Design of Compact Single-Section Directional Coupler for Butler Matrix Beam-forming MIMO

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Abstract

This paper demonstrates a new design of 3 dB coupler operating in UWB frequency band between 3.1 GHz and 10.6 GHz. Together with UWB phase shifter, this coupler is claimed to be one of the key factors in designing a Butler Matrix that can operate in very wide frequency range. Butler Matrix has been seen to be the most preferable technique to realize the beam-forming network besides provide compact in size and more cost-effective. The arrangement between beam-forming and multiple-input and multiple-output (MIMO) can broaden the coverage and capacity of users for wireless communication system. The proposed coupler design was accomplished in multilayer microstrip-slot technology by employing broadside coupling technique. The initial dimension of the coupler was obtained using a simple mathematical formula and finalized using CST Microwave Studio simulator. The simulation results show the coupler is having a very tight coupling of 3 dB ± 2 dB, the return loss and isolation are better than 21 dB and the phase difference performance is in the range of $90^0 \pm 2^0$ over the designated band. The designed device occupies an area of 25 mm x 15 mm.

1. Introduction

Recently, multiple-input and multiple-output (MIMO) technology has attracted attention of many researches in wireless communications' area as it offers significant advantages in transmitting signal from base station to mobile station compare to the conventional way. In contrast to other methods, Butler Matrix has been seen to be the most preferable approach to realize the beam forming MIMO especially for the ultra wideband frequency range. Together with UWB phase shifter, a UWB coupler can construct a new form of Butler Matrix that can be use in the beam-forming MIMO. Most of the coupler that realized in common planar technology such as microstrip and stripline can only cover a certain narrow frequency band. In order to have the coupler to operate in ultra wide frequency range, one of the well-known techniques that can be applied is by employing multilayer microstrip-slot technology [1-7]. The proposed design reported in [8] shows that a very compact coupler has been constructed and it has the capability to operate almost over 4:1 frequency range. The complexity in the circuit design due to the used of the capacitive disc below the slot line as reported in [8], had encouraged Garcia [9] to demolish the need of the capacitive disc and presented his own design by widening the size of the slot below the microstrip layer and claimed that it could be the main factor to achieve the ultra wideband performance. Other than that, another 3-dB coupler design rules have been proposed by Schiek [10] and Hoffmann and Siegl [11] which both of this research eliminate the capacitive disc underneath the slot in order to get the ultra wideband performance but unfortunately, the electrical performance was not as broad as reported in [8] and [9]. Apart from that, a coupler design reported in [1] shows an outstanding result by providing a very tight coupling over the ultra wide band frequency from 3.1 GHz to 10.6 GHz. In this paper, a design of multilayer microstrip-slot diamond-shaped coupler will be proposed as an alternative to achieve UWB operating frequency. This coupler is one of the components that will be used to construct a Butler Matrix; one of the techniques in realizing the beam-forming MIMO.

2. Design and Analysis

The configuration of the proposed coupler presented in this paper is shown in Fig. 1. As observed in Fig.1, the coupler consists of three conductor layers with two substrates interleaved between each of the layers. The top conductor layer includes ports 1 and 2, meanwhile bottom conductor layer include ports 3 and 4. Both of this top and bottom layers are coupled through the slot in the common ground plane. The design initiated with calculating the dimension of the coupler using a simple mathematical formula.

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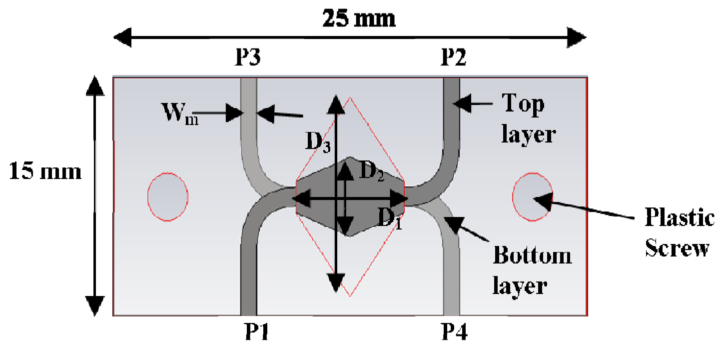

Fig. 1. The configuration of the proposed coupler including microstrip ports.

