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Design and Implementation of a Beam Forming Network for a Phased Array Antenna

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ABSTRACT

This dissertation presents a beam forming network (BFN) for phased array antenna-based on coherently radiating periodic structure (CORPS). The elements of CORPS are selected in such a way to obtain broad band characteristics, good return loss and good isolation between the radiating elements. These elements were arranged in such a way that the BFN naturally produces Gaussian amplitude. This methodology reduces the complexity of the conventional phased array design making it more flexible and minimizing the loss of energy inside the structure. A phase shifter design is proposed for the CORPS. The entire BFN's sub-blocks have been designed for the frequency band of 5.925 GHz to 6.425 GHz, which find applications in communication satellite, fixed wireless systems.

Keywords: Coherently radiating beam forming network, phased array antenna, fixed phase shifter, defected ground structure, power distribution network, adaptive beam forming

1. INTRODUCTION

Phased array antenna (PAA) have the potential to increase the system capacity of modern wireless networks. It provides a significant increase in capability over the directional antenna designs. Phased array antennas utilize beam steering that allows all energy to be focused on the intended receiver, thereby increasing its throughput[1]. Beam steering can be instantaneous which can be executed with electronic control, avoiding the mechanical and inertial problems of a rotating array. Since beam steering is controlled electronically, the direction of antenna's main beam can be steered rapidly in comparison with a mechanically steered antenna. Electronic steering is achieved by controlling the phase of the signals transmitted and/or received by the antenna elements. Phase shifters are the devices used to control the phase of the signal and are the heart of a phased array antenna system[2].

Antenna Array + Phase Shifter + Power Dividing n/w= PAA System

Beamforming can be achieved using the combination of power distribution and phase shifting circuits, in which signals will experience constructive and destructive interferences to achieve spatial selectivity. It has many applications in wireless communications, biomedical field and radar. Among the two categories of beam-forming techniques adaptive beam formers are used to detect the signal of interest at the output of sensor array[3].

This paper provides insight into the performance of the beam forming network (BFN) based on the more flexible and energy efficient structure known as CORPS-BFN. First, we proposed a power distribution network incorporating coherently periodic radiating structure (CORPS) to satisfy the output port's power requirement and the limits of scattering parameters for the entire structure. Finally a fixed-phase shifter with appropriate phase shift based on defected ground structure (DGS) is presented. Thus, these two sub-blocks when implemented together can form an efficient BFN for phased array antenna system. A novelty has been introduced in combining these two sub-blocks of BFN, where the number of phase shifters used is reduced.

2. WORKING PRINCIPLES

Phased Array Antenna system consists of three main sub blocks namely power distribution network, phase shifting circuit and an array of radiating elements, in which the main beam of the antenna is steered to the desired direction in accordance to the distribution of the power to the output ports and the phase that is being provided by the phase shifter block. Power distribution network is implemented by coherently radiating periodic structures (CORPS) structure. When CORPS concepts applied to BFNs, it is known as C-BFNs[4]. This structure is more advantageous as it reduces the complexity of conventional phased antenna array systems, improves the antenna radiation characteristics (directivity, suppression of grating lobes, beam shaping), reduces physical variables of system (area, weight), loss of energy inside the structure is highly limited and it is more flexible.

A C-BFN consists of alternate repetitive combination of two types of nodes namely splitting node (SN) and recombining node (RN). SNs are also responsible for the interconnection between layers of the network. The RNs recombine the power

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entering through its input-ports. A vector sum of the field throughout a RN will result in the recombination process. A general configuration for a planar C-BFN consists of K input ports and K+ [number of layers] output ports. General-split nodes are such that have one input port and M output-ports. At each output port is delivered an M^{th} part of the power introduced at input port, as expressed in Eqn. (1)

$$J_s = \sum_{i=1}^{M} |E_i e^{(j\theta_i)}|^2 G_s \quad (1)$$

where, J_s is the power delivered by the M output ports of SN, G_s is the real part of the admittance seen at output ports, E_i and θ_i with i=1, 2,….M are the magnitude and phase of each of the i output ports, respectively.

