



# OPEN Design and fabrication of a compact microstrip hybrid ring coupler with harmonic reduction for L band radar system

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In this paper, a compact hybrid ring coupler is designed, simulated, and fabricated to achieve both size reduction and unwanted harmonic suppression in the L-band frequency range. As the demand for miniaturized and high-performance microwave components increases, reducing the footprint of passive devices such as couplers has become a key objective in modern electronic design. The proposed coupler integrates a specially designed resonator between its ports to effectively suppress unwanted harmonics, ensuring improved signal integrity and enhanced operational efficiency. Through this approach, 2nd to 10th harmonics are successfully eliminated, minimizing interference and improving overall system performance. The proposed design operates at a center frequency of 1.4 GHz, achieving an exceptionally low insertion loss of 0.3 dB. Additionally, it demonstrates a remarkable 70% reduction in size compared to conventional couplers while maintaining excellent isolation and phase balance. The design and simulation of the rat-race coupler were conducted using Advanced Design System (ADS) software, and the device was fabricated using a Rogers RT/duroid 5880 substrate with a thickness of 20 mil and a dielectric constant of 2.2. Experimental validation confirms strong agreement between simulated and measured results, highlighting the effectiveness of the proposed structure in achieving compactness and superior performance. This novel design presents a promising solution for modern microwave applications requiring highly efficient, compact, and low-loss couplers.

**Keywords** Compact rat race coupler, Elimination of unwanted harmonics, Insertion loss, Microstrip, Resonator, Size reduction

Power dividers and directional couplers are passive microwave components used for distributing or combining power<sup>1–3</sup>. In power dividers, the input signal is divided into two or more output signals, while in combiners, two or more signals are combined at the input and presented at the output. Dividers and combiners come in various configurations, such as three-port networks, four-port networks, and even those with more ports, where three-port networks are configured as T-junctions and four-port networks as directional couplers. Ideally, power dividers and combiners are lossless. In power dividers, two or more signals are input, and at the output port, they are divided into two or more signals with reduced power. In power combiners, two or more signals are taken from the input and combined at the output<sup>4</sup>.

A 180-degree hybrid ring coupler or rat-race coupler (RRC) is a four-port network that creates a 180-degree phase difference between two output ports. Its functionality is as follows: when power is applied to port 1, it is evenly divided in-phase between ports 2 and 3, while port 4 remains isolated. However, if power is applied to port 4, it is evenly divided between ports 2 and 3 with a 180-degree phase difference, and port 1 is isolated.

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Another capability of the hybrid ring can be its combining property, such that when power is applied to ports 2 and 3, their sum appears at port 1, and their difference appears at port 4. For this reason, port 1 is referred to as the sum port and port 4 as the difference port<sup>4</sup>.

Recent advancements in the design and functionality of hybrid couplers have introduced innovative approaches to enhance compactness, harmonic suppression, and multi-band operation. A novel reconfigurable coupler was proposed, integrating rat-race and branch-line functionalities with adjustable frequency, bandwidth, and power division ratios, enabling versatile applications in modern microwave systems<sup>5</sup>. A dual-band, dual-mode coupler was also developed, utilizing artificial transmission lines with open split-ring resonators to achieve a compact and efficient design. This coupler functions as both a branch-line and rat-race coupler, accommodating multiple frequency bands<sup>6</sup>. Furthermore, the incorporation of composite right/left-handed unit cells has enabled the realization of compact couplers that exhibit dual-mode operation, functioning as both branch-line and rat-race couplers on an integrated passive device process<sup>7</sup>. Another noteworthy design introduced a dual-band rat-race coupler with high band ratios, offering high isolation and low insertion loss for advanced wireless communication systems<sup>8</sup>. A dual-band hybrid coupler was introduced, operating effectively as a branch-line coupler at lower frequencies and transitioning to a rat-race coupler at higher frequencies, making it ideal for feeding antenna arrays<sup>1</sup>. Also, open stubs<sup>9–11</sup> and different resonators<sup>12,13</sup> are employed to improve the suppression band and miniaturize the structure of the couplers and other microwave devices<sup>14,15</sup>.

In<sup>16</sup>, the structure of the defective microstrip structure (DMS) is utilized to design a compact rat race coupler with the aim of eliminating unwanted harmonics and reducing size. By incorporating DMS, it is observed that the third harmonic signal decreases by 25 dB compared to a conventional hybrid coupler. Additionally, this structure also consistently reduces the occupied area by 25% of the usual case. Finally, through the analysis of normal and irregular modes, the ABCD precursor matrix for the proposed gear drive is extracted<sup>16</sup>.

The designed coupler in<sup>17</sup> introduces the proposed structure of a heptagonal RRC operating at the fundamental frequency of 9.0 GHz, capable of both miniaturization and harmonic suppression. The RRHC design is based on a T-shaped structure in the ground plane and a Defected Ground Structure (DGS) at the bottom, occupying small area of a conventional RRC<sup>17</sup>.

In<sup>18</sup>, the aim is to design a RRC for compactness, utilizing an asymmetric T structure to achieve maximum compactness alongside a wide range of harmonic suppression functionalities. A lossless transmission line model is used for designing equations. The designed coupler in this article occupies compact size<sup>18</sup>.

The presented coupler in<sup>19</sup> describes a method of size reduction and outlines a harmonic suppression band for a rat race coupler. It utilizes compacted resonator cells, where the proposed equivalent circuit is a resonant synthesis circuit. The proposed coupler occupies smaller space compared to a typical rat race coupler<sup>19</sup>.

The method in<sup>20</sup> details the development of a compact RRC through three phases. Initially, the RRC circuit layout is simulated using a mathematical pattern. Subsequently, the layout undergoes refinement using electromagnetic simulation software, EM tuning. The layout in<sup>20</sup> demonstrates that the coupler occupies a small space compared to a regular sample.

The presented study in<sup>21</sup> discusses the design process of a branch line coupler with unwanted harmonic elimination. It occupies small area compared to a regular coupler and provides wide harmonic suppression band beyond operating frequency.