By following the guidelines in [12], to have a 3-dB coupling coupler, equation (1) and (2) are applied in order to obtain the characteristic impedances of the even- and odd-mode [12]:

$$Z_{0e} = Z_0 \sqrt{\frac{\left(1+10^{-\frac{C}{20}}\right)}{\left(1-10^{-\frac{C}{20}}\right)}} \quad (1)$$

$$Z_{0o} = Z_0 \sqrt{\frac{\left(1-10^{-\frac{C}{20}}\right)}{\left(1+10^{-\frac{C}{20}}\right)}} \quad (2)$$

where the C is the numerical value of the coupling factor in decibel and Z_0 is the characteristic impedance of the microstrip ports of the coupler.

As the value of Z_0 is equal to 50 ohm and the C is equal to 3 dB, the values for Z_{0e} and Z_{0o} calculated from (1) and (2) are 120.9 ohm and 20.7 ohm, respectively. Using even- and odd-mode analysis approach as presented in [13] the width of the microstrip realizing Z_{0o} can be determined using equation (8) or using static formulas stated in equations (4) and (5) meanwhile, for the width of the microstrip realizing Z_{0e} can be determine using equation (3) and (5).

$$Z_{0e} = \frac{60\pi}{\sqrt{\varepsilon_r}} \frac{K'(k_1)}{K(k_1)} \quad (3)$$

$$Z_{0o} = \frac{60\pi}{\sqrt{\varepsilon_r}} \frac{K'(k_2)}{K(k_2)} \quad (4)$$

$$\frac{K(k)}{K'(k)} = \begin{cases} \frac{2}{\pi} \ln\left(2\sqrt{\frac{1+k}{1-k}}\right), & for\ 0.707 \le k \le 1 \\ \frac{\pi}{2\ln\left(2\sqrt{\frac{1+\sqrt{1-k^2}}{1-\sqrt{1-k^2}}}\right)}, & for\ 0 \le k \le 0.707 \end{cases} \quad (5)$$

where $K(k)$ is the first kind elliptical integral and $K'(k) = K\left(\sqrt{1-k^2}\right)$. Equation (6) and (7) were used to determine the values for k_1 and k_2, respectively:

$$k_1 = \sqrt{\frac{sinh^2\left(\frac{\pi w_s}{4h}\right)}{sinh^2\left(\frac{\pi w_s}{4h}\right) + cosh^2\left(\frac{\pi w_p}{4h}\right)}} \quad (6)$$

$$k_2 = \tanh\left(\frac{\pi w_p}{4h}\right) \quad (7)$$

Where h is the substrate thickness which is 0.508 mm, w_p is the width of the microstrip patches and w_s is width of the microstrip slot.

$$\frac{W}{h} = \begin{cases} \frac{8e^A}{e^{2A}-2} & , \frac{W}{h} < 2 \\ \frac{2}{\pi}\left[B - 1 - \ln(2B-1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left(\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}\right)\right] & , \frac{W}{h} > 2 \end{cases} \quad (8)$$

The width of the microsrip transmission line W_m realizing Z_o is also determined by using equation (8), and the value obtained by using the equation is 1.18 mm. Finally, by using equation (9), the length of the microstrip section can be calculated.

$$\lambda_e = \frac{\lambda_o}{\sqrt{\mathcal{E}_e}} \quad (9)$$

Formulas (3)–(9) are the equations needed to obtain the initial dimension of the coupler. Then by using the CST Microwave Studio simulator and formulas as reported in [1], the optimized values of the coupler were found as follows: D_1 = 6 mm, D_2 = 8 mm, D_3 = 10 mm and W_m = 1.18 mm (for 50Ω microstrip line).

The simulated S-parameters for the design coupler are shown in Fig. 2. The simulated results show that both return loss and isolation are better than 21 dB between 3.1 GHz and 10.6 GHz. Moreover, based on the same figure, it shows that the coupling provided by this coupler is in the range of 3 dB ± 2 dB across the same band frequency. The phase difference of $90^0 \pm 2^0$ is achieved across the designated band frequency which is shown in Fig. 3. It can be observed from Figure 2 and 3, the performance of this coupler can be recognized to be used in many ultra-wide band applications.

