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A simple 90° hybrid branchline coupler with wideband phase balance for 5G applications

Ümit Can Ünal[1], Kamil Karaçuha[2], Sehabeddin Taha İmeci[3]

A 90° hybrid coupler operating at a central frequency of 5.40 GHz is introduced, offering high-performance characteristics with compact dimensions of 616.65 mm² (33.3 mm × 18.5 mm). These features are achieved while maintaining a design that makes it easy to produce. The unique aspect of this microstrip FR4 substrate-based design is the consistent S-parameters, which remain steady despite changes in structural dimensions, thereby making it adaptable to fabrication variations. The reported S-parameters measured in 5.4 GHz are as follows: $|S_{11}|= -29.46$ dB, $|S_{21}|= -4.11$ dB, $|S_{31}|= -3.96$ dB, and $|S_{41}|= -21.23$ dB. This hybrid coupler operates over a bandwidth of 0.8 GHz (16%), demonstrating remarkable performance within this spectrum. In addition to its design, the coupler exhibits robust resilience against changes in substrate parameters and structural dimensions, ensuring reliability during the fabrication process. Following thorough simulation studies, a physical prototype of the coupler was constructed and subjected to laboratory measurements. The experimental results align closely with the simulation data, validating the accuracy and predictability of the design. In comparison with other studies and designs documented in the literature, this compact, high-performance 90° hybrid coupler exhibits clear advantages in terms of size, isolation, phase deviation, and structural complexity. Therefore, the benefits and applicability of this presented structure in the context of microwave circuits and systems are underscored. It's noteworthy to mention that the central frequency of 5.4 GHz falls within the sub-6 GHz 5G band range.

Keywords: fabrication tolerance, hybrid coupler, microwave circuits, microstrip design, S-parameters

1 Introduction

Directional couplers, notably the 3 dB varieties, have proven essential in multiple applications within the field of microwave technology, such as phase shifters and diagram-forming circuits [1]. However, these devices require a careful balance between parameters like the area, bandwidth, phase difference, and attenuation in the frequency band [2].

A notable direction in the research for compact devices has been the exploration of microstrip cells with significantly smaller dimensions compared to devices with traditional transmission lines [2]. While this approach offers some promise, our design further simplifies the structure, making it more tolerant to fabrication variations.

Furthermore, dual-polarized microstrip antennas have emerged as potential solutions for wireless communications systems [3, 4]. While these systems demonstrate dual-polarized radiation, good impedance matching, high port isolation, and compact feeding, they do not present the same robust resilience against changes in substrate parameters and structural dimensions as observed in our proposed hybrid coupler.

In the realm of miniaturization, the microstrip branch-line 3 dB hybrid coupler (BLHC) has been proposed as a significant platform, notably in Long Term Evolution (LTE) applications [5]. Techniques like meander lines, slots, and parasitic coupling have been employed to achieve miniaturization [3, 5].

Finally, narrow-wall 3 dB couplers, developed using MEMS processing methods, have shown promising simulation results, including favorable Voltage Standing Wave Ratio (VSWR), power distribution difference, and phase difference between output ports [6]. However, our hybrid coupler design demonstrates comparable performance while providing a superior S-parameter consistency, despite potential alterations in structural dimensions.

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[1]Fatih Sultan Mehmet Vakıf University, Department of Electrical and Electronics Engineering, Istanbul, Türkiye
[2]Istanbul Technical University, Department of Electrical Engineering, Istanbul, Türkiye
[3]College of Engineering and Technology, American University of the Middle East, Egaila, 54200, Kuwait
karacuha17@itu.edu.tr

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The field of microwave engineering has seen an impressive array of designs for 3 dB couplers, each with its unique characteristics. Among these, a 90-degree 3 dB coupler featuring an ultra-wideband and compact size stands out, utilizing elliptically shaped microstrip lines for broadside coupling through an elliptically shaped slot [7]. While this approach shows promise, our proposed coupler maintains a competitive edge by leveraging a microstrip layout that provides similar performance over a broad bandwidth of 0.8 GHz and a more straightforward manufacturing process.

