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Beamforming Networks to Feed Array Antennas

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Abstract

A beamforming Network (BFN) to feed phased array antenna using butler matrix is designed and simulated. BFNs are designed in S band and the frequency of operation is 3.5GHz. The BFN is designed with suitable phase shifters and couplers to obtain various phase changes to steer the beam in the required direction which will be useful in communications. The simulated results show that the beam forming network is able to produce a phase shift of 0.2 degree.

Keywords: Beamforming Networks, Butler Matrix, Couplers, Phased Array Antenna, Phase Shifters

1. Introduction

Array of antennas has to be fed so as to steer the radiation in the required direction which finds lot of applications in present day satellite, wireless and mobile communications. Beam steering should be done with high resolution to scan radiating patterns in various directions. Scanning can be achieved either by electronic or mechanical means. Mechanical scanning is not normally preferred because of the inherent delay, inaccuracy, poor resolution and also low speed which do not find significance in satellite or especially in military applications. Electronic scanning is preferred and can be accomplished by Beamforming Networks (BFNs). In general RF BFNs can be classified in to two types as quasi-optical and circuit types. Quasi-optical type includes hybrid Ruze lens or Rotman lens method. But this method has high reflections, mutual coupling effect. Circuit type includes couplers, phase shifters and microstrip transmission lines to create multiple beam patterns[1]. Blass matrix, Nolen matrix and Butler matrix are few examples of circuit type BFNs. The beam and element transmission lines are terminated with matched loads to reduce reflections but this in turn reduces efficiency. Moreover Blass matrix is lossy because of the resistive terminations. Nolen matrix is not preferred because of unbalance power distribution in the matrix structure. Butler matrix is known as lossless canonical forms of multiple BFNs as they require a less number of elements. Butler matrix provides high isolation between input and output. It provides linearity in phase with respect to the position of output and even a small increment in phase can be obtained depending on selection of input.

2. Proposed Solution

In order to design BFN to feed phased array antenna we are using 4 X 4 Butler matrix with a combination of 3dB Branchline couplers and variable analog active phase shifters and fixed phase shifters[2]. The design of BFN using butler matrix architecture is slightly altered in order to obtain a continuous phase variation from –90 degrees to +90 degrees with a high resolution of 0.2 degrees for a change in voltage of 0.05 volts. Voltage is varied from 0 to +1V maximum and resistance is varied from 0 to 10 Ω maximum in small steps to achieve a high resolution. Alone with a voltage variation we can achieve a resolution of 2 degrees but with a small variation in resistance with small change in voltage yields us a better resolution as mentioned before. The performance of butler matrix depends critically on coupler and phase shifters, they are designed independently as described below.

3. Beamforming Networks

Beamforming of array antennas is to achieve directional signal transmission and reception. Conventional beam formers are classified in to two types as analog and digital feed systems. We prefer analog beam formers compared

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to digital as digital beam formers suffers from receiver channel imbalance, amplitude and phase errors, A/D converter offset errors and frequency dependent errors. The advantages of BFNs are high SNR, interference prevention and rejection and high network efficiency. BFNs used in array antennas must satisfy integration of array antenna elements by reducing number of connectors and microstrip lines which results in compact design, losses should be reduced and the design must be affordable[4].

The number of antenna elements in an array is spatially arranged and are electrically connected to provide a directional radiation pattern. The interconnection between the elements known as feed network provides fixed phase resulting in phased array antenna as shown in Figure 1. The performance of phased array antenna is dependent on the geometry of array elements, radiation patterns, orientation and polarization of elements. Each element of an array radiates a vector directional pattern that has both angle and radial dependence of the elements. For distances very far from the elements far field dominates when compared to near field and in general the radiation from K^{th} element is given by

$$E_k(\theta, \phi) = f(\theta, \phi)\exp(-jK_0R_k)/R_k$$

The vector function of angle $f(\theta, \phi)$ is called element pattern and depends on type of element used. R is the distance.

