A Switched Multibeam Antenna Array using Butler Matrix Feed Network

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Abstract

In this paper, Smart Antenna system of 4-element microstrip linear array antenna with Butler matrix beam forming network is designed, analyzed and implemented using microstrip technology in completely planar structure. The performance of this smart antenna system is analyzed and the beam forming features are monitored as function of geometrical antenna and Butler matrix parameters at frequency 2.4 GHz.

Keywords: Beam forming network, Butler Matrix, Microstrip Antenna, Switched Beam

1. INTRODUCTION

Smart antennas have been characterized as one of the most prominent devices in wireless communication. Electronic scanning of antennas is used in a variety of applications and can be accomplished using beam forming networks (BFNs). Butler Matrix [1] is an N×N passive microwave network that consists of ‘N’ input and ‘N’ output independent ports. It is used as a feed to an array of antennas to generate a set of ‘N’ orthogonal beams, which scans the array generated beam. Thus a Butler Matrix is considered to be a significant component of a (BFN) beamforming network [2] and widely used in Smart antennas [6]. The matrix is easy to be implemented using micro strip with an advantage of ease in fabrication, compactness and low cost.

A 4×4 Butler matrix is designed to form orthogonal beams and the switching is obtained at the end of the array of 4 patch antennas. Basically a 4×4 matrix consists of four 90 degree hybrids, two 0 dB cross-overs and two 45 degree phase shifters. The end four antenna elements are designed for optimum feed position, along with the element spacing, using Method of Moment (MoM), to get a proper VSWR value, maintaining gain characteristics.

2. DESIGN AND ANALYSIS

A simple 4×4 Butler matrix is show

For simulation, though the data was considered for a range of 2 to 3 GHz frequency, but the individual component designs were done at 2.4 GHz. The final design was done on FR4 board, with substrate height of 1.6mm, εr = 4.4, tanδ = 0.0027, with all terminations offered at 50 Ω. The 90 degree hybrid pull out at the port side thickness is 1.141 mm. Along the major width-side arm (thickness 1.932mm), the tapering done at 45 degree gave a proper isolation at port 2.

![Figure 1](image)

Figure 1. Block diagram of 4×4 Butler matrix array

2.1 Zero dB cross-over coupler

Crossover coupler shown in Fig 2 was first designed by cascading two hybrids. But the branch increased thickness did not give proper isolation at port 4; as well as zero degree phase was not obtained at port 3. All its arm thickness was then redesigned at 1.414 mm, again with tapering at 45 degree along the port arm side.
For the phase shifter [7] shown in fig 3, the phase shift is given by, \( \phi = \frac{2\pi}{\lambda_g} l \), where the wavelength is given by, \( \lambda_g / \sqrt{\varepsilon_{\text{eff}}} \).

Finally the single patch antenna [9] was designed, with an inset feed at a length of 33.33 % of the total length. However when the array of four patches was placed together, it is observed that maximum radiated field obtained at normal to the structure surface. Hence to take care of this new problem of the fringing fields along the width, the patch length is extended on both sides by additional length given by,

\[
\text{Leff} = \text{L} + 2\Delta L
\]

where,

\[
\Delta L = \frac{0.412h (\varepsilon_{\text{reff}} + 0.3)(W/h + 0.264)}{(\varepsilon_{\text{reff}} - 0.258)(W/h + 0.8)}
\]

\[
\text{Leff} = c/ 2f_0 \sqrt{\varepsilon_{\text{reff}}}
\]

Quadrature hybrids are 3dB directional couplers with 90° phase difference in in the outputs of the through and coupled arms. This type of hybrid is often made in Microstrip or stripline and is also known as branch-line hybrid. With all ports matched, power entering port 1 is evenly divided between ports 2 and 3, with a 90° phase shift between these outputs. No power is coupled to ports 4.