Coupling theories such as Bethe hole coupling have been applied to create broadband directional couplers [8]. Here, coupling waveguide folding was used to achieve miniaturization by reducing the coupler's length. However, our design offers an additional advantage of more compact dimensions (33.3 mm × 18.5 mm) without the need for complex folding or resizing procedures.

For high-frequency applications, the wideband waveguide narrow-wall short-slot 3 dB coupler has been proposed [9]. This design emphasizes low fabrication cost and compact size, achieved through the optimization of the oversized coupling region length and impedance matching block size. Although this coupler exhibits commendable performance, our design is capable of achieving similarly high-quality results across a broader frequency range without compromising on cost-effectiveness or size.

The use of traditional meandering methods in the design of branch line couplers is also noteworthy [10]. By bending the microstrips of the branch line coupler inwards, this design successfully reduces the structure's size by increasing the effective dimension of the geometry. Yet, our hybrid coupler design takes a different approach, using microstrip FR4 substrate technology to achieve comparable miniaturization while maintaining better fabrication tolerance.

Reconfigurable 3-dB directional couplers have gained attention for their ability to shift from a branch-line coupler to a rat-race coupler by merely adjusting the voltage applied to the varactors [11]. While such flexibility is beneficial, our coupler design takes a different approach. It focuses on robustness, performance, and ease of manufacturing rather than reconfigurability, delivering excellent performance across a broad bandwidth and compact dimensions.

Previous research has demonstrated the potential of microstrip couplers based on substrate-integrated waveguide technology [12]. This type of coupler has the advantage of being more compact and lighter, making it suitable for a variety of applications. However, the design and fabrication process can be complex and may not provide the desired performance across all frequency ranges. Our proposed coupler overcomes these challenges by leveraging the simplicity of FR4 substrate technology while providing excellent bandwidth performance.

Advancements have also been made in the design of branch line couplers by incorporating defective ground structures [13]. While this approach can significantly improve the coupler's performance, it also increases the complexity of the design and fabrication process. In contrast, our coupler design avoids this complexity by achieving optimal performance through the use of traditional microstrip technology, which also ensures better fabrication tolerance.

Lastly, multi-layered branch-line couplers have been introduced to achieve miniaturization and enhance performance [14]. While these structures indeed provide a high degree of miniaturization, they also present challenges in fabrication and design due to their complex multi-layered structure. Our design stands out in this regard, providing an optimal balance between size, performance, and simplicity, ensuring efficient and cost-effective fabrication without compromising on the quality of performance [15].

With these considerations, the design and application of our proposed hybrid coupler take a significant step forward, offering an advanced solution to the constant challenge of creating compact, high-performance couplers in the field of microwave technology. Our novelty is to keep the design simple by employing a symmetrical solution providing good isolation and less phase deviation. We present a 90-degree microstrip FR4 substrate hybrid coupler. Our design, characterized by a broad operating bandwidth, compact size, and fabrication tolerance, offers a robust and cost-effective solution to the ongoing demand for high-performance couplers in the microwave technology sector. Our proposed hybrid coupler achieves this balance, operating at a central frequency of 5.40 GHz while maintaining a compact size.

2 Fundamental formulas

The theory and aim of a 90° Hybrid Branchline Coupler for 5G revolve around designing a component that efficiently splits an input signal into two equal signals with a precise 90-degree phase difference, particularly optimized for 5G applications. We aim to have the coupler specifically for frequencies within the 5G spectrum, typically in the sub-6 GHz range, ensuring compatibility and efficiency within the 5G communication bands. To have high efficiency, low loss, and high isolation, parametric studies are done and provided in the following chapters. The mathematics background is given here. In RF/microwave engineering, a 90-degree hybrid coupler – also referred to as a quadrature hybrid – is an essential part. It is intended to either combine two signals while preserving the phase difference or split an input signal into two equal signals with a 90-degree phase difference between them [16]. The symmetric solution for a matched, lossless, reciprocal 4-port device is (ideally) presented in its scattering matrix [16]:

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

Its behavior concerning signal transmission and reflection at each port is described by the S-parameter matrix. For a perfect match, $|S_{11}|$ and $|S_{22}|$ should ideally be zero (on a linear scale). It is anticipated that $|S_{21}|$ and $|S_{21}|$ will be $1/\sqrt{2}$ (in linear scale). To achieve complete isolation between outports, $|S_{41}|$ must be zero. In the operational frequency region, the phase difference between Ports 2 and 3 should be 90^{o}, aside from the amplitudes. It is important to attain a phase difference of 90 degrees. The physical geometry and electrical length of the coupler's constituent parts allow for this phase shift.

