(Online) ISSN 2303-4521
Periodicals of Engineering and Natural Sciences *Original Research*
Vol. 14, No. 1, January 2026, pp.1-12

Detailed analysis of a 3 dB microstrip hybrid coupler

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ABSTRACT

This work presents the design, analysis, and experimental verification of a 3 dB microstrip hybrid coupler operating at 2.4 GHz. The proposed layout incorporates four resonator elements which were introduced to improve isolation while preserving a stable 3 dB power division. The coupler was implemented on a low-cost FR4 substrate. An EM-based parametric analysis was carried out to study the influence of the main geometric dimensions and to determine which parameters most strongly affect performance. Based on this study, the final design provides nearly equal power levels at ports 2 and 3 isolation better than -45 dB, and good input matching at the target frequency. A prototype was fabricated and measured, and the measured results follow the simulated response closely. The use of resonator loading provides improved isolation without increasing the size or needing multilayer structures, representing the main contribution of this work.

Keywords: Planar hybrid coupler, WiMax applications, Resonator-based design, EM simulation, Low-cost substrate.

1. Introduction

Hybrid couplers are widely used in many microwave systems, including antenna arrays, mixers, modulators, amplifiers, and phase-shifting networks [1]-[3]. In most applications, the coupler must be designed, simulated, and fabricated according to specific performance requirements. Microstrip hybrid couplers remain popular because they offer simple geometry, low fabrication cost, and easy integration with printed circuits [1]. They can support resonant structures that provide the required 90-degree phase shift and maintain stable coupling and return-loss performance after fabrication [1]. During our initial design attempts, we observed that compact hybrid couplers involve several trade-offs. As the structure is reduced in size, the return loss often increases and the isolation level degrades which leads to imbalance in the coupling factor [2]. This effect becomes more noticeable when symmetrical resonator sections are scaled down and the spacing between resonators and ports is reduced [1], [2]. Although rectangular branch-line couplers can be described using even and odd-mode analysis [3], we found during implementation that practical designs are sensitive to small variations in branch length, separation distance, and impedance, especially when standard PCB fabrication limits are involved. For this reason, several techniques have been proposed in the literature to address these issues. Defected ground structures (DGS) are commonly used to reduce circuit size and suppress harmonics, and they can also shift the operating frequency [4]. However, these approaches require additional ground modifications which were not preferred in this work due to fabrication simplicity. Alternative geometries, such as circular layouts, have also been reported to improve return loss [5]. In our assessment, these structures are more sensitive to dimensional variation and may lead to unstable isolation performance, making them less suitable for low-cost FR4 implementations. Other works examine the use of different slot shapes, tolerance-limited spacing, and optimized DGS layouts to enhance bandwidth or maintain stable S-parameters [5], [6]. Parametric studies remains a common strategy to correct these issues and achieve the desired performance for a given application. [6]

Additional improvements have been reported using matching-network-based directivity enhancement, symmetrical subdivisions of the coupler, or stepped-impedance structures that maintain simple fabrication while improving phase balance [7], [8]. Meandered-line hybrid couplers provide compactness and acceptable return loss, although they may introduce slight degradation in isolation [9]. Planar quadrature techniques can extend bandwidth but do not significantly improve return loss or coupling factor [10]. Multilayer directional couplers, composite right/left-handed (CRLH) structures, and even superconducting transmission lines have been proposed to enhance directivity or reduce loss, however, they require more complex or higher-cost fabrication [11], [12]. Other geometries, such as uniplanar, rectangular-slot, ring, slow-wave, and cascaded configurations, offer potential benefits in miniaturization, isolation, or coupling factor but often at the expense of increased sensitivity or fabrication complexity [13]-[17]. Broadband or fragmented-structure couplers have also been explored, however improvements in directivity may reduce bandwidth [18], [19]. Some designs expand bandwidth using floating ground planes or integrated waveguide techniques, but may suffer from reduced isolation, increased imbalance, or a more demanding tuning process [20]-[22].