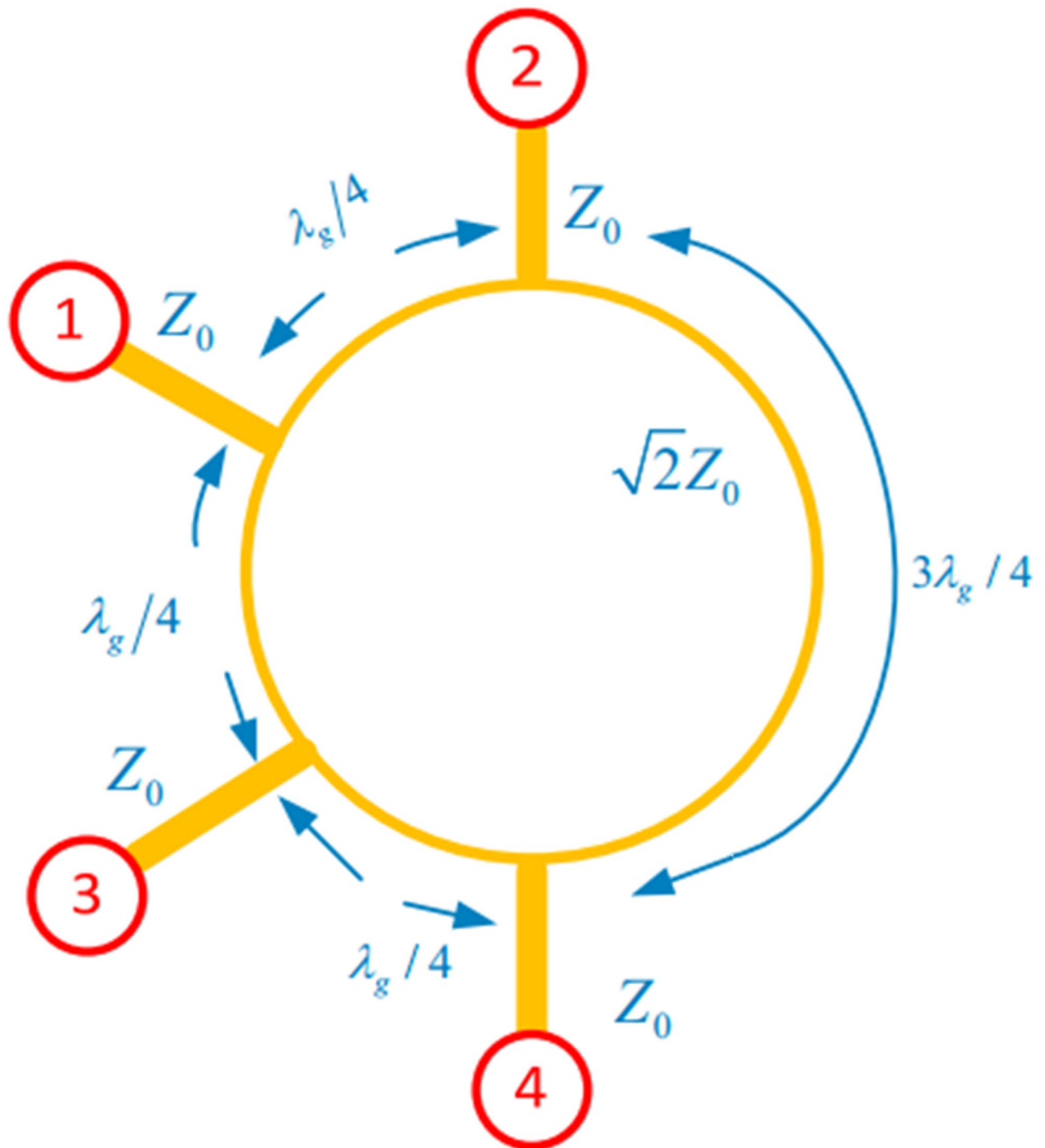
In this paper, a compact rat-race coupler is designed, simulated, and fabricated to achieve both significant size reduction and improved harmonic suppression. The proposed design introduces a specially designed resonator between the coupler ports, effectively eliminating harmonics from the second to the tenth order while reducing the overall footprint by 70% compared to conventional designs. Operating at 1.4 GHz, the coupler achieves minimal insertion loss and maintains a precise phase response, making it highly efficient for modern microwave applications. The combination of compact size, superior harmonic suppression, and low-loss performance makes this design a practical and reliable solution for high-frequency systems.

## Traditional hybrid ring coupler

Figure 1, shows the traditional hybrid ring coupler, providing a baseline for comparison with the proposed design. This figure emphasizes the structural simplicity and functional limitations of the conventional coupler. While the traditional coupler effectively divides or combines power, it lacks the design elements necessary for harmonic suppression and size reduction, which are critical for modern microwave applications. The absence of harmonic suppression mechanisms often results in interference and degraded performance in high-frequency systems. This comparison underscores the advancements introduced in the proposed coupler, particularly in terms of miniaturization and improved frequency response.

## Design of the resonator

A new resonator is proposed into the traditional hybrid ring coupler to enhance harmonic suppression and achieve significant size reduction. This modification eliminates second, third, and fourth-order harmonics while reducing the coupler's overall footprint significantly compared to conventional designs, enhancing its performance for modern applications. Figures 2 and 3 illustrate the layout and frequency response of the designed resonator. Figure 2 presents the physical layout of the resonator, showing its compact structure and the integration of elements designed to achieve size reduction and harmonic suppression. The resonator's configuration is key to enhancing performance by minimizing unwanted harmonics, which can otherwise degrade signal integrity. Figures 4a and b demonstrate the frequency response of the resonator, highlighting its capability to operate effectively at the target frequency of 1.4 GHz while eliminating second, third, and fourth-order harmonics. This combination of structural efficiency and precise frequency control plays a crucial role in optimizing the performance of the hybrid ring coupler. The cutoff frequency of the designed resonator is located



**Fig. 1.** Layout of the traditional hybrid ring coupler featuring a circular topology for power division and combination in microwave applications. The design follows a conventional microstrip implementation, resulting in a large footprint.

at 4.6 GHz and also there two transmission zero obtained near 6.2 GHz and 7.8 GHz. The dimensions of the proposed resonator are listed as follows:  $L = 10.1$ ,  $W_1 = 1.6$ ,  $L_1 = 0.5$ ,  $S_1 = 0.1$ ,  $L_2 = 4.3$ ,  $S_2 = 0.5$ ,  $L_3 = 3$ ,  $W_2 = 0.1$ .

#### Analyze of the proposed resonator

The equivalent LC circuit of the proposed resonator and its simplified version are shown in Fig. 4. In Fig. 4(a), the detailed circuit representation includes inductive and capacitive is presented. The simplified version in Fig. 4(b) reduces the complexity of the circuit while maintaining essential electrical characteristics, allowing for easier analysis of the fundamental resonant frequencies and impedance transformations. This equivalent circuit aids

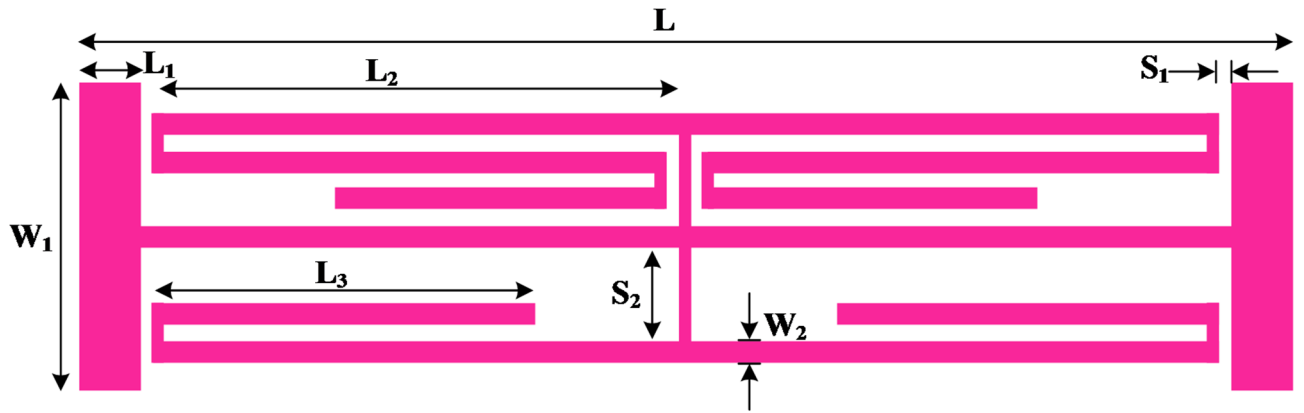


Fig. 2. Layout of the proposed resonator with a planar structure, incorporating two meandered branches designed for harmonic suppression and size reduction.

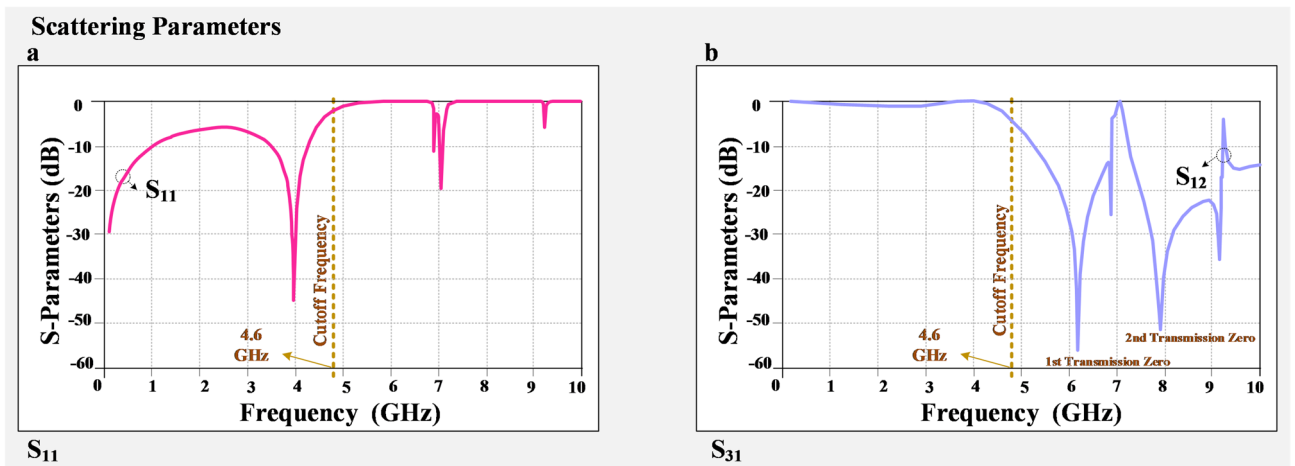


Fig. 3. Simulated frequency response of the proposed resonator, demonstrating the presence of two transmission zeros. The scattering parameters of (a)  $S_{11}$  and (b)  $S_{22}$  are illustrated.