In designing a 90° hybrid coupler, several mathematical concepts and formulas come into play. These formulas help to understand, analyze, and design the coupler accurately provided in [16]. In the following sub-sections, details are provided for the design considerations. Please note that hybrid couplers in general have four ports with 50 Ω impedances (in simulation program and real life) as provided in Fig. 1.

2.1 Impedance matching

Impedance matching plays a crucial role in maximizing power transfer and minimizing reflections. The characteristic impedance (Z_0) of a transmission line is ascertained by the formula (2) [16]

$$\mathrm{Z}_0 = \sqrt{(\mathrm{Z}_1\mathrm{Z}_2)}\,, \qquad (2)$$

where Z_1 and Z_2 are the impedance of two transmission line segments and Z_0 is the matching impedance value of the transmission line segment not to have reflections. It should be noted that this formulation is valid for the quarter-wavelength impedance transformers [16].

2.2 Phase difference

Since phase terms are periodic due to having sinusoidal inputs, the phase difference (Δφ) between the second and the third output ports of a coupler is calculated using the formula (3) [16]

$$\Delta\varphi = \frac{2\pi\Delta d}{\lambda}, \qquad (3)$$

where Δd is the difference in path length and λ is the wavelength.

2.3 Coupling factor

The coupling factor (C) provides a measure of power division between two output ports. It is calculated using formula (4) [16]

$$C = 10\log 10\left(\frac{P_1}{P_2}\right), \qquad (4)$$

where P_1 is the power delivered to the coupled port and P_2 is the power delivered to the isolated port.

2.4 Directivity

Directivity (*D*) indicates the degree to which power is isolated from the input to the output in a coupler. It is determined using formula (5) [16]

$$D = 10\log 10\left(\frac{P_2}{P_3}\right), \qquad (5)$$

where P_2 is the power delivered to the coupled port and P_3 is the power delivered to the isolated port.

2.5 Return loss

Return loss (RL) is an indication of the reflections from the coupler and can be calculated using formula (6) [16]

$$\mathrm{RL} = -20\log 10|\Gamma|, \qquad (6)$$

where Γ is the reflection coefficient.

These mathematical representations provide a foundation for understanding the characteristics and behavior of the proposed 90° hybrid coupler, which will be further elaborated in the subsequent sections.

3 Designing the coupler

As demonstrated in Fig. 1, the circuit diagram of the coupler illustrates its elementary structure. This simplicity does not compromise performance; instead, it enhances the coupler's feasibility and applicability across various applications. The design was modeled and simulated using SONNET Software, an electromagnetic (EM) simulation program that provides a high consistency between simulation results and real-life environment measurements [17].

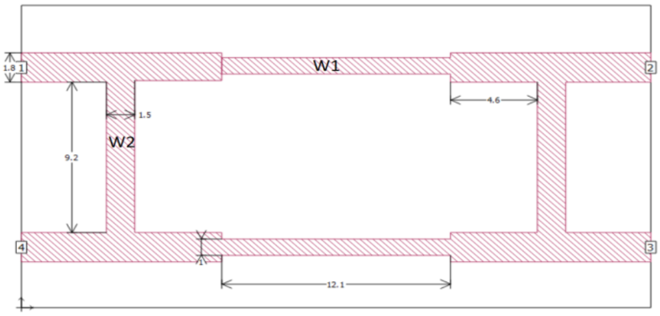

Fig. 1. Top view of the microstrip coupler

The current study introduces a coupler design, which consists entirely of rectangular structures, highlighting simplicity and ease of implementation. As illustrated in Fig. 1, the design presents a two-dimensional view of the proposed 4-port structure. Unlike the complex geometries in previous designs, our proposed coupler uses a simplistic layout, offering an advantage in terms of fabrication ease and implementation.