Although these techniques achieve improvements in size, isolation, bandwidth, or directivity, many of them depend on multilayer structures, complex resonant cells, special substrates, or fabrication-sensitive geometries. Therefore, there is a need for a simple, single-layer microstrip hybrid coupler that provides stable 3 dB power division, good return loss, and high isolation on a low-cost substrate. In this work, we propose a microstrip hybrid coupler that uses four resonator elements to enhance isolation and maintain equal power division using a compact, single-layer FR4 implementation. A detailed EM-based parametric study is carried out to identify the most influential geometric parameters and optimize the structure for operation at 2.4 GHz. The fabricated prototype shows close agreement between simulation and measurement, demonstrating the effectiveness of the resonator-based structure.

2. Design details

2.1. Theoretical background

A 3 dB hybrid coupler divides the input power equally between two output ports while maintaining a 90-degree phase difference. This behavior can be understood by viewing the structure as a symmetrical network that supports even and odd signal paths. When the physical lengths and impedances of these paths are properly balanced, the power splits equally between the direct and coupled ports and ideally no power reaches the isolated port. In the proposed resonator-loaded design, the geometric parameters directly influence these conditions. The resonator widths control the local impedance and therefore effect input matching. The slit distances between resonators determine the strength of electromagnetic coupling from one section to the next in which influences isolation and the balance between the two output signals. Small changes in these dimensions also shift the electrical length of the signal path and modify the phase relation between the outputs. During EM simulation, these effects appear clearly in the S-parameter results. Parameters related to impedance mainly effect the return loss, coupling-related parameters effect the transmitted power and isolation and parameters related to electrical length influence the output phase difference. These relationships provide the physical basis for the parametric study presented in the next section. The hybrid coupler is designed using its S-parameter description to understand the power distribution among the output ports. Under ideal conditions, the input signal is equally divided between ports 2 and 3, and the reflected power at the input port is negligible. There is another technique by using Artificial Neural Network (ANN) to improve the analysis of the patch antennas. [23,24]. Ideally, no power should appear at the isolated port. In practice, however, the system is non-ideal, and small mismatches are observed in the simulations. These results provide a realistic indication of the expected S-parameter behavior after fabrication and experimental testing. The dimensions of the resonator structures (W_1, H_1, W_2, H_2) and the slit separations (L_1, L_2, L_3) were not chosen arbitrarily. The initial layout was based on the standard $\lambda/4$ hybrid coupler design at 2.4 GHz. After this, each parameter was refined through an EM-based sweep in Sonnet Sofware. The final values were selected to achieve low return loss, equal power split between ports 2 and 3, and isolation better than -45 dB. Very small dimensions caused mismatch and imbalance while larger dimensions increased unwanted coupling. The selected values represent the best trade-off between performance and fabrication limits.

2.2. Overall design description

The proposed layout uses four resonator-like sections placed along the main signal paths. These resonators were added during the design stage to improve input matching and to keep the coupling factor and insertion loss close to 3 dB at both output ports. A rectangular geometry was selected, as it can be fabricated more reliably on FR4 and helps reduce errors related to alignment and milling accuracy.

We selected a four-resonator configuration to improve isolation while keeping the overall circuit size unchanged. During the EM-based design and tuning process, we found that using fewer than four resonators led to insufficient isolation and produced an imbalance greater than 0.5 dB between S21 and S31. When additional resonators were added, the structure became more lossy and unwanted parasitic coupling appeared which in turn degraded the return loss. Based on these observations, the four-resonator arrangement provided the most reliable balance between isolation, power division, and physical size.

The four-resonator arrangement provided the best balance between performance and physical size. Compared to related works such as DGS-based or stepped-impedance couplers, the resonator-loaded structure achieves isolation below -45 dB on a low-cost FR4 substrate without adding extra layers or ground modifications. It also keeps the physical size within normal manufacturing limits and does not require narrow slots or complex etching. These points represent the main contribution of the proposed design.

