Democratic and Popular Republic of Algeria
Ministry of Higher Education and Scientific Research
University of Mohamed Boudiaf - M'sila

1985
جامعة محمد بوضياف - المسيلة
Université Mohamed Boudiaf - M'sila

Faculty: Technology
Field: Sciences and Technologies
Department: Electronics
Section: Telecommunications
Specialty: Telecommunications Systems

Thesis submitted for the award of

the Academic Master's degree

Presented by: Yacine TAYAB & Aymen Cherf-eddine ZIANE

Titled

A Novel Design of Rat-Race divider for 5G Applications

Defended before the jury composed of:

Dr. ZERDOUMI Zohra	University of M'sila	President
Dr. GARAH Messaoud	University of M'sila	Rapporteur
Dr. KENANE El-Hadi	University of M'sila	Co-rapporteur
Dr. SAHED Mohamed	University of M'sila	Examiner

Academic year: 2023 /2024

Acknowledgments

We extend our sincerest thanks to **Dr. M. GARAH** for his supervision and support during the completion of my master's thesis in communication systems. Special thanks are extended to **Dr. H. KENANE**, whose assistance was paramount, especially during the practical phases of our research. A big thanks for the **Ph.D. student Amel SILA** for her assistance to us at critical times.

Our thanks also to **Dr. ZERDOUMI Zohra** and **Dr. SAHED Mohamed** for accepting to judge our work

Our gratitude also goes to the head of the electronics department, **Dr. M. TABBAKH**, for his unwavering support and encouragement. We are also grateful to all the teachers of the specialty telecommunication systems for each with its name for their enriching teachings.

Additionally, we would like to acknowledge for our colleagues for their companionship and mutual support. Finally, our heartfelt appreciation is directed to everyone who played a role in this endeavor, contributing both directly and indirectly to my success.

Dedication

To my generous parents, whose unwavering support and love have been my constant guide.

To my precious wife, for her patience, understanding, and endless encouragement during two years of master's study.

To my beloved sons: Abdessamie & Abdelbadie who bring joy and inspiration to every day of my life.

To all my brothers and sisters, and their families, for their companionship and belief in me.

To my friends: Moussa, Lahcéne, Fares, Taher for their camaraderie and good cheer.

To my co-workers at Condor: Walid, Khaled and all member of QC teams at the Refrigerator's BU for their help and support during my master's study.

And to all those who have contributed, from near or far, to this achievement your part in my journey will always be cherished I am deeply thankful for all whose contribution to my success.

Yacine TAYAB

Dedication

To my generous parents, whose unwavering support and love have been my constant guide.

To all my brothers and sisters, and their families, for their companionship and belief in me.

To all my friends, without exception, for their camaraderie and good cheer.

And to all those who have contributed, from near or far, to this achievement your part in my journey will always be cherished I am deeply thankful for all whose contribution to my success.

Aymen ZIANE

Summary

Chapter I: State of the art

Chapter II: Analytical Study of Standard Rat-Race Divider

Chapter III: Parametric study of rat-race divider

Chapter IV: Optimization of a rat race divider

List of Figures

List of Tables

Introduction

In the radiofrequency communication systems where microwave frequencies, ranging from 1 GHz to 300 GHz, are widely used for satellite communications and numerous other applications, several components are used, whether they are passive or active. Among these components, we find dividers or couplers, which serve to divide power and distribute it uniformly to microwave circuits.

The power dividers [1] offer distinct advantages for high-power applications due to its grounded isolation resistance design, which facilitates efficient heat dissipation. Power dividers are also essential components in modern wireless communication systems due to various considerations in their microwave component design, such as cost, weight, and manufacturability.

The main function of a power divider is to split an input signal into multiple signals according to the circuit/system requirements.

Our primary goal during this optimization process is outlined in three points:

- ✓ Learn a fundamental theory of a rat race divider.
- ✓ Conduct an in-depth parametric study of a rat race divider to observe the effects of different parameters on its characteristics and performance.
- ✓ Optimize a rat race divider using CST Studio.

This work aims to enhance the rat race divider for 5G applications. The structure of this thesis is as follows: In the first chapter we give an overview of fundamental theory of a rat race divider including a state of the art of this one. In the second chapter, we deal with analytical study of standard Rat-Race divider. In the third chapter, we explore the parametric study of rat-race divider to observe the effects of different parameters on its characteristics and performance. The fourth chapter deals with the optimization of a rat race divider for 5G applications using the CST simulator. Finally, the conclusion summarizes our work and presents new research perspectives in this field.

Chapter I: State of the art

I.1 Introduction

The rat race divider, known as a passive component in microwaves, is used to divide power and distribute it evenly in RF and microwave communication systems. It is a four-port coupler, with each port placed at one-quarter wavelength (λ) away from the other around the top half of the ring. The bottom half of the ring is three-quarter wavelengths (λ) in length. It has three branches which are 90-degree phase shifted from each other, and one branch that provides a 270-degree phase shift. [1]

Power dividers, including the rat race divider, play a crucial role in wireless communication systems. Two well-known and widely used power divider designs are the Wilkinson power divider and the Gysel power divider. While the Wilkinson power divider is commonly employed, the Gysel power divider offers distinct advantages for high-power applications due to its grounded isolation resistor design, which facilitates efficient heat dissipation. However, the Gysel power divider is larger in size compared to the Wilkinson power divider because of the inclusion of four additional quarter-wavelength transmission lines. Therefore, reducing the size of the Gysel power divider while maintaining its advantages is an important research objective.

The 180-degree Ring divider, another name for the rat-race divider, has been known in microwave engineering for many decades. It is used in numerous applications such as mixers, phase shifters, filters, or baluns. In the classical literature, the rat-race divider is usually analyzed using even and odd-mode decomposition. In addition to the traditional analysis methods, an additional theoretical treatment can be applied by directly applying network analysis without further symmetry considerations. This results in a very simple and descriptive formula providing insight into the divider's theoretical full range frequency characteristics using Y-parameters. The analytical expressions derived from this method are confirmed by simulations and measurement.

When an input signal is applied at one port, the outputs at two other ports are equal in magnitude but 180 degrees out of phase. This is a characteristic of the rat-race divider when used as a power divider. In conclusion, the rat-race divider is a versatile and widely used component in RF and microwave systems. Its unique structure and properties make it suitable for a variety of applications, and its behavior can be analyzed and understood through various theoretical approaches. [1]

Scattering matrix for 180° hybrid ring divider is given by: [3]

$$[S] = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & -1 \\ 1 & 0 & 0 & 1 \\ 0 & -1 & 1 & 0 \end{bmatrix}$$

This research aims to delve into the aspects of rat race dividers, a type of four port coupler commonly used in RF and microwave systems. It discusses the definition, features, and applications as the pros and cons of rat race dividers compared to other types of couplers. Additionally, it showcases the response and performance measurements of rat race dividers using S parameters and Smith charts. The study concentrates on equally split rat race dividers functioning at a frequency or, within a narrow bandwidth without delving into factors like parasitic elements, losses or manufacturing inaccuracies that may impact these couplers. Furthermore, it does not touch upon the design and fine tuning of rat race dividers, for particular use cases or scenarios.