The proposed coupler operates with a bandwidth of 0.8 GHz in the C-band frequency region, which is a notable area of interest in microwave communication systems. The dimension of the coupler is 33.3 mm × 18.5 mm, embodying a compact design that is advantageous for numerous applications. The design has an “H” shape with an equal-length arm given. The coupler is symmetrical, significantly improving fabrication tolerance and ease of production.

In a departure from more complicated designs, the proposed coupler does not contain any curves or angular shapes. Instead, it relies on an entirely rectangular arrangement, enhancing the design's simplicity and manufacturing feasibility. The use of standard FR4 as the dielectric material further adds to the simplicity and applicability of this design, as FR4 is widely used in the industry for similar fabrications. Figure 2 has the 3D view of the coupler.

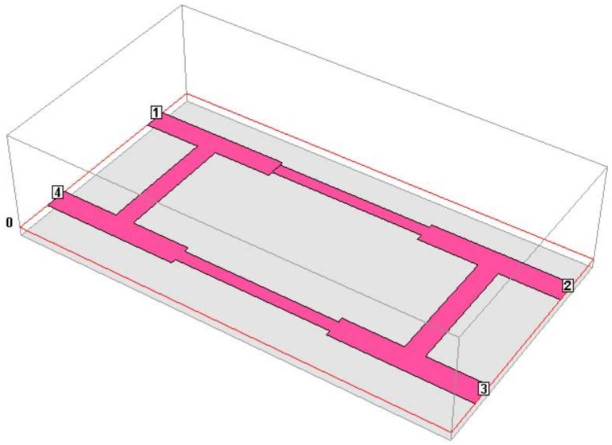

Fig. 2. Three-dimensional view of the microstrip coupler

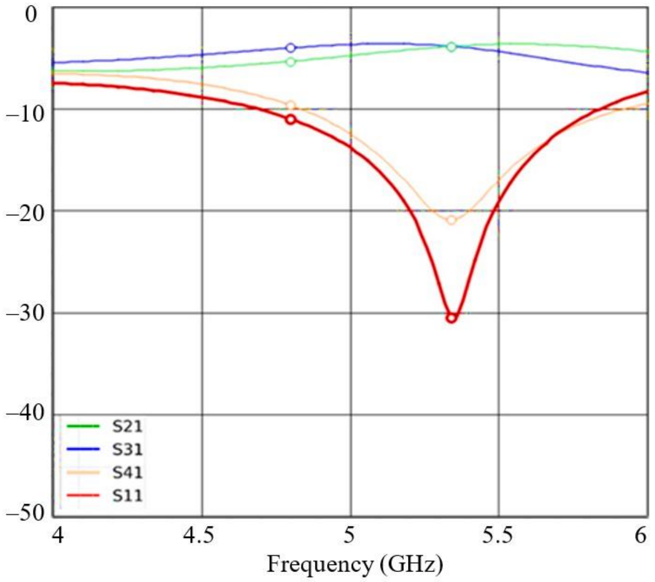

Fig. 3. The S-parameters graph (magnitude in dB versus frequency) for the main design

The S-parameter analysis of our coupler design, illustrated in Fig. 3, indicates an achievement of the desired values. The insertion loss, denoted by $|S_{12}|$ and $|S_{13}|$, remains an impressively good amplitude balance of around 0.2 dB across the operational bandwidth, highlighting the design's high efficiency.

Additionally, we performed a current distribution analysis at the frequency of 5.4 GHz, which is a key factor in determining the coupler's performance under high-frequency conditions.

As illustrated in Fig. 4, the simulated current distribution proves that the two output-coupled ports (2 and 3) have the same color (–3 dB less than the input (1) port). The isolated port (4) also shows much less power (dark blue) since almost no power goes to port 4. Current values associated with colors can be seen in a legend at the center of the figure.