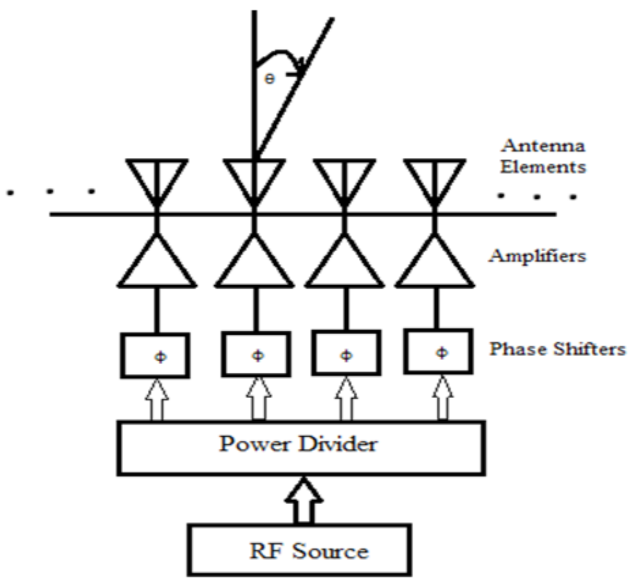

Figure 1. Phased array antenna.

4. Design of Butler Matrix, Phase Shifters and Couplers

It is a beam forming network that uses a combination of couplers and phase shifters to provide commutating and beam steering. All power amplifiers operate at equal power and scanning of even small steps can be achieved[4]. It creates linear phase mode excitations in circular array antennas which supports various communication applications. It operates over a narrow frequency band to maintain specified beam directions.

$$\text{phase difference} = \pm (2n - 1)\,\Pi / N.$$

N is referred as the order of the matrix.

Using the variable $v = (d/\lambda)(\sin\theta - \sin\theta_i)$ where d/λ is element spacing in wavelength and θ_i is the axis of the i^{th} beam measured from broad side. The Butler beam pattern is given by

$$F(v) = \sin(N\pi v)/(N \sin \pi v)$$

Beam position for any spacing is given by $\sin\theta_i = \pm\frac{i\lambda}{2Nd}$, i = 1, 2, 3, … $(N-1)$.

The corresponding inter element phase shift with spacing,

$$d = \frac{\lambda}{2} \text{ is } \alpha_i = \beta d \sin\theta_i = i\frac{\pi}{N}$$

where, $\beta = \frac{2\pi}{\lambda}$ is the wave number.

A phase shifter is a microwave network which provides a controllable phase shift of the RF signal. Design of phase shifter depends on range of operating frequencies, limits of the phase change and accuracy of equipment. Simplest phase shifter consists of resistor and a capacitor or a resistor and an induction coil which provides us fixed phase shifters[5]. Variable phase shifters can be designed using BJT, FET, Varactor diode or a PIN diode. Phase shifters are broadly classified in to two types as active versus passive and analog versus digital. Phase shifters designed using resistors, inductors and capacitors are normally fixed and passive phase shifters which are lossy in nature. Phase shifters designed using active elements are active analog phase shifters which provides high gain and continuous variations of phase. Digital phase shifter provides discrete set of phase shifts. Normally in military applications and satellite communications analog variable phase shifters are preferred because of their capability to provide high gain and continuous phase change. Variable analog phase shifters are the control devices used in number of applications like accelerators, microwave communication and measurements, phased array radars, feed forward system, adaptive antenna combining and so on. The variable and fixed phase shifters are designed at operating frequency of 3.5 GHz are as shown in Figure 2 and Figure 3 respectively.

Couplers are the devices used the couple the power from input port to output port. Two widely used couplers are Branchline and Ratrace couplers[6]. Branchline couplers are used in the proposed model and its S parameters are shown in Figure 4 and Figure 5 respectively.

The proposed design is as shown in Figure 6. Implementation of the block is done is ADS and simulation is carried out using fixed phase shifters, variable

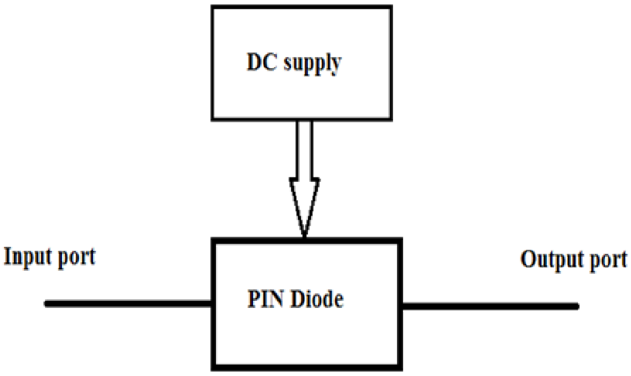

Figure 2. Variable phase shifter.