The overall size and slit spacing were intentionally kept within practical limits to prevent fabrication issues that may result from overly narrow gaps and strong coupling.

2.3. Dielectric Substrate and EM Simulation Environment

An FR4 substrate with a dielectric constant of 4.4 and a thickness of 1.55 mm was used for implementation. The structure was simulated in Sonnet software with a fine mesh of 0.01–0.05 mm to capture the effects of resonator edges and coupling gaps. Simulations with alternative dielectric materials confirmed that the general behavior of the design remains stable with only a small shift in resonant frequency.

2.4. Characteristic impedance

All ports were designed for a characteristic impedance of 50 Ω. The resonator dimensions and slit distances were tuned to maintain this impedance throughout the structure while achieving the desired even-odd mode behavior described earlier. Figure 1 presents a dual-branch structure in which the input power splits and propagates along two paths. The power division at ports 2 and 3 is equal. By choosing appropriate values for the characteristic impedances Z_{os} and Z_{op}, the design can be adapted to the intended application, leading to the relationships reported in [25].

$$S_{11} = 0 \quad (1)$$

$$S_{41} = 0 \quad (2)$$

This behavior follows from the ideal assumption that no power reaches the isolated port, which results in zero return loss.

$$S_{21} = -\frac{jZ_{os}}{Z_o} \quad (3)$$

$$S_{31} = -\frac{Z_{os}}{Z_{op}} \quad (4)$$

By applying the conservation of energy principle [24, 25] and assuming that the conditions given in (1) and (2) are zero, the scattering matrix derivation becomes simpler.

$$\therefore\ S_{11} = S_{41} = 0 \rightarrow$$

By applying the principle of energy conservation [25]

$$|S_{21}|^2 + |S_{31}|^2 = 1 \quad (5)$$

By inserting (3) and (4) into (5), we obtain

$$\left|-\frac{jZ_{os}}{Z_o}\right|^2 + \left|-\frac{Z_{os}}{Z_{op}}\right|^2 = 1$$

$$\left(\frac{Z_{os}}{Z_o}\right)^2 + \left(\frac{Z_{os}}{Z_{op}}\right)^2 = 1 \ (6)$$

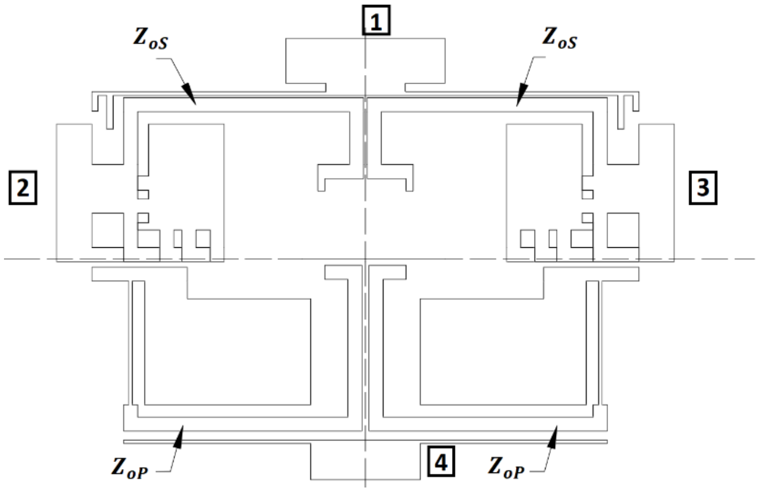

Figure 1. Layout of the hybrid coupler with labeled input, direct, coupled, and isolated ports.

