Design and Simulation of Microstrip Butler Matrix Elements Operating at 2.4GHz for Wireless Applications

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Abstract— In the proposed paper, the study of the design of Butler Matrix Elements is presented. The design presented in this paper consists of Microstrip 90^0 Hybrid coupler, 3dB crossover coupler, and 45^0 phase shifter. These elements are designed to work in ISM frequency band i.e. at 2.4GHz, which can be used for wireless applications such as Bluetooth, WLAN, and other wireless applications. The design is implemented on a FR-4 epoxy substrate with dielectric constant of $\varepsilon_r = 4.4$ .The design and simulation is carried out in CST studio. Simulated results show good agreement with theoretical calculation.

Index Terms— Butler Matrix Element, Hybrid Coupler, Crossover Coupler, Phase shifter,Beam Steering system Element,Smart Antenna Element.

1 Introduction

In recent years, mobile and wireless communication systems have experienced an increasing number of users, requiring a huge expansion of cellular communication systems. The 'Smart Antenna' system seems to provide a solution for this problem [1]. Smart antennas are introduced to improve the performance of wireless systems [2] and increase their capacity by spatial filtering, which can separate spectrally and temporally overlapping signals from multiple users. Several studies related to these systems have been addressed by researchers [3-4]. One should know that smart antennas are mainly based on the use of these beam forming networks [5]. It usually operates over a narrow frequency band to maintain the specified beams directions. The Butler matrix is one of the beams forming network, with N input/output port and N input/output antenna elements, producing N orthogonal beam at different locations [1]. Butler matrix was easily implemented using the microstrip due to numerous advantages such as low profile, easy fabrication and low cost [1]-[4]. The Butler Matrix consists of 90^0 Hybrid Coupler, 45^0 phase shifter and 3dB crossover coupler [2].

The branch line couplers providing an equal power division/combination and quadrature phase difference are one of the basic circuit components for balanced mixers, power amplifiers, array antennas, modulators, and filters. However, the conventional branch-line coupler design methods, based on $\lambda/4$=4 transmission line length, provide a narrow band. Also, size is comparable to the wavelength, so the dimensions are quite large at lower wireless frequencies. The conventional branch line coupler [6] comprises of four quarter-wavelength transmission lines. Microstrip lines are used to design compact planar branch-line couplers [7].

In the proposed paper, the design of Butler Matrix elements is presented. These elements include a 90^0 Hybrid Coupler, 3dB crossover coupler, and a 45^0 phase shifter. For design FR-4 substrate with dielectric constant of 4.4 is used. These elements are implemented and simulated in CST studio. The simulation results show that all the elements give the best possible results at 2.4GHz which can be used for wireless applications.

2 Design Consideration

As seen in Fig.1, the 4x4 Butler matrix used includes two crossovers, 4 blocks of hybrid couplers (-3dB/ 90^0) and finally 2 Phase shifters (45^0) [8] connected by crossover coupler. All the elements of Butler Matrix are designed using FR-4 substrate having a dielectric constant of 4.4. These elements are designed and optimized to operate at the ISM band frequency i.e. 2.4GHz for wireless applications such as Bluetooth, WLAN, and other applications.

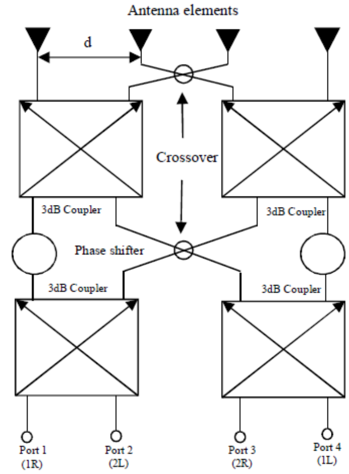

Fig.1: Butler Matrix

The transmission line model analysis is used to calculate the dimensions of microstrip elements. At low frequencies,

ISSN 2229-5518

(ε_{reff}) it remains constant and can be expressed in terms of stripline dimensions and substrate dielectric constant (ε_r):

