Implementation of a Broadside Switched-Beam Antenna Array Using a Butler Matrix Feed Network

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Abstract: This paper presents a compact beamforming network designed to achieve broadside radiation when integrated with a microstrip antenna array. The steering mechanism employs a planar Butler Matrix (BM), which is composed of compact 90° 3 dB microstrip couplers. Antenna elements are spaced at 0.3λ, allowing intentional overlap that shifts the main beam away from broadside, thereby producing a prominent grating lobe in the broadside direction. Both full-wave electromagnetic simulations and experimental measurements confirm that the design delivers broadside coverage, high gain, and a compact form factor. The prototype exhibits good agreement between simulated and measured S-parameters, validating effective impedance matching and beam steering performance.

Keywords: Beamforming, Broadside Radiation, Butler Matrix, Microstrip Miniaturization, Grating Lobe.

1. INTRODUCTION

Since he inception of Butler matrix (BM) [1], researchers have put extensive effort in the realization of BM in a microstrip technique and other various technologies such as multi-layered [2], coplanar waveguide (CPW) [3], Swap port coupler [4], open-stubs [5], and substrate integrated waveguide (SIW) technology [6]. The design of Butler matrices in classical form is based on transmission lines which are responsible for the bulky layout of the device. This is mostly due to the presence of fixed phase shifters, crossovers, and hybrid couplers employed in the design, with all their dimensions constrained by quarter wavelength transmission lines (TL), which usually posed some challenges, most especially at lower frequencies [7].

Microstrip technique is the simplest method of realizing BM as presented in [8]. But, due to the $\lambda/4$ wavelength requirement of the couplers and the 45^0 phase shifters involved in the BM, the circuit size becomes very large which makes it suitable only for applications higher frequency region. This large circuit are needs to be reduced to have a compact system suitable for applications at all frequencies. Recently, size miniaturization of BM becomes an active research area most especially at lower frequency bands. In [9], a planar transmission line was replaced with artificial transmission lines for the purpose of designing a compact BM. Multi-layered packaging technologies are another option for realising a miniaturized BM as presented in [10]. Further size reduction of the BM using the advanced complementary metal-oxide semiconductor (CMOS) technology was reported in [11]. High level of miniaturization of the BM was achieved. In [12], a lumped-element was used to replace the $\lambda/4$ wavelength TL of the phase shifters and the $3dB$ hybrid couplers of the BM with the aim of reducing the size of BM. This technique drastically makes the BM compact in size.

Other researchers proposed a miniaturized BM by means of eliminating crossovers [13], elimination of phase shifters, and crossovers [14]. In [15] coplanar-waveguide was reported, the coplanar-waveguide couplers utilize electromagnetic coupling via a slot in a common ground plane, therefore, in the resulting circuit the transmission-line crossovers. A compact BM presented in [16] uses thin-film passive device technology. The complete BM was miniaturized by substituting the λ/4 transmission line (TL) with a bridged-T coil. With this technique, the size of the BM produces was drastically reduced without sacrificing the performance of the BM significantly. Lumped-element equivalent of λ/4 TL was applied in [17] using thin-film technology to produce a compact BM. Even though, the circuit size reduces tremendously, but the bandwidth reduces proportionately because the conversion is usually applicable at a single frequency only. Another famous design problem of BM is that the use of crossover points inevitable. To design a functional BM by avoiding crossing, a multi-layered technique is being used, this technique has the advantage of making the BM compact and at the same time eliminates the use of crossovers as proposed in [18].

Classical BM, in which, it comprises of four hybrid couplers ($C1 - C4$), two-phase delays having 45^0 phase shift and 2- crossovers as shown in Fig. 1. From this Figure, the input ports are designated as $P1 - P4$ where the BM is excited, $A1 - A4$ are the outputs ports where antenna arrays are connected. These arrays radiate based on the choice of an appropriate input signal.

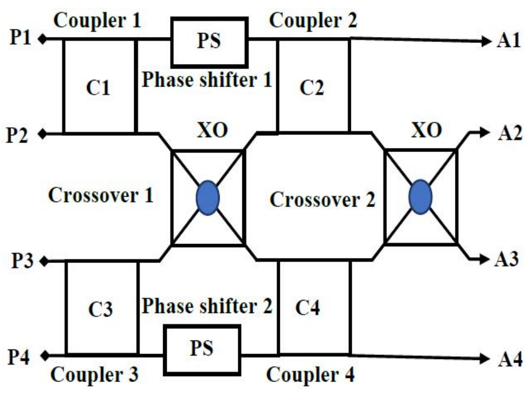


Fig. 1. Block diagram of a conventional 4 x 4 Butler matrix

In this paper, the design and implementation of a beam steering network that produces broadside beams when it is fed with an antenna array is proposed. A miniaturized BM was implemented as the beam steering network that produces the broadside beam. This is contrary to the assertion made in [19] that it is not possible to use Butler matrices with 90^0 hybrids couplers to produce a beam at broadside. In addition to the production of broadside beam, the proposed BM utilizes a miniaturized couplers which reduces the physical size of the BM and in turn lowers the cost of production.