As shown in Figure 1, the structure is symmetric with respect to the vertical axis. This symmetry was used in the analysis to establish the relationship reported in [25].

$$Z_{os} = Z_o \cdot |S_{21}| = Z_o\sqrt{1 - |S_{31}|^2} \qquad (7)$$

And that

$$Z_{op} = Z_{os} \cdot |S_{31}|^{-1} \rightarrow$$

Using the expression given in (7), we evaluated the parameter values required for the proposed structure.,

$$Z_{op} = Z_{os} \cdot \left(\sqrt{1 - |S_{21}|}\right)^{-1} \qquad (8)$$

These relationships show that, under ideal conditions, the input signal does not reach port 4. This allows the isolation to be treated as zero in the theoretical analysis. Based on the conservation of energy, the corresponding relationship between the characteristic impedances can then be established. In the actual design process, however, the final S-parameters were evaluated numerically using Sonnet Software through geometric optimization. Based on this parametric analysis, the proposed design was found to provide acceptable performance in terms of input matching, coupling level, insertion loss, and isolation.

3. Parametric study and comparison with prior works

The proposed design consists of four resonator sections placed around the adjacent ports. The last two resonators were included to provide additional attenuation and to keep the isolation level below -45 dB. During the layout stage, the slit dimensions were adjusted and the largest practical separation was selected to remain within fabrication limits. As shown in Table 1, variations in the resonator width or height lead to only small changes in isolation performance. Compared with the optimized design, the maximum observed deviations are approximately 5 dB in return loss, 0.18 dB in insertion loss, and about 1.70 dB in the coupling factor.

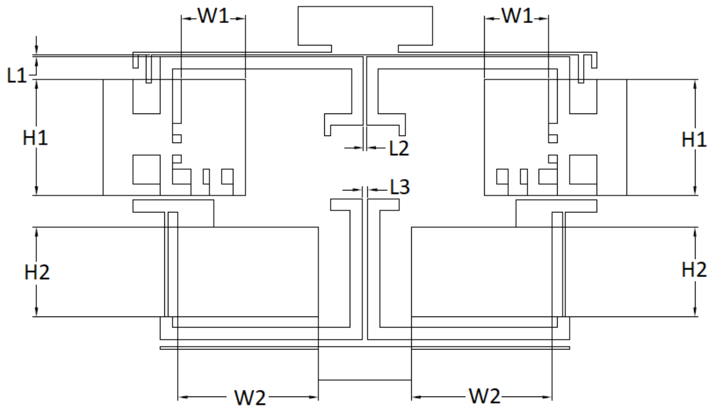

Figure 2. Geometrical parameters of the design, including resonator dimensions and separation distances used for parametric analysis

Based on the results in the tables, variations in resonator height, width, and separation distance shown in Figure 1 lead to satisfactory performance using the rectangular geometry. The obtained S-parameters indicate that the proposed design improves size and performance compared with earlier designs. Moreover, since the separation between the input, direct, and coupled ports remains within practical limits, further size reduction beyond standard manufacturing constraints is not required due to the extensive parametric analysis performed.

Table 1. Simulated S-parameter results for different combinations of W_1 and H_1

Operating Band (GHz)	W1 (mm)	H1 (mm)	$S_{11}[dB]$	$S_{21}[dB]$	$S_{31}[dB]$	$S_{41}[dB]$
2.20-2.45	3.42	4.8	-19.8	-3.07	-3.07	-49.9
2.25-2.45	2.14	4.0	-18.3	-3.30	-3.30	-43.6
2.21-2.44	2.0	5.0	-20.0	-3.15	-3.15	-45.5
2.25-2.48	3.0	5.0	-17.7	-3.08	-3.08	-48.9
2.26-2.48	4	5	-16.6	-3.07	-3.07	-44.2
2.25-2.56	4.5	4.7	-18.0	-3.14	-3.14	-42.8
2.30-2.53	4.6	4.7	-14.4	-3.13	-3.13	-46.9
2.20-2.45	1.5	3	-17.9	-3.19	-3.19	-47.1
2.30-2.50	2.5	3.5	-15.8	-3.09	-3.09	-49.6
2.30-2.52	2.0	4.5	-15.2	-3.09	-3.10	-43.5

The parameter W_1 mainly affects the impedance matching and the balance between S_{21} and S_{31}. As shown in Table 1, increasing W_1 beyond 3.42 mm causes a noticeable imbalance in the 3 dB split while smaller values increase the return loss. The value W_1=3.42 mm provides the best trade-off by keeping the split difference below 0.1 dB and maintaining isolation better than -45 dB. For this reason, it was selected as the optimal value in the final design.