A C-BFN configuration with 1 input port, M- output ports and N-layers is shown in Fig. 1. In general, the power values after each layer correspond to the Pascal's Triangle coefficients normalised by the addition of its in-row coefficients. Binomial approximations are used to obtain the Pascal's triangle coefficients, as follows:

$$(1+y)^N = \sum_{n=0}^{N} \binom{N}{n} y^n \quad (2)$$

where N in Eqn. (2) is the number of layers used in the power distribution network and y is a user-defined variable.

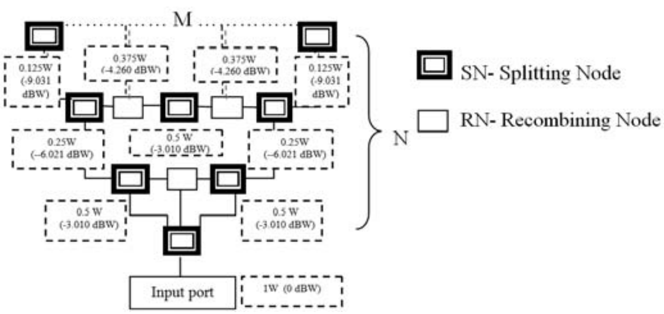


Figure 1. C-BFN structure with 1 input port, M-output ports and N-layers. Dotted boxes shows the power values obtained after each layer.

Phase shifter is a key element in the phased array antenna system[5], which provides the required phase shift by varying the effective path length of a transmission line. Defected ground structure (DGS) is an etched periodic or non-periodic cascade configuration in ground of a planar transmission line, which provides a slow wave structure .The periodic DGS increases the slow wave factor, resulting in longer electrical length for the same physical length. This disturbance will alter the characteristics of a transmission line. Generally DGS-based phase shifters are more advantageous, these decrease the return loss, enhance the bandwidth of performance, reduce the mutual coupling and increase the overall gain of the system.

3. CORPS ELEMENT FOR POWER DISTRIBUTION NETWORK

Considering technological limitations, measurement facilities available, the search for the implementation of SN and RN has been focused on planar technology, specifically on strip-line based elements. One such implementation is using Gysel cell (Gysel power divider), which provides improvements in isolation levels at the ports. It is important to mention that the use of Gysel cell is not the unique solution available to implement a CORPS-BFN[6]. Instead, Circular In-phase hybrid ring power divider can also be used but it is hard to tune its physical parameters for optimisation. The conventional Gysel power divider consists of five ports, that couples a half of the power of input port (port 1) to its output insertion ports (port 2 and port 3) and isolates its isolation ports (port 4 and port 5). Matching of frequency, isolation between ports, and transmission requirements are achieved setting the impedance of the line accordingly.

The conventional Gysel power divider configuration use lines with impedance of Zo at input ports, impedances of √2 Zo (electrical length of λ/2) between port 2 and 3, of zo/√2 (electrical length of λ/2) among ports 4 and 5 and, in the rest of the ring the impedance is usually set to zo (electrical length of λ/4), shown in Fig. 2(a).

