Mountain-Shaped Coupler for Ultra Wideband Applications

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Abstract. *This paper demonstrates a novel mountain-shaped design for a compact 3-dB coupler operating at ultra-wideband (UWB) frequencies from 3.1 GHz to 10.6 GHz. The proposed design was accomplished using multilayer technology in which the structure is formed by three layers of conductors interleaved by a layer of substrate between each conductor layer. Simulation was carried out using CST Microwave Studio; the result was then compared with results from rectangular and star-shaped couplers that implemented the same technique. The results obtained show that the proposed new coupler has better performance compared to both rectangular and star-shaped coupler designs in terms of return loss, isolation, and phase difference. The coupler was fabricated and measured; the measurement results satisfactorily agree with the simulation results.*

Keywords

Ultra-wideband frequency, coupler design, beam-forming, Butler matrix, multilayer technology.

1. Introduction

Beginning the 1960s, ultra-wideband (UWB) technology began to be used in many applications, for instance, in communication and radar systems. In February 2002, the Federal Communications Commission (FCC) of the United States allocated a UWB frequency band from 3.1 GHz to 10.6 GHz. Since then, more applications have been investigated for operation in this UWB allocation. One such application is an imaging technique to detect breast cancer [1], [2].

A Butler matrix is a beam-forming network that provides various beams in different directions. With the use of a Butler matrix in UWB microwave imaging, it is easier, safer, and faster to scan and detect cancerous cells in the breast, due to the advantage derived from generating multiple beams simultaneously [3], [4]. To design a Butler matrix, one must first design the main components, which consist of a phase shifter, crossover, and coupler. All components must operate in the UWB frequency band in order to construct a UWB Butler matrix.

It is very challenging to design a coupler with very tight coupling over a very wide frequency band. One of the most popular methods to solve this problem is the use of coupled transmission line, as reported in [5]. However, to achieve tight coupling with reasonable strip widths and gaps, a Lange coupler needs a substrate with very high dielectric permittivity. In contrast, lower dielectric constant substrate leads to narrower strip widths and gaps in the coupler, which increases the complexity of fabrication.

Alternative techniques to achieve tight coupling include using a slot-coupled directional coupler at the expense of narrow bandwidth. To overcome the bandwidth issue of this technique, one solution is to use multilayer technology in the coupler design, as proposed in [6]. Differing from the design proposed in [6], another solution is proposed by de Ronde [7]. This coupler design successfully achieves compact size and is capable of operating almost 4:1 frequency range. However, the complexity of the design is increased by inclusion of a capacitive disc below the slot line. Later, Garcia [8] proposed an improvement to de Ronde's design, in which widening the slot size below the microstrip layer successfully enhances coupler bandwidth without involving complex circuit design. Several other coupler designs are proposed in [9-11], but unfortunately none manages to produce tight coupling over the UWB frequency band. Tab. 1 summarizes the bandwidth covered by the designed coupler, as compared to couplers described in other research.

The coupler design reported in [12-14] shows that these couplers manage to provide very tight coupling over the whole UWB frequency range. The designed coupler is based on the same concept as Tanaka in [6], but with different slot shapes. Further, as reported in [12], besides elliptical, there are other shapes that can be used in the coupler design, but performance differs depending on the shape of the coupler itself [15]. Thus, analysis of different coupler shapes is critical to analyzing the performance of the coupler design. Tab. 2 summarizes the shapes and size of the proposed coupler compared to the other couplers mentioned above.

Coupler Design	Bandwidth performance
Coupler using multilayer microstrip transition [10]	3 GHz to 9 GHz (6 GHz)
Coupler based on coplanar CRLH waveguides [11]	9.9 GHz to 14.7 GHz (4.8 GHz)
Coupler with CPW multilayer slot-coupled [12]	6 GHz
Proposed coupler	3.1 – 10.6 GHz (7.5 GHz)

Tab. 1. Bandwidth: Literature comparison.

Coupler Design	Size of the shaped geometry
Coupler with elliptical shape [13]	7.4 mm x 4.8 mm
Coupler with lozenge shape [14]	8.8 mm x 6.0224 mm
Coupler with diamond shape [15]	8 mm x 6 mm
Proposed coupler	8 mm x 5.15 mm

Tab. 2. Size: Literature comparison.