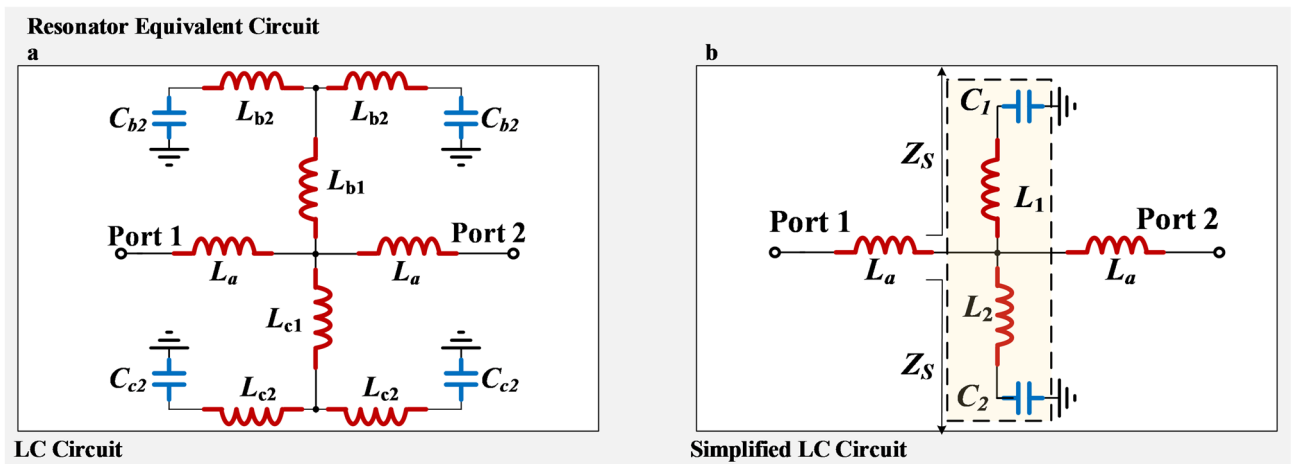


Fig. 4. (a) Equivalent LC circuit of the proposed resonator and (b) its simplified version.

in understanding the resonator filtering effect by modeling how energy is distributed and attenuated at various harmonic frequencies.

The  $Z_s$  parameter, which is equal to the parallel combination of the  $L_1C_1$  branch and the  $L_2C_2$  branch, can be written as shown in Eq. (1). The obtained value of  $Z_s$  can be simplified as written in Eq. (2).

$$Z_s = \left( L_1 S + \frac{1}{C_1 S} \right) \left( L_2 S + \frac{1}{C_2 S} \right) / \left( (L_1 + L_2) S + \left( \frac{1}{C_1} + \frac{1}{C_2} \right) \frac{1}{S} \right) \quad (1)$$

$$Z_s = \frac{C_1 C_2 L_1 L_2 S^4 + (C_1 L_1 + C_2 L_2) S^2 + 1}{C_1 C_2 (L_1 + L_2) S^3 + (C_1 + C_2) S} \quad (2)$$

Then, the transfer function can be derived to analyze the behavior of the proposed resonator in the frequency domain, as expressed in Eq. (3).

$$H_S = \frac{R}{\left( L_a S + \frac{Z_s (R + L_a S)}{R + Z_s + L_a S} \right) (R + L_a S)} \quad (3)$$

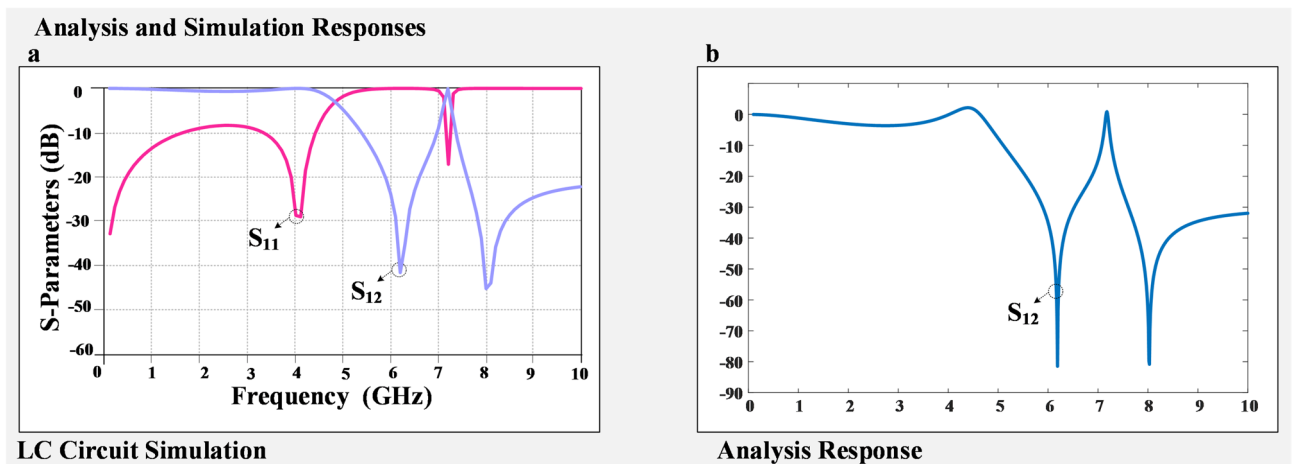
The simulated frequency response of the equivalent LC circuit of the proposed resonator, along with the analyzed extracted response, are shown in Fig. 5. The appropriate values of the resonator parameters, i.e.,  $L_a = 2.4$  nH,  $C_1 = 0.27$  pF,  $L_1 = 2.4$  nH,  $C_2 = 0.23$  pF, and  $L_2$ , can be calculated from Eq. (3) to achieve the desired frequency response, which in this design  $L_2$  is equal to 1.7 nH.

### Design of the proposed hybrid ring coupler

Figures 6 and 7 presents the layout and frequency response of the initially designed hybrid ring coupler. Figure 6 illustrates the physical structure of the coupler, which follows the conventional hybrid ring design but incorporates preliminary design adjustments to optimize its functionality. Figures 7a and b demonstrate the frequency response of this initial design, showing its operation at the frequency of 1.4 GHz. While the design effectively performs basic coupling functions, the absence of advanced resonator integration leads to the presence of unwanted harmonic frequencies and a larger overall size. This initial design serves as a stepping stone for the proposed coupler, which further enhances harmonic suppression and significantly reduces size, addressing the limitations observed in this version.

The initial coupler achieves a 37% size reduction in the occupied area, and the applied resonators between the coupler ports eliminate unwanted harmonics. The insertion loss is obtained equals to 0.3 dB. The phase response of the initially designed hybrid ring coupler is illustrated in Fig. 8. According to Fig. 8, the phase values of the initial coupler at the operating frequency equals to:  $\angle S_{21} - \angle S_{31} = 6^\circ$ ,  $\angle S_{34} - \angle S_{24} = -179^\circ$ . The overall size of the initially designed hybrid ring coupler is  $60.9 \text{ mm} \times 31.5 \text{ mm}$ , equivalent to  $0.39 \lambda \times 0.2 \lambda$ . Compared to a conventional hybrid ring coupler with a size of  $0.5 \lambda \times 0.25 \lambda$ , this design achieves a 37% reduction in the occupied area. The dimensions of the applied branches in the initial hybrid ring coupler are  $L_4 = 27.3 \text{ mm}$  and  $W_4 = 2.1 \text{ mm}$ .

