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A simple-geometry hybrid branchline microstrip coupler for wireless communication systems

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ABSTRACT

This work presents a hybrid branch-line microstrip coupler with a simple geometry operating at 2.68 GHz. The design is intended for low-cost implementation on an FR-4 substrate and takes fabrication limitations into account. A fully symmetric layout based only on rectangular branches is used, and the structure is analyzed with full-wave electromagnetic simulations in Sonnet Suites. To verify the design, a prototype is fabricated and measured. The measured results indicate that the coupling and insertion loss are close to −3.07 dB at the center frequency, while the input return loss and isolation remain better than −25 dB. The proposed coupler exhibits a fractional bandwidth from 2.14 GHz to 2.95 GHz, where the main S-parameters remain within acceptable limits. A parametric study is also carried out to evaluate the impact of dimensional variations, substrate properties, and dielectric thickness on the scattering parameters, demonstrating the robustness of the proposed geometry. Owing to its simple layout, measured performance, and use of an inexpensive substrate, the presented coupler is suitable for practical microwave front-end and signal-splitting applications.

Keywords: Branch-line coupler, Hybrid microstrip, Sonnet Suites Software, FR-4 substrate, passive components.

1. Introduction

Microwave and millimeter-wave systems are built on the foundations of passive microwave components like power dividers and couplers [1-3]. The branch line directional coupler was first proposed by Reed and Whaler in 1956. Between couplers and power dividers, there is a phase shift. The low and high frequency of action of couplers is always distinguishable. Multilayer substrate topologies like the broadside-coupled strip-line method are extensively researched because the spacing between the lines in a symmetric coupled line section must be short to generate relatively strong coupling. A branch line coupler can be utilized with power divider [4]. In the research papers [5,6], the utilization of the standard geometry is provided together with the overall comprehension of the power dividers using the microstrip technology. Furthermore, multistage of the well-known Wilkinson power divider is used in [7] and provides decent insights on how to modify the geometry such that the division of the power is achieved with minimal deviation. A branch line coupler [8] is a four-port network device with 90 phase difference between two coupled ports. The device can function as an I/Q signal splitter or combiner and is commonly used in transmit–receive microwave systems. The purpose of this model is to compute the S-parameters and observe matching, isolation, and coupling in the vicinity of the operation frequency. Because branch line couplers are symmetrical, it should be possible to use either of the ports for input power and still have the same results [8]. Strong isolation and the ability to use any of the ports as inputs or outputs while maintaining the same frequency are among the design features. Directivity is one of the most significant qualities in a coupler, as proposed in [9]. Although the present work does not focus on ultra-wideband power dividers, understanding their characteristics helps to contextualize the key S-parameter behavior of branch-line couplers. [10,11]. In addition, various geometries have been proposed where the center frequency is approximately 2 GHz with designs that vary from rectangular to T-shaped [12,13]. Furthermore, the S-parameters observed in [12,13] suggest that the modification in terms of the patch sizes and shapes significantly impacts the overall results such that the most simplistic designs can be improved to the point where one can have the half power delivered to the coupled and directed ports. Regarding the conductive materials, they are etched into a dielectric surface to form a microstrip. The ground plane, which supports the entire system, is linked to the dielectric surface. Rectangular, square round, triangular, annular, or elliptical patches are all possible. Although microwave technology is known for its use in wireless communications, new technologies and applications have emerged over time [14]. Couplers are passive devices with three or four ports that are widely utilized in microwave engineering. The two most prevalent types of couplers are waveguide and microstrip couplers. Couplers that use microstrip transmission lines are placed in a different category, while branch line and rat-race couplers are separated [15,16].The utilization of the planar branch line coupler with various substrates can yield suitable results especially in minimizing the tangent losses observed with various lossy substrates with minor changes in the overall geometry with a modified Q factor [17].Additionally, one may design a branch coupler with various transmission and suppression modes such as differential and common modes leading to increased return loss and isolation factors [18].Coupled line cells may be used to achieve 3-dB branch line coupling and the composition to right- and left-handed unit cells has been presented to provide a decent agreement between simulated and measured data [19].One may infer from the above literature that, by varying the geometry and the dielectric substrate as well as by making use of the transmission line and power division of the coupler, one may design a functional device that may perform in the acceptable region with high resemblance between the measured and the simulated data.

Recent studies have continued to investigate planar branch-line hybrid couplers using modified geometries and different substrate technologies. For example, Imeci et al. [3] reported a 3-dB microstrip hybrid directional coupler operating at 2.27 GHz with measured validation and compact layout. While such designs demonstrate satisfactory performance, they often employ geometry modifications optimized for a specific operating band or substrate. In this work, a symmetric branch-line coupler with only rectangular sections is used and implemented on an FR-4 substrate. The goal is to keep the geometry simple and suitable for fabrication, rather than aiming for extreme miniaturization or very wide bandwidth. In the literature, many branch-line couplers use complex geometries, multilayer structures, or low-loss substrates to improve performance. These approaches can work well, but they often increase cost and fabrication effort, which limits their use in low-cost microwave systems. In addition, several studies primarily focus on optimized final designs, with limited discussion on the sensitivity of the coupler performance to dimensional and substrate variations.

The problem addressed in this work is the realization of a practical branch-line hybrid coupler that maintains stable 3-dB power division, acceptable isolation, and input matching when implemented on a lossy and widely available FR-4 substrate, without relying on intricate geometrical features or multilayer processing.

The aim of this study is to design, fabricate, and experimentally validate a simple-geometry hybrid branch-line microstrip coupler operating at 2.68 GHz, and to assess its robustness through a systematic parametric study. The objectives include full-wave electromagnetic simulation, fabrication and measurement of a prototype, and evaluation of the effects of dimensional variations, substrate properties, and dielectric thickness on the scattering parameters.

The main contributions of this work include the design and experimental validation of a fully symmetric, rectangle-only branch-line hybrid coupler implemented on an FR-4 substrate. Measured S-parameter results are presented to demonstrate stable 3-dB power division together with acceptable isolation and input matching around the center frequency. In addition, a comprehensive parametric analysis is carried out to illustrate the robustness of the proposed geometry with respect to variations in physical dimensions and substrate characteristics.

2. Design Methodology

The procedure of designing the Compact Hybrid Branch Line Coupler was to build a symmetrical structure with quarter-wavelength sides such that the power is split equally between the through and the coupled ports. The whole coupler is 40.0 mm by 19.6 mm. The design consists only of rectangles which are symmetric with the other side/opposite side rectangles. This hybrid branch-line coupler employs a fully symmetric geometry with rectangular branches, which distinguishes it in terms of layout simplicity and fabrication convenience. The details of the hybrid branch line coupler are presented in the following sections. The initial dimensions of the coupler are selected based on standard quarter-wavelength branch-line principles at the target frequency, while the final geometry is refined through full-wave electromagnetic simulation to account for substrate losses and practical fabrication effect.

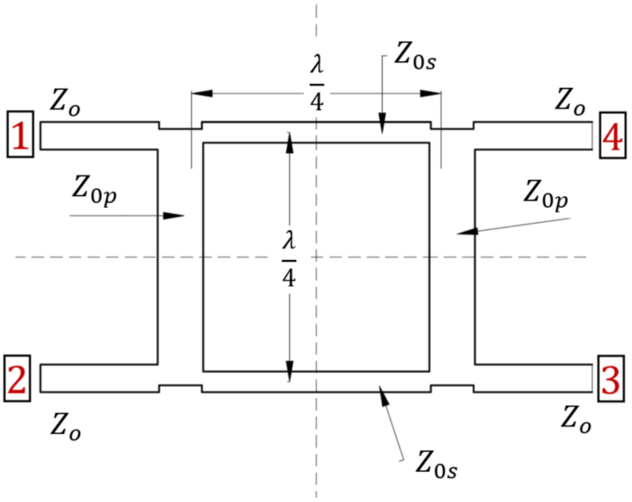

Figure 1 Impedances for the proposed design of the branch line coupler with s and p subscripts signifying the impedance in series and parallel, respectively

2.1. Theoretical Background and Operating Principle

This subsection outlines the theoretical background and operating principle of an ideal 3-dB branch-line hybrid coupler to provide context for the proposed design. The analysis is based on standard scattering-matrix formulations commonly used for branch-line couplers and is included to clarify the expected power-splitting behavior, matching, and isolation characteristics. It should be noted that this formulation represents ideal operating conditions and is not intended as a full analytical synthesis of the specific physical geometry presented in this work. Since the objective is to design the branch line coupler, one may start with the scattering matrix so that the analysis is performed based on how incident and reflected waves are transmitted in the coupler, and how the appropriate 3-dB is achieved at the directed and coupled ports. Taking the symmetric structure in the middle portion of the coupler we may define our $S_{11}, S_{21}, S_{31}, S_{41}$ parameters of the scattering matrix as [20,21]. Here, Sij denotes the scattering parameter representing the transmission from port j to port i, and all ports are assumed to be terminated with a characteristic impedance of 50 Ω.

$$S_{11} = 0 \tag{1}$$

$$S_{21} = -\frac{Z_{0p}}{Z_0} \tag{2}$$

$$S_{31} = -\frac{Z_{0s}}{Z_{0p}^{1}} \tag{3}$$

$$S_{41} = 0 \tag{4}$$

By utilizing the principle of energy conservation and assuming ideal operating conditions where the return loss and isolation are negligible, the following relations can be obtained [21].

$$|S_{21}|^2 + |S_{31}|^2 = 1 \tag{5}$$

Plugging the values from (2) and (3) into equation (5) [21]:

$$\frac{Z_{0p}^2}{Z_0^2} + \frac{Z_{0s}^2}{Z_{0p}^2} = 1 \tag{6}$$

This implies that in order to achieve the most suitable results with the minimal isolation and return loss, Equation (6) must hold true. It should be noted that the characteristic impedance (Z_0) is 50Ω in our case, and both the measurement and the simulation are carried out with the given characteristic impedance. Due to the symmetry, one observes that [21]

$$S_{mn} = S_{nm} \quad (7)$$

$$S_{11} = S_{14} = S_{41} = S_{44} = S_{22} = S_{23} = S_{32} = S_{33} = 0 \qquad (8)$$

$$\therefore S = \begin{bmatrix} 0 & -\frac{Z_{0p}}{Z_0} & -\frac{Z_{0s}}{Z_{0p}} & 0 \\ -\frac{Z_{0p}}{Z_0} & 0 & 0 & -\frac{Z_{0p}}{Z_{0s}} \\ -\frac{Z_{0s}}{Z_{0p}} & 0 & 0 & -\frac{Z_{0p}}{Z_0} \\ 0 & -\frac{Z_{0p}}{Z_{0s}} & -\frac{Z_{0p}}{Z_0} & 0 \end{bmatrix}$$

Based on the scattering matrix, the incident power in the best-case scenario is split between the directed and the coupled ports providing 3-dB or half power at each of the ports [21,22]. In this best-case scenario, the reflected wave and the incident wave reaching Port 4 are negligible, and thus are assumed to be 0 in our mathematical derivation. The above relations describe the ideal conditions required for equal power division and high isolation in a branch-line coupler. These conditions are used as guiding principles in selecting the initial symmetry and quarter-wavelength configuration of the proposed geometry, while the final dimensions are determined through electromagnetic simulation to account for practical implementation effects.

3. Parametric Study and Robustness Analysis

This parametric study is used to see how the proposed branch-line coupler behaves when practical variations are applied. The purpose is not to optimize the design, but to check its robustness. Variations in physical dimensions, substrate properties, and dielectric thickness are considered to observe their effect on the scattering parameters. This analysis provides insight into the stability of the proposed geometry under realistic implementation conditions.

The parametric study examines the effects of variations in widths, lengths, and substrate properties on the scattering parameters of the proposed design. In the following tables one may observe how each S-parameter changes with the minor change in the provided specifications and this process is somewhat crucial for making the most suitable design given that we are operating in the acceptable region in terms of the input match, insertion loss, coupling and isolation factors.

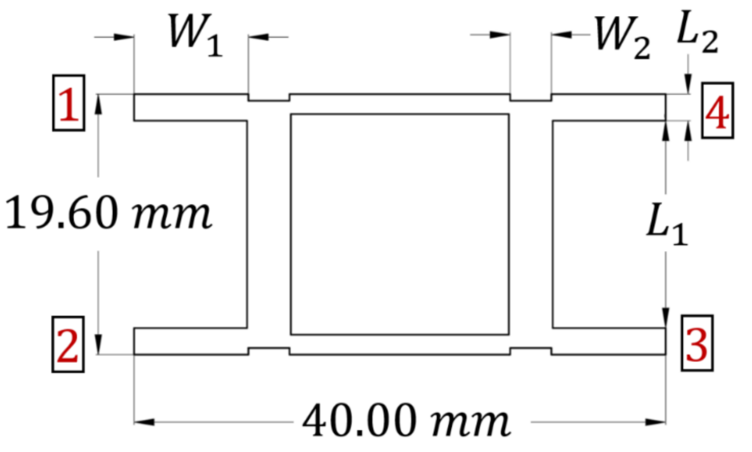

Figure 2. The specification of the widths and lengths of the geometry utilized in the parametric study (on the left), and the fabricated design of the proposed design (on the right)

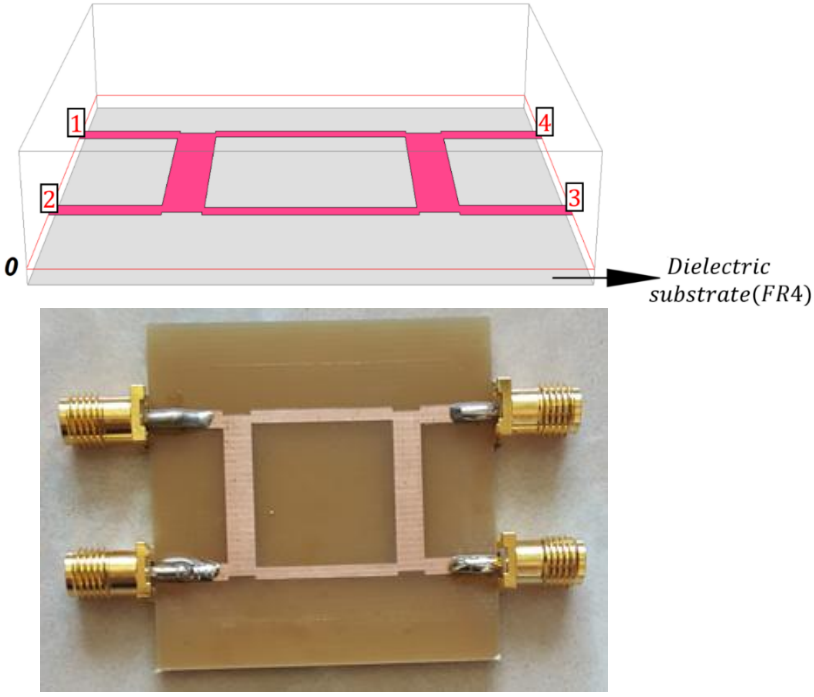

Figure 3. 3D representation of the proposed design with the specified dielectric layer of FR-4 together with the metal and air layers

Only a small portion of the parametric study is presented here due to the constraints associated with publication. Prior to presenting the results we would like to point out the layers present in the 3D design. It can be observed that the metal is etched on the dielectric substrate(FR-4) with a layer of air.

Table 1. The value of thickness and ε_r for Air and FR-4

Dielectric layers	Thickness $(\boldsymbol{h})[\boldsymbol{mm}]$	$\boldsymbol{\varepsilon_r}$
Air	11.00	1.00
FR-4 Substrate	1.55	4.4

3.1. Effect of Width (W1) Variation on Scattering Parameters

Table 2. Changing the width (W_1) of the proposed hybrid branch line coupler

Width$(\boldsymbol{W_1})$ $[\boldsymbol{mm}]$	$\boldsymbol{S_{11}}$ $[\boldsymbol{dB}]$	$\boldsymbol{S_{21}}$ $[\boldsymbol{dB}]$	$\boldsymbol{S_{31}}$ $[\boldsymbol{dB}]$	$\boldsymbol{S_{41}}$ $[\boldsymbol{dB}]$	Bandwidth (GHz)
8.6	**-30.32**	**-3.01**	**-3.01**	**-30.31**	**2.14-2.95**
8.0	-30.05	-3.15	-3.18	-32.39	2.20-3.02
7.5	-29.18	-3.13	-3.12	-31.02	2.22-3.06
5.5	-25.16	-3.22	-3.22	-34.16	2.35-2.92
4.0	-18.22	-3.52	-3.53	-35.57	2.42-3.10
10.5	-31.75	-3.28	-3.26	-30.66	2.01-2.86
11.5	-28.99	-3.36	-3.35	-32.27	1.86-2.72
12.0	-26.18	-3.45	-3.46	-32.36	1.83-2.70

The results indicate that moderate variations in the branch width lead to small changes in coupling and insertion loss, while acceptable matching and isolation are preserved over the operating band, indicating tolerance to dimensional variations.

3.2. Effect of Branch Width (W2) on Coupler Performance

Table 3. Changing the width (W_2) of the proposed hybrid branch line coupler

Width(W_2) $[mm]$	S_{11} $[dB]$	S_{21} $[dB]$	S_{31} $[dB]$	S_{41} $[dB]$	Bandwidth (GHz)
3.1	**-30.32**	**-3.01**	**-3.01**	**-30.31**	**2.14-2.95**
2.5	-25.15	-3.27	-3.28	-30.19	2.13-2.94
2.0	-24.22	-3.23	-3.25	-36.62	2.12-2.94
1.5	-21.10	-3.25	-3.26	-32.67	2.18-2.95
1.0	-25.72	-3.12	-3.13	-34.57	2.16-2.95
3.5	-35.75	-3.10	-3.11	-36.88	2.26-2.85
4.5	-30.99	-3.16	-3.15	-35.77	2.27-2.85
5.5	-28.52	-3.35	-3.36	-29.66	2.29-2.82

The results show that variations in the branch length mainly influence the coupling and insertion loss levels, which is consistent with quarter-wavelength behavior, while the overall power-splitting operation remains within the acceptable range.

3.3. Effect of L1 Variation on Scattering Parameters

Table 4. Changing the length (L_1) of the proposed hybrid branch line coupler

Length(L_1) $[mm]$	S_{11} $[dB]$	S_{21} $[dB]$	S_{31} $[dB]$	S_{41} $[dB]$	Bandwidth (GHz)
3.1	**-30.32**	**-3.01**	**-3.01**	**-30.31**	**2.14-2.95**
2.5	-25.15	-3.27	-3.28	-30.19	2.13-2.94
2.0	-29.18	-3.13	-3.12	-31.02	2.12-2.94
1.5	-25.16	-3.22	-3.22	-34.16	2.18-2.95
1.0	-18.22	-3.52	-3.53	-35.57	2.16-2.95
3.5	-31.75	-3.28	-3.26	-31.66	2.26-2.85
4.5	-28.99	-3.36	-3.35	-32.27	2.27-2.85
5.5	-26.18	-3.45	-3.46	-32.36	2.29-2.82

It can be observed that minor changes in the length have a significant impact on the coupling and the insertion loss factors. In addition, the bandwidth is affected as well by the size of the geometry due to the inverse relationship between the wavelength and the frequency.

3.4. Effect of L2 Variation on Scattering Parameters

Table 5. Changing the length (L_2) of the proposed hybrid branch line coupler

Length(L_2) $[mm]$	S_{11} $[dB]$	S_{21} $[dB]$	S_{31} $[dB]$	S_{41} $[dB]$	Bandwidth (GHz)
15.6	**-30.32**	**-3.01**	**-3.01**	**-30.31**	**2.14-2.95**
13.5	-31.52	-3.21	-3.21	-33.72	2.23-3.02
12.5	-30.18	-3.14	-3.16	-32.05	2.25-3.07
10.5	-27.23	-3.19	-3.21	-22.52	2.30-3.13
8.0	-23.99	-3.62	-3.62	-35.39	2.45-3.05
16.6	29.21	-3.13	-3.12	-25.77	2.12-2.83
18.0	-27.23	-3.26	-3.25	-29.56	2.01-2.72
19.5	-25.33	-3.55	-3.56	-23.77	1.91-2.62

These results indicate that although the electrical length affects the detailed scattering behavior, the proposed geometry continues to maintain functional 3-dB power division under moderate dimensional changes.

Similar observation is obtained after simulating the second length of the proposed design where the acquired results presented were the most suitable ones due to the half power being split across second and third ports and the isolation and input match being below the aforementioned -10dB mark. Additionally, one may modify the design with various substrates in order to achieve more accurate results. In the following sub-section the rectification of various substrates is utilized in providing the reader with the full picture on the overall parametric study and how each change affects the S-parameters.

3.5. Effect of Dielectric Substrate (ε_r) on Coupler Characteristics

Table 6. Changing the dielectric substrate (ε_r) of the proposed hybrid branch line coupler

Dielectric Substrate	S_{11} $[dB]$	S_{21} $[dB]$	S_{31} $[dB]$	S_{41} $[dB]$	Bandwidth (GHz)
FR-4 ($\varepsilon_r = 4.4$)	**-30.32**	**-3.01**	**-3.01**	**-30.31**	**2.14-2.95**
Arlon 25 ($\varepsilon_r = 3.56$)	-28.23	-3.03	-3.02	-29.55	6.5-8.02
ESL41050 ($\varepsilon_r = 13.5$)	-22.58	-2.73	-2.79	-25.19	1.15-2.62
ArlonDi522 ($\varepsilon_r = 2.5$)	-28.66	-3.42	-3.43	-39.91	2.87-3.97
Rogers RO3006 ($\varepsilon_r = 6.5$)	-19.27	-2.52	-2.64	-21.11	5.45-7.12
Rogers RO3210 ($\varepsilon_r = 10.8$)	20.58	-3.66	-3.62	-20.55	7.20-9.11
Rogers RT6202 ($\varepsilon_r = 2.94$)	-28.99	-3.11	-3.12	-35.78	28.5-30.05
Taconic RF-30($\varepsilon_r = 3.0$)	-19.73	-3.35	-3.36	-23.89	7.55-8.68

The results demonstrate that variations in dielectric constant mainly shift the operating frequency and affect the coupling level, while the proposed geometry continues to exhibit functional behavior across different substrate types.

From the dielectric substrate table we may infer that the design is somewhat stable. The major difference is observed with coupling and insertion loss factors, which is expected given that simulation with various substrates affects the S-parameters and the appropriate bandwidth more substantially. Furthermore, it is worth noting that dielectric substrates play an integral role in designing the microstrip couplers due to the significant implication on the frequency bandwidth and the appropriate resonant frequency.

3.6. Effect of Substrate Thickness on Scattering Parameters

Table 7. Changing the dielectric height(h) of the proposed hybrid branch line coupler

Dielectric height(h) $[mm]$	S_{11} $[dB]$	S_{21} $[dB]$	S_{31} $[dB]$	S_{41} $[dB]$	Bandwidth (GHz)
1.55	**-30.32**	**-3.01**	**-3.01**	**-30.31**	**2.14-2.95**
1.65	-32.52	-3.11	-3.25	-35.23	2.14-2.96
1.8	-25.31	-3.45	-3.46	-27.15	2.14-2.95
2.5	-16.13	-3.56	-3.37	-18.52	2.14-2.95
1.0	-35.77	-3.12	-3.13	-31.89	2.14-2.94
0.5	-27.98	-2.86	-2.98	-26.18	2.14-2.95

These results show that the scattering parameters change with substrate thickness, especially in terms of matching and coupling behavior. This indicates that thickness control during fabrication is important, although acceptable performance is still maintained for moderate variations. From the data, it can be seen that the S_{21} and S_{31} parameters are more affected when the substrate thickness is changed. Since FR-4 is a lossy dielectric material, the obtained performance levels remain within an acceptable range. For clarity, the parametric results are presented in tables to allow direct comparison of different design parameters and to highlight general trends rather than detailed optimization.

The parametric analysis shows that the proposed branch-line coupler keeps stable power division and acceptable scattering performance when practical variations are applied. This supports its use in real implementations rather than ideal optimization cases. When all parametric results are viewed together, it becomes clear that some design parameters affect the performance more than others. Changes in branch lengths mainly influence the coupling and insertion loss because they are related to the effective electrical length. On the other hand, moderate variations in branch widths, substrate properties, and thickness mainly lead to frequency shifts and loss changes, while the basic 3-dB power division is still preserved. This behavior indicates that the geometry provides a reasonable balance between performance stability and fabrication tolerance for planar microwave designs.

4. Comparison between simulated and measured results

Figure 4 depicts the simulated results. The input match and the isolation factor are approximately -30.32dB and given that the results are below the -10dB line, it can be stated that the simulated results for S_{11} and S_{41} are acceptable. Furthermore, regarding the insertion loss and the coupling factor, the simulated results depict -3.01 for both of the parameters deeming them acceptable as well. It should be noted that despite the lossy substrate, the simulated and the measured results were in agreement, having resonance at approximately 2.68GHz. In addition, the observed differences can be attributed to substrate losses and fabrication tolerances inherent to practical microstrip implementations; nevertheless, the measured results confirm acceptable performance, with S_{11} and S_{41} values of approximately −25 dB and −27 dB, respectively, which are reasonably close to the simulated value of about −30 dB. Moreover, coupling and insertion loss parameters cross 2.68GHz at around -3.07dB and therefore the presented design has reached the expected values that were obtained in the Sonnet software.

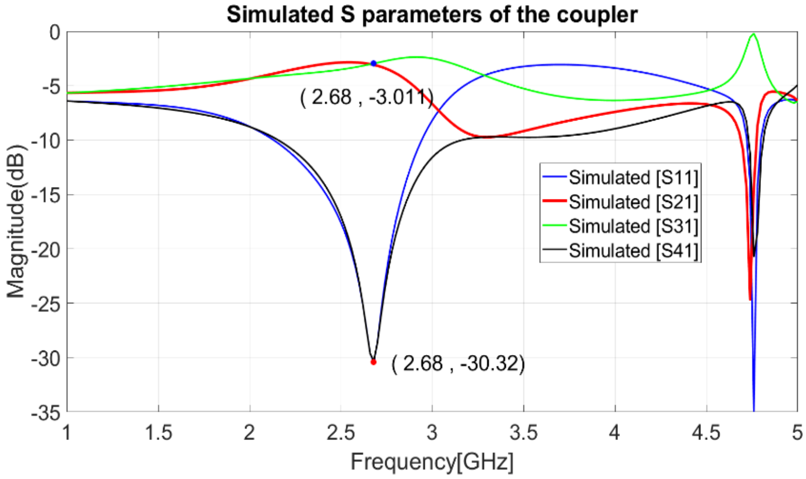

Figure 4. Simulated S parameters of the proposed hybrid branch line coupler

As mentioned in the opening paragraph of this section, the simulated results have provided a decent design of the hybrid branch line microstrip coupler with the resonant frequency for FR-4 substrate at 2.68GHz with acceptable S parameters. The current distribution graph in Figure 5 displays the current in A/m over the coupler. One can observe that, at the Port 1, the current is the highest due to the incident waves flowing from Port 1 to the other ports and the small amount is reaching Port 4, whereas Ports 2 and 3 receive approximately 2.3-2.5 A/m, almost dividing it perfectly between the two ports.

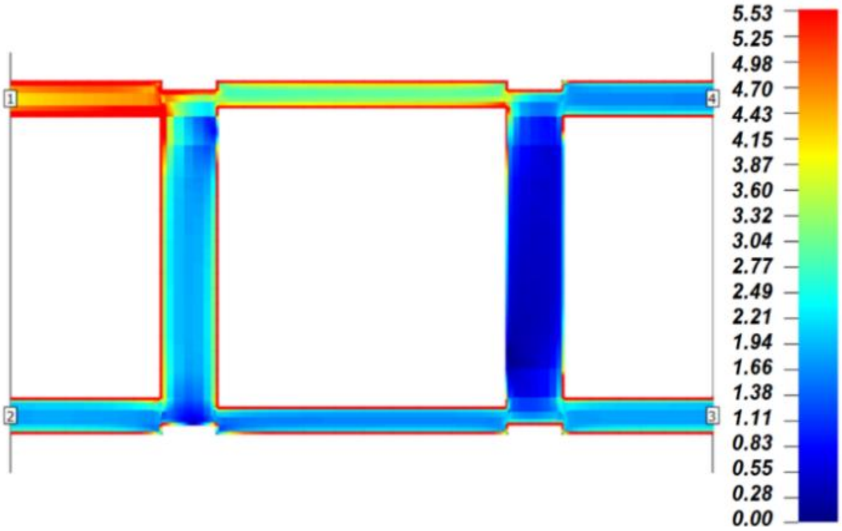

Figure 5. Current Distribution of the hybrid branch line microstrip coupler

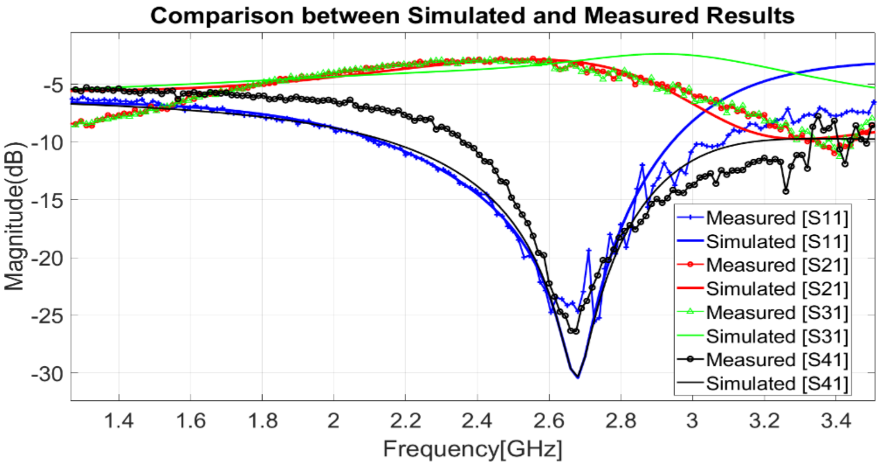

Figure 6. Comparison between Measured and Simulated results of the proposed design

As shown in Figure 6, the measured results generally agree well with the simulated data. A noticeable difference is observed in the S_{11} response; however, this deviation remains within an acceptable range for the intended operation. The coupling response also shows some variation compared to simulation, but it still crosses the −3 dB level at the center frequency of 2.68 GHz, which confirms proper power division. These results indicate that the proposed coupler operates reliably despite practical imperfections.

The comparison between simulated and measured data confirms that stable 3-dB power division is achieved when the coupler is implemented on a lossy FR-4 substrate. Small differences between simulation and measurement, particularly in the coupling behavior, are mainly caused by fabrication tolerances, substrate losses, and connector effects. Such differences are commonly observed in practical microstrip circuits, and they do not affect the main operating function of the coupler. The current distribution results are included to qualitatively verify the power flow within the structure. A higher current level is observed at the input port, while nearly equal current levels appear at the through and coupled ports. Only a small current is present at the isolated port. This behavior is consistent with the measured isolation performance and confirms proper signal transmission, rather than radiative behavior, which is not the goal of branch-line coupler designs. From a practical point of view, the main advantage of the proposed design is its simple and fully symmetric geometry, which makes fabrication easier and reduces sensitivity to moderate dimensional variations, as also observed in the parametric study. The use of an FR-4 substrate allows low-cost implementation, although it limits bandwidth and increases dielectric loss compared to low-loss substrates. Possible future work may include the use of alternative substrates, multilayer structures, or integration of the coupler into larger microwave front-end systems, depending on application needs.

5. Conclusion

The hybrid branch-line backward-wave microstrip coupler studied in this work shows acceptable performance in terms of input matching, isolation, coupling, and insertion loss when implemented on a low-cost FR-4 substrate. Both simulation and measurement results indicate stable 3-dB power division between the through and coupled ports at the center frequency of 2.68 GHz. This confirms that the symmetric geometry used in the design operates as intended. The coupler uses a simple layout based only on rectangular sections, which makes fabrication easier and reduces sensitivity to moderate dimensional changes, as also observed in the parametric study. Although FR-4 introduces higher dielectric losses and limits the achievable bandwidth compared to low-loss substrates, the measured performance remains within acceptable limits for practical use. Due to its simple geometry, measured validation, and moderate bandwidth, the proposed coupler can be applied in planar microwave subsystems such as signal splitting, power monitoring, and calibration circuits in RF front-end designs. Overall, this study focuses on practical implementation and robustness rather than aggressive optimization, making the design suitable for low-cost and fabrication-friendly applications.

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