I.1.2 Types of RF couplers

There are kinds of RF couplers utilized in RF and microwave systems; [2]

- ✓ **RF Couplers:** These devices have four ports, including a primary input and output line, a coupled line, with an output and an internal termination on the fourth port.
- ✓ **Bidirectional RF Couplers:** Similar to couplers but without termination on the port. The main line power is linked to the output of the line while reflected power is linked to the reflected output.
- ✓ **Dual Directional RF Couplers:** These are four port devices comprising two couplers. They can be connected sequentially with the main line output of one coupler linked to another; or combined into a device with one line and two secondary lines.
- ✓ **90° Hybrid Couplers:** These couplers divide the input signal into two signals with a 90-degree phase difference.
- ✓ **180° Hybrid Couplers:** These couplers split the input signal into two signals, with a 180-degree phase difference.

Each type of RF divider possesses features and applications. The selection of the divider is based on the needs of the RF or microwave system where it will be utilized.

I.1.3. Definition of rat-race divider

A rat race divider is a device, with four ports arranged in a transmission line that spans 1.5 wavelengths. The top half of the ring features the four ports positioned one quarter wavelength while the bottom half serves as a delay line. These ports are linked to the ring through quarter wave transformers with an impedance value of $Z_0/\sqrt{2}$, where Z_0 represents the systems impedance. The ring itself has an impedance of $Z_0\sqrt{2}$ equaling 70.7 ohms in a 50-ohm system setup. Refer to the illustration, for a representation of how a rat race divider is structured and configured. [1]

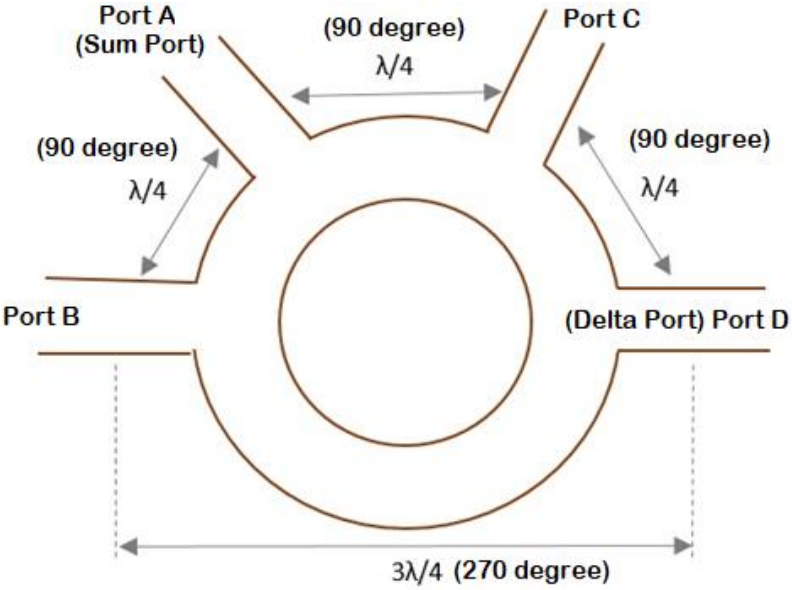


Figure I.1: Rate race divider [1]

I.1.3.1 Rat-race divider characteristics

The rat-race divider has some characteristics: [4]

- ✓ **Coupling Factor:** The ratio of input port power (P1) to the coupled port power (P3) in decibels.

$$C = 10\log\frac{P_1}{P_3} = -20\log\beta\ dB \qquad (1.1a)$$

- ✓ **Directivity:** The ratio of the coupled port power (P3) to the isolated port (P4) in decibels.

$$D = 10\log\frac{P_3}{P_4} = 20\log\frac{\beta}{|S_{14}|}\ dB \qquad (1.1b)$$

- ✓ **Isolation:** The ratio in decibels of power at an isolated port power (P4) to the input port power (P1) in decibels.

$$I = 10\log\frac{P_1}{P_4} = -20\log|S_{14}|\ dB \qquad (1.1c)$$

- ✓ **Insertion Loss:** The ratio of input port power (P1) and output port power (P4) in decibels.

$$L = 10\log\frac{P_1}{P_2} = -20\log|S_{12}|\ dB \qquad (1.1d)$$

- ✓ **Impedance Match:** The voltage standing-wave ratio (VSWR) or the input or output port reflection coefficient provides the matching in the directional divider.
- ✓ **Power Split:** The difference between the coupling and insertion loss in decibels.

I.1.3.2. Advantages and Disadvantages of rat-race divider:

The rat-race divider has several advantages and disadvantages: [5]

advantages:

- ✓ They provide return loss at their connection points.
- ✓ Good isolation is maintained between the ports.
- ✓ Excellent amplitude/phase imbalance is achieved within the range of 2.20 to 3.30 GHz, in the band.
- ✓ They act as a tee without needing any matching components unlike traditional magic tees.
- ✓ Suitable for applications such as mixers, amplifiers, antenna feed networks and power combiners/dividers.
- ✓ They offer a bandwidth.

disadvantages:

- ✓ Bandwidth compared to devices.

- ✓ Larger physical footprint due to the extended distance between certain ports making them less ideal for compact microwave devices, with space constraints.
- ✓ Depending on their design type (microstrip, strapline or waveguide) they may inherit some disadvantages associated with these structures.

I.2. State of art

I.2.1. Generalized broadband coupled-line based rat-race divider with arbitrary power division ratios and free terminated impedances.