Zo – Characteristics Impedance

λ – Wavelength of operation

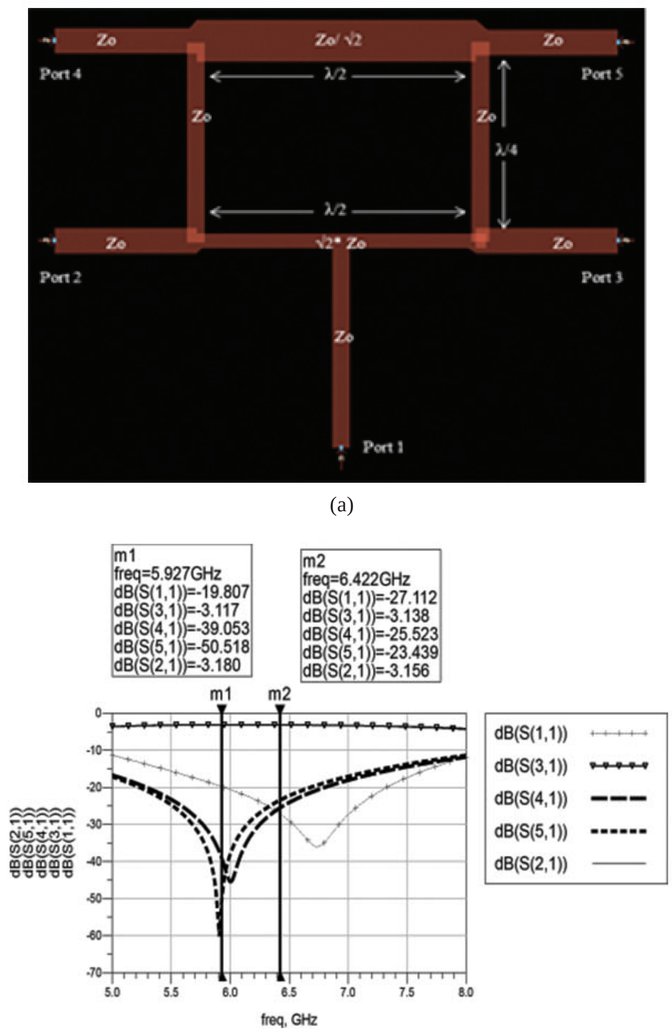


Figure 2. Gysel power divider: (a) Layout in ADS, and (b) Simulated return loss (S_{11}), insertion losses (S_{21}, S_{31}) and isolation losses (S_{41}, S_{51}).

A prototype has been build using microstrip technology which is designed to work at 5.925 GHz to 6.425 GHz. The dielectric substrate used is RT_Duroid5880 with specifications in Table 1.

Table 1. Substrate specifications

Substrate Specifications	
Dielectric constant (ε_r)	2.2
Tangent loss (tan δ)	0.0009
Substrate thickness (H)	15 mil (0.381 mm)
Conductor layer thickness (T)	20 μm

Simulation results are obtained using ADS 2011.05. The electrical behaviour of the design can be analysed with the help of scattering (S) parameters. The expected scattering parameters values are as shown[7] in Table 2.

Table 2. Scattering parameter's expected values

S Parameters (dB)	Expected Values
Return loss S_{11}	< -20 dB
Insertion loss S_{21} S_{31}	>-3 dB
Isolation S_{41} S_{51}	<-20 dB

From the Fig. 2(b), the power division (insertion loss S_{21} and S_{31}) obtained at port 2 and port 3 is -3 dB with maximum deviation of 0.18 dB over the BW 5.9 GHz to 6.4 GHz. The simulated return loss more or less coincides with the expected value and maximum isolation is also obtained at ports 4 and 5.

4. THREE-LAYERED C-BFN STRUCTURE

A three-layered CORPS BFN structure with one input and four outputs has been designed by alternative iteration of splitting node and recombination node. A Gysel cell can acts like a SN because it delivers equal in-phase power division in ports 2 and 3, while isolates ports 4 and 5. Additionally, using the reciprocity properties of SN and RN, Gysel cell can also be used as RN only, altering its relative position in the system[8]. So, a complete CORPS-BFN can be implemented using Gysel cells, as shown in Fig. 3(a). Simulated scattering parameters in Fig. 3(b) shows the insertion loss values at the output ports corresponds to the Pascal's Triangle coefficients, which is normalised by the addition of its in-row coefficients for the frequency band 5.925 to 6.425 GHz with maximum deviation of 0.81 dB from the desired power values.

5. FIXED-PHASE SHIFTER IMPLEMENTATION

Phase shifter block has been designed using defected ground structure (DGS). DGS has found immense applications in the design of microwave devices[9,10]. Various DGS structures have been analysed and it is concluded that dumbbell shaped DGS provides maximum phase shift. The length, width of the dumbbell arm and radius of the dumbbell head: Fig. 4(a) is 1.101mm, 0.5 mm and 0.360mm, respectively, Fig. 4(b) is 0.771 mm, 0.085 mm and 0.7827 mm, respectively and Fig. 4(c) is 1.180mm, 0.328 mm and 0.764mm, respectively.