The Butler matrix connected to the patch array [11] shown in Fig 1. The VSWR graph is shown in Fig 5 is at a value of 1.67 at 2.4 GHz.
The current distribution on the patch surface is shown in Fig. 6. The lowest current densities are located at the patch corners and the strongest currents (in red) are around the end of the slot and slits. Therefore, the surface current path is effectively lengthened by the slot and slits resulting in lower resonance frequency. However the element spacing was kept constant throughout the four patch antennas [12].

![Figure 8. HFSS Butler Matrix Design](image)

A 4 × 4 BM consists of four couplers, four phase shifters and two crossovers. The arrangement is shown in Fig. 8. The first four ports (Ports 1, 2, 3 and 4) are input ports, and the remaining ports are outputs. Consider an array fed by the BM, with consecutive antenna elements separated by d. Four square patches, studied in earlier section, by design of single patch, laid on the FR4 substrate are separated by distance d ≈ 43mm i.e. λ/2 distance between centers of patch.

![Figure 9. Measured Voltage standing wave ratio (VSWR) of Butler Matrix](image)

Fig. 9. Shows measured VSWR at port 1, with marker m1, m2, m3, m4, m5 and m6. Fig. 6.48 Shows Impedance using smithchart for port 1, with marker m1, m2, m3, m4, m5 and m6.

![Figure 10. Measured Smith chart results for Impedance](image)

The simulated total gain in 3D pattern is shown figure 11. which is 5.112 dBi along the bore-sight direction. The radiation patterns of gain and directivity have a very similar shape. This is due to the loss on the substrate. The highest gain shown along the z-direction with red colour at the peak.
Figure 11. Gain of Patch Antenna

Figure 12. Simulated radiation pattern when all four input ports are excited.

Figure 12 shows simulated radiation pattern in the form of gain when all ports are excited by the antenna array. The radiation pattern by taken keeping $\phi = 90^0$ at resonant frequency 2.4Ghz.

Figure 13. Four beam switching

The total beam steering of the four individual beams is shown in Fig 7. It is observed that the beam has switched at 18 degree (shown in different colors). However during the appearance of the forth beam, there is a side lobe formation, due to which its gain has reduced.

The beam positions as per the progressive phase shifting at the feed end could be realized. Due to paper size constraints, the figures cannot be discussed at length.

Figure 15 shows Simulated Return Loss of Integrated Patch antenna with Butler Matrix for port 1 and port 2, with marker m1 nad m2 showing the RL below $-15\, \text{dB}$. In the same manner Figure 16 shows Return Loss (RL) for port 3 and port 4 with marker m1 and m2.

The design consists of a uniformly spaced linear array of four square patch antenna, and a feed network consisting of a $4 \times 4$ BM. A basic requirement for a good function of the circuit is to avoid coupling loss. It also has very good Isolation between input ports.
This proves that the logical flow of the design process is correct. Return loss of all ports is greater than $-10\, \text{dB}$ which is the achievement for this design. The Butler matrix without patch shows simulated results at 2.2 GHz due to small mismatch in interconnection of Butler elements. But in case of integrated patch with Butler it gives

![Figure 15](image1.png)

**Figure 15.** Simulated Return loss at port 1 and 2 of Antenna array fed by BM

![Figure 16](image2.png)

**Figure 16.** Simulated Return loss at port 3 and 4 of Antenna array fed by BM

3. CONCLUSION

A 4×4 Butler matrix has been designed for the excitation of microstrip array antenna to steer the beams in different desired directions. Most important thing about the simulated structure is that it can be easily implemented using simple material for construction with minimum cost. The planar design, simulation and implementation of a smart antenna system using microstrip antenna array with Butler Matrix beamforming network for wireless applications in the ISM-band at 2.45 GHz is done. The Butler matrix is also fabricated together with the patch antenna array to study about the radiation patterns over the frequency band of 2.45 GHz. The Beamforming/feeder network is designed using a 4×4 Butler matrix, and realized using 4 quadrature hybrids, 2 phase shifters and 2 crossover circuits. To verify modeling and simulation procedures, the main basic elements such as patch antenna, directional coupler, and cross coupler are fabricated and measured. Good agreement between measurements and simulations is obtained which validates the design.

References