In [6], the authors designed a broadband rat-race divider based on coupled lines with arbitrary power division ratios and open-ended terminations. The circuit is fabricated on an RO4350B substrate with a relative permittivity of 3.66, a loss tangent of 0.037, and a thickness of 1.524 mm. The final parameters are: R1,2,3,4 = 50/40/60/75Ω, C = -6.1dB, Z1,3,4,5 = 50.22/75.69/140.72/37.11Ω, Z0e = 123.29Ω, Z0o = 41.66Ω, θ1,3,4 = 85/82.49/103.78°, θ5 = 22°, θ0 = 60.33° (Z2 = 111.38Ω and θ2 = 280.98°), and k^2 = -6 dB

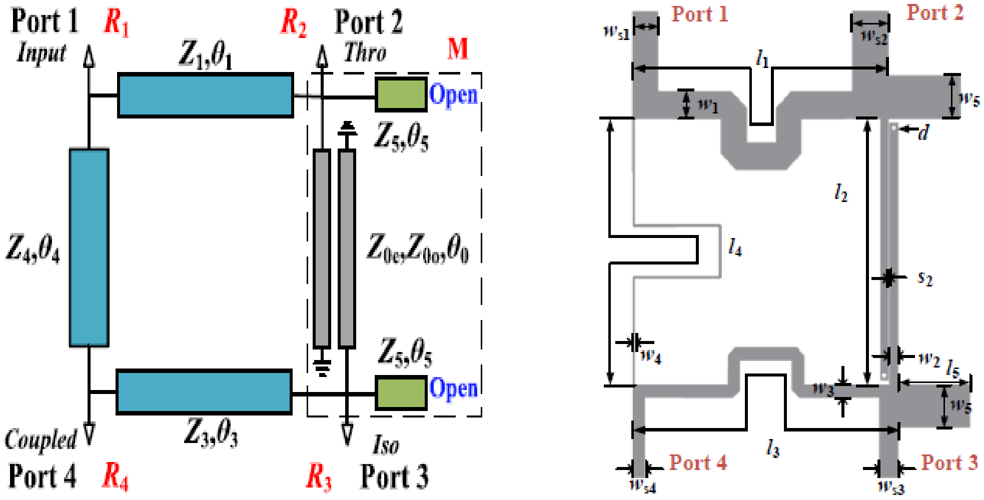


Figure I.2: (a) The circuit schematic of rat-race divider., (b) layout of rat-race divider [6]

The simulation and measurement data show that the bandwidth of |S11|, |S22|, |S33|, and |S44| with a return loss of 15 dB is approximately 51.69% in the frequency range of 0.66 to 1.12 GHz. It is noted that for a 15 dB return loss bandwidth of |S11|, the measured bandwidth is 89.72% (0.59–1.55 GHz), and the measured isolation below -15 dB extends up to 1.22 GHz. The measured parameters |S41| and |S21| are approximately 7.90 dB and 1.10 dB at 1 GHz, respectively. The measured phase responses of ∠|S41/S21| and ∠|S23/S43| are 1.47° and 180.41° at 1 GHz.

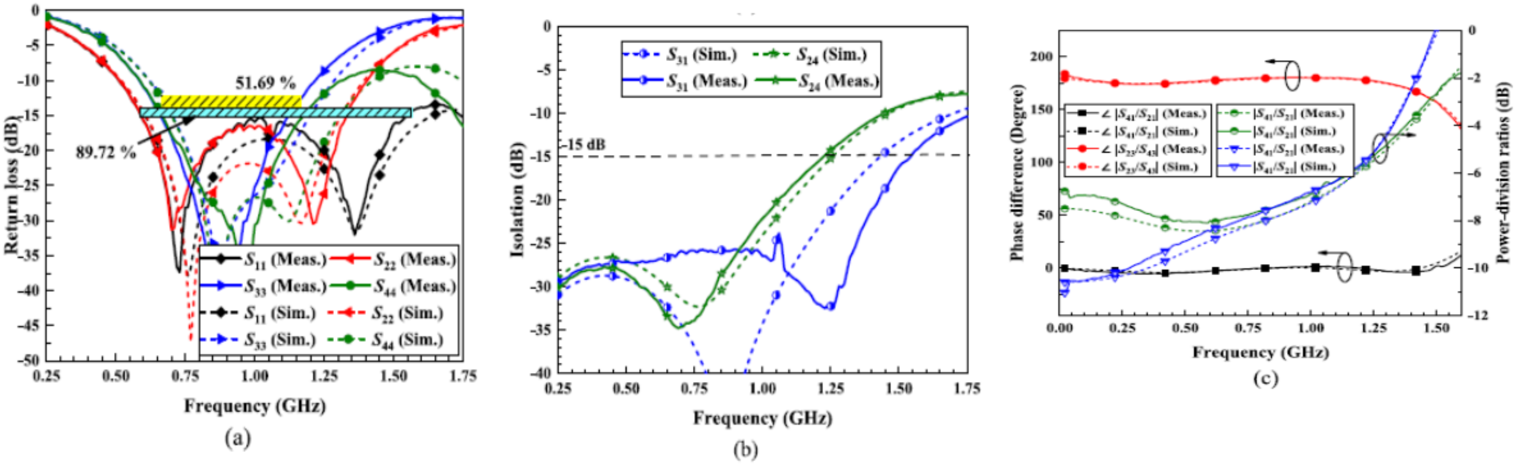


Figure I.3: Simulated and measured results of rat-race divider, (a) Return loss, (b) isolation and (c) phase responses and power imbalances. [6]

This design allows for freely customizing power division ratios, and its ability to reach a wide range of frequencies helps save a lot of sizing space. It provides a simple circular model that offers greater versatility in its use for various applications.

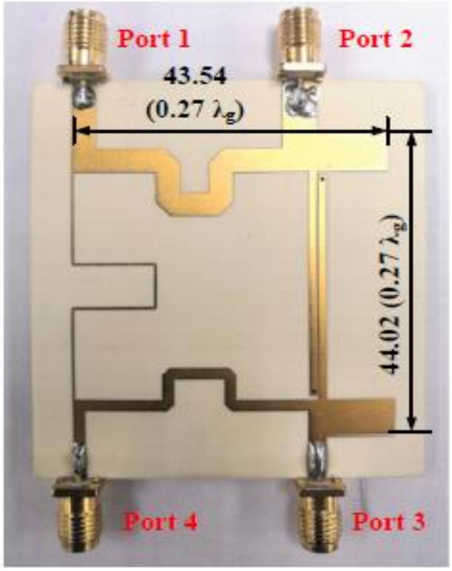


Figure I.4: Design of rat-race divider [1]

I.2.2 Miniaturized Design of Rat-Race Divider by Utilizing T-shape stubs

The authors presented in this article [7] the development of an important passive component in microwave, the 180° quadrature hybrid coupler for the upper LTE frequency band (1.7 - 2.7 GHz), which is achieved by replacing the wave transmission line (3λ/4) of a conventional coupler with their equivalent T-shaped line section, resulting in a significant size reduction. The miniaturized 180° quadrature hybrid coupler (RRHC) is designed on a low-cost material using an FR-4 substrate material with a dielectric constant (4.3), substrate thickness (h = 1.570 mm). The design and simulated results are validated by the Method of Moments using Agilent Technologies' Advance Design System (ADS) tool. The implemented size of the quadrature coupler is76.11x37.24 mm², representing a 28% reduction compared to conventional couplers for the higher frequency band.