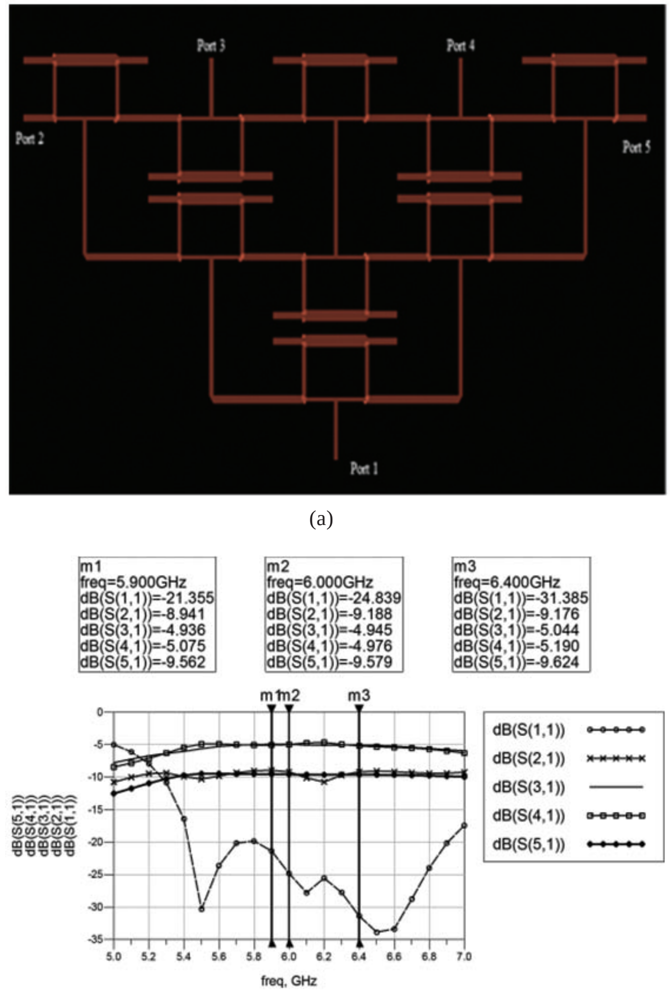


Figure 3. CORPS: (a) Layout in ADS, and (b) Simulated return loss (S_{11}) and insertion losses (S_{21}, S_{31}, S_{41}, S_{51}).

6. NOVELTY INTRODUCED IN THE BEAM FORMING NETWORK

The conventional way of combining the designed power distribution block and the phase shifter block requires two different phase shifters, if a 3x1 linear array of PAA is considered. So specific BFN with a single-phase shifter is considered where the phases at the output ports are a linear representation of phase at input ports[11]. Number of phase shifters used in this BFN is less compared to the conventional BFN[11]. This research introduces a novelty in the existing layout structure by replacing the two input port structures with a single input port conventional Gysel power divider as shown in Fig. 5.

Figure 5(a) shows the single layer BFN,where the input ports P1 and P2 will have unitary amplitude, but with different phase,

Input Port 1: $Ae^{(j\Theta)}$ and Input Port 2: $Ae^{(j(\Theta+\Delta\Theta))}$ where A is 1 and $\Delta\Theta$ is the phase shifting between ports (in this case 60 deg)[11]. Figure 5(b) shows the novelty introduced in the structure where only one input port is used and the required phase shift is obtained by placing a phase shifter at one of the output arms of the power divider (in this case, a bend