Figures 9 and 10 illustrates the layout and frequency response of the proposed hybrid ring coupler. Figure 9 shows the physical structure of the coupler, which incorporates six additional branches into the initial design. These branches were specifically introduced to address the discrepancy in the operating frequency, as the initial coupler operated at 2 GHz, whereas the target frequency is 1.4 GHz. The added branches effectively shift the operating frequency to 1.4 GHz, aligning the coupler's performance with the desired specification. Furthermore, the enhanced design significantly improves the stop band characteristics and achieves superior harmonic



**Fig. 5.** (a) Frequency response of the simulated equivalent LC circuit of the proposed resonator and (b) the analyzed extracted response.

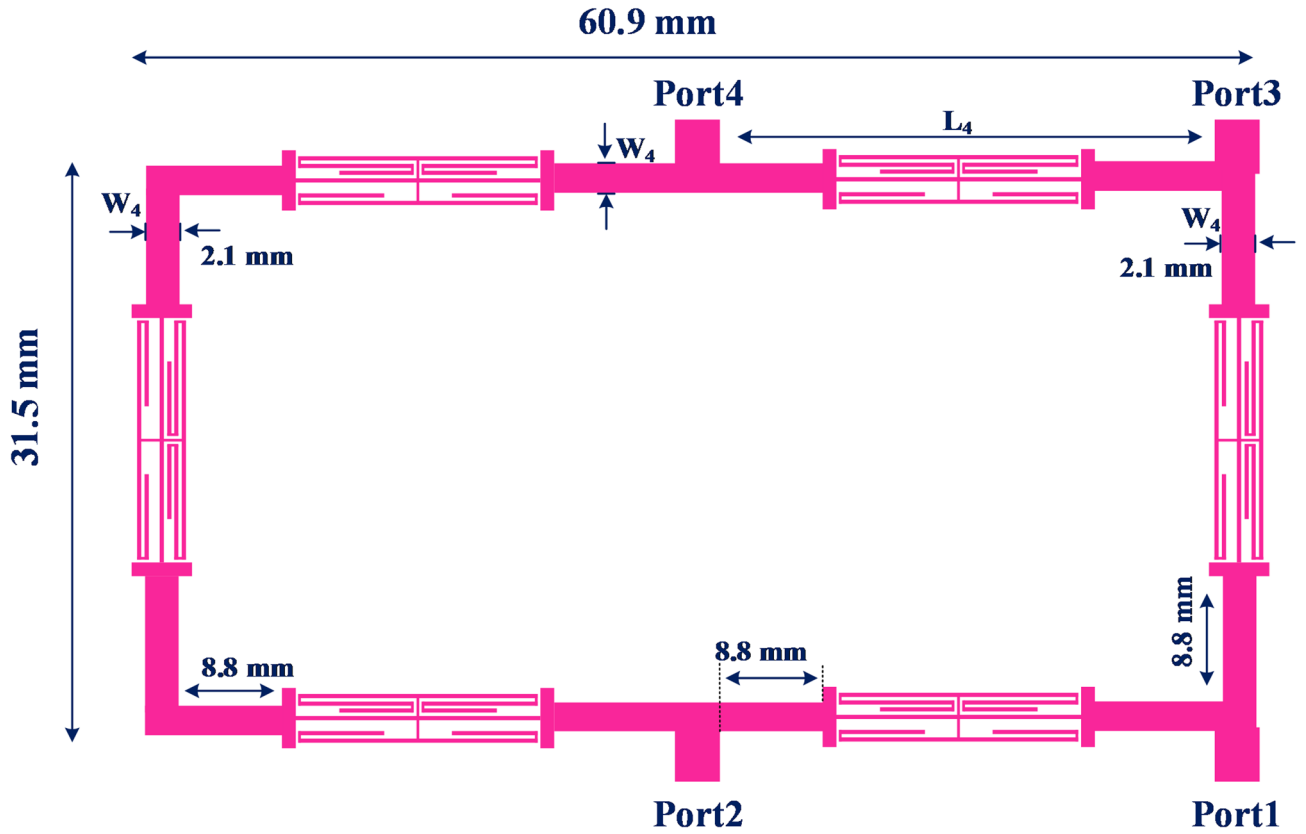


Fig. 6. Layout of the initially designed hybrid ring coupler incorporating six proposed resonators.

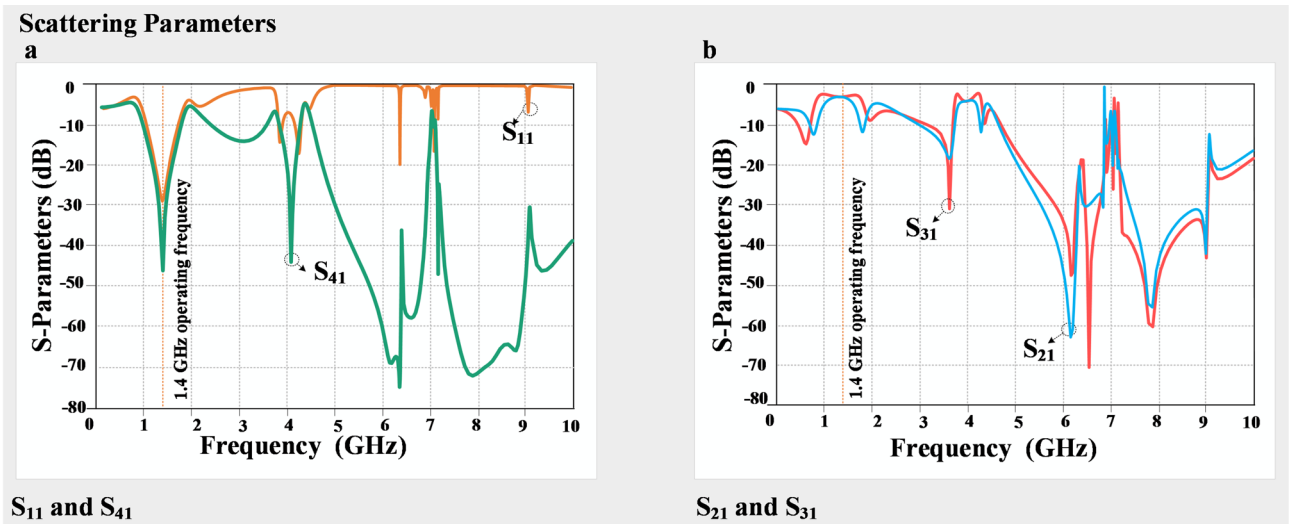


Fig. 7. Simulated frequency response of the initially designed hybrid ring coupler. The scattering parameters of (a)  $S_{11}$ ,  $S_{41}$ , (b)  $S_{21}$ , and  $S_{31}$  are illustrated.

suppression, effectively eliminating second, third, and fourth-order harmonics. Figure 8 highlights these improvements in the frequency response, demonstrating the coupler’s optimized performance and its suitability for high-frequency applications.

The size of the final hybrid ring coupler is reduced by 70%, compared to the conventional coupler. The proposed coupler has dimensions of  $43 \text{ mm} \times 22.1 \text{ mm}$ , equivalent to  $0.27 \lambda_g \times 0.14 \lambda_g$ . The dimensions of the added six branches in the coupler structure are  $W_0 = 1.9 \text{ mm}$  and  $L_0 = 12.8 \text{ mm}$ .