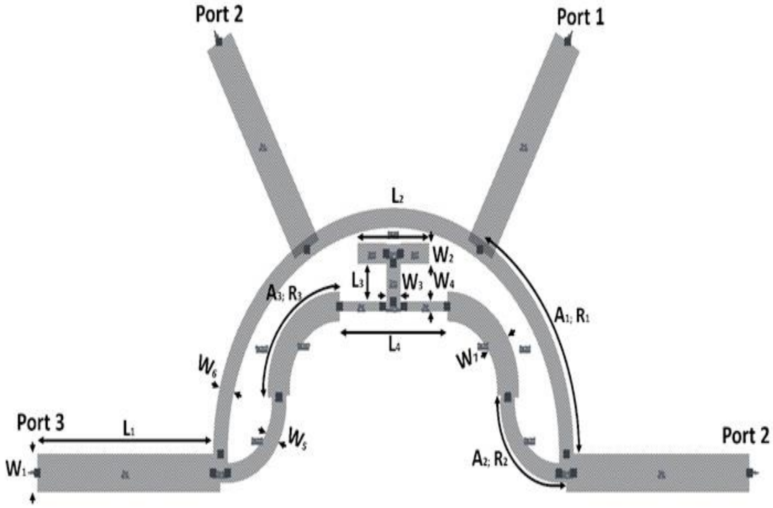


Figure I.5: Dimensions of proposed rat-race hybrid divider. [7]

The simulation results of the dispersion parameters for the proposed quadrature hybrid divider are shown in the figure. As we can see, the insertion loss on the direct port (S12) is around -2.98 dB, but for the coupled port (S13), it is around -3.048 dB. The isolation (S14) and reflection coefficient (S11) are greater than -20 dB over 65% of the bandwidth (from 1.7 GHz to 2.7 GHz) and less than -30.5 dB at the resonance frequency. In terms of phase, the phase difference between the output signals (S13) and (S24) of the divider is illustrated in the figure, with a phase shift of 180.003° at the resonance frequency.

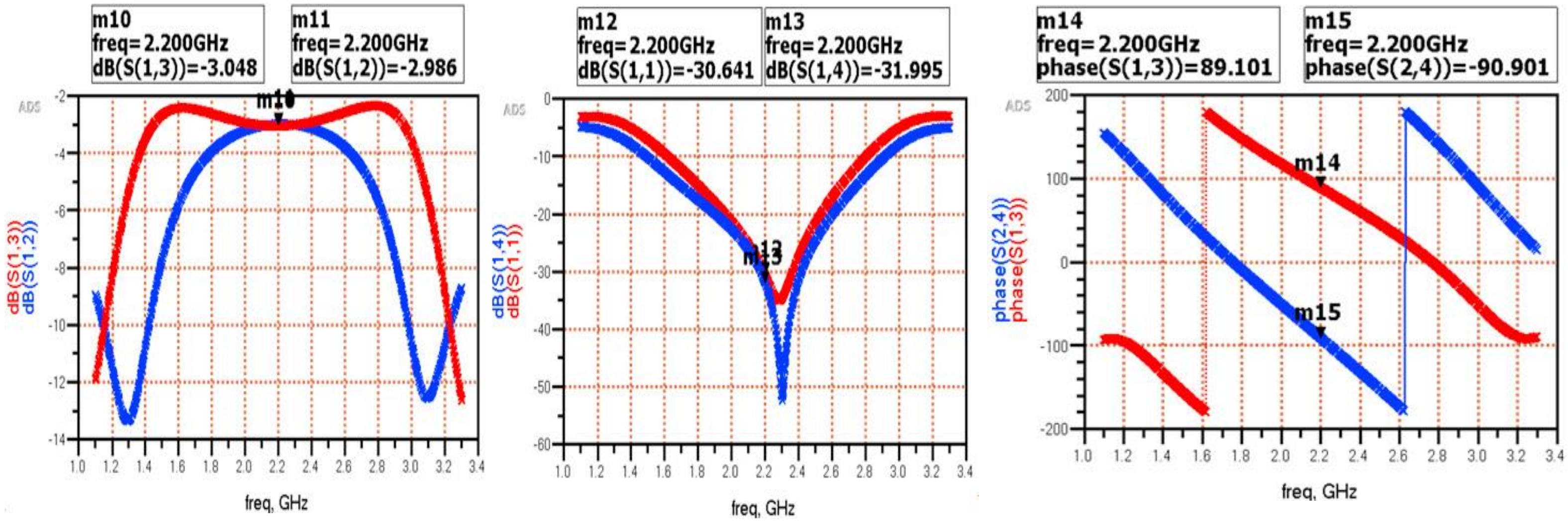


Figure I.6: The S parameters simulation results of proposed divider, (a) Insertion loss of through port & coupled port, (b) Return loss & Isolation S_{13} (c) phase difference between S_{21} and S_{41} [7]

The complete specifications summary of the proposed rat-race type hybrid coupler and a detailed comparison of the results with the conventional model are provided, which can be better appreciated by comparing the obtained results. The corresponding performance analysis in terms of bandwidth and miniaturization requirements is also provided.

I.2.3 Design and validation of miniaturize Rat Race Divider based microstrip Balun

This study [8] introduces a small Balun that offers increased bandwidth and better isolation between output ports utilizing an interdigital capacitor (IDC). Firstly, a Rat Race Divider (RRD) is initially crafted, followed by the proposal of a Balun where the isolation port is substituted with a 50 Ω isolation resistor. The suggested transmission line (TL) is crafted with an IDC along a high impedance TL in parallel. By using an equivalent p-circuit, the proposed TL is examined and refined to achieve an impedance of 70.7 Ω. The Balun is both designed and constructed, with the simulated and real-world results aligning. The fractional bandwidth (FBW) for the RRD and Balun stands at 37.5% and 33% respectively around the central frequency of 2.4 GHz. The dimensions of the proposed Balun are 0.51 λg x 0.22 λg. This setup is cost-effective, flat, and compact.