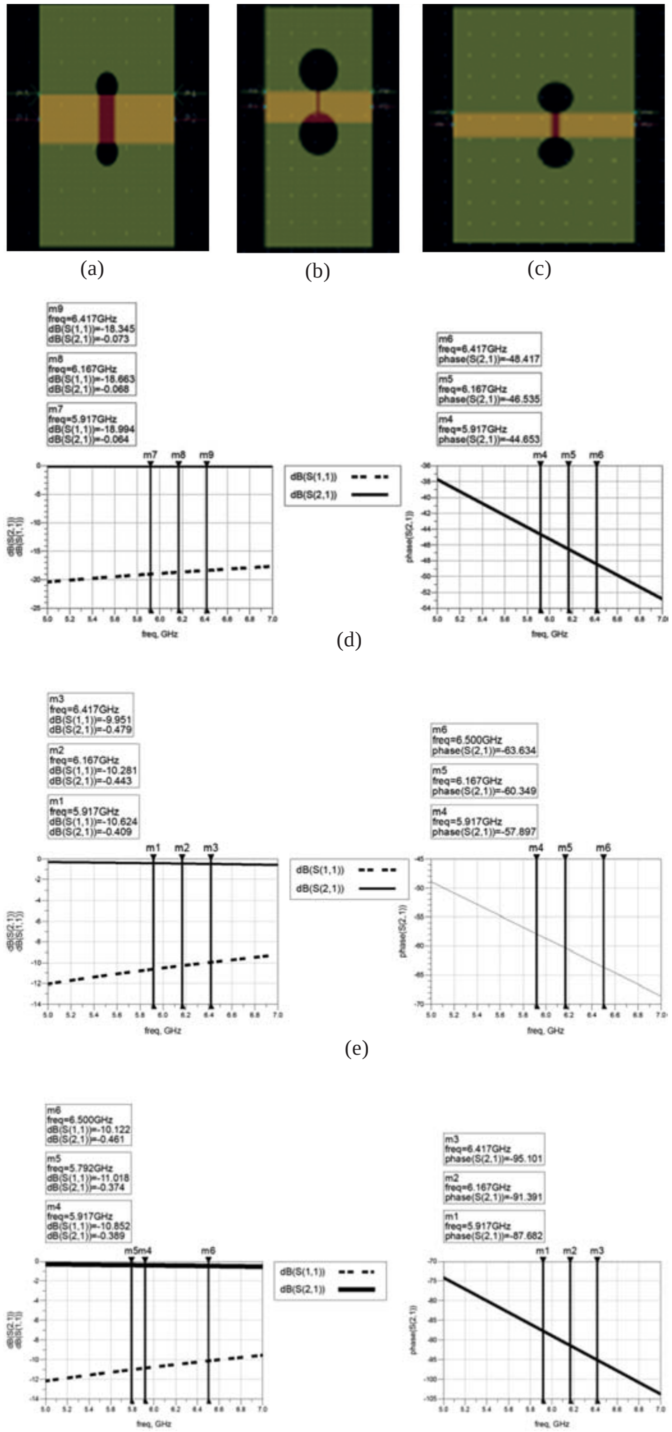


Figure 4. Phase shifter: (a) Layout of -45° in ADS, (b) Layout of -60° in ADS, (c) Layout of -90° in ADS, (d) Magnitude and phase plot of -45° phase shifter, (e) Magnitude and phase plot of -60° phase shifter, and (f) Magnitude and phase plot of -90° phase shifter.

corresponding to 60 deg is introduced). The return, insertion losses and phase differences at the output ports of the proposed BFN were analysed to make sure that magnitude plot satisfies the power distribution as per the Pascal's Triangle coefficients and $\Delta\Phi(10,11)$ and $\Delta\Phi(11,12)$ are a lineal representation of phase at port1 as shown in Fig. 5(c) and Fig. 5(d).

