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Implementation of 180° Hybrid Ring Coupler Design in Microstrip with VNA Measurement for 5G Applications

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Abstract-Problem: This paper presents the design, simulation, and experimental implementation of a 180° hybrid ring coupler in microstrip technology with coupler line width 1 mm. The hybrid ring, also known as a quadrature coupler, is a fundamental component in microwave and RF circuits, offering efficient power splitting with a 180° phase difference between its output ports. **Approch:** The design process involves careful consideration of microstrip transmission line dimensions, substrate material properties, and impedance matching for optimal performance. **Findings:** The proposed design is realized on RT/duroid material parameters with a dielectric substrate thickness of 0.8 mm, center conductor ring circumference is 1.5λ and the microstrip transmission lines are patterned according to calculated dimensions port line length 10 mm, width 2 mm to achieve the desired phase relationship and power division. Electromagnetic simulation software tool HFSS is employed to validate and optimize the design before fabrication. After the simulation phase, the microstrip hybrid ring coupler is fabricated for impedance 50 ohms and characteristic impedance is $\sqrt{2}Zo$. Vector Network Analyzer (VNA) measurements are conducted to evaluate the performance of the implemented coupler. The measured S-parameters are compared with simulation results to validate the accuracy of the design and to identify any deviations between the simulated and measured responses. The results of the VNA measurements are presented frequency for 3 GHz resonance with return loss of more than 16 dB and over 2-6 GHz scale, demonstrating the performance of the microstrip 180° hybrid ring coupler in terms of power division, insertion less than 1 dB, good isolation, and phase difference between output ports. **Conclusion:** The paper concludes with a discussion of the achieved performance and potential applications of the designed microstrip hybrid ring coupler in microwave and RF systems, such as phase shifters, balanced mixers, and signal distribution networks. The presented design process and measurement methodology provide insights into the practical implementation of microwave components using microstrip technology.

Keywords: Coupler, Directional coupler, Hybrid, HFSS, Microstrip, Microwave, Network Analyzer, Quadrature coupler, Rat-race, VNA.

1. Introduction

Microwave hybrid rings, also known as hybrid couplers or directional couplers, are fundamental passive components used in microwave and radio frequency (RF) circuits. They play a crucial role in many applications, including telecommunications, radar systems, satellite communications, and wireless technologies. The primary purpose of a hybrid ring is to split or combine electromagnetic signals efficiently. These couplers provide a means of coupling energy from one transmission line to another while maintaining a well-defined phase relationship between the coupled signals. They are particularly useful for dividing power equally between two ports or combining signals with minimal loss and isolation between the ports. Hybrid rings are typically classified into four types based on their directional properties. They are 3 dB Hybrid Ring, 3 dB Rat-Race Hybrid Ring, 90° Hybrid Ring, 180° Hybrid Ring.

3 dB Hybrid Ring is used to equally split an input signal into two output ports with 3 dB power division between them. These couplers are commonly employed in balanced amplifiers, power combiners, and signal sampling applications.

3 dB Rat-Race Hybrid Ring is a specific form of the 3 dB hybrid that is especially useful in phase-shifting and phase comparison applications.

90° Hybrid Ring equally divides an input signal into two output ports with a 90-degree phase difference between them. They are widely used in various RF systems, such as power dividers and combiners, and are crucial components in balanced amplifiers and modulators.

180° Hybrid Ring is also known as a quadrature or branchline coupler, this type of hybrid ring equally divides an input signal into two output ports with a 180-degree phase difference between them. It is often used in balanced mixers, phase shifters, and other applications requiring phase division.

The design of microwave hybrid rings involves careful consideration of the physical layout, transmission line properties, and coupling mechanisms to achieve the desired performance characteristics. Traditionally, these components were realized using microstrip, stripline, or waveguide technologies, depending on the frequency range and application requirements. Designing hybrid rings also requires careful attention to factors such as impedance matching, isolation, power handling capabilities, and the frequency range of operation. Advanced design techniques, including computer-aided design (CAD) tools and electromagnetic simulation software, are commonly employed to optimize and fine-tune the performance of hybrid couplers.

In conclusion, microwave hybrid rings are essential components in modern RF and microwave systems, providing efficient power splitting and combining functions with well-defined phase relationships between signals. Their versatility and wide range of applications make them indispensable in various communication and radar technologies.