This paper presents a novel design for a mountain-shaped coupler. This coupler represents an enhancement of the star-shaped coupler reported in [15]. The difference from the latter design is that the edge of the coupler is contoured to become concave-shaped, since it is found that the concave shape has better performance compared to convex shape. Moreover, the edge formed by the star-shaped coupler leads to discontinuity, which gives rise to additional losses. The simulation result from this coupler is compared to the rectangular and star-shaped couplers introduced in [15] to observe the differences and test the theory reported. Then, the mountain-shaped coupler is fabricated to evaluate the accuracy of the simulation results in the real environment. Roger RO4003C with height of 0.508 mm and dielectric constant of 3.38 is used in the fabrication process. Results from the simulation and measurement are compared and discussed in Section 2 below.

2. Coupler Design

Fig. 1 shows the configurations of the mountain-shaped coupler. As shown in Fig. 1(a) and Fig. 1(c), the top and bottom layers of the proposed coupler consist of mountain-shaped microstrip lines, while the middle layer, as shown in Fig. 1 (b), is the ground plane, which consists of a mountain-shaped slot. Fig. 1(d) shows the complete coupler construction. Port 1 (P1) and Port 2 (P2) are located at the top of the conductor layer, while Port 3 (P3) and Port 4 (P4) are located at the bottom of the conductor. Fig. 1(e) shows that the coupler consists of three conductor layers interleaved by two substrates between each conductor layer.

The design initiates with a rectangular shape by using a simple mathematical formula from [6], [16]. Subsequently, the method and mathematical equation introduced in [12] is employed. Hence, the elliptical-shaped coupler is obtained.

As reported in [15], one way to change the shape from an ellipse to a star shape is by changing the value of n in

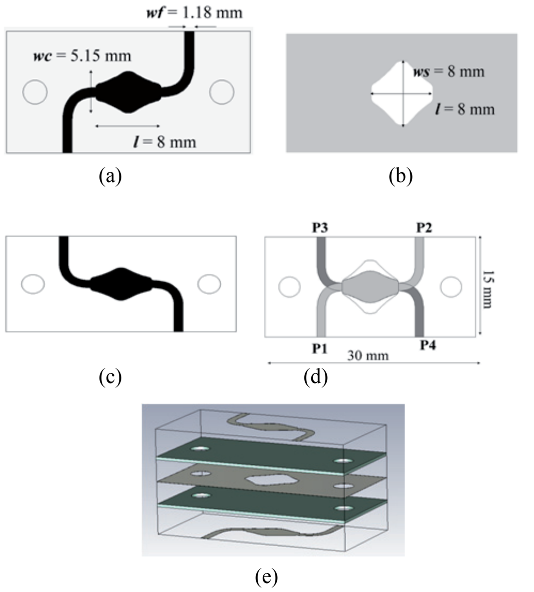

Fig. 1. Configuration of mountain-shaped coupler: (a) Top layer. (b) Middle layer. (c) Bottom layer. (d) Whole coupler. (e) Dimensional view.

the tapering function equations, $f_1(x)$ and $f_2(x)$, as follows:

$$f_1(x) = \frac{w_c - w_f}{2\left(e^{\frac{nl}{2}} - 1\right)}\left(e^{nx} - 1\right) + \frac{w_f}{2}, \tag{1}$$

$$f_2(x) = \frac{w_s - w_f}{2\left(e^{\frac{nl}{2}} - 1\right)}\left(e^{nx} - 1\right) + \frac{w_f}{2}. \tag{2}$$

The parameters in the equation are as follows: w_f is the width of the input/output ports, l is the length of the coupled structure, w_c is the maximum width of the coupled patches at the top and bottom layer, and w_s is the maximum width of the slot at the middle layer. All of these quantities above are in millimeters. Parameter n is used to change the shape of the coupler and also yields different performances of the coupler itself. The graphical definition of the parameters used in the equations is shown in Fig. 2.