Table 2. Simulated S-parameter results for different combinations of W_2 and H_2

Operating Band (GHz)	W2 (mm)	H2 (mm)	$S_{11}[dB]$	$S_{21}[dB]$	$S_{31}[dB]$	$S_{41}[dB]$
2.20-2.45	7.52	4.8	-19.8	-3.07	-3.07	-49.9
2.22-2.42	7	4	-18.7	-3.12	-3.12	-49.2
2.23-2.41	6	4	-19.2	-3.10	-3.10	-48.7
2.25-2.40	5	4	-20.0	-3.12	-3.12	-43.2
2.31-2.48	3	3	-18.4	-3.14	-3.14	-41.6
2.30-2.52	2	3.8	-18.6	-3.16	-3.16	-46.9
2.33-2.53	3	4.8	-19.0	-3.14	-3.14	-44.5
2.31-2.54	8	4.8	-17.4	-3.20	-3.20	-35.3

The parameter H_1 influences the coupling strength and the internal field distribution of the resonator. Values smaller than the selected one increased mismatch while larger values reduced isolation. The chosen value provides a balanced compromise between good matching and stable isolation.

Table 2 shows that variations in the resonator height H_2 and width W_2 have a strong impact on the input matching, with changes exceeding 10 dB when the resonator dimensions are increased to their maximum values. The other S-parameters are also affected, and the isolation level decreases to approximately -35 dB. The operating frequency range shifts slightly, by about 0.01-0.05 GHz.

Table 3. Simulated S-parameter results for different values of the separation distances L_1, L_2, and L_3

L1 (mm)	L2, L3 (mm)	$S_{11}[dB]$	$S_{21}[dB]$	$S_{31}[dB]$	$S_{41}[dB]$
0.1	(0.16, 0.32)	-19.8	-3.07	-3.07	-49.9
0.1	(0.16,0.16)	-19.5	-3.06	-3.06	-45.7
0.15	(0.16, 0.32)	-18.9	-3.08	-3.08	-50.1
0.15	(0.25, 0.25)	-19.6	-3.08	-3.08	-52.4
0.2	(0.2, 0.2)	-18.9	-3.08	-3.08	-49.2
0.2	(0.3, 0.1)	-20.1	-3.10	-3.10	-48.1
0.3	(0.1, 0.1)	-19.5	-3.09	-3.09	-46.5
0.3	(0.3, 0.3)	-20.4	-3.10	-3.10	-46.9

The slit distances L_1, L_2, and L_3 mainly affect the isolation between the output ports. The results indicate that isolation is very sensitive to L_2 and L_3, while L_1 has less impact. The selected values maintain isolation below -45 dB and keep the 3 dB split stable, making them suitable for the final structure.

A simple tolerance check was carried out to confirm that the optimized geometry is robust under normal FR4 manufacturing variations. In practical fabrication, the board milling accuracy is typically within ±0.1 mm and the dielectric constant of FR4 may vary by ±0.2. When these variations were applied to the optimized structure in the EM simulation, the main effects were seen in the resonator widths W_1 and W_2, which slightly changed the return loss. Small changes in slit distances L_2 and L_3 influenced isolation by less than ±2 dB. Even under these tolerances, the design maintained isolation better than -40 dB and kept the difference between S_{21} and S_{31} below 0.3 dB. This shows that the proposed coupler is tolerant to normal fabrication deviations.