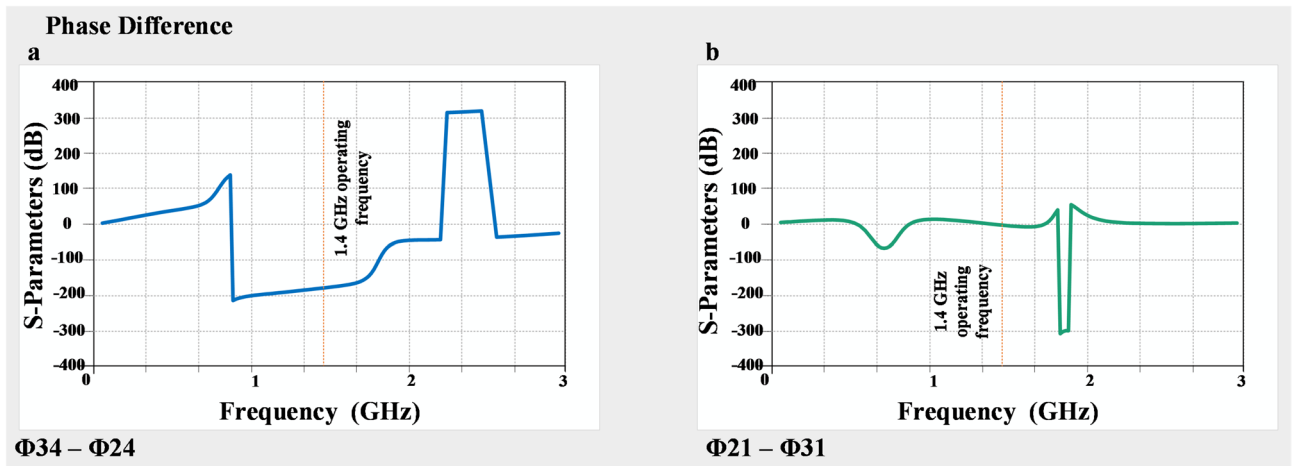


Fig. 8. Simulated phase response of the initially designed hybrid ring coupler.

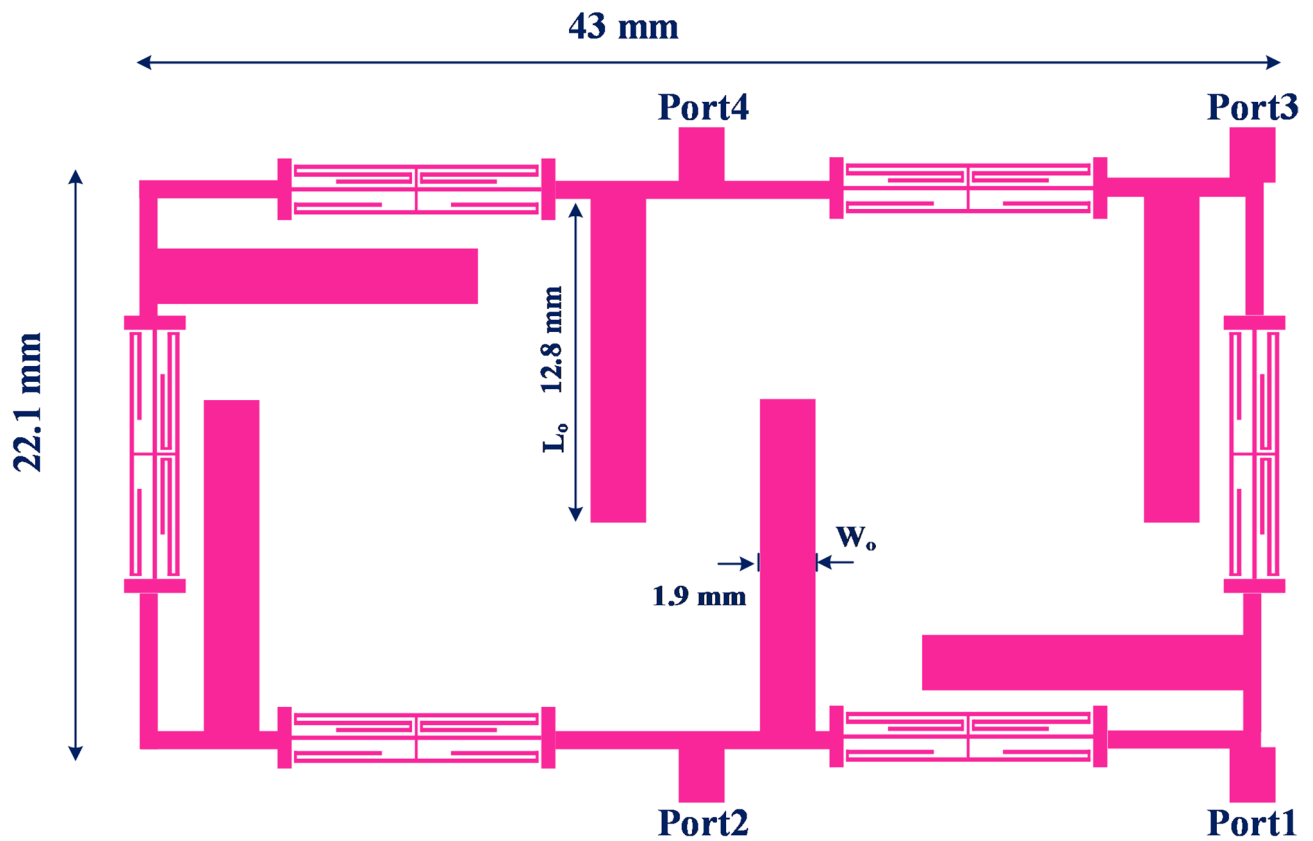
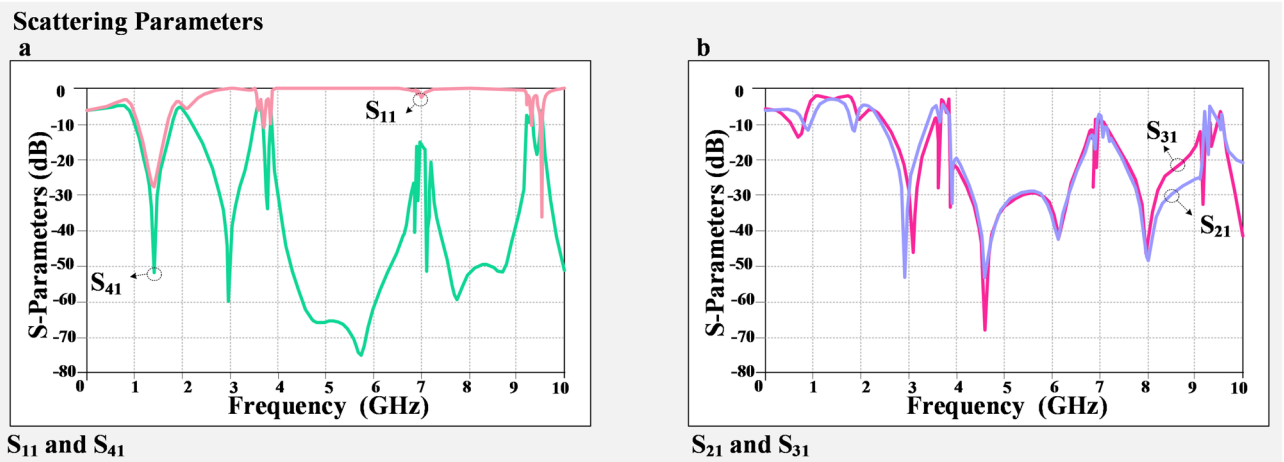