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \qquad (1)$$

Also, due to the fringing effect, the electrical length of the strip increases by the distance of 2ΔL. In the transmission line model, ΔL is expressed as:

$$\Delta L = h * 0.412\frac{(\varepsilon reff + 0.3)(\frac{w}{h} + 0.264)}{(\varepsilon reff - 0.258)(\frac{w}{h} + 0.8)} \qquad (2)$$

and is used to compute the actual length (L) of the Microstrip line as:

$$L = \frac{1}{2 f_r \sqrt{\varepsilon_{reff}}\sqrt{\mu_0 \varepsilon_0}} - 2\Delta L \qquad (3)$$

The width of transmission line at resonating frequency can be expressed as:

$$L = \frac{1}{2 f_r \sqrt{\mu_0 \varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r + 1}} = \frac{\upsilon_0}{2 f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \qquad (4)$$

2.1 Hybrid Coupler

Quadrature hybrids are 3dB directional couplers which generate 90^0 out of phase at the outputs of the coupler [6]. Fig. 2 shows the layout of a directional coupler. When the impedance of the entire ports matched, the power entering at port 1 is evenly divided between port 2 and 3 with a 90^0 phase shift between them. And port 4 is isolated since there is no power coupled between port 1 and port 4[8]. Through even-odd mode analysis, we can show [6] that the S-matrix as follows:

$$S = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix} \qquad (5)$$

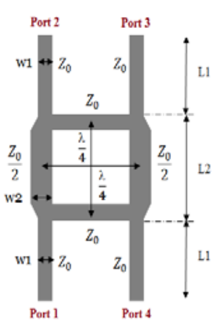

Fig. 2: Schematic of Microstrip Hybrid Coupler

Basically, the 90^0 hybrid coupler is made by two main transmission lines shunt connected by the two secondary branch lines. It has two 50Ω and two 35.4Ω transmission lines with length $\lambda/4 = 4$ [6]. So the perimeter of the square is approximately equal to one wavelength.

TABLE 1 OPTIMIZED PARAMETER FOR HYBRID COUPLER

Parameters	Values
W1	3.4mm
W2	5.2mm
L1	17.124mm
L2	16.737mm
Z_0	50Ω

The dimensions of 50Ω and 35.4Ω transmission line, calculated using eq.(1) - eq.(4) are L1=17.124mm W1=3.4mm, L2=16.737mm and W2=5.2mm. The final optimized dimensions of the 90^0 hybrid coupler are as shown in TABLE-1.

2.2 Crossover Coupler

This component ensures the crossing of two transmission lines. It is also called 0 dB coupling. Reference [10] mentioned that the coupling between the two transmission lines, constituting the cross-coupling, is relatively low. Furthermore, it states that the combination of two hybrid couplers allows obtaining a cross-coupling. Fig.3 shows the geometry adopted for the achievement of this device whose corresponding S matrix [6][10] can be written as follows:

$$S = \begin{bmatrix} 0 & 0 & j & 0 \\ 0 & 0 & 0 & j \\ j & 0 & 0 & 0 \\ 0 & j & 0 & 0 \end{bmatrix} \qquad (6)$$

TABLE 2 OPTIMIZED PARAMETER FOR CROSSOVER COUPLER

Parameters	Values
W1	3mm
W2	3.5mm
W3	4mm
L1	16mm
L2	16.736mm

The theoretically calculated values of microstrip transmission line, used for implementing microstrip crossover coupler using eq.(1)-(4) are W1=3.059mm, L1=17.124mm, W2=5.223mm, L2=16.737mm, W3=8.371mm, L2=16.386mm.

ISSN 2229-5518

Finally, these values are optimized so as to get the desired output which is mentioned in Table-2.

2.3 Phase Shifter

A 4x4 Butler Matrix has two 45^0 phase shifter. Microstrip transmission lines are used to implement each phase shifter [6].