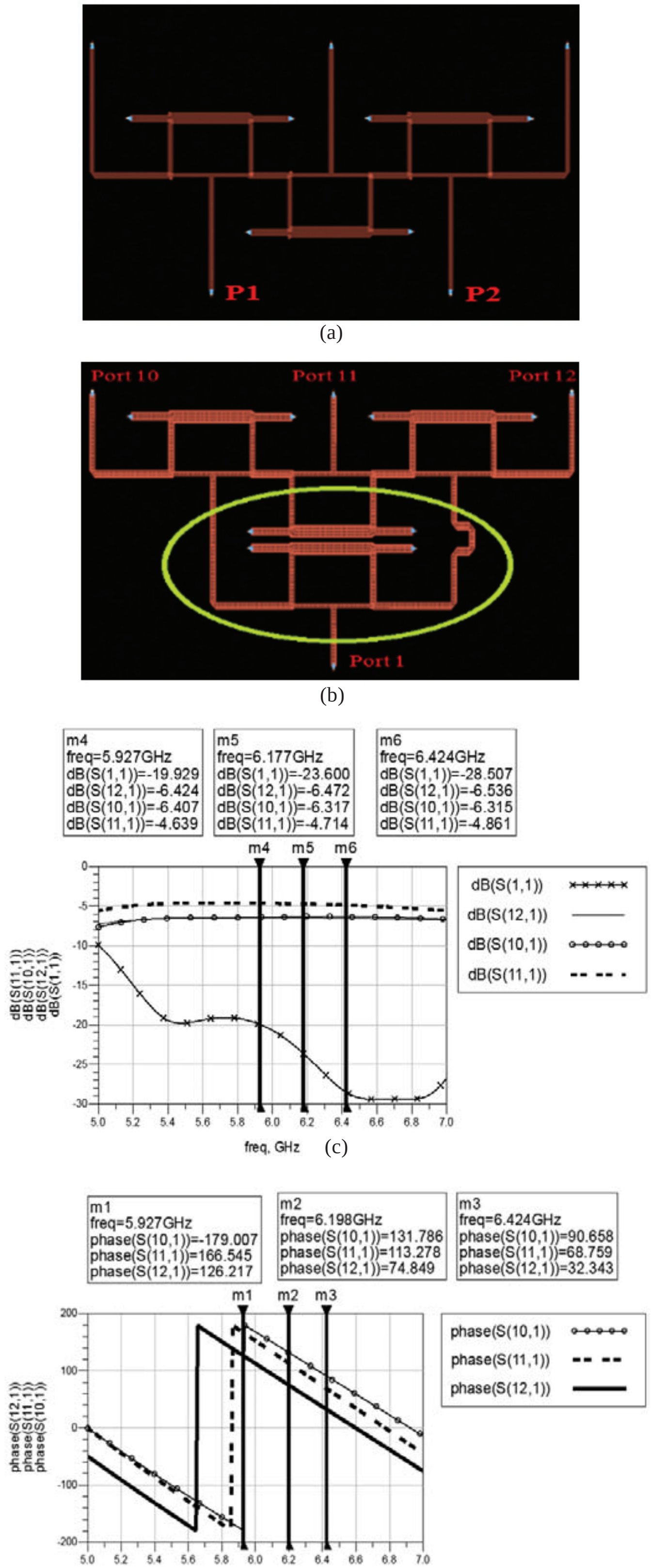


Figure 5. (a) Layout structure of BFN[11], (b) Layout of novelty introduced BFN ,where the encircled part shows the novelty introduced session, (c) Magnitude plot of novelty introduced one Input Port Structure, and (d) Phase plot of novelty introduced one Input Port Structure.

7. ENTIRE PHASED ARRAY ANTENNA IMPLEMENTATION

In general the combination of BFN and the array of radiating elements form the PAA[12], so a rectangular patch antenna has been designed which resonates within the required band of frequency (at 6.175 GHz). The dimensions *W* and *L* of the antenna are given by[13],

$$W = \frac{\lambda}{2}\left(\frac{\varepsilon_r + 1}{2}\right)^{\frac{1}{2}} \tag{3}$$

where, Frequency, f =6.175 GHz (centre frequency)

Wavelength of operation, λ=c/f (c=3*10^8 m/s)

Dielectric constant, ε_r =2.2

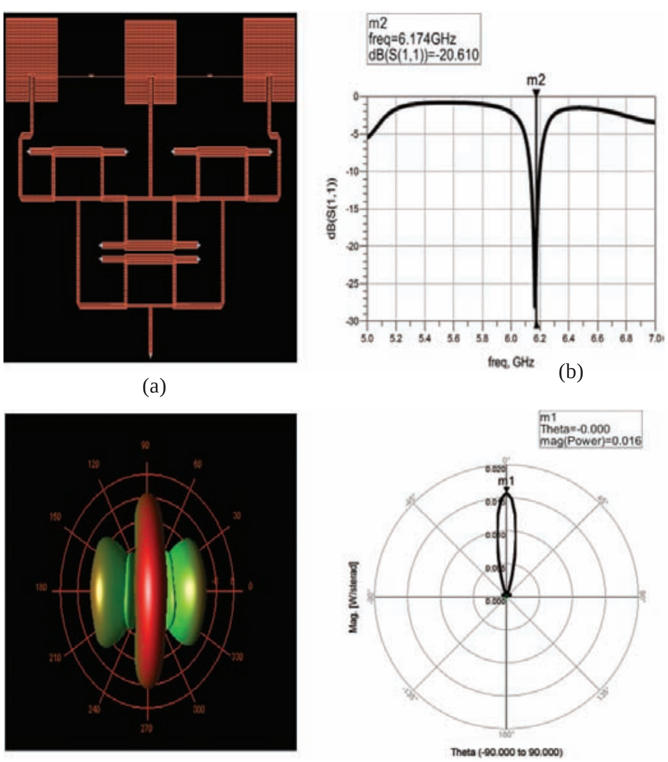
Substrate height, *h*= 0.381 mm

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

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{12h}{W}\right]^{-\frac{1}{2}} \tag{5}$$

Thus the length and width of the rectangular patch antenna are obtained from Eqns (3), (4), and (5) as Length, *L* =16.207 mm and Width, *W* =19.204 mm.