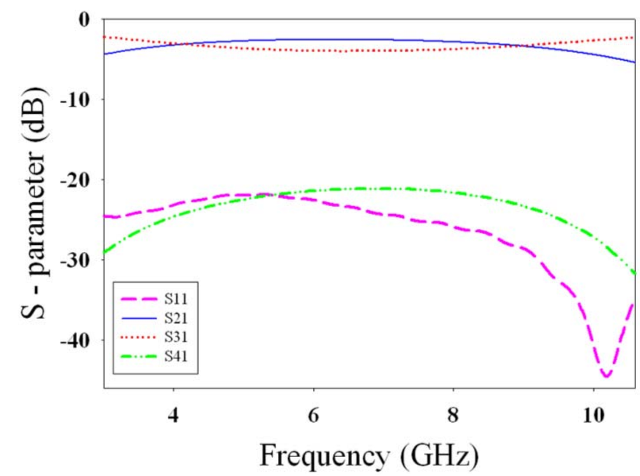

Fig. 2. S-parameter performance of the diamond shaped coupler

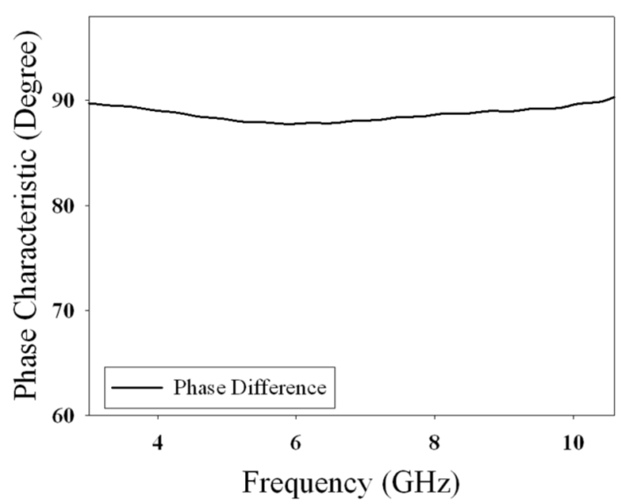

Fig. 3. Phase difference performance of the diamond shaped coupler

3. Conclusion

In this paper, a new design of 3-dB coupler has been presented. The dimension of the coupler was initialized by using simple mathematical equation and finalized using the CST Microwave simulator. The simulation result shows that the coupler is having good results where both return loss and isolation are better than 21 dB and the coupling provided by the coupler is in the range of 3 dB ± 2 dB across the band. Meanwhile, $90^0 \pm 2^0$ phase differences between S21 and S31 are also achieved across the same band. This coupler is one of the components that can be used to construct a Butler Matrix for the purpose of the beam-forming MIMO application. This coupler should be significantly attractive due to its compact size and good performance.

4. Acknowledgement

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5. References

1. M.E. Bialkowski and A.M. Abbosh, "Design of compact directional couplers for UWB applications," *IEEE Trans Microwave Theory Tech.,* vol. 55, no. 2, pp. 189-194, Feb. 2007

2. Abbosh, A. M., Design of a Broadband Quadrature Directional Coupler. *Asia-Pacific Microwave Conference, APMC* . 2007.

3. Abbosh, A. M. and Bialkowski, M. E., Design of ultra wideband 3DB quadrature microstrip-slot coupler. *Microwave and Optical Technology Letters*, 2007.

4. Traii, M., Nedil, M., Gharsallah, A. and Denidni, T. A. A novel wideband butler matrix using multi-layer technology. *Microwave and Optical Technology Letters*, 2009.

5. Seman, N. and Bialkowski, M. E. Design and analysis of an ultrawideband three-section microstrip-slot coupler. *Microwave and Optical Technology Letters*, 2009.

6. Moscoso-Martir, A., Wanguemert-Perez, J., Molina-Fernandez, I. and Marquez-Segura, E.Slot-Coupled Multisection Quadrature Hybrid for UWB Applications. *IEEE Microwave andWireless Components Letters*, 2009. 19(3): 143-145.

7. Bialkowski, M., Abbosh, A., Kan and Hing. Design of compact component for ultra wideband, *IEEE Conference Proceedings*, 2007.

8. F. C. de Ronde, "A new class of microstrip directional couplers," *IEEE MTT-S Int. Microw. Symp. Dig.,* pp. 184-189, May 1970.

9. J.A Garcia, "A wide-band quadrature hybrid coupler," *IEEE Trans. Microwave Theory Tech.,* vol. MTT-19, no. 7, pp. 660-661, Jul. 1971.

10. B. Schiek, "Hybrid branchline couplers-Useful new class of directional couplers," *IEEE Trans. Microwave Theory Tech.,* vol. MTT-22, no. 10, pp. 804-869, Oct. 1974.

11. R.K. Hoffmann and J. Siegl, "Microstrip-slot coupler design-Part I and II," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, no. 8, pp. 1205-1216, Aug. 1982.

12. David M Pozar, "*Microwave Engineering*", Wiley, USA, 2005.

13. Wong, M., Fouad Hanna, V., Picon, O. and Baudrand, H. Analysis and design of slot-coupled directional couplers between double-sided substrate microstrip lines. *IEEE Transactions on Microwave Theory and Technirues*, 1991.