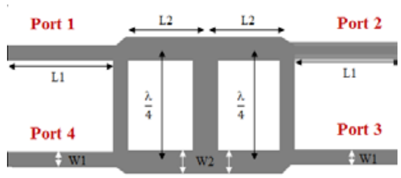

Fig. 3: Schematic of Microstrip Crossover Coupler

The length 'L' of the transmission line requires to introduce phase shift of 45^0 is given by the formula [9]:

$$L = \theta . \frac{\lambda_g}{360} \qquad (7)$$

Where, θ is the phase shift and the wavelength λ_g can be expressed as:

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{reff}}} \qquad (8)$$

Where, λ_0 is the free space wavelength and ε_{reff} is the effective dielectric constant of the line.

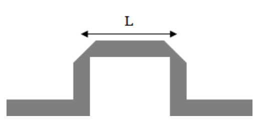

Fig.4: Schematic of Microstrip Phase Shifter

The theoretically calculated length of transmission line for 45^0 phase shifter using equation (7) and equation (8) is 8.547mm. Fig. 4 represents the layout of 45^0 phase shifter.

3 Result And Discussion

The designs of all components of Butler Matrix are implemented and simulated in CST studio. The design is implemented on a FR-4 substrate with dielectric constant of 4.4.

3.1 Hybrid Coupler

The result of optimized Hybrid Coupler is as shown in Fig.5. From fig.5, it can be seen that the reflection coefficient S11 is -22.645dB at 2.4GHZ, which indicates good input impedance matching.

The transmission coefficient S41 is -27.26dB at 2.4GHz which means there is good isolation between port 1and port 4. The transmission coefficient S21 is -3.363dB andS31 is -3.534dB at 2.4GHz, which indicates input power is equally distributed between port 2 and port 3 respectively.

Fig.6 shows the 'Frequency vs. Phase' characteristics of a hybrid coupler. In fig.6, the phase of transmission coefficient S21 is 82.717^0 and phase of transmission coefficient S31 is -7.349^0 at 2.4GHz. The phase shift between port 2 and port 3 is 90^0 which indicate that the theoretical calculations are in good agreement with simulated results.

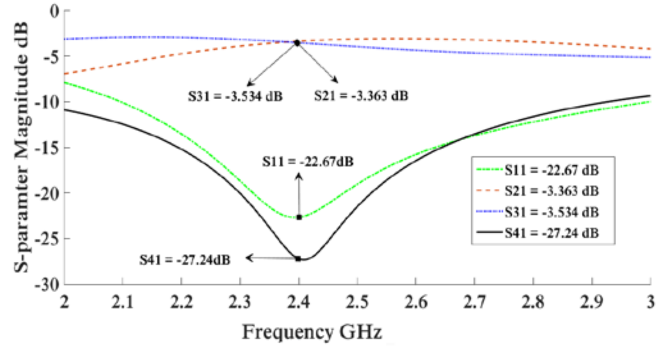

Fig.5: S-parameter plots for hybrid coupler

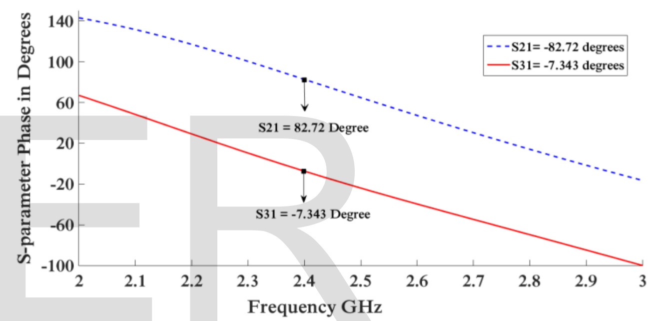

Fig.6: Frequency vs. Phase plot of hybrid coupler

3.2 Crossover Coupler

Crossover coupler can be yielded by cascading two hybrid couplers[11].The theoretical values of microstrip transmission line to design crossover coupler calculated using eq.(1)-eq.(4) are W1 = 3mm, W2 = 3mm, W3 = 5.4mm, L1 = 17.124mmand L2 = 16.736. These values are optimized to get best possible results, which are W1 = 3mm, W2 = 3.5mm, W3= 4mm, L1 = 16mm and L2 = 16.736mm.