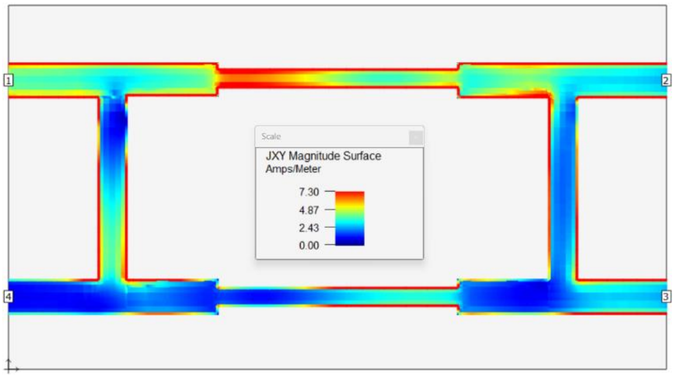

Fig. 4. Current distribution of the coupler at 5.4 GHz

As can be seen in Fig. 5, the final fabricated design of our proposed coupler showcases the result of meticulous attention to detail and thorough consideration of the theoretical modeling. The fabrication process began with the selection of a high-quality FR4 substrate due to its standard application in the industry and favorable characteristics. The precise design pattern was transferred onto the substrate using a high-precision photolithography process, ensuring the accurate replication of our modeled design. Careful attention was given to maintaining the dimensions and geometries of the individual elements, particularly the simple yet effective rectangular structure. The result is a compact and highly symmetrical coupler, validating the benefits of our straightforward and innovative design. Notably, the high degree of symmetry in the design also simplifies the fabrication process and increases the fabrication tolerance, reducing potential errors and mismatches. This practical manifestation of our theoretical design, as shown in Fig. 5, indicates its feasible integration into real-world communication systems.

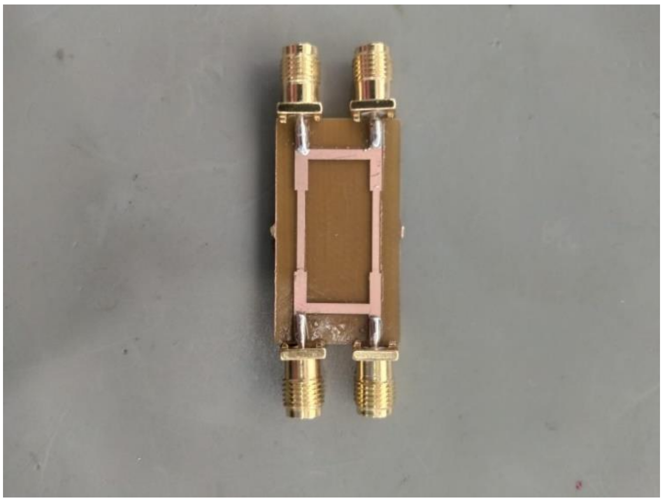

Fig. 5. Fabricated design of the proposed circuit

Figure 6 shows the good match between simulated and measured S-parameters. These concrete results reinforce our assertion that our design ensures efficient energy transfer and power division, making it a compelling option for implementation in various applications. In light of these results, we anticipate that our proposed coupler will make a significant contribution to the field, offering a simple, compact, and effective solution for numerous applications that require highly efficient and versatile couplers. Table 1 compares and shows the difference between the simulation results and the measured results at 5.4 GHz. In summary, our proposed coupler design, with its simplicity, compactness, broad operational bandwidth, and low insertion loss, is set to be a valuable addition to the domain of microwave technology. Its ease of fabrication and implementation make it an attractive option for various applications in microwave communication systems.