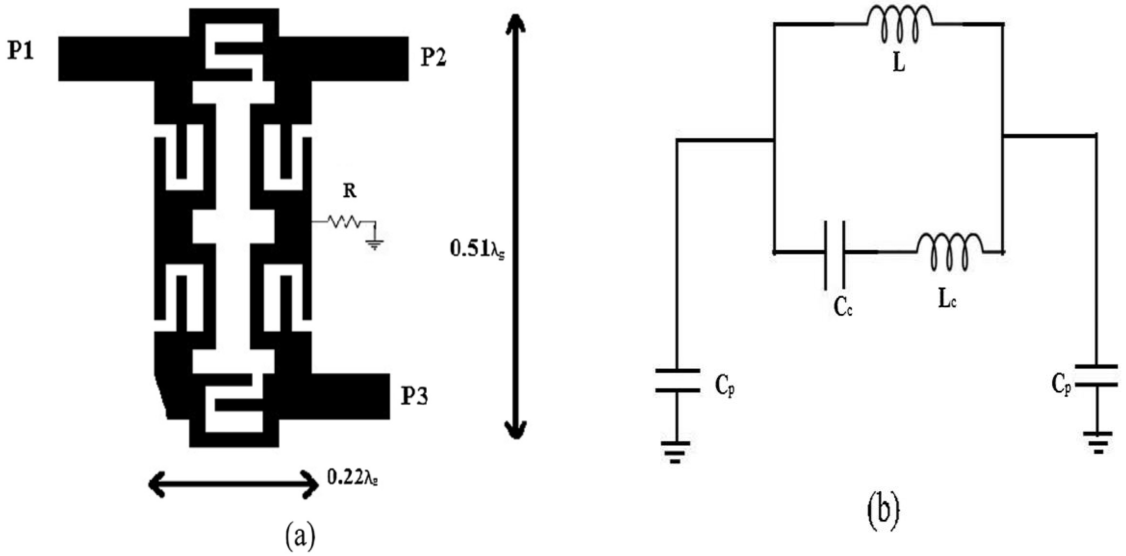


Figure I.7: (a) Prototype of proposed Balun, (b) Equivalent circuit of transmission line. [8]

The RRD 3 dB has been designed on an FR4 substrate, with a dielectric constant of 4.4, a substrate height of 1.6 mm, and a loss tangent of 0.02. The conventional transmission line (TL) is replaced by the proposed TL to achieve a compact RRD with enhanced bandwidth. The figure illustrates the simulated S parameters response of the proposed RRD. The input signal also splits between port 2 and port 4 at the central frequency of 2.4 GHz. The isolation at port 3 and the reflection at port 1 are both below -20 dB. The phase difference between port 2 and port 4 is 180°.

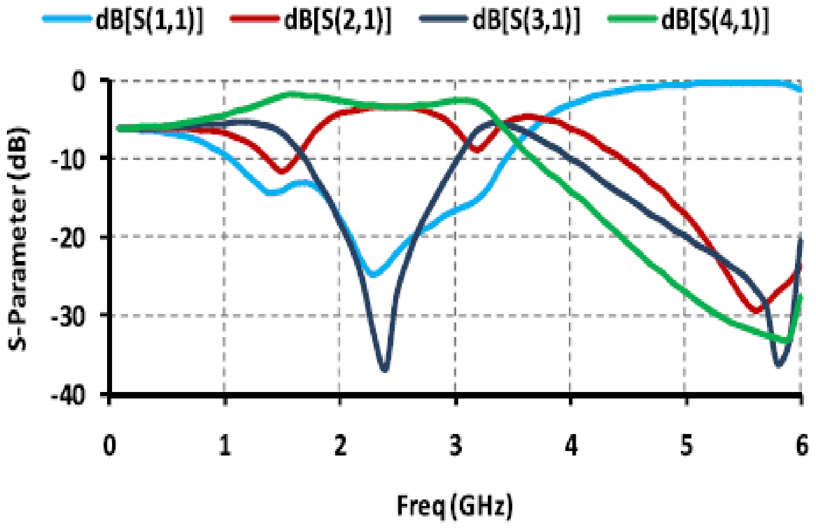


Figure I.8: S-parameter of rat-race divider. [8]

In this work, a compact balun designed to operate at 2.4 GHz is introduced by eliminating the isolation port from the Rat Race divider (RRD). Instead of the traditional quarter-wavelength TL section, an Interdigital capacitor is introduced in parallel with a high impedance TL. The simulated and measured results are in good agreement, and the output ports demonstrate strong isolation. The prototype is compact, cost-effective, offers improved bandwidth, and enhances the isolation between the output ports. This design is suitable for practical applications in microwave communication circuits.

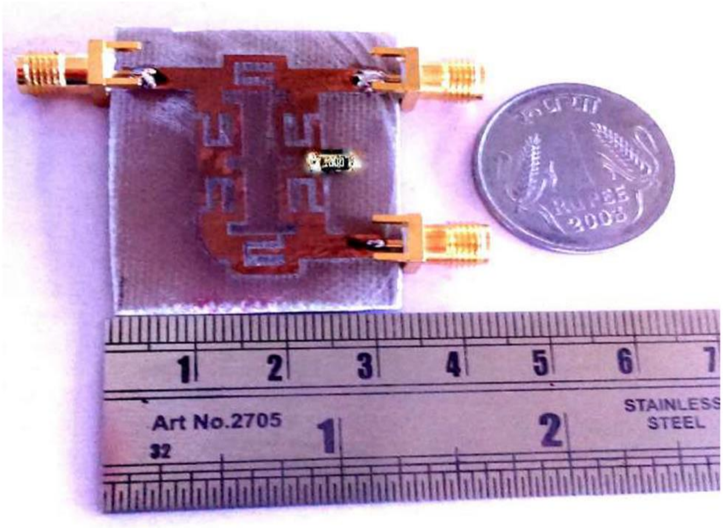


Figure I.9: Fabricated compact Balun prototype. [8]

I.2.4 Design of Rat-Race Divider Based Analog Pre-Distortion Circuit for 5G Applications

This topic discusses the design of an innovative circuit for Analog Pre-Distortion Amplifier based on the Rat-Race Divider, for 5G applications. In this context, the research covers the design of a circuit that utilizes Analog Pre-Distortion techniques based on the Rat-Race divider as an essential part of the design. The circuit aims to provide a pre-distortion stage that operates predictively to minimize distortions in the wide-band signal used in 5G applications of wireless communication networks

Regarding the selected substrate, a backlight PCB was chosen with specifications including dielectric constant: 5, thickness: 1.35 mm, relative ratio: 1, conductivity: 5.8e7, cover height:

1.00541e+33 mm, and conductor thickness: 0.127 mm. For the 900-phase shifter, a layout was designed at 3.5 GHz using a program called Dip Trace. The dimensions (in centimeters) for the WPD, HC, and RRD structures are 2.9 × 1.72, 3.3 × 1.5, and 4 × 3.4, respectively

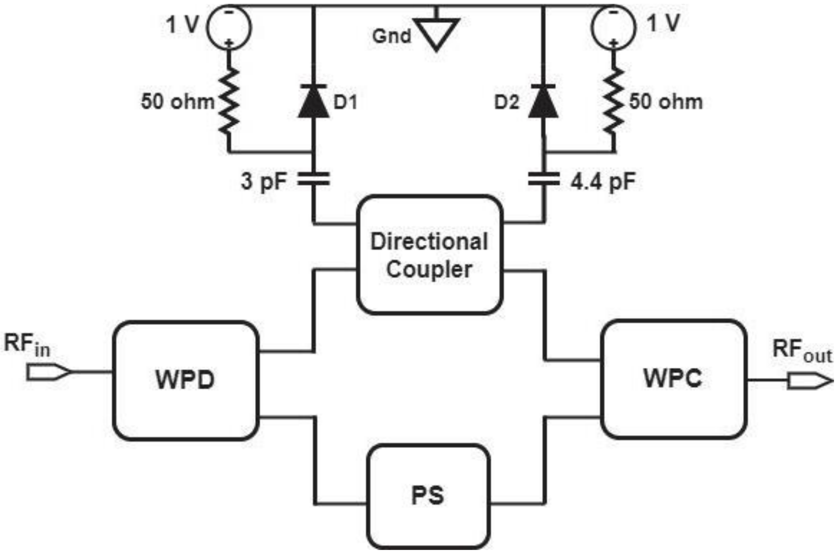


Figure I.10: Proposed Analog Pre-distorter. [9]

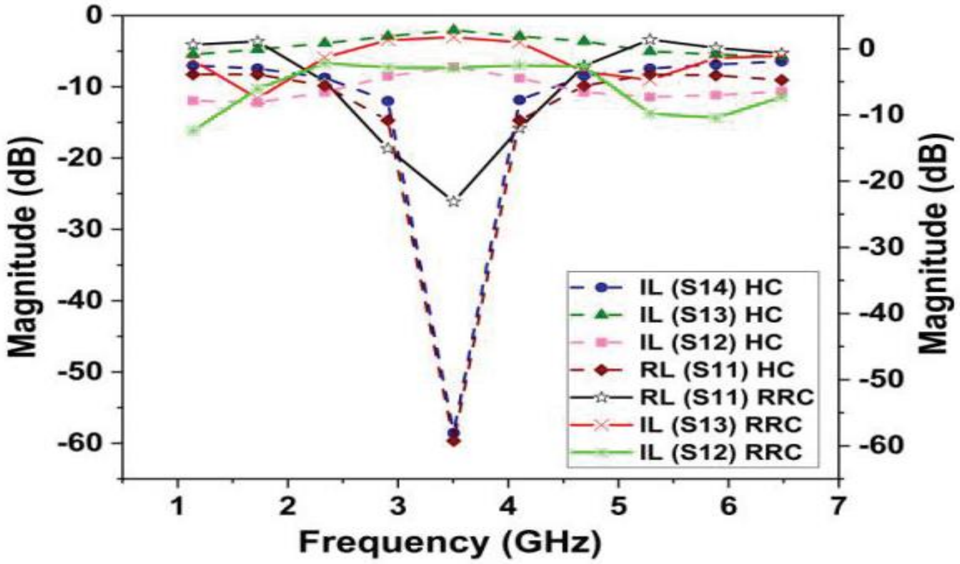


Figure I.11: S parameter Analysis of HC and RRD [9]

APD1 comprises Wilkinson Power Dividers (WPD), Hybrid Couplers (WPC), Hybrid Couplers (HC), and Phase Shifters (PS), while APD2 consists of Wilkinson Power Dividers (WPD), Hybrid Couplers (WPC), Rat-race Dividers (RRD), and Phase Shifters (PS). A tone simulation (HB-1 tone) was conducted with an input signal power of 10 dBm for both APDs to generate AM-AM and AM-PM plots that depict the reverse response of the power amplifier (PA) as shown in Figure. Upon analyzing the AM-AM results for both APDs, it was observed that the AM-AM response underwent slight changes after reaching an RF transmit power of 35 dBm. Additionally, the AM-PM behavior exhibited nonlinearity with a phase error of approximately 44°after the RF Power reached 35 dBm. The IMD levels for the second, third, fourth, and fifth harmonics for both APDs were shown in Figure. Comparing the IMD levels, it was noted that APD1 demonstrated lower IMD points compared to APD2, indicating that APD1 offers enhanced linearity when compared to APD2 under the specified conditions.

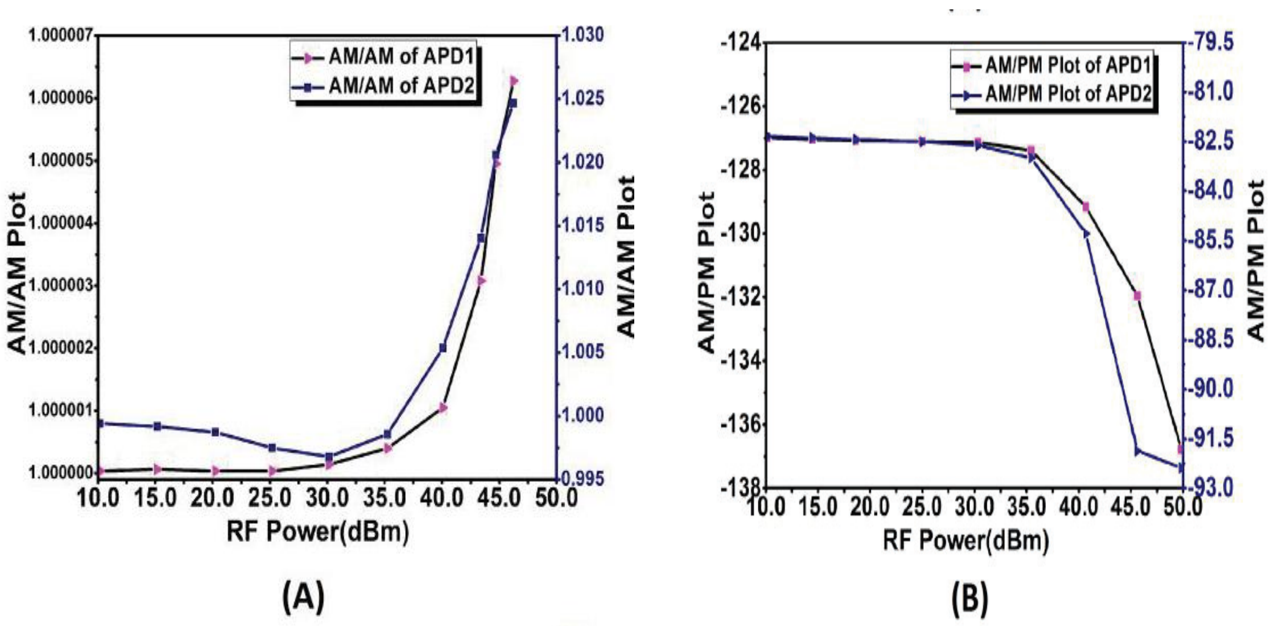


Figure I.12: (A) AM-AM plot of APD1 and APD2 (B) AM-PM plot of APD1 and APD2.[9]

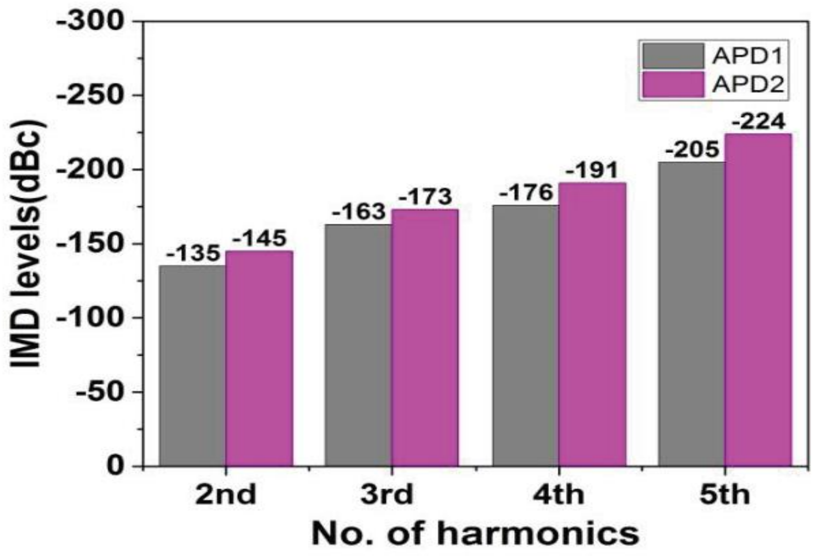


Figure I.13: IMD levels vs No. of harmonics of APD1 and APD2. [9]

I.2.5 Modelling, analysis and testing of an active element based wide-band frequency tunable compact rat-race hybrid

The authors of this article [10] present a detailed mathematical modelling and analysis of a wideband frequency-reconfigurable hybrid at 180 degrees, followed by experimental verification. The device is designed by replacing the basic quarter-wavelength lines λ/4 with equivalent low-pass varactor circuits, allowing for a compact dimensional efficiency (0.16 λ _ 0.18 λ _ 0.008 λ at 1.6 GHz) of 70% compared to the conventional structure. The operational frequencies of the hybrid are adjusted by simultaneously tuning six active varactor diodes in reverse-biased mode, demonstrating a wide tenable operational bandwidth (83%, $|S_{11}|$ < _10 dB and 68.4% due to matching of transmission coefficients).

To validate the mathematical formulation of the proposed device, the circuit is simulated using a commercial EM simulator, and a manufactured prototype is also tested. For this design, the value of Z_x is chosen as 128 Ω (width = 0.093 λ g) to make the device compact. The length of the modified transmission line is h = 33.5 and the capacitance value (Cx) = 0.85 pF for an operating frequency of 2.2 GHz. The proposed rat-race hybrid is designed on a 60-mil thick FR-4 substrate, and its circuit layout designed using ANSYS DESIGNER-15. the simulation results of the circuit, which have a response identical to that of a conventional rat-race hybrid operating at 2.2 GHz.

It has an insertion loss of 3.1 dB with a phase difference of 0; 180 degrees between the appropriate output ports.

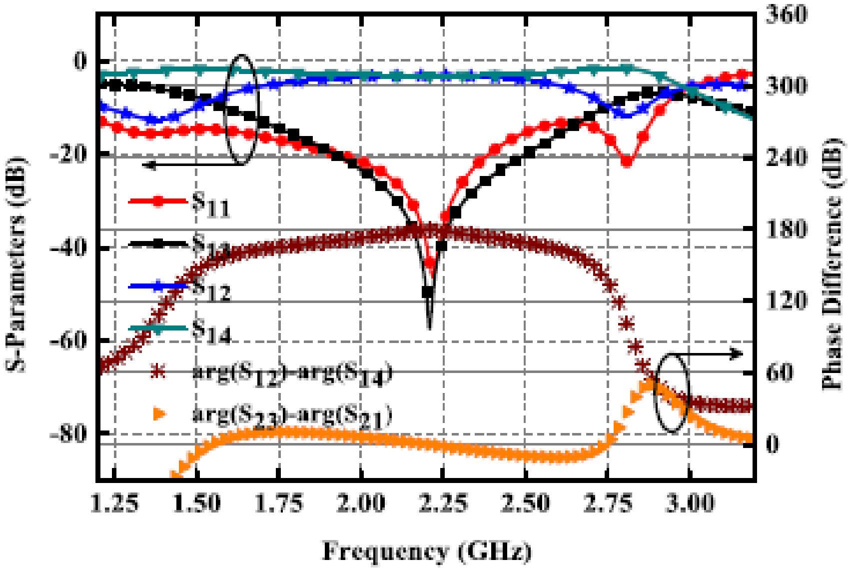
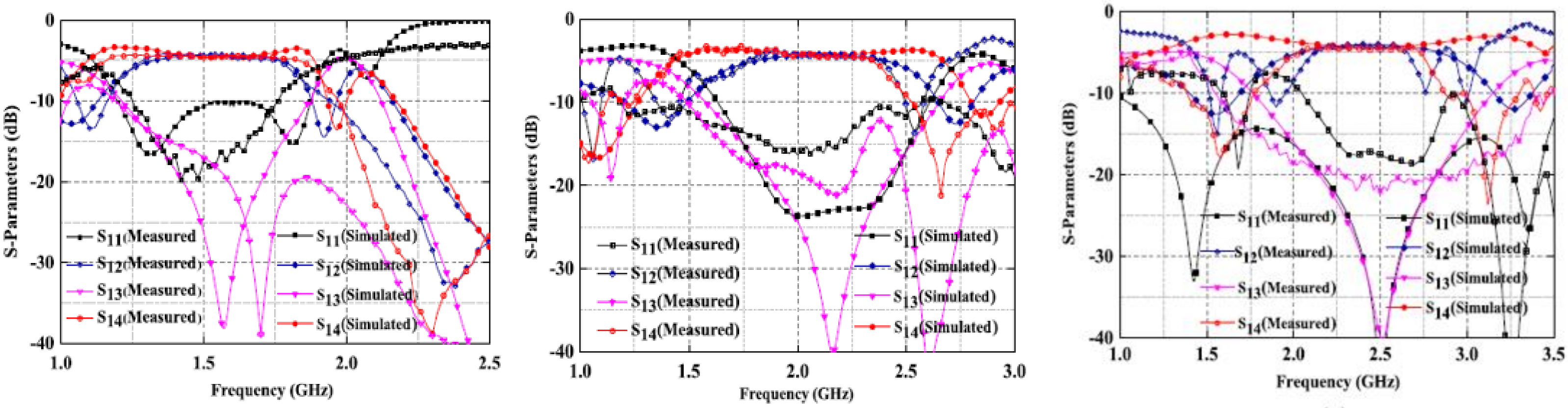


Figure I.14: Simulated S-parameters and phase response of the circuit model of the proposed rat-race. [10]

The simulation and measurement results obtained using the vector network analyser (Agilent-E5071C) for capacitance values of 1.77 pF (0.5 V), 0.48 pF (7.0 V), and 0.3 pF (19 V) are shown in the graph. The graph confirms that the proposed device can be used at different intermediate frequencies between 1.2 and 2.9 GHz by varying the varactor capacitance from 1.77 pF to 0.3 pF. The device exhibits impedance bandwidths ($|S_{11}| < 10$ dB) ranging from 1.2 to 1.75 GHz, 1.6 to 2.35 GHz, and 2.1 to 2.9 GHz for

operating frequencies of 1.6 GHz, 2.05 GHz, and 2.5 GHz, respectively.



(a) (b) (c)

Figure I.15: Simulated and measured S-parameters at different reverse biased voltages (a) 0.5 V (1.77 pF), (b) 7.0 V (0.48 pF), (c) 19.0 V (0.3 pF). [10]

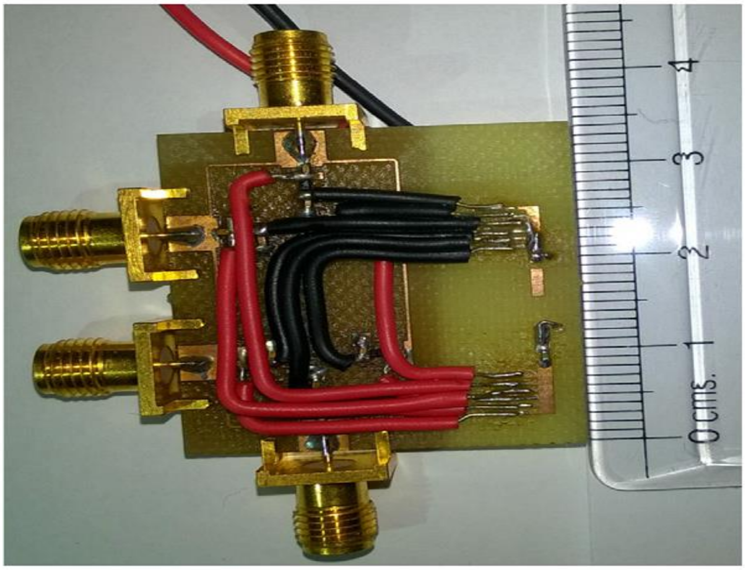


Figure I.16: Fabricated prototype of rat-race [10]

I.3 Conclusion

In this chapter, we have presented a theoretical study of a rat race divider. We discussed some of its features, as well as its benefits and drawbacks. In the next chapter, we will perform an analytical study of standard rat-race divider.

Chapter II: Analytical Study of Standard Rat-Race Divider

II.1. Introduction

The rat-race divider, with its unique ability to divide signals into even and odd modes, plays a pivotal role in microwave devices. In the even mode, characterized by synchronous signal movement, equal distance traveled by the signal in each arm, and equal time delay along each arm, precise signal distribution is achieved. Conversely, the odd mode, with its asynchronous signal movement, unequal distance traveled by the signal in each arm, and different time delays along each arm, provides an alternative method of signal distribution. These distinct characteristics enable the rat-race divider to utilize different arms for achieving specific time delays and directing signals efficiently, enhancing the functionality of microwave devices.

II.2. Definition Even-odd mode rat-race divider

In rat-race divider, the concept of "even mode" and "odd mode" is used to describe how symmetrical signals interact inside microwave devices. When analyzing the internal operation of this type of devices, it appears that there is an interaction between the even mode and odd mode in the rat-race divider. [11]

The Rat-Race Divider can divide the signal into two modes: Even Mode and Odd Mode.

II.2.1. Even Mode

- ✓ In this mode, the signal moves synchronously in all the different arms of the divider.
- ✓ The difference in the distance traveled by the signal in each arm is equal.
- ✓ There is an equal time delay along each arm of the divider.

II.2.2. Odd Mode

- ✓ In this mode, the signal moves asynchronously in all the different arms of the divider.
- ✓ The difference in the distance traveled by the signal in each arm is not equal.
- ✓ There is a different time delay along each arm of the divider.

This Rat-Race Divider utilizes these characteristics to distribute signals in a specific manner, using the different arms to achieve specific time delays and direct signals in a specific way.

In the even-odd mode analysis technique, the waveguide structure can be decomposed into two simpler circuits based on the even and odd modes of the structure. The even mode refers to the case where the electric fields of the two components are symmetric with respect to the midplane of the structure, while the odd mode refers to the case where the electric fields are anti-symmetric.

By decomposing the waveguide structure into even and odd modes, we can analyze each mode separately and then combine the results to understand the overall behavior of the structure. This technique simplifies the analysis process and helps in understanding the wave behavior in complex waveguide structures. [11]

II.3. Even-odd mode analysis

To analyze the hybrid-ring divider, an even–odd-mode method is used. We assume that a wave of unit amplitude A1 = 1 is incident at port 1.and the schematic circuit of the branch-line divider in normalized form, to Z0. [11]

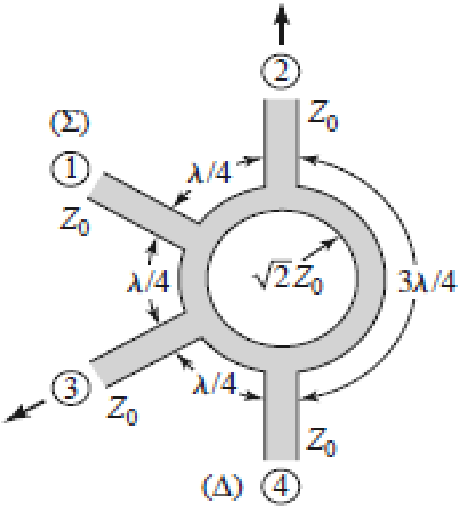


Figure II.1: A ring hybrid, or rat-race in microstrip line or strapline form.[11]

This wave is divided into two components at the ring junction. The two component waves arrive in phase at ports 2 and 3, and 180° out of phase at port 4. By using the even–odd-mode analysis technique, this case can be decomposed into a superposition of two simpler circuits, as shown in Figures II.2 and II.3.