2. Literature Review

This section has the survey about hybrid ring coupler design. Pozar, David M.[2012] published hybrid ring in neatly. Manoj Kumar Shukla, et al [2011] analyzed Microstrip Ring Hybrid Power Divider performance. Chandravilash Rai, et al [2022] designed Dual-band Circularly Polarized Hybrid Ring Cylindrical Dielectric Resonator Antenna for Wireless Applications in C and X-Band Wireless Personal Communications. S.Manikandan, et al [2021] designed Compact Rat Race Coupler for WLAN Receivers. Chung-Yi Li, et al [2021] discussed Hybrid Ring- and Tree-Topology RoF Transmission System with Disconnection Protection Hosseini, Sayed et al [2020] designed a Branch-line Microstrip Coupler Using Spirals and Step Impedance Cells for WiMAX Applications. Sukhdas Ahirwar, et al [2019] developed a Compact Rat-Race Coupler, B. Pavithra, et al [2018], designed Compact 180 Degree Hybrid Coupler Using T-shape Structure, P. Abinaya, et al [2016], presented Dual-Band Patch Hybrid Coupler. K. Verma et al [2016] designed wideband 90° branchline hybrid coupler. T.Jayachitra, et al [2014] developed Hybrid Coupler. D.C. Dhubkarya et al [2012] Simulated the characteristics of 3 GHz microstrip racetrack hybrid ring. M. H. A. Davis, [1953] presented Microwave hybrid circuits. R. Levy, [1969] designed quadrature hybrid couplers. S. B. Cohn, [1964] discussed Microwave band pass filters using parallel coupled transmission lines. J. H. Schoeffler, [1976] designed branch line hybrid ring couplers. Nishikawa and T. Ohira, et al discussed [1990] Novel rat-race hybrid circuit.

Proctor,David et al [1976], patented Microstrip Hybrid Ring Coupler. From the survey, coupler design is identified.

3. Objective of this work

The aim of this article is to bring about the hybrid ring coupler design and analysis with pocket vector network analyzer.

4. Hybrid Ring Design

A. Hybrid Ring Calculation

The design of a microwave hybrid ring involves several key calculations to determine the dimensions and properties of the coupler. Here, it is provided a basic outline of the calculations for a 3 dB 90° branch line hybrid ring, which is a commonly used type of hybrid coupler. The design is displayed in figure I. It is noted that the following calculations assume ideal transmission lines and do not consider manufacturing tolerances or other non-ideal effects. The schematic diagram is displayed in figure II.

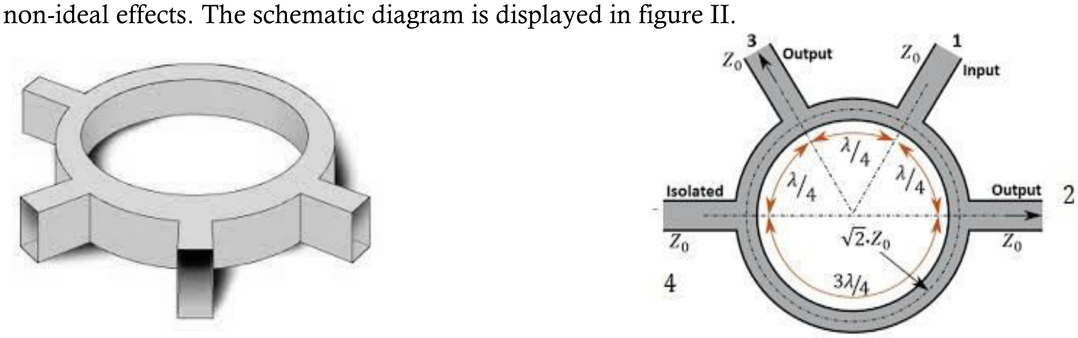

Figure I. Hybrid coupler ring and design with four ports P1-P4.

The electrical length of the transmission lines is determined by the phase difference between the coupled signals. For a 90° hybrid, the phase difference should be 90 degrees. The electrical length (θ) can be calculated using the following formula:

$\theta = 90°$ -------(1)

The physical length of the transmission lines can be determined based on the desired operating frequency and the velocity of propagation of the transmission line. The formula to calculate the physical length (L) is:

$L = (\theta / 360) * \lambda$ -------(2)

Where:

λ = wavelength at the operating frequency

Calculate the Impedance:

The characteristic impedance of the transmission lines is a critical parameter in hybrid ring design. For a branch line hybrid coupler, the characteristic impedance should be Z0 = 2 * Zo (Zo is the characteristic impedance of the main transmission line).