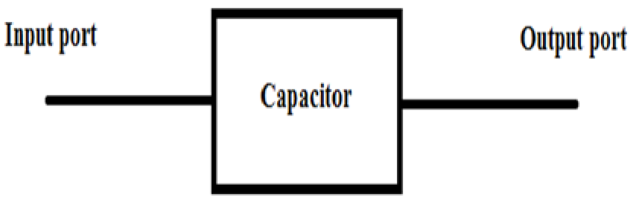

Figure 3. Fixed phase shifter.

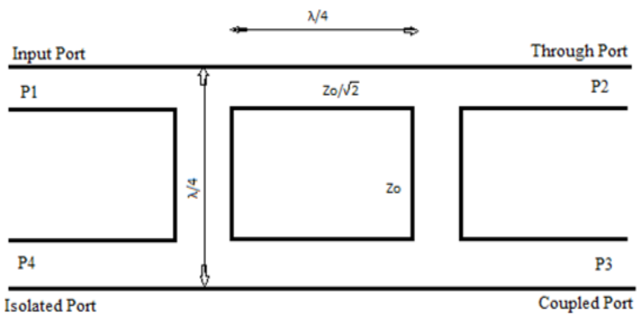

Figure 4. Branchline Coupler.

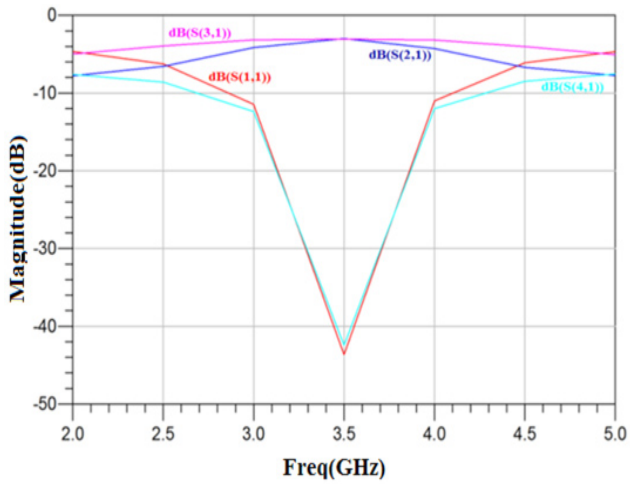

Figure 5. S parameters graph of Branchline Coupler.

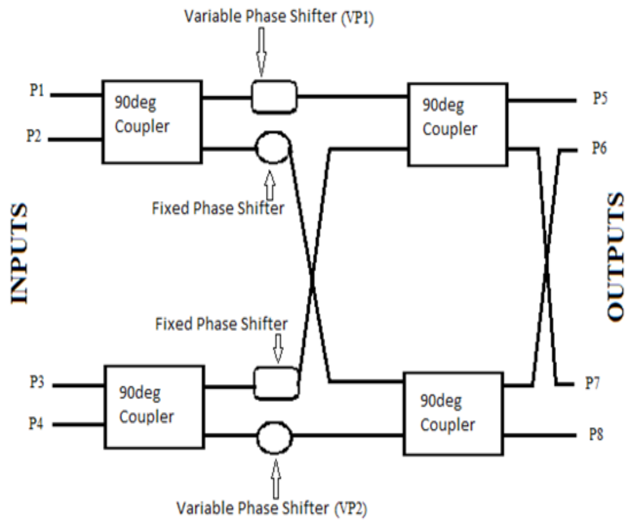

Figure 6. Block diagram of the implemented BFN.

phase shifters independently in BFN and then together they are combined to get a high resolution.

5. Simulation Results

Simulated results are shown in Figure 7, Figure 8 and Figure 9. From Figure 7 it is observed that there is a linear variation in the phase at the output ports for varactor voltages of 0.25 V and 0.45 V. The variation of phase with different varactor voltages is shown in Figure 8. Figure 9 shows the variation of phase for different varactor voltages. The values are tabulated for various changes in input voltages applied to variable phase shifters. The tabulation is shown in Table 1.

