ-plane (H-plane) and YZ-plane (E-plane) at 12.5 GHz are shown in Figure 7. The co- and cross-polarization radiation patterns indicate that the main radiation pattern is at least 20 dB greater than the unwanted radiation pattern in the broad side direction ($\theta = 0$ and $\Phi = 0$).

The interested parameters of the fabricated antenna array are presented in Table 3. The past research work related to the array configuration used in this work is compared in Table 4.



(a) (b)

(c) (d)

Figure 7. (a) Co-polarization of E-plane. (b) Cross polarization of E-plane. (c) Co-polarization of H-plane. (d) Cross polarization of H-plane.

Table 3. Analysis of results of fabricated array.

Sl. No.	Parameter	value
2	Return Loss	−29.6 dB
3	VSWR	1.36
4	Gain	14.7 dB
5	Side Lobe Level	−21 dB
6	Bandwidth	1.8 GHz

Table 4. Comparison of results of the present work with past relevant research.

Reference no.	Year	No. of elements	Resonant Frequency (GHz)	Gain (dB)	Side lobe Level (dB)	Bandwidth (GHz)
[9]	2000	1×10	5.8	16.3	−20	0.9
[10]	2017	1×5	10	8.97	−13.61	0.24
[11]	2017	1×6	1.8	−23.1	−21.3	1.7
[12]	2018	1×2	2.5	4.17	−18.2	0.7
Present work	–	1×12	12.5	14.2	−21	1.8

4. CONCLUSION

A rectangular microstrip antenna array is designed and fabricated to generate sector shaped beam pattern with amplitude excitation control. Woodward-Lawson array synthesis method is used to generate the amplitude coefficients necessary to generate excitation amplitude. The widths of the transmission lines are varied with respect to proportions of amplitude coefficient values. The port is connected at the left most edge of the array using microstrip line feed. A linear configured array consisting of twelve patches is fabricated on an FR-4 dielectric substrate of constant 4.4 and height 0.8 mm. Performance metrics are measured at 12.5 GHz by synthesizing the widths of patch elements based upon coefficients. The simulated and measured sector patterns of a twelve element patch antenna array are compared. The array has a compact size of 112 mm×3.4 mm×0.8 mm. The fabricated antenna was tested using network analyzer. But fabricated antenna pattern has more ripples than the simulated pattern as widths optimization is according to the amplitude coefficients and cannot be exact due to the properties of components used. The same method can be used to generate many typical shapes and improve the accuracy by optimizing the values with any optimization algorithm.

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