The coupling length (d) is determined the coupling strength between the main transmission line and the coupled line in the hybrid. The coupling length can be calculated using the following formula:

$d = (\lambda / 4) * \text{sqrt}(2)$ -------(3)

The width of the coupled line is essential to achieve the desired coupling coefficient. The coupling coefficient (k) is typically set to 0.707 for a 3 dB hybrid. The formula to calculate the coupled line width (w) is:

$k = (Zo - Zc) / (Zo + Zc)$ -------(4)

Where:
Zc = characteristic impedance of the coupled line
Using the coupled line width (w) calculated in the previous step, the physical width of the coupled line can be determined based on the PCB substrate's dielectric constant (ε_r). The formula to calculate the physical width (W) is:
$W = (w * Zo) / sqrt(\varepsilon_r)$ -------(5)

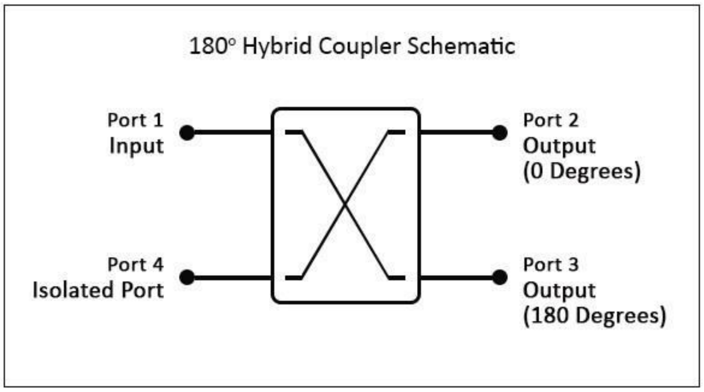

Figure II. Schematic diagram of Hybrid Coupler

Based on the calculated dimensions (L, W, d), the layout of the hybrid ring can be designed on the chosen substrate (e.g., microstrip or stripline). This design may be further optimized using electromagnetic simulation tools to fine-tune the performance and ensure the desired characteristics are achieved. The equivalent circuit is shown in figure III.

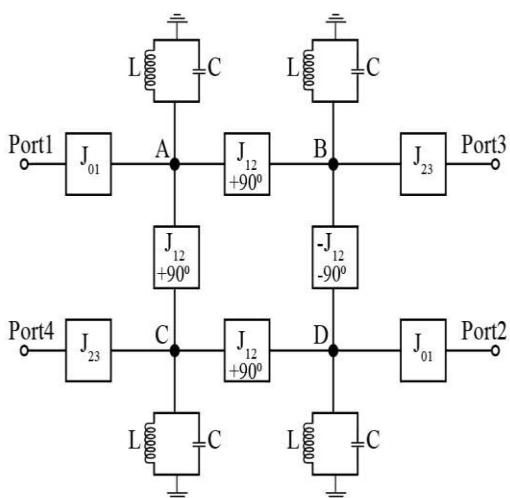

Figure III. Hybrid ring Equivalent Circuit

It's important to note that these calculations provide a basic starting point for the design of a 90° branch line hybrid ring. For more advanced or specific designs, additional considerations and optimizations might be necessary, such as adding impedance tapering, adjusting dimensions for bandwidth, and taking into account the impact of manufacturing processes.

Table 1 Hybrid Coupler Design specifications

Parameters	Values
Coupler line width	1 mm
Coupler line circumference	1.5λ
Port line width	2 mm
Port line length	10 mm
Substrate thickness	0.8 mm
Dielectric constant	2.2
Resonating Frequency	3 GHz