The results show that variations in the slit dimensions cause only minor changes in performance, indicating that the proposed geometry is not highly sensitive and is expected to provide reliable results after fabrication and measurement. Although reducing the slit width can increase the coupling factor, this option is not practical due to fabrication limitations and was therefore avoided to prevent unnecessary complexity and mismatch between simulation and measurement. As shown in Table 4, changing the dielectric substrate results in only small performance variations compared to FR4, while the operating frequency can be shifted over a wide range from 1.6 GHz to 3.2 GHz.

It should also be noted that, despite the use of a lossy FR4 substrate, the proposed design achieves satisfactory performance. The substrate losses influence the fabrication outcome, since ideal values cannot be achieved with FR4. In this design, even small losses are important because the goal is to divide the input power equally between ports 2 and 3, resulting in coupling and insertion loss levels close to -3 dB.

The parametric analysis shows that the resonator widths W_1 and W_2 have the strongest effect on return loss and the balance between the two output ports. The slit distances L_2 and L_3 mainly control the isolation level while L_1 has only a minor influence. The height parameters H_1 and H_2 affect the internal coupling of the resonators and must remain within a narrow range to avoid mismatch. These observations explain why the optimized values provide the best overall performance, including stable 3 dB power split and isolation better than -45 dB. The results also show which parameters should be prioritized during manual tuning to improve the design efficiently.

Table 4. Simulated S-parameter performance for different dielectric substrates and operating frequency ranges

Substrate	Operating Band (GHz)	$S_{11}[dB]$	$S_{21}[dB]$	$S_{31}[dB]$	$S_{41}[dB]$
FR4 ($\epsilon_r = 4.4$)	2.20-2.45	-19.8	-3.07	-3.07	-49.9
Rogers RT6010 ($\epsilon_r = 10.2$)	1.84-1.98	-24.8	-3.06	-3.06	-55.1
Arlon AD300A ($\epsilon_r = 3.0$)	2.36-2.54	-25.4	-3.02	-3.02	-46.0
Nelco MW9350 ($\epsilon_r = 3.7$)	2.87-3.24	-24.6	-3.08	-3.08	-47.7
Taconic CER-10($\epsilon_r = 10$)	2.32-2.42	-25.2	-3.05	-3.05	-51.2
Dupont 9K7($\epsilon_r = 7.1$)	2.71-2.85	-26.8	-3.02	-3.03	-54.2
Kerafol CT800 ($\epsilon_r = 5.3$)	2.34-2.90	-23.3	-3.20	-3.19	-50.7
Gallium Arsenide ($\epsilon_r = 12.9$)					
ESL 41010 ($\epsilon_r = 7.5$)	2.18-2.36	-23.8	-3.17	-3.17	-53.1

Table 5 has a comparison with similar papers in literature.

Table 5. Comparison of advantages and limitations of previous designs and the proposed design

References	Advantages	Disadvantages
Proposed Design	-Provides stable and reliable operation -Low implementation cost -Suitable for WiMAX-related applications -Can be implemented on different dielectric substrates with comparable performance -Maintains accurate S-parameter performance within the intended frequency band -Compact physical size	Performance varies across substrates due to dielectric loss tangent differences -Requires extensive parametric tuning because of sensitivity to small geometric variations
[1]	-Low-cost implementation -Compact structure -Acceptable S-parameter performance -Good performance for a specific dielectric substrate	- Requires extensive parametric optimization to achieve stable operation
[2]	-Compact size -Cost-effective design -Stable S-parameter behavior -Fabrication-friendly geometry	-Performance degrades on lossy substrates -Power balance between output ports can be improved -Very narrow slits required to enhance coupling
[3]	-Low-cost design -Applicable to a wide range of RF systems -Simple fabrication process -Easily modified for different specifications	- Requires extensive parametric tuning to obtain optimal results
[4]	-Low-cost implementation -Simple and reliable structure -Straightforward design procedure -Applicable to multiple RF systems	-Narrow operating bandwidth -Slit dimensions must be carefully adjusted -Significant parametric optimization required
[5]	-Low-cost implementation -Simple and reliable structure -Straightforward design procedure -Applicable to multiple RF systems	-Geometry can be further optimized -Performance is sensitive to dimensional changes -May not perform consistently on different lossy substrates