Table 1. Difference between the simulation results and the measured results

Parameters	Simulation	Measured	Difference
$\lvert S_{31}\rvert$ (dB)	3.74	4.11	–0.37
$\lvert S_{21}\rvert$ (dB)	3.74	3.96	–0.22

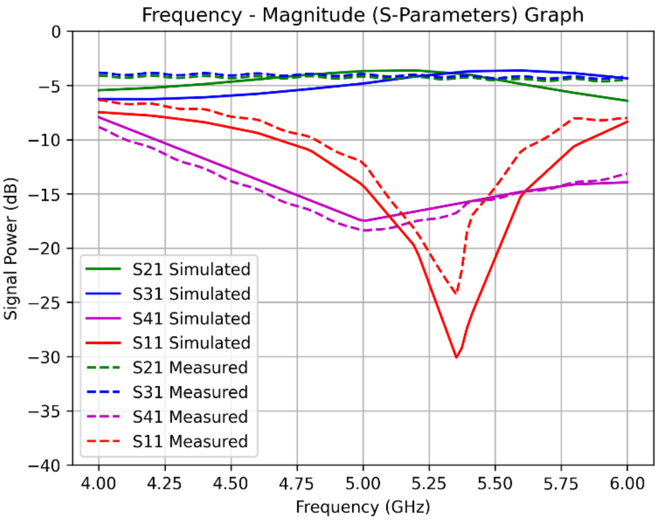

Fig. 6. Measured result of the coupler

Finally, Fig. 7 shows that this coupler is hybrid so it has 90 degrees phase difference between the output ports at 5.4 GHz. It should be highlighted that; the phase variation in the operating regime is almost constant and equal to 90 degrees as is required. Having symmetrically placed two H-shaped shaped dividers leads to constant phase variation in the operating regime since the path where the EM waves propagate is entirely symmetric for any wavelength in the operating regime.

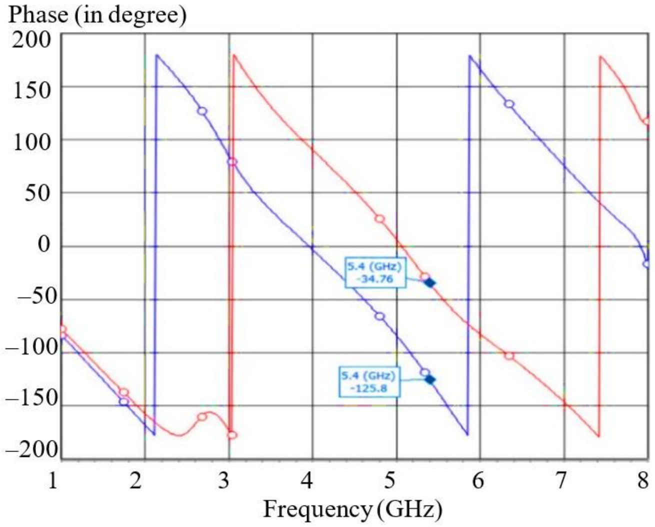

Fig. 7. Phase deviation of two ports of 90° coupler S_{12} (blue) and S_{13} (red)

4 Parametric study

After getting good results in the design, it is possible to improve our work one step further by performing a parametric study [16]. In Fig. 2, width 1 and width 2 are shown of which parametric studies were made.

Table 2. Changes made to width 1

W1 (mm)	Frequency (GHz)	$\lvert S_{11}\rvert$ (dB)	$\lvert S_{21}\rvert$ (dB)	$\lvert S_{31}\rvert$ (dB)	BW (GHz)
1.4	5.25	–28.76	–4.10	–3.90	0.8
1.2	5.32	–29.55	3.82	–3.81	0.8
1	5.4	–30.86	–3.74	–3.74	0.8
0.8	5.51	–31.45	–3.92	–3.96	0.8
0.6	5.62	–32.46	–4.01	–4.05	0.8

As seen in Tables 2 and 3, insertion losses (for the coupled and thru ports are) closest to –3 dB when w1=1 mm and w2=1.5 mm (S_{21} and S_{31} are –3.74 dB). It also proves that the S-parameters are not changed much when we deviate from those two values, proving that fabrication tolerances are at acceptable levels.