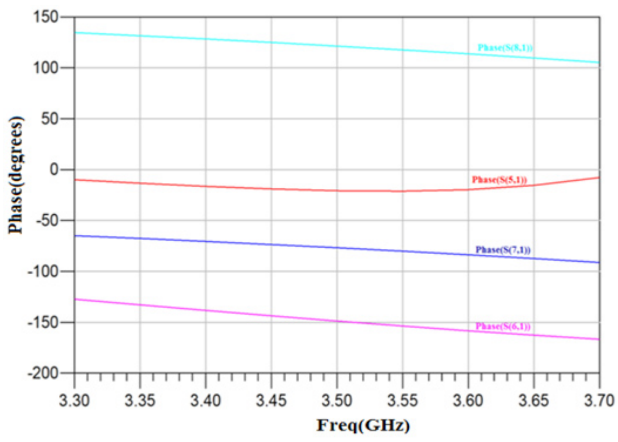

Figure 7. Phase versus frequency variation with respect to 0.25V and 0.45V as inputs to variable phase shifter.

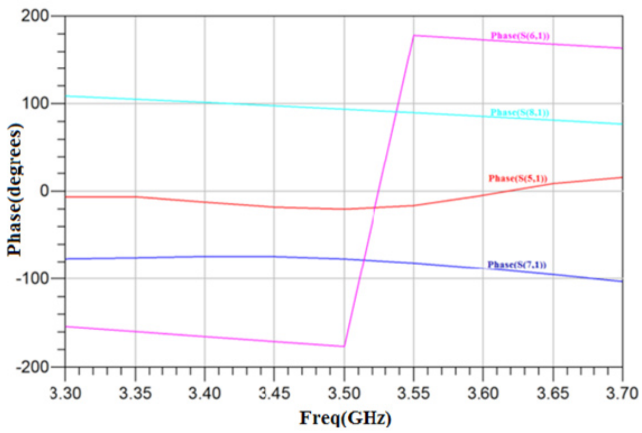

Figure 8. Phase versus frequency variation with respect to 0.2V and 0.6V as inputs to variable phase shifter.

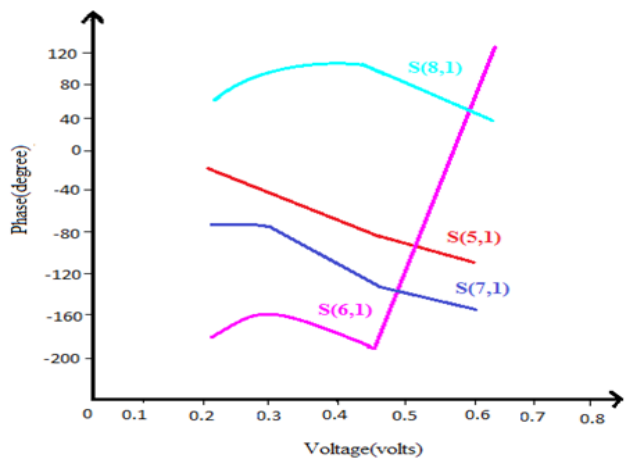

Figure 9. Phase versus Voltage variation for change in input voltage applied to variable phase shifter employed in the design of BFN.

Table 1. Tabulation of output phase in degrees for the change in input voltage applied to variable phase shifter

VP1(V)	VP2(V)	P5(deg)	P6(deg)	P7(deg)	P8(deg)
0.2	0.6	−20.55	−176.75	−76.87	93.46
0.25	0.45	−20.79	−148.89	−76.86	121.33
0.3	0.5	−21.05	−172.03	−77.14	98.19
0.45	0.55	−81.84	−175.87	−137.96	94.34
0.6	0.75	−105.31	133.44	−161.55	42.65

6. Conclusion

BFNs to feed phased array antenna is designed in S band and simulated. With the proposed design continuous phase variation from −90 degrees to +90 degrees with respect to input phase is obtained by varying an voltage from 0 to +1V maximum and resistance is varied from 0 to 10 Ω maximum in small steps to obtain a high resolution of 0.2 degrees. All the components are designed to operate at 3.5 GHz. Isolation of greater than −21 dB is achieved between various input ports. In future, work can be extended to circular array antennas which again find a huge importance in communications.

7. References

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