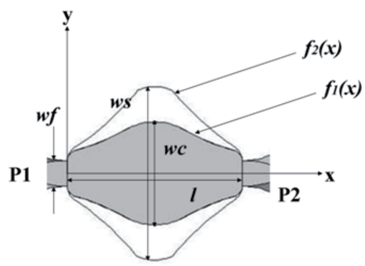

Fig. 2. Graphical definition of the parameter used in the equation.

There are four conditions of n that can be employed in the equation: positive value, negative value, zero value, or infinite. All these conditions lead to different performances. A positive value of n leads to a convex shape, hence a negative value of n leads to a concave shape.

An example of a concave shape is an ellipse shape. For an ellipse shape, the value of n is -0.9, whereas to change the shape to a star shape, the value of n is changed to 1. In this case, the ellipse shape represents concave shape, and the star shape represents convex shape. Therefore, to test the performance of the star-shaped coupler, a calculation and simulation study is undertaken. Hence, to examine the effect of the concave performance in the design, the edge of the star-shaped design is contoured accordingly so that it can be transformed into a mountain-shaped coupler, which can be considered a concave shape. Using CST Microwave simulator with the initial values, the optimized parameters of the coupler are determined and shown in Tab. 3.

Coupler Parameter	Dimension (mm)
D1	5.2
D2	8.1
D3	8
wf	1.18

Tab. 3. Dimensions of coupler design.

3. Analysis

The proposed coupler was analyzed by simulation using CST Microwave studio. The comparison of the return loss and isolation between the rectangular-shaped coupler proposed by Tanaka in [6], [17], the star-shaped coupler as proposed in [15], and the mountain-shaped coupler are shown in Fig. 3 and Fig. 4, respectively.

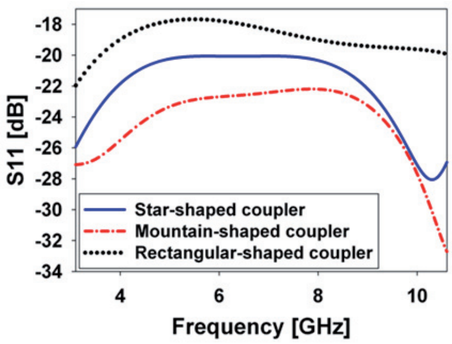

Fig. 3. Comparison of return loss simulation results between rectangular-shaped, star-shaped, and mountain-shaped couplers.

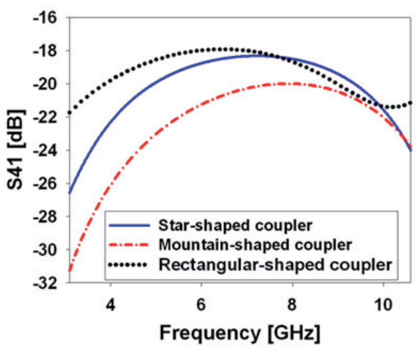

Fig. 4. Comparison of isolation simulation results between rectangular-shaped, star-shaped, and mountain-shaped couplers.

The simulated results in Fig. 3 and Fig. 4 show that both return losses for rectangular-shaped and star-shaped couplers are better than 17.6 dB and 20 dB, respectively, while the isolation results of the rectangular-shaped and star-shaped couplers are better than 17.8 dB and 18 dB, respectively. For the mountain-shaped coupler, the return loss and isolation loss are better than 22.5 dB and 21 dB, respectively. It is observed that the mountain-shaped coupler has better performance in terms of return loss and isolation compared to the rectangular and star-shaped couplers by up to 4.9 dB and 3.2 dB, respectively.

For through output and coupling, shown in Fig. 5 and Fig. 6, the result shows that the mountain-shaped coupler gives the best performance, approximately -3 dB ± 1 dB, compared to the other two design-shaped couplers.

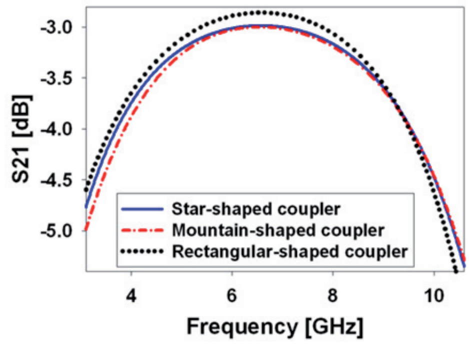

Fig. 5. Comparison of through output simulation results between rectangular-shaped, star-shaped, and mountain-shaped couplers.