5. Simulation Of Hybrid Ring

The simulation of a microwave hybrid ring is performed using electromagnetic simulation software, Ansys HFSS, tools. These software packages allow engineers and researchers to model, analyze, and optimize the performance of microwave components, including hybrid rings, based on their physical layout and material properties. Ansys HFSS is used in this work. Here are the general steps involved in simulating a microwave hybrid ring:
It is started by defining the physical layout of the hybrid ring using the software's design environment. This includes setting up the transmission lines, coupling sections, and other necessary components. It is specified that the dimensions, material properties, and the substrate on which the hybrid ring is implemented.
It is assigned appropriate material properties to the conductors, substrate, and other relevant components. The dielectric constant (εr) and loss tangent (tan δ) of the substrate are crucial in determining the performance of the hybrid ring.
The input and output ports of the hybrid ring is defined for signal excitation and measurement. Also, appropriate boundary conditions are set to represent the open or terminated ends of the transmission lines.
The simulation is run to analyze the electromagnetic behavior of the hybrid ring. The software will solve Maxwell's equations numerically to calculate the electric and magnetic fields, and from that, the software will determine the S-parameters (scattering parameters) and other relevant performance metrics of the hybrid ring. The simulation diagram is shown in figure IV.

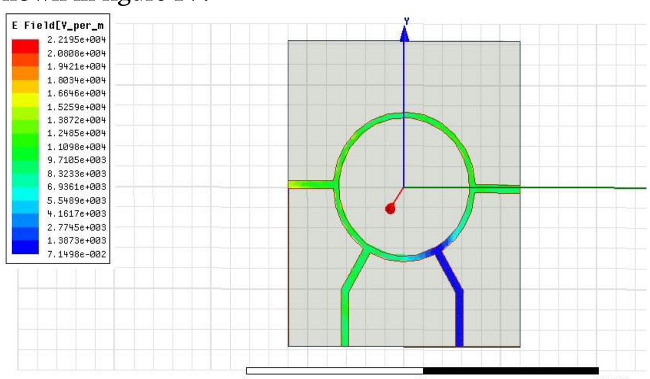

Figure IV. Simulated Hybrid coupler

Once the simulation is completed, the results are analyzed to understand the coupling behavior, power division, phase relationships, and other characteristics of the hybrid ring.
If the simulation results do not meet the desired performance criteria, it is needed to optimize the design. The dimensions, coupling length, transmission line width, or other parameters are modified to achieve the desired

performance. After making design changes, the simulation process is repeated to evaluate the effects of the modifications. Iterative optimization may be required to fine-tune the hybrid ring's performance. Once the simulation results meet the desired requirements, it is essential to verify the design using physical prototypes or fabricate the hybrid ring for practical use.

Table 2 Hybrid ring coupler function

Input exciting port	Output port	Isolated port	Phase difference in degrees
1	2,3	4	180
2	1,4	3	180
3	1,4	2	0
4	2,3	1	0

S-parameters i.e, S12=S13=1; S21=1, S24=-1; S31=S34=1; S42=-1, S43=1
S11=S44=0; S32=S33=0; S22=S23=0; S11=S14=0

That the accuracy of the simulation results depends on the precision of the model and the accuracy of the material properties used. Always it is cross-verified our simulation results with physical measurements whenever possible to ensure the simulation reflects real-world behavior accurately. The ideal S-matrix is given in figure V.

$$S = \frac{-j}{\sqrt{2}} \begin{vmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & -1 \\ 1 & 0 & 0 & 1 \\ 0 & -1 & 1 & 0 \end{vmatrix}$$

$$\begin{bmatrix} 0 & S_{12} & 0 & S_{14} \\ S_{21} & 0 & S_{23} & 0 \\ 0 & S_{32} & 0 & S_{34} \\ S_{41} & 0 & S_{43} & 0 \end{bmatrix}$$

$$\frac{-i}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 & -1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ -1 & 0 & 1 & 0 \end{pmatrix}$$

Figure V. Scattering-matrix of Hybrid Ring coupler

The input and output ports of hybrid ring are displayed in table 1.