Based on the results in the tables, the proposed design shows both advantages and limitations, as is the case for most reported coupler designs. The observed limitations mainly arise from non-ideal components and unavoidable losses. As a result, some dielectric substrates do not perform as well as low-loss materials; however, the achieved results remain close to the ideal case in practical implementations. In addition, many reported designs prioritize compact size to avoid fabrication issues. It is also observed that most designs rely heavily on parametric analysis rather than purely analytical derivations, with EM simulation tools being used to correct deviations and to predict S-parameter behavior after fabrication.

4. Comparison of simulated and measured results

The simulated results for the proposed microstrip hybrid coupler in the 2.3-2.4 GHz band show an input return loss of approximately -19.86 dB. At the two output ports, the insertion loss and coupling factor remain close to -3.07 dB. The isolation level obtained from the simulation reaches about -49.92 dB, indicating effective suppression at the isolated port. The operating frequency range spans from 2.20 GHz to 2.45 GHz, which corresponds to a fractional bandwidth of approximately 10.8%. This bandwidth was considered sufficient for WiMAX applications that require a stable 3 dB power division.

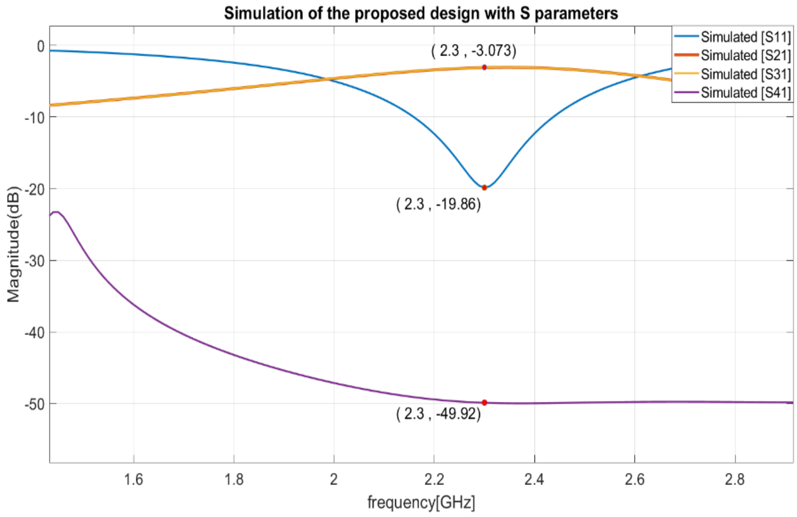

Figure 3. Simulated S-parameter response of the proposed microstrip hybrid coupler

Figure 3 shows the simulated S-parameter response of the proposed design. From these results, the coupler maintains an equal power division between the two output ports while preserving strong isolation over the operating band. The isolation level remains better than -50 dB, indicating that only a very small amount of power reaches the isolated port. From the simulated response, this behavior is consistent with the expected operation of a hybrid coupler and shows that the resonator-loaded configuration suppresses unwanted coupling paths effectively. Based on these results, the performance of the proposed design could be further improved by optimizing the dielectric substrate. FR4 was selected because it is low cost and widely available, however, it introduces dielectric losses and manufacturing tolerances that limit ideal performance. Despite these constraints, the simulated S21 and S31 responses remain closely aligned, showing a stable 3 dB power split that is not very sensitive to small changes in the slit dimensions. During the tuning process, we observed that larger variations in the resonator dimensions could introduce mismatch or instability in the return loss. This observation highlights the importance of careful fabrication and calibration for the proposed design.

Figure 4 shows the fabricated prototype of the coupler implemented on an FR4 substrate. During fabrication, natural variations in substrate permittivity, copper thickness, and milling accuracy were present which resulted in measurable differences when the measured results were compared with the simulations. These differences are expected for FR4-based designs and are mainly caused by dielectric tolerance, fabrication precision, and connector losses.