2. DESIGN OF MINIATURIZED 3 DB COUPLER

The design equations of the $\lambda/4$ wavelength transmission line (TL) and its T shaped equivalent circuit were accomplished using ABCD matrices as outlined in [20]. The size of a conventional coupler was drastically reduced by replacing it with an equivalent T section of the TL using the designed equations outlined in the same paper. In this design, care was taken to ensure that the impedance ratios were selected such that, the impedance of the original TL and that of the equivalent T-section are within the realizable boundary of microstrip technology.

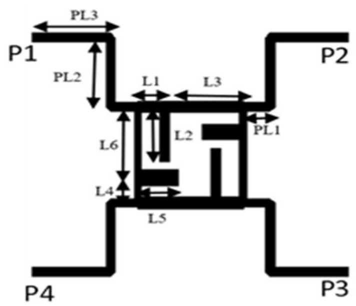


Fig. 2. Schematic of the miniaturized coupler

From the schematic diagram of the coupler shown in Fig. 2, P1 and P4 are the input and the isolation ports, whereas P2 and P3 served as the output ports. All the lengths (L) represent the physical lengths of the sections as indicated in the Figure. To obtain the impedances of the sections within the realizable range for microstrip technology, the impedance ratios were carefully chosen according to [20]. In this case, M was chosen to be 1.7 which gives an impedance Z_1 = 60Ω, and with K = 2.6, Z_2 = 23.1Ω. From the designed curve presented in [20], the impedances of the vertical arm of the coupler (35Ω) was used to obtain the corresponding electrical length that arm and are represented as: Z_1 = 60Ω, Z_2 = 23.1Ω, Z_3 = 60Ω, $\theta_1 = 17^0$, $\theta_2 = 39^0$, and $\theta_3 = 48^0$ respectively. Similarly, for the horizontal arm having an impedance of Z_0 = 50Ω, by selecting K = 3.3 and M = 1.5, the impedances are computed to be: Z_1 = 75Ω, Z_2 = 22.7Ω, Z_3 = 75Ω, and their electrical lengths are $\theta_1 = 16^0$, $\theta_{12} = 31^0$, and $\theta_3 = 58^0$. Fig. 3 shows the layout and simulation results of the miniaturized coupler.

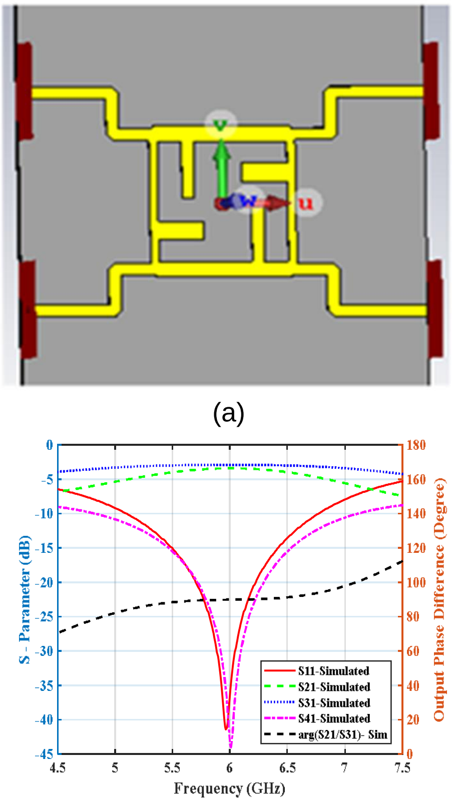


Fig. 3. (a) Layout of the miniaturized coupler; (b) S- parameter results of the coupler

The miniaturized crossover was designed from the coupler shown in Fig. 3. It was implemented by cascading the two 90° miniaturized couplers designed. The miniaturized BM, crossover, and phase shifters were used to form the proposed BM as explained in the next section.

3. DIAMOND-SHAPED PATCH ANTENNA

A diamond-shaped microstrip patch antenna working at 6 GHz was designed for the purpose of integrating on the proposed BM. The parameters of a diamond-shaped microstrip patch antenna are calculated from the equations given in [21]. Computer Simulation Technology (CST) studio suite was used to simulate all the designs. An optimal dimension of 26 mm × 14.2 mm × 0.245 mm was obtained from the CST-MWS 2024.