The repetition of this rectangular patch forms the required array structure. Figure 6 shows initially designed PAA without any phase shift at its input side. The return loss and the radiation pattern have been analysed. The radiation plot shows the main beam's initially position is at 0 deg, Θ_s = 0 deg.



(a) (b) (c) (d)

Figure 6. (a) Layout of PAA without phase variation at its input, (b) Simulated return loss (S_{11}) of PAA, (c) 3-D view of far field radiation pattern, and (d) 2-D plot of radiation pattern.

8. CORPS BASED BFN WITH ARRAY OF RECTANGULAR PATCH (WITH PHASE VARIATION)

A phase variation of 60 deg has been introduced at the input side by bending the microstrip line as shown in Fig. 7(a). Fig. 7(b) ensures that the entire structure resonates at 6.175GHz. In this case, the beam-steering angle obtained from radiation plot (in Fig.7(d)) is 6 deg where the expected Θ_s is obtained from Eqn. (6),

$$\Theta s = \sin^{-1}\left[\frac{\triangle\varphi.\lambda}{360°.d}\right] \tag{6}$$

Θ_s = 5.22°.

where,

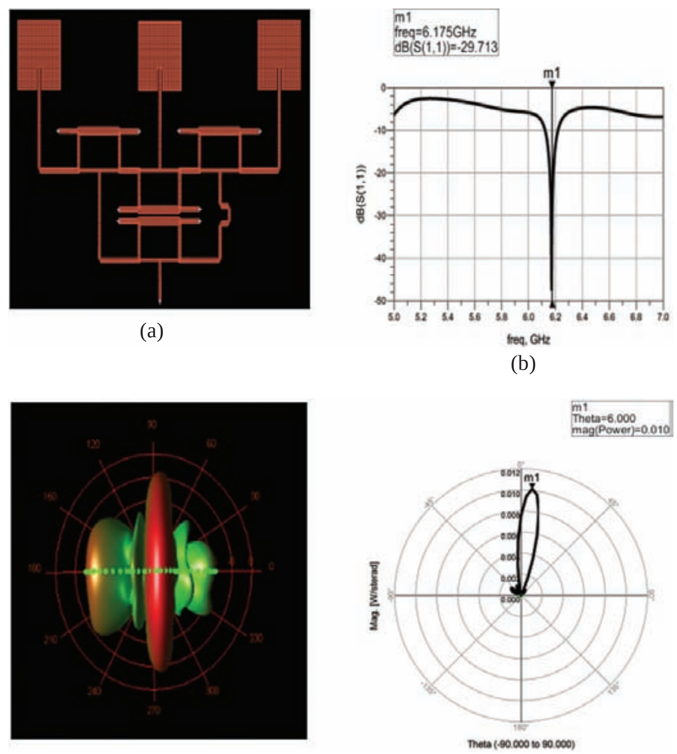
Θ_s is beam steering angle,

d is distance between the radiating elements,

λ is wavelength of operation,

Δφ is phase shift between two successive elements.

Thus the obtained Θ_s is near the expected value with small variation of 0.78°.



(a) (b) (c) (d)

Figure 7. (a) Layout of PAA with phase variation of 60 deg at its input side, (b) Simulated return loss (S_{11}) of PAA, (c) 3D view of far field radiation pattern, and (d) 2D plot of radiation pattern.

9. CORPS BASED BFN WITH ARRAY OF RECTANGULAR PATCH IN PRESENCE OF FINITE GROUND PLANE

The proposed phase shifter block for the BFN is based on DGS[14,15], so the entire PAA has been analysed in the presence of finite ground plane as shown in Fig. 8(a), where the initial position of the main beam is at 3° as shown in Fig. 8(c). Then the bended structure has been replaced with the dumbbell