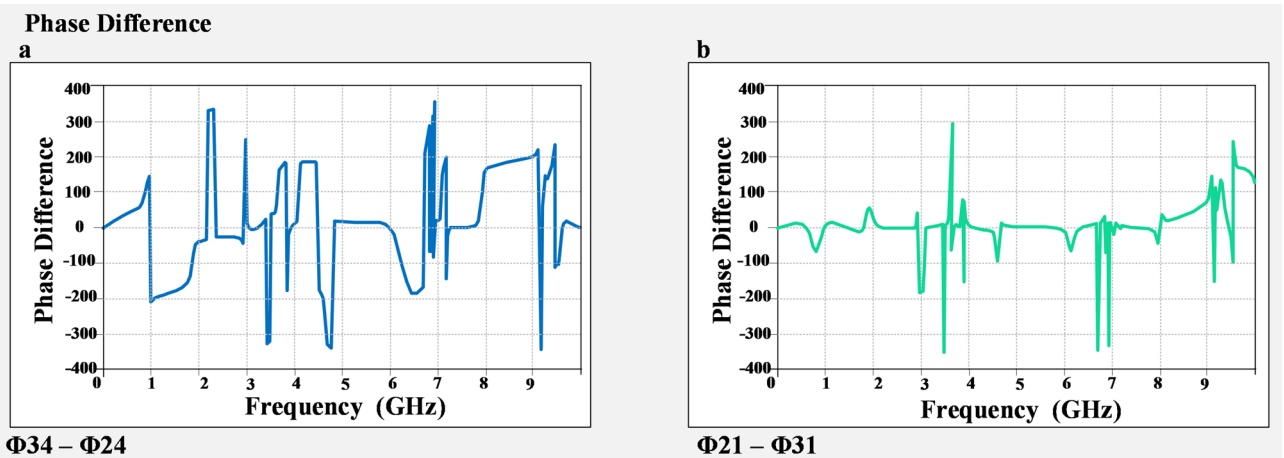
Fig. 9. Layout of the proposed hybrid ring coupler incorporating six proposed resonators and six open-ended stubs.

Figure 11 depicts the simulated phase response of the proposed hybrid ring coupler. The figure demonstrates the coupler's capability to maintain a consistent and well-defined phase difference between its output ports at the operating frequency of 1.4 GHz. This precise phase response is critical for ensuring effective power division and combination in microwave applications. The design improvements, including the addition of six branches, not only shift the operating frequency but also refine the phase balance, minimizing phase errors and enhancing overall performance.

These enhancements make the proposed coupler a reliable solution for applications requiring high precision and harmonic suppression.



**Fig. 10.** Simulated frequency response of the proposed hybrid ring coupler. The scattering parameters of (a)  $S_{11}$ ,  $S_{41}$ , (b)  $S_{21}$ , and  $S_{31}$  are illustrated.



**Fig. 11.** Simulated phase response of the proposed hybrid ring coupler. (a) The phase difference between ports 3 and port 4. (b) The phase difference between ports 3 and port 2.

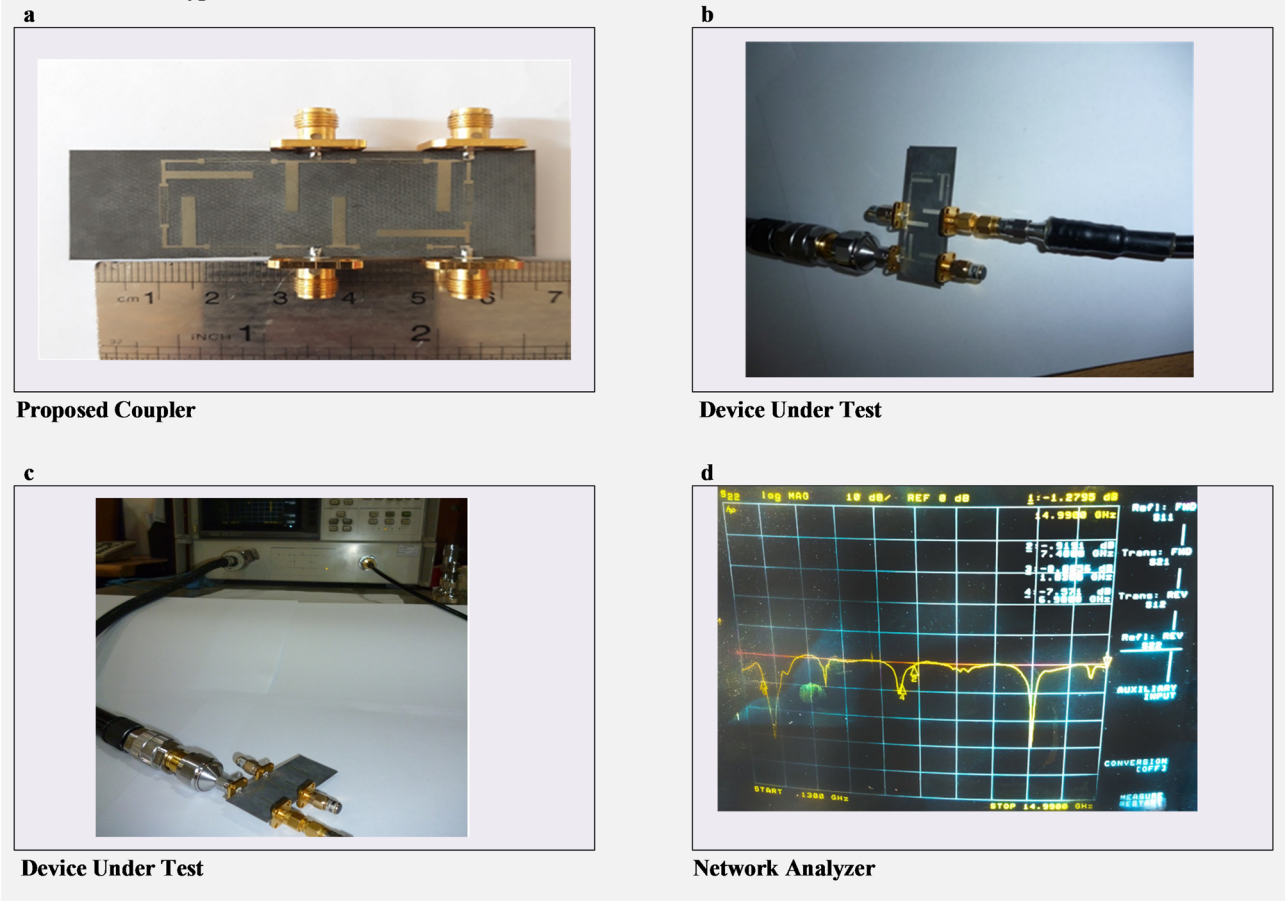
In this study, the proposed coupler was designed and simulated using the Layout environment of ADS software. The designed prototype is fabricated using a Rogers RT/duroid 5880 substrate as shown in Fig. 12.

As seen in Fig. 12, the fabricated device was tested using an HP 8720D vector network analyzer (VNA) to measure the S-parameters of the proposed coupler. This model offers a frequency range of 50 MHz to 20 GHz, providing accurate measurements for RF and microwave devices. To ensure precise results, the calibration was carried out using the Short-Open-Load-Thru (SOLT) method. This method was chosen due to its effectiveness in eliminating systematic errors, including directivity, source match, load match, and reflection tracking errors. The SOLT calibration was performed using high-quality calibration standards to achieve optimal accuracy. Regarding measurement uncertainties, several factors were considered to minimize their impact. Care was taken to ensure consistent connections during measurements to avoid errors caused by connector variations. High-quality, low-loss cables were used, and efforts were made to minimize bending and movement to reduce fluctuations in the measured results. Additionally, measurements were conducted in a stable temperature environment to avoid potential errors caused by temperature variations. The network analyzer was allowed to warm up before use to reduce drift-related uncertainties, and periodic recalibration was performed as needed.

The proposed coupler features a planar structure with a simple layout, making it easy to fabricate using standard PCB manufacturing techniques. Unlike some advanced microwave components, this design does not include lumped elements, defected ground structures (DGS), electromagnetic bandgap (EBG) structures, or any other elements that require extra fabrication steps. This ensures a straightforward manufacturing process without the need for specialized equipment or additional processing.

Since the design is fully planar, it allows for easy and cost-effective mass production while maintaining high performance. For large-scale manufacturing, alternative low-cost dielectric materials can be considered instead of Rogers RT Duroid 5880, ensuring affordability without significantly affecting electrical properties.

## Fabricated Prototype



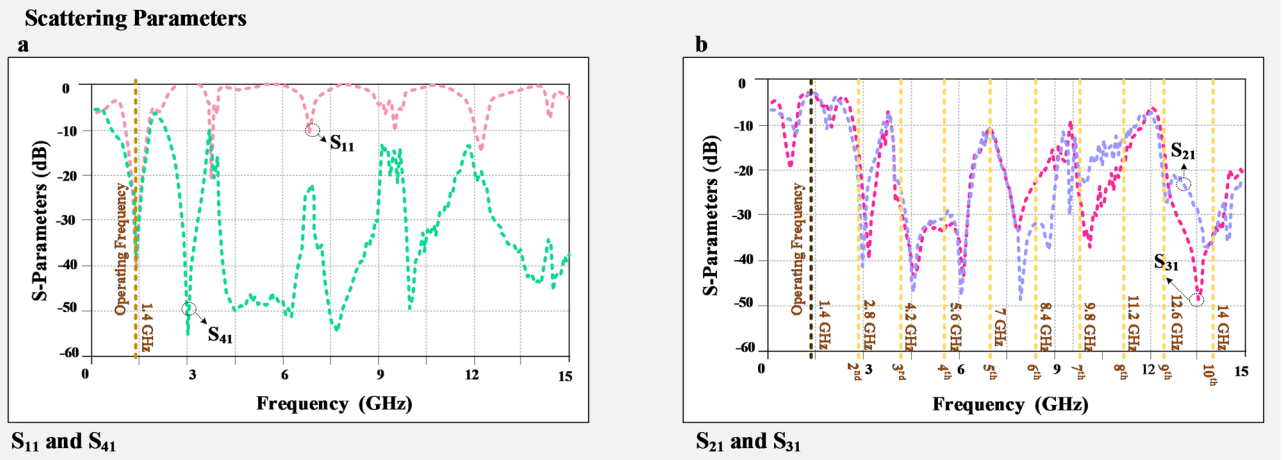
**Fig. 12.** Photographs of the fabricated prototype: (a) proposed coupler, (b) and (c) fabricated device under test, and (d) measured results using a network analyzer model.

The absence of complex structures also improves consistency in production, leading to better output quality and reliability. With its simple fabrication process and efficient performance, the proposed coupler is well-suited for both research applications and large-scale implementation in modern microwave systems.

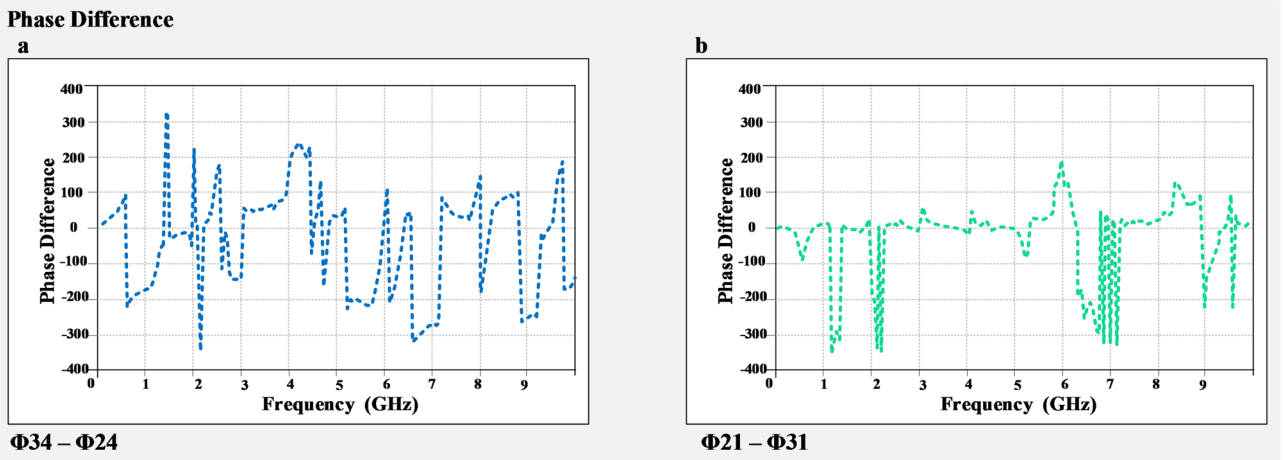
Figures 13 and 14 show the measured results of the fabricated coupler. As shown in Fig. 13, the simulated coupler at the center frequency of 1.4 GHz has the insertion loss of -3.3 dB, indicating a loss of 0.3 dB, which is a desirable value compared to conventional designs. The resonator used between the coupler ports eliminates second, third, and fourth-order harmonics. According to the measured results, the proposed coupler attenuates the second to tenth harmonics as follows: 18 dB (2nd), 25 dB (3rd), 31 dB (4th), 11 dB (5th), 23 dB (6th and 7th), 14 dB (8th), 16 dB (9th), and 35 dB (10th). Additionally, as depicted in Fig. 14, the phase diagram of the simulated coupler at the center frequency equals to:  $\angle S_{21} - \angle S_{31} = 1.56^\circ$ ,  $\angle S_{34} - \angle S_{24} = -181.5^\circ$ . Additionally, the phase difference values of the fabricated coupler parameters, presented in Fig. 14, equals to:  $\angle S_{21} - \angle S_{31} = 10^\circ$  and  $\angle S_{34} - \angle S_{24} = -181.2^\circ$ .

Although the experimental results closely match the simulation results, some measurement uncertainties and possible sources of error should be considered. Fabrication tolerances, such as slight variations in substrate thickness, conductor width, and etching accuracy, can impact the impedance matching and phase response. Additionally, connector and soldering losses may introduce small deviations in insertion loss measurements. Another source of uncertainty comes from the calibration of the network analyzer, where minor inaccuracies in the calibration process can slightly affect the measured scattering parameters. Environmental factors, including temperature and humidity variations, may also influence the performance of the coupler during testing. Despite these factors, the simple planar structure of the proposed coupler minimizes complexity and reduces the likelihood of significant deviations, ensuring that the measured performance remains highly reliable.

To further highlight the performance and superiority of the proposed design, a detailed comparison with existing methods has been conducted and summarized in Table 1. As seen, the proposed rat race coupler demonstrates several advantages over existing designs. The proposed coupler operates at 1.4 GHz and demonstrates significant harmonic suppression, eliminating second to tenth harmonics, which is an improvement over most existing designs that typically suppress only lower-order harmonics. Additionally, the proposed coupler exhibits superior insertion loss, with simulation and measurement values of 0.1 dB and 0.3 dB, respectively, which are lower than those of other designs. Furthermore, the proposed design achieves a 70% size



**Fig. 13.** Measured frequency responses of the proposed hybrid ring coupler. The scattering parameters of (a)  $S_{11}$ ,  $S_{41}$ , (b)  $S_{21}$ , and  $S_{31}$  are illustrated.



**Fig. 14.** Measured phase response of the proposed hybrid ring coupler. (a) The phase difference between port3 and port 4. (b) The phase difference between ports3 and port 2.

Reference	Frequency (GHz)	IL21 (dB)	IL31 (dB)	RL (dB)	Isolation (dB)	Size Reduction (%)	Harmonic Suppression
17	0.9	NR*	NR*	44	39	69	2nd and 4th
18	1	3.53	3.34	30	35	66	2nd to 6th
19	2.4	3.52	3.65	22	20	55	2nd and 3rd
22	1.45	3.19	NR	20	20	54	3rd and 5th
23	1.5	3.25	3.37	15	43	57	None
24	1.8	3.2	3.2	35	35	74	2nd to 7th
25	0.6	3.26	3.31	22	30	62	3rd to 7th
26	3	4	4	18.5	20	None	2nd
27	2.25	NR*	NR*	30	20	50	None
28	0.95	3.4	3.5	12	45	47	2nd and 4th
29	2.45	4	4	10	20	63	None
This Work	1.4	3.2	3.3	42	38	70%	2nd to 10th

**Table 1.** Comparison of the proposed rat race coupler with existing designs, highlighting operating frequency, harmonic suppression, insertion loss, return loss, isolation, and size reduction. \*NR: Not Reported.

reduction, outperforming the size reduction percentages of prior works, making it highly efficient and compact for modern applications.

## Conclusion

In this paper, a compact rat race coupler with harmonic suppression was designed, simulated, and fabricated for L-band radar applications. The proposed coupler integrates a resonator between its ports, achieving a significant reduction in size (70%) compared to conventional designs while effectively eliminating second, third, and fourth-order harmonics. Simulation and measurement results demonstrated excellent agreement, with an insertion loss of 0.1 dB (simulation) and 0.3 dB (measurement) at the operating frequency of 1.4 GHz. The optimized phase response and harmonic suppression validate the effectiveness of the proposed design. The fabricated coupler's compact size, high performance, and compatibility with modern microwave systems make it a promising solution for various high-frequency applications.

## Data availability

Data availability statement: The corresponding author can be contacted on reasonable request.

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## References

- Zaidi, A. M. et al. A dual-band rat-race coupler for high band ratio wireless applications. *IEEE Trans. Instrum. Meas.* **70**, 1–6 (2021).
- Roshani, S., Yahya, S. I., Khazaei, S., Roshani, S. & Karami, B. Design and Fabrication of a Microstrip Low-Pass Filter with a Wide Stopband Using a Windmill-Shaped Resonator, *ARO-THE SCIENTIFIC JOURNAL OF KOYA UNIVERSITY*, vol. 12, no. 2, pp. 201–208, (2024).
- Mohammadi, N. et al. A Wilkinson power divider with harmonic suppression through low-pass filter for GSM and LTE applications. *Sci. Rep.* **14** (1), 2429 (2024).
- Pozar, D. M. *Microwave Engineering: Theory and Techniques* (Wiley, 2021).
- Zhu, X., Yang, T., Chi, P. L. & Xu, R. Novel reconfigurable filtering rat-race coupler, branch-line coupler, and multiorder bandpass filter with frequency, bandwidth, and power division ratio control. *IEEE Trans. Microwave Theory Tech.* **68** (4), 1496–1509 (2020).
- Ghaffarian, M. S., Moradi, G., Khajehpour, S., Honari, M. M. & Mirzavand, R. Dual-band/dual-mode rat-race/branch-line coupler using split ring resonators, *Electronics*, vol. 10, no. 15, p. 1812, (2021).
- Ghaffarian, M. S., Moradi, G. & Mousavi, P. Dual band/dual mode branch-line/rat-race coupler using artificial transmission line, in *2019 27th Iranian Conference on Electrical Engineering (ICEE)*, : IEEE, pp. 1622–1626. (2019).
- Chu, H. N., Li, G. Y. & Ma, T. G. Dual-mode coupler with branch-line/rat-race responses on integrated passive device process, in *2019 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP)*, : IEEE, 82–84. (2019).
- Abdulbari, A. A. et al. New design of wideband microstrip branch line coupler using T-shape and open stub for 5G application. *Int. J. Electr. Comput. Eng.* **11** (2), 1346 (2021).
- Kumar, K. V. P. & Alazemi, A. J. A flexible miniaturized wideband branch-line coupler using shunt open-stubs and meandering technique. *IEEE Access.* **9**, 158241–158246 (2021).
- Feng, W., Duan, X., Shi, Y., Zhou, X. Y. & Che, W. Dual-band branch-line couplers with short/open-ended stubs. *IEEE Trans. Circuits Syst. II Express Briefs.* **67** (11), 2497–2501 (2020).
- Roshani, S., Azizian, J., Roshani, S., Jamshidi, M. & Parandin, F. Design of a miniaturized branch line microstrip coupler with a simple structure using artificial neural network, *Frequenz*, vol. 76, no. 5–6, pp. 255–263, (2022).
- Mandal, S. & Ghosh, C. K. Low mutual coupling of microstrip antenna array integrated with dollar shaped resonator. *Wireless Pers. Commun.* **119** (1), 777–789 (2021).
- Roshani, S. et al. Mutual coupling reduction in antenna arrays using artificial intelligence approach and inverse neural network surrogates, *Sensors*, vol. 23, no. 16, p. 7089, (2023).
- Roshani, S. et al. Design of a compact quad-channel microstrip diplexer for L and S band applications, *Micromachines*, vol. 14, no. 3, p. 553, (2023).
- Kazerooni, M. & Aghalari, M. Size reduction and harmonic suppression of rat-race hybrid coupler using defected microstrip structure. *Progress Electromagnet. Res. Lett.* **26**, 87–96 (2011).
- Song, W., Deguchi, H. & Tsuji, M. A novel heptagonal microstrip rat-race hybrid coupler with harmonic suppression and size reduction, in *Proceedings of the IEEE International Symposium on Antennas and Propagation*, 2012: IEEE, pp. 1–2. (2012).
- Velidi, V. K., Shrivastava, S. & Sanyal, S. A compact-size microstrip rat-race coupler with high performance, in *IEEE Technology Students' Symposium*, 2011: IEEE, pp. 57–60.
- Gu, J. & Sun, X. Miniaturization and harmonic suppression rat-race coupler using C-SCMRC resonators with distributive equivalent circuit. *IEEE Microwave Wirel. Compon. Lett.* **15** (12), 880–882 (2005).
- Bekasiewicz, A. & Kurgan, P. A compact microstrip rat-race coupler constituted by nonuniform transmission lines. *Microw. Opt. Technol. Lett.* **56** (4), 970–974 (2014).
- Lian, G. et al. A new miniaturized microstrip branch-line coupler with good harmonic suppression. *Progress Electromagnet. Res. Lett.* **67**, 61–66 (2017).
- Sung, Y., Ahn, C. & Kim, Y. S. Size reduction and harmonic suppression of rat-race hybrid coupler using defected ground structure. *IEEE Microwave Wirel. Compon. Lett.* **14** (1), 7–9 (2004).
- Chang, W., Liang, C. & Chang, C. Y. Wideband high-isolation and perfect-balance microstrip rat-race coupler. *Electron. Lett.* **48** (7), 382–U117 (2012).
- Lalbaksh, A. et al. Design of a compact planar transmission line for miniaturized rat-race coupler with harmonics suppression. *IEEE Access.* **9**, 129207–129217 (2021).
- Reddy, V. R., Velidi, V. K. & Rao, B. P. Wideband harmonic suppressed compact rat-race coupler using triple stub m-shape unit. *Progress Electromagnet. Res. Lett.* **96** (1), 81–90 (2021).
- Dong, G., Wang, W., Wu, Y., Liu, Y. & Tentzeris, M. M. Filtering rat-race couplers with impedance transforming characteristics based on terminated coupled line structures. *IET Microwaves Antennas Propag.* **14** (8), 734–742 (2020).
- Srisawat, S. et al. Compact Design of an S-Band Rat Race Hybrid Coupler with Enhanced Phase Balance Using Parallel Coupled-Lines, in *2024 8th International Conference on Information Technology (InCIT)*, : IEEE, pp. 490–495. (2024).

28. Velan, S., Kanagasabai, M., Pakkathillam, J. K., Palaniswamy, S. K. & Tippuraj, R. R. Spurious passband suppression in compact microstrip Rat-Race coupler deploying modified split rings and coupled microstrip lines. *Wireless Pers. Commun.* **109**, 2733–2740 (2019).
29. Maddio, S., Pelosi, G., Righini, M. & Selleri, S. An optimized compact rat race at 2.45 ghz. *Progress Electromagnet. Res. M.* **108**, 115–126 (2022).

### Author contributions

Sa.R., and So.R. conceived the idea. M. M., So. R. and Sa.R. did the simulations and optimization. So.R., S.I. Y, Sa.R., and M.A. C., developed the main idea for useable applications and designed the different structures. M. A., F. H., F. A. H. and Sa.R. did the proposed the circuit models. S. I. Y, M. M., M. K. and So.R. performed the measurements. M. M., Sa.R., and M. A. C., M. A., wrote and S. I. Y, M. K. and So.R edited the manuscript. All authors contributed to the discussion.

### Declarations

### Competing interests

The authors declare no competing interests.

### Additional information

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