Fig. 4 shows the geometry, radiation pattern, and the return loss of the single element patch antenna. From this Figure, it can be observed that a return loss better than $-33\,dB$ was realized with an excellent radiation pattern having a gain of $4.41\,dB$, side lobe level of $-17\,dB$ and $3dB$ angular beamwidth of 84.8 degree.

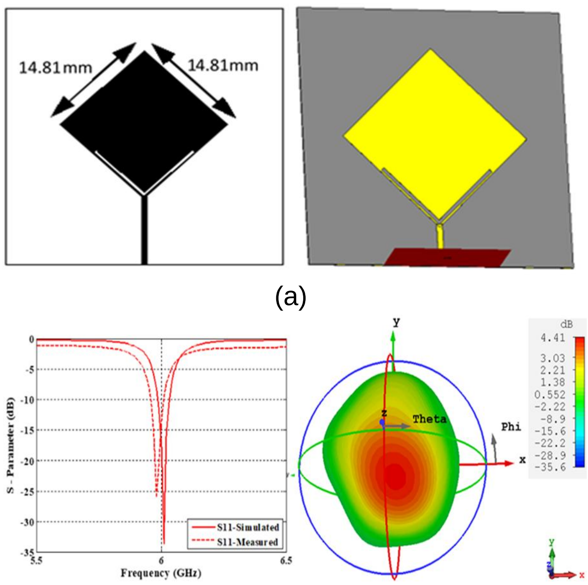
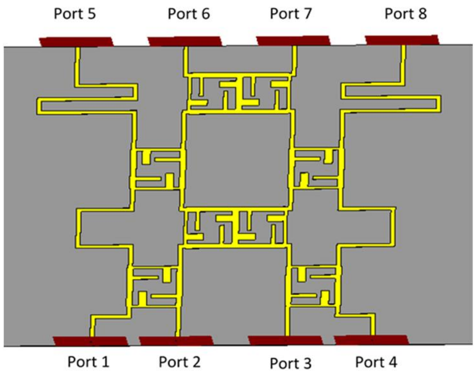


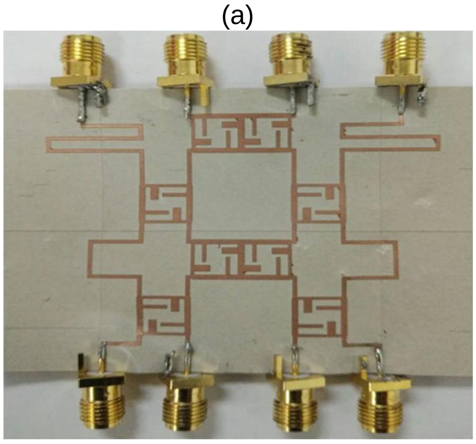
Fig. 4. (a) Layouts of Single Element Patch Antenna; (b) Return Loss and Radiation Pattern of the Single Element Patch Antenna

4. MINIATURIZED BUTLER MATRIX

The miniaturized 3 dB coupler together with the crossovers designed in the previous section were used for the design of the miniaturized 4 x 4 BM. The design was done in a modular manner where every component is treated independently. One of the couplers from the input side of the BM was first simulated alongside with the 45^0 phase shifter and the crossover to obtain an output result usually multiple integral of 45^0. Fig. 5 shows the circuit layout and the fabricated miniaturized BM without antenna array.



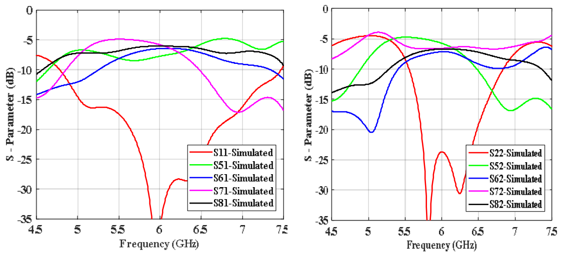
(a)



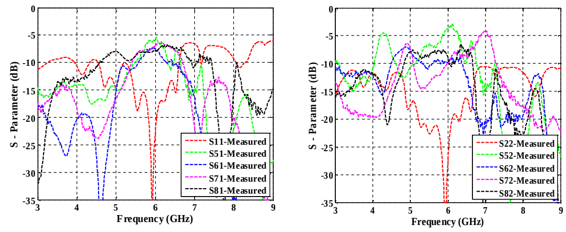
(b)

Fig. 5. The miniaturized Butler matrix, (a) the complete layout; (b) the photograph of the fabricated BM

Fig. 6 shows the scattering parameter results of the BM extracted from the full-wave simulator. The results presented are validated by means of measurement using a 4-port vector network analyser (not shown here) and the performance characteristics obtained from the measured results of the BM by exciting all the ports separately are in closed agreement.