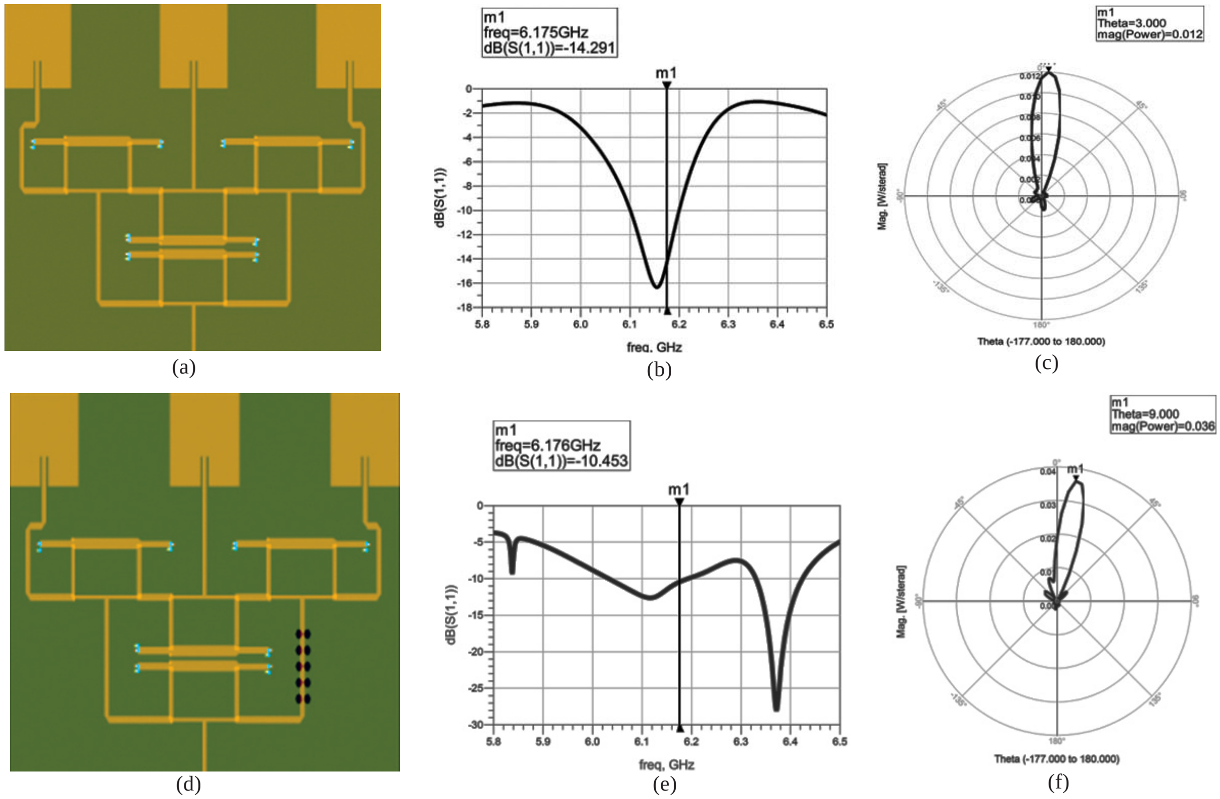


Figure 8. (a) Layout of PAA with finite ground plane without any phase variation, (b) Simulated return loss (S_{11}) of PAA with finite ground plane without any phase variation, (c) Radiation pattern of PAA with finite ground plane without any phase variation, (d) Layout of PAA with finite ground plane and DGS-based phase shifter at its input, (e) Simulated return loss (S_{11}) of PAA with finite ground plane and DGS-based phase shifter at its input, and (f) Radiation pattern of PAA with finite ground plane and DGS based phase shifter at its input.

shaped DGS for a phase variation of 60° at the input side as shown in Fig. 8(d). Similar to previous case these structures also resonate within the required band of frequency and the main beam is steered from 3° to 9° after introducing DGS in the ground plane as shown in Fig. 8(f). So the beam steering angle is 9°-3°=6°, which coincides with the expected value with small variation of 0.78°. Both the layout structures also resonate within the required frequency band as shown in Figs. 8(b) and 8(e).

10. CONCLUSIONS AND FUTURE WORK

This paper has shown the implementation of the basic elements of a beam forming network in phase array antenna for the frequency band of 5.925 GHz to 6.425 GHz, which finds applications in communication satellite, fixed wireless systems [16]. The power distribution network designed is simple and efficient satisfying the limits of return loss and insertion losses. The proposed DGS-based phase shifter provides appropriate phase shifts which controls the steering of the main beam in PAA. A novelty has been introduced in combining the CORPS-based power distribution network and the phase-shifter block along with the array of rectangular patch antenna to form an efficient PAA. The future scope of the work is to replace the fixed phase-shifter part with a variable phase-shifter block.

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