Figure 4. Fabricated coupler using an FR4 substrate as the dielectric.

A comparison between the simulated and measured S-parameters is shown in Figure 5. The two sets of curves follow the same general trend, with only small differences in return loss, insertion loss, and isolation. Importantly, the measured power split remains close to 3 dB at both output ports and the isolation stays better than -45 dB across the intended band. This close agreement confirms that the fabricated coupler behaves in accordance with the simulations and validates the accuracy and practicality of the proposed design.

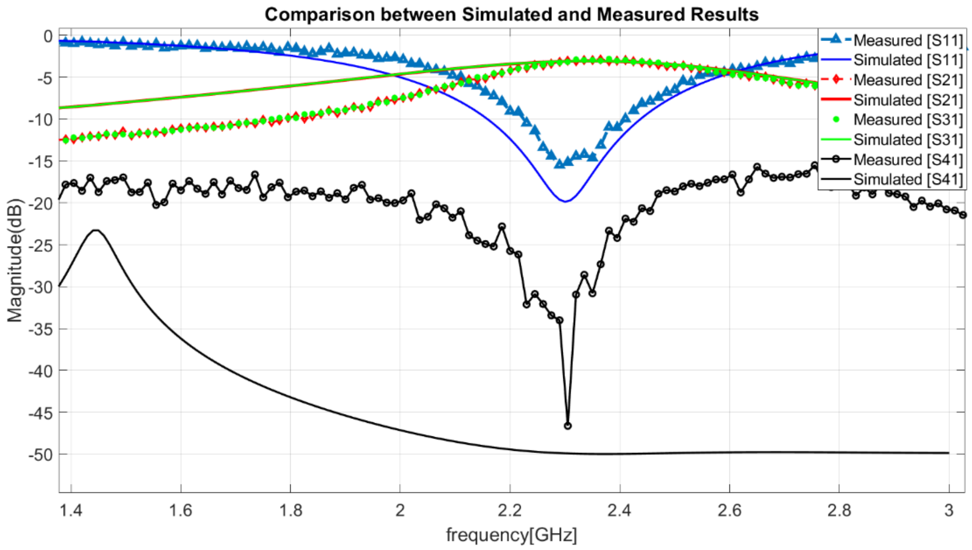

Figure 5. Comparison of the simulated and measured results for the proposed design.

5. Conclusion

This paper presented the design, analysis, and experimental validation of a 3 dB microstrip hybrid coupler that uses four resonator elements to improve isolation and maintain a stable 3 dB power split on a low-cost FR4 substrate. Through the parametric study, we identified the geometric parameters that most strongly affect performance with the resonator widths W1 and W2 and the slit distances L2 and L3 showing the highest influence. Based on these results, the final design provides good return loss, balanced output levels at both output ports, and isolation better than -45 dB at 2.4 GHz. The fabricated prototype showed good agreement with the simulated results, confirming the validity of the proposed approach. The main limitation of the design is the use of FR4, which introduces dielectric loss and tolerance variations that slightly affect matching and isolation. In addition, the structure is narrowband and optimized for a single frequency. Future work may focus on extending the bandwidth using multi-section or tapered resonator structures, improving isolation through defected ground or multilayer techniques, or applying automated optimization methods to further refine the geometry. Investigating alternative substrates with lower loss could also enhance overall performance. Some recent publications were found in literature showing the same microstrip producing techniques with similar geometries and analysis methods [27-29].

Declaration of competing interest

The authors declare that they have no any known financial or non-financial competing interests in any material discussed in this paper.

Funding information

No funding was received from any financial organization to conduct this research.

Author contribution

The contribution to the paper is as follows: X. Author, Y. Author: study conception and design; Y. Author: data collection; X. Author, Y. Author. Z. Author: analysis and interpretation of results; X. Author: draft preparation. All authors approved the final version of the manuscript.

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