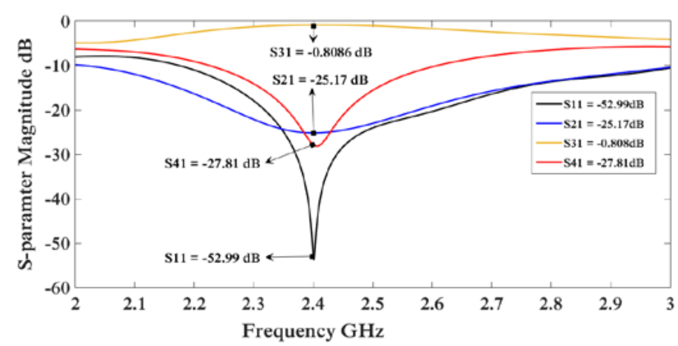

Fig.7: Simulated results of s-parameters of crossover cou-

Fig.7 shows the simulated results of crossover Coupler. The reflection coefficient S11 is -53.06dB, transmission coefficient S21 is -25.14dB, coupling coefficient S31 is -0805dB and isolation coefficient S41 is -28.16dB at 2.4GHz. These results show that the crossover coupler is having a good isolation between port 1 & port 4 and between port 1 & port 2. Also there is a good coupling between port 1 & port 3.

2.3 Phase Shifter

It should be remembered that phase shift is a linear function of the frequency since we have used an easy transmission line for the implementation of this device.

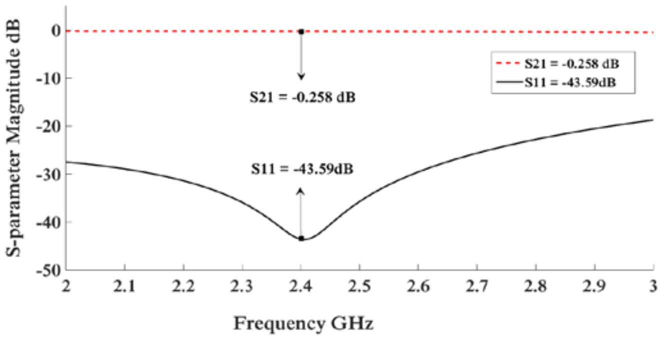

Fig.8 Simulated results of s-parameter of phase shifter

Fig.8 depicts the simulation of S-parameters of Phase Shifter. From the fig.8, it can be seen that the transmission coefficient S21 is -0.258dB at 2.4GHz which means almost all of the input power from port 1 is transferring to port 2. Also, reflection coefficient S11 is -43.062dB at 2.4GHz, which shows good input impedance matching at port 1.

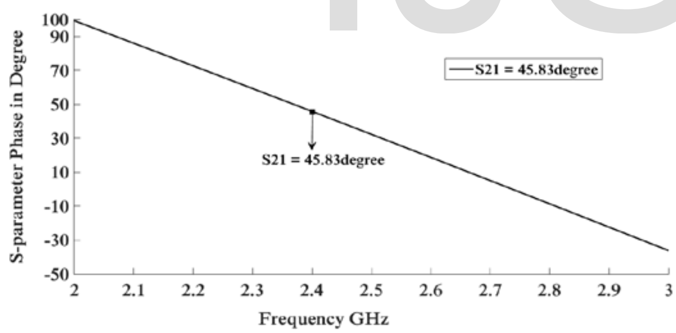

Fig.9: Frequency vs. phase characteristics of phase shifter

Frequency Vs. Phase characteristics of transmission coefficient S21 are shown in fig.9. From the fig.9, it can be seen that the transmission coefficient S21 phase shift, at 2.4GHz, is 45.591^0 . With this, we can infer that the phase shift between port 1 and port 2 is almost 45^0 .

4 Conclusion

This paper presents the simulation and implementation of Butler Matrix elements for wireless application at 2.4GHz. Theoretical calculations of individual elements are carried out using standard formulae and are optimized to get the best possible results. Implementation and simulation of each element are carried out in CST Studio. Results show that there is good agreement between theoretical and simulated results.

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