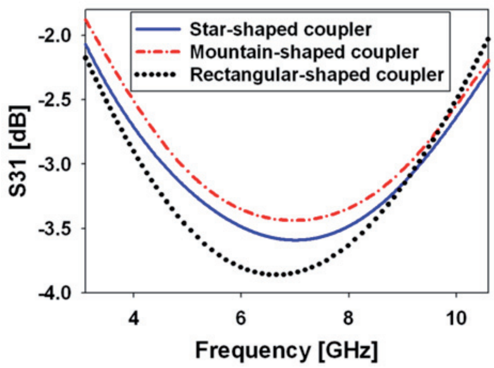

Fig. 6. Comparison of coupling simulation results between rectangular-shaped, star-shaped, and mountain-shaped couplers.

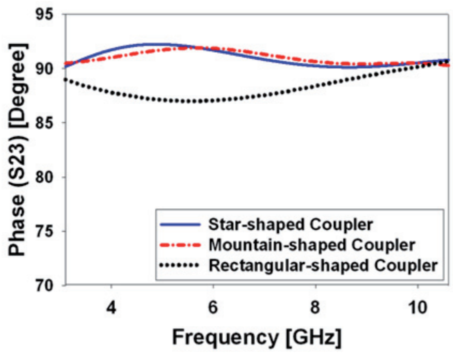

Fig. 7. Comparison of phase difference simulation result between star-shaped and mountain-shaped couplers.

Fig. 7 shows the simulation result of phase difference between two output ports for the star-shaped and mountain-shaped couplers. Based on the result, the phase difference of the rectangular-shaped coupler is $90^0 \pm 3.7^0$ and the phase for the star-shaped coupler is $90^0 \pm 2.3^0$, whereas, the phase difference for the mountain-shaped coupler is $90^0 \pm 1.8^0$. Like return loss and isolation, the phase difference for the mountain-shaped coupler also shows better performance compared to the other two design-shaped couplers up to 1.9^0.

Tab. 4 shows the outcome of the comparison between the three designs. Based on the S-parameter and phase difference simulation results, the mountain-shaped coupler is observed to have better performance compared to the rectangular- and star-shaped couplers. It is found that the shape of the mountain itself, which is more ellipse shaped, having a concave-shaped design, and positive value of *n*, lead to better performance. This supports the theory described in [15], which states that concave shaped couplers have better performance compared to other shapes studied in the literature.

Parameter	Star-shaped coupler	Mountain-shaped coupler	Rectangular-shaped coupler
S11	-20 dB	-22 dB	-17.6 dB
S21	-3 dB ±2 dB	-3 dB ±2 dB	-3 dB ±2.1 dB
S31	-3 dB ± 2 dB	-3 dB ±1dB	-3 dB ±2 dB
S41	-18 dB	-21 dB	-17.8 dB
Phase Differences	$90^0 \pm 2.3^0$	$90^0 \pm 1.8^0$	$90^0 \pm 3.7^0$

Tab. 4. Comparison results between star-shaped, mountain-shaped and rectangular-shaped designed coupler.

4. Measurement Results and Discussion

To verify the performance of this coupler, a prototype was fabricated. Fig. 8 shows the fabricated coupler.

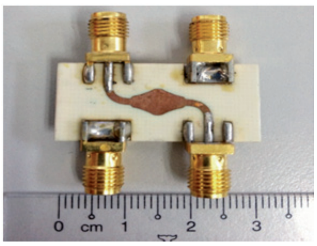

Fig. 8. Fabricated mountain-shaped coupler.

Rogers RO4003C substrate with $\varepsilon_r = 3.38$ and thickness 0.508 mm was used for coupler development. The fabricated coupler is measured by using a vector network analyzer (VNA). Then, the collected data is plotted using Sigmaplot software.

The measured results are then compared with simulated results. Fig. 9 and Fig. 10 show comparison of simulation and measurement results of scattering parameter performance and phase difference performance of the mountain-shaped coupler, respectively.