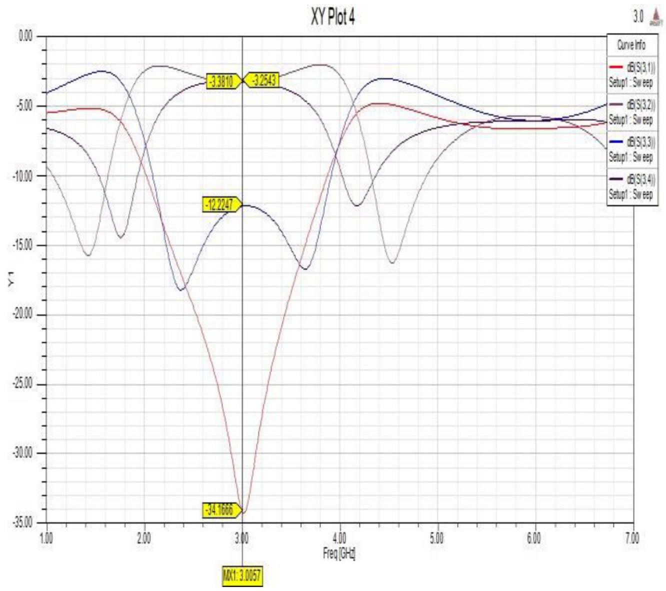

Figure VI. Characteristic curves for Port1

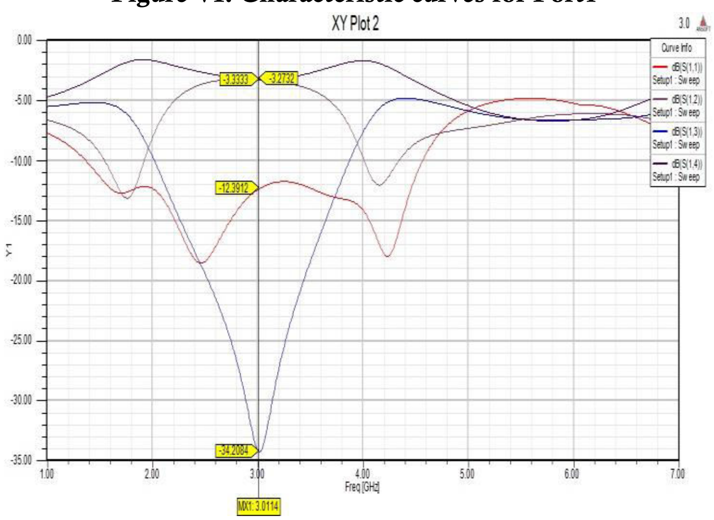

Figure VII. Characteristics curves for port 3

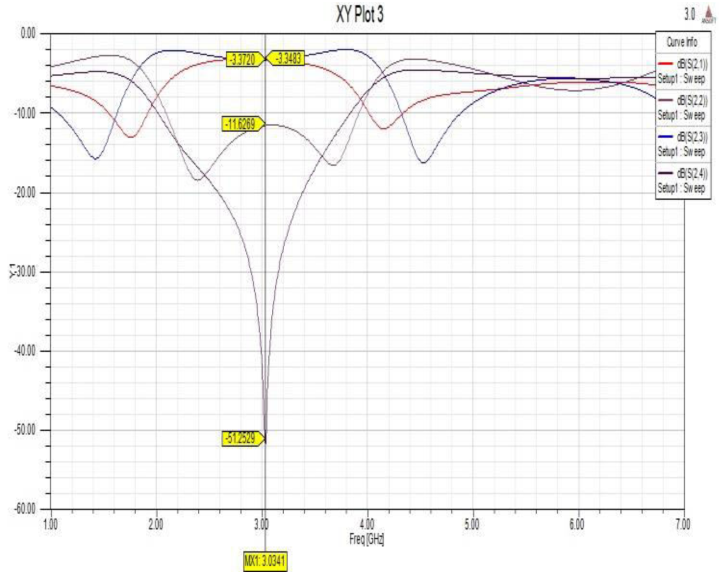

Figure VIII. Characteristic curves for Port2

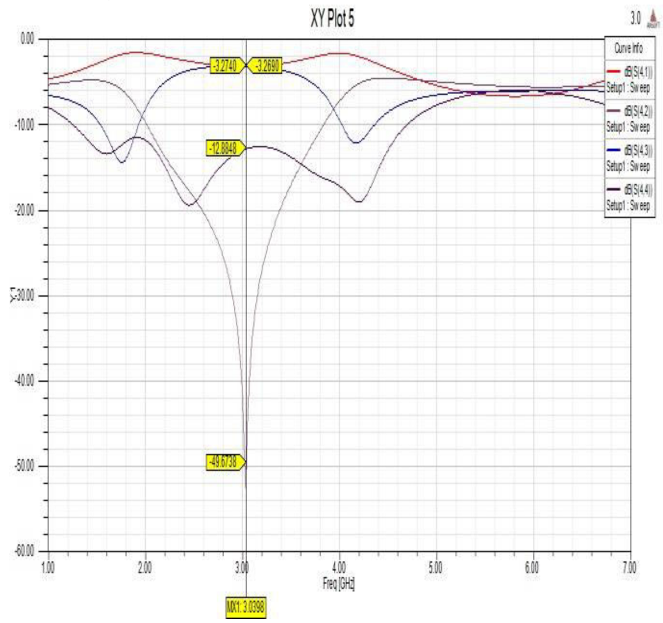

Figure IX. Characteristic curves for port 4

6. Measurement of Fabricated 180 Degree Hybrid Coupler With VNA

Measuring a fabricated 180-degree hybrid coupler with a Vector Network Analyzer (VNA) involves characterizing its S-parameters (Scattering Parameters). S-parameters describe how the coupler behaves in terms of signal reflection and transmission at different frequencies. Here's a step-by-step guide on how to do this: The Requirements are given in the following. Vector Network Analyzer (VNA): This instrument is used to measure the S-parameters of the hybrid coupler. VNAs are available in various frequency ranges; ensure your VNA covers the frequency range of our coupler. It must be fabricated and ready for testing. Suitable coaxial cables and connectors are used to connect the VNA to the coupler. A calibration kit is used appropriate for our VNA's frequency range.

The Procedure to Setup the VNA is given below: By turning on the VNA and let it warm up for the recommended time. it is ensured that the VNA is properly calibrated before starting the measurements. The calibration kit is used to match the frequency range we are working with. The calibration kit is connected to the VNA and follow the VNA's calibration procedure. This step removes the systematic errors introduced by cables and connectors and ensures accurate measurements.

The procedure to Connect the Hybrid Coupler: one port of the VNA is connected to one of the coupler's input ports using a suitable coaxial cable and connector. Termination (a 50-ohm load) is connected to the other input port of the hybrid coupler to ensure accurate measurements. one of the output ports of the coupler to a cable that connects to another port on the VNA. Now, the other output port of the coupler open or terminated, depending on our measurement requirements.

Measurement Setup is given with the following procedure: The VNA is configured to perform a two-port S-parameter measurement (S11, S21, S12, and S22). The measurement frequency range is set and resolution bandwidth based on our specific requirements. If it is interested in both magnitude and phase information, the VNA is configured to display both.

These procedure is used to take Measurements: The measurement on the VNA is initiated. The VNA will sweep through the defined frequency range and record the S-parameter data. The measurements will typically include the magnitude (amplitude) and phase of the S-parameters.

For analyzing the Data the following procedure is given: Once the measurements are complete, the data is saved for further analysis. The S-parameter data is analyzed to understand how the hybrid coupler behaves at different frequencies. The insertion loss, isolation, return loss, and other parameters are calculated based on the S-parameter data.

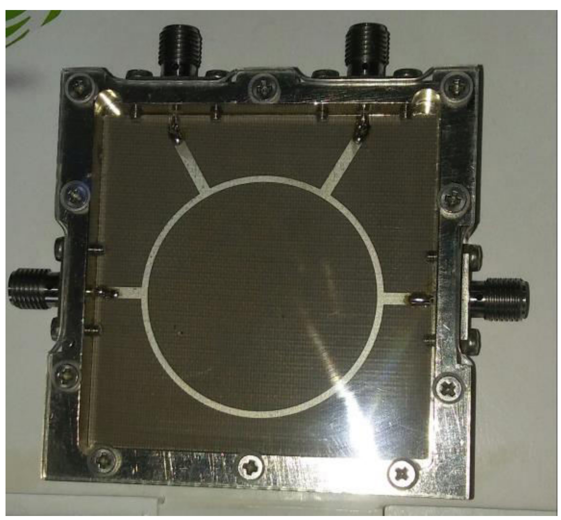

Figure X. Fabricated hybrid ring coupler picture

7. Results and Discussion

If necessary, the measurements are repeated for different terminations (open, short, load) on the unused output port of the hybrid coupler. The measurements and results are documented, including the frequency range and conditions under which the measurements were taken. Measuring a 180-degree hybrid coupler with a VNA allows us to characterize its performance and verify that it meets our design specifications. The S-parameter data can be used for further analysis and optimization in your RF or microwave system. The hybrid ring designed is fabricated as a prototype and shown in figure X. It is tested with pocket vector network analyzer instrument. The measured results are is displayed in the following figures.

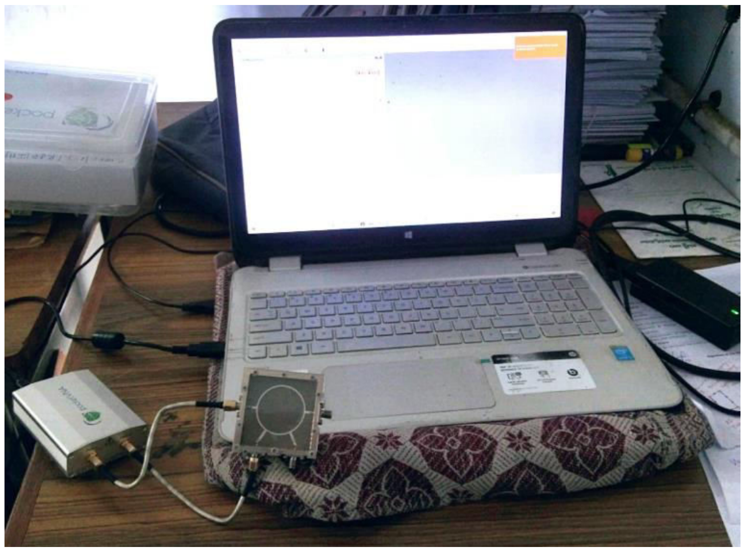

Figure XI. Fabricated Hybrid coupler with VNA

At the simulation, the following results were obtained and displayed in figure V, S24, S42 values -29.1 dB and the insertion loss of S21, S23, S41, S43 values are -3.52 dB. The simulated return loss for S11=-20 dB, S22=-30.2 dB, S33=-17 dB and S44=-25 dB. On the Vector Network Analyzer, prototype is measured. At this measurement results, isolation loss of -28.4 dB for S24 and S42 is arrived from the measurement. The insertion loss S21, S23 and S41, S43 of -3.41 dB is received. The return loss of S11, S22, S33, S44 is -19.1 dB, -28.8 dB, -15.01 dB, -24.1 dB respectively. The testing is shown in figure XI.

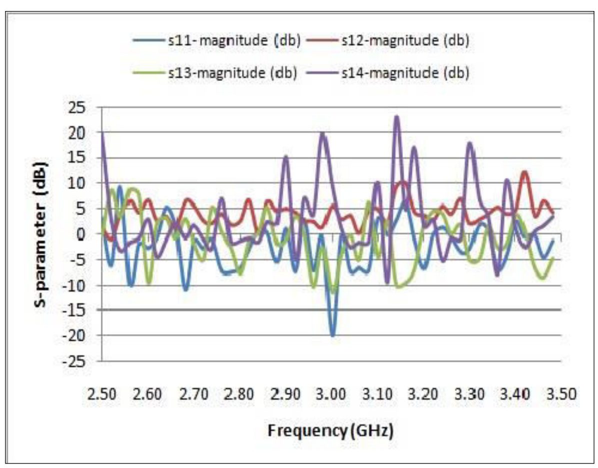

Figure XII. Hybrid ring S11, S12, S13, S14 Simulation results.

8. Conclusion

The microwave hybrid rings, also known as hybrid couplers or directional couplers, are designed, analyzed with VNA instrument. These components find widespread application in various fields, including telecommunications, radar systems, satellite communications, and wireless technologies. The design of a microwave hybrid ring involves port line length of 10mm, width of 2mm and coupler line width of 1mm. Parameters such as Impedance matching, power handling capabilities, isolation loss less than -20 dB, insertion loss of around 3.5 dB and phase relationships are acceptable range. While the calculations provide a starting point, designing an effective microwave hybrid ring often requires optimization and fine-tuning using electromagnetic simulation software tool HFSS. Additionally, considering manufacturing tolerances and material properties is crucial to ensure the performance meets the desired specifications. As technology continues to advance, microwave hybrid ring designs evolve to cater to higher frequencies, wider bandwidths, and other specific requirements. Researchers and engineers continue to explore novel techniques to improve the performance of these components and integrate them into modern communication systems. Overall, microwave hybrid rings designed, tested in RF and microwave engineering, enabling efficient signal splitting and combining with well-controlled phase relationships, contributing to the development of various wireless and communication technologies.

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