Table 3. Changes made to width 2

W2 (mm)	Frequency (GHz)	|S11| (dB)	|S21| (dB)	|S31| (dB)	BW (GHz)
1.3	5.29	28.65	–4.07	–3.94	0.8
1.4	5.33	29.84	–3.89	–3.83	0.8
1.5	5.4	30.86	–3.74	–3.74	0.8
1.6	5.47	29.45	–3.94	–3.89	0.8
1.7	5.51	28.41	–4.04	–4.01	0.8

5 Conclusion

In this study, the presented simple 3-dB coupler differentiates itself not only with its type or operational concept but also with a unique amalgamation of beneficial features, effectively standing out in its category. This differentiation is due to its compactness, simplicity, and high fabrication tolerance rates, all thanks to the features outlined. Through several parametric studies, we have observed that the scattering parameter values remain relatively unchanged after manipulating various elements, confirming the design's robustness in terms of fabrication tolerance. The S–parameters, according to the measured results, are as follows: $|S_{11}|= –24.46$ dB, $|S_{21}|=4.11$ dB, $|S_{31}|= –3.96$ dB, and $|S_{41}|= –17.2$ dB. The phase variation is only 0.8°. Due to employing FR–4, the loss is evitable but, the main motivation here is to have almost equal power division and as low as possible phase deviation between S12 and S13 concerning good isolation (S14).

In conclusion, based on these results, it has been demonstrated that this design will provide a successful production tolerance rate. Therefore, the 3 dB microstrip directional coupler with a bandwidth of 0.8 GHz (15%) offered in this study, with its properties mentioned above, would serve as a uniquely beneficial product in many applications such as sub–6 GHz 5G applications. Compared to similar ones in its class in the literature on RF couplers, it stands out distinctively.

This collection of research articles provided in Table 4 explores various innovative designs and optimizations of branch line couplers (BLCs) for diverse frequency bands and applications [18]. An article introduces a compact dual-band BLC operating at 2.45 GHz and 5.08 GHz, utilizing an unbalanced composite right/left–handed transmission line and achieving impressive frequency response characteristics [19]. Another work presents a novel microstrip quadrature hybrid coupler with a unique structure, exhibiting small size, low phase imbalance, high isolation, and good return loss, making it suitable for GSM applications at 1.8 GHz [20].

Additionally, planar microstrip BLCs with improved phase and amplitude stability bandwidth, tailored for ISM 433 MHz applications, are introduced, showcasing significant size reduction without compromising key performance parameters [21]. A miniaturized BLC operating at 2.4 GHz for Wireless LANs is proposed, featuring excellent isolation and minimal phase imbalance, along with a remarkably small footprint of 175.1 mm² [22]. Furthermore, a tunable branch–line coupler designed for operation at 5.7 GHz demonstrates performance enhancements with the inclusion of taped line feed structures, achieving wideband response and favorable insertion loss and coupling factor at the target frequency [23]. A compact branch–line coupler for wide harmonics suppressions is also designed with a similar approach proposed in this article [24]. These studies collectively contribute to the advancement of branch-line coupler technology across a range of frequencies and applications. In Table 4, the comparison with the previously designed recent couplers is provided. As it is seen, the proposed design has the advantage of stable characteristics. The difference between |S21| and |S13| are small and the return loss value is better than several studies in Table 2. Besides, the phase variation between the ports is very successfully achieved. Compared to other studies, it has an immune to phase variation.

Table 4. Comparison of the proposed coupler with previous studies

Ref.	RL (dB)	Isolation (dB)	$\lvert S_{21}\rvert$ (dB)	$\lvert S_{31}\rvert$ (dB)	Phase var.	Impedance bandwidth	Size (λ_g^2)
[18]	34.68	23.1	3.45	3.79	0.9°	21%	–
[19]	42	–	3.8	3.55	–	6%	0.087
[20]	29	29.7	3.5	3.02	2.1°	–	0.027
[21]	16.6	20.8	3.54	3.57	2.15°	30%	0.285
[22]	26.4	28.68	2.97	3.65	3°	10%	0.049
[23]	17.6	18	3.1	3.1	0.8°	15%	0.042
[24]	20	20	22	22	0.7°	26%	0.01
Conv. coupler	35	35	–	–	–	10%	0.063
Our work	24.46	17.2	4.11	3.96	0.8°	16%	0.260

In Table 2, “phase var.” stands for $\pm 90° +$phase variation between S_{21} and S_{31}.

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