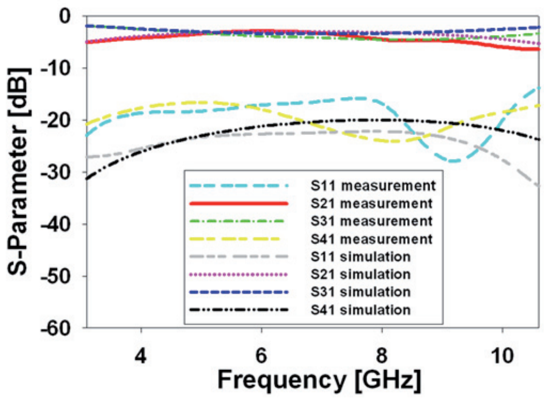

Fig. 9. S-Parameter comparison between simulation result and measurement result for mountain-shaped coupler.

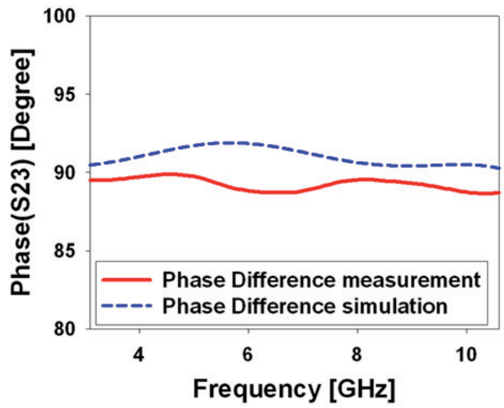

Fig. 10. Phase difference comparison between simulation result and measurement result for mountain-shaped coupler.

As noted from the results presented in Fig. 8, for simulated S-parameters, S11 = -22.5 dB, S21 = 3 ± 2 dB, S31 = 3 ± 1 dB, and S41 = -21 dB. On the other hand, for measurement, S11 = -12 dB, S21 = 3 ± 2 dB, S31 = 3 ± 1 dB, and S41 = -18 dB. Fig. 10 shows the comparison of the simulation and measurement results of phase difference between Port 2 and Port 3. As observed, the phase difference is $90^0 \pm 1.8^0$ for the simulation, and $90^0 \pm 5^0$ for measurement over the designated band. Tab. 5 shows conclusions from the comparison between both simulated and measured results for the mountain-shaped coupler.

Parameter	Simulation	Measurement
S11	-22 dB	-12 dB
S21	-3 dB ± 2 dB	-3 dB ± 2 dB
S31	-3 dB ± 2 dB	-3 dB ± 1 dB
S41	-21 dB	-18 dB
Phase Difference between (the output) ports 2 and 3	$90^0 \pm 1.8^0$	$90^0 \pm 5^0$

Tab. 5. Comparison between simulated and measured results for mountain-shaped design coupler.

As observed in Fig. 9 and Fig. 10, there are slight dissimilarities between simulation and measurement results. There are several reasons that may cause the fabricated coupler not to perform as well as the simulation result. A recent literature review shows, specifically in [18], that the existence of an air gap can have a large impact on fabricated coupler performance in terms of return loss, isolation, and phase difference.

Further, fabrication is done manually and the accuracy of the alignment may not be as exact as that in the simulation. A small misalignment can contribute to degradation of coupler performance. In addition, use of non-conductive glue to hold the multi-layer of substrates together introduces unwanted air gap traps between the substrates. To overcome these problems, high-accuracy machines should be used for the fabrication process.

5. Conclusion

In this paper, a design of a 3-dB coupler for ultra-wideband (UWB) application is proposed. The design is accomplished using multilayer technology in which the structure is formed by three layers of conductors and interleaved by a layer of substrate between each of the conductor layers. Simulation was carried out using CST Microwave Studio, then the result was compared with star-shaped coupler results. The difference from the initial design is that the edge of the coupler is contoured, because it was found that the concave shaped coupler has better performance compared to convex shaped couplers. Moreover, the edge in the star-shaped coupler leads to discontinuity, which gives rise to additional losses. This is due to the mountain-shaped coupler's nearly ellipse shape with a positive value of n. This proposed coupler should be quite attractive for UWB applications, owing to its compact size and good performance.

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