(a)



(b)

Fig. 6. Simulated and measured S-parameter results showing the reflection and transmission coefficients when port 1 and port 2 are excited.

5. ANTENNA BEAM STEERING

To further test the beam steering capability of the miniaturized BM, it was integrated with the antenna array as shown in Fig. 7 Unlike in the conventional spacing of the array on the BM, in this case, the inter-elements distance between the array is reduced to 0.3λ due to the compact nature of the BM. This results in overlapping of the array which eventually produced a very large back lobe resulting in a broad beam at zero degrees as depicted in Fig. *8*

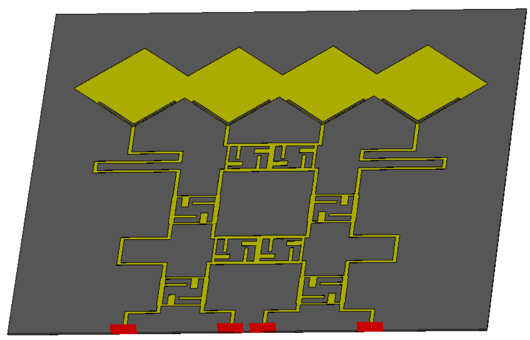
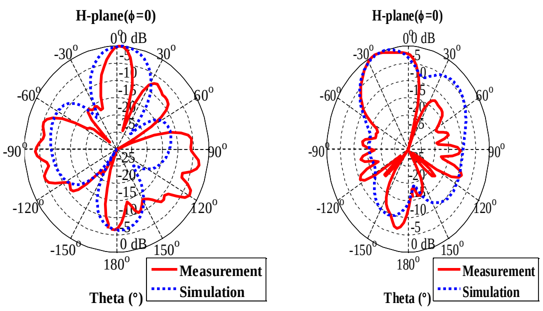


Fig. 7. Layout of the miniaturized Butler matrix with antenna array.

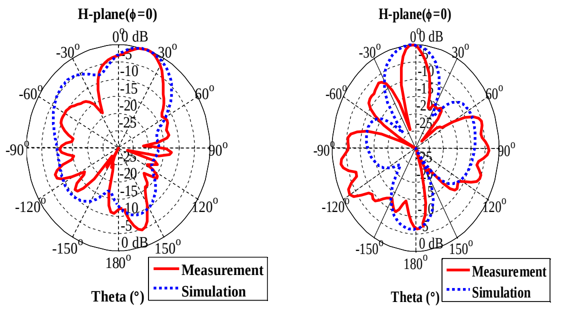
Even though a BM with broadside beams was presented in [22], the BM has to be modified before realizing the broadside beam. The trick behind obtaining the broadsides beams in this paper was the compactness of the antenna array which eventually resulted in diminishing of the main lobe and enlargement of the back lobes. In this case, the main beam becomes far away from the zero axis and therefore produces a very strong grating lobe, which overshadows the main beam and is deposed at the broadside. No modification was made from the BM side. However, a technique of creating some slots at the ground of the array and overlapping the patches helped to reduce the mutual coupling among the arrays due to their closeness.

When power is injected into port 1 and 2 separately, the beam patterns are tilted to an angle of $\pm 22.5.0^0$ and 0.0^0 respectively. Similarly, due to symmetry of the BM, when power is excited at port 3 and port 4, quite similar patterns are observed but beam deposed with opposite sign to those obtained by exciting port 2 and 1 respectively. The radiation pattern results in polar forms are extracted, processed, and plotted alongside the measured patterns and presented in **Erreur ! Source du renvoi introuvable.**.

From **Erreur ! Source du renvoi introuvable.**, when port 1 is excited with energy, the main beam angle is deposed at $+22.5^0$ and when the power is excited to port 2, the main beam angle switched to 0.0^0. Similarly, due to symmetry of the BM, when power is excited at port 3 and port 4, the main beams deposed at $+24.35^0$ and 0.0^0 respectively.



(a) (b)



(c) (d)

Fig. 8. Radiation Pattern from the Miniaturized BM When: (a) Port 1 is excited; (b) Port 2 is excited; (c) Port 3 is excited; (d) Port 4 is excited

6. CONCLUSION

This paper presented a BM completely from 90°-3dB couplers in planar microstrip technology that produces a broadside beam. This was achieved by feeding the BM with completely overlapped antenna array separated by 0.3λ as against the conventional 0.3λ spacing. It is obvious that when the arrays are spaced below 0.5λ, there would be mutual coupling among the arrays. This configuration along with slots help to makes the BM produce the main beam far away from the broadside axis which results in a very strong grating lobe that overshadowed the main beam and is deposed at the broadside. The validity of this BM was demonstrated by comparing the simulation results of the return losses, transmissions, and radiation pattern with measurements, the measurement results showed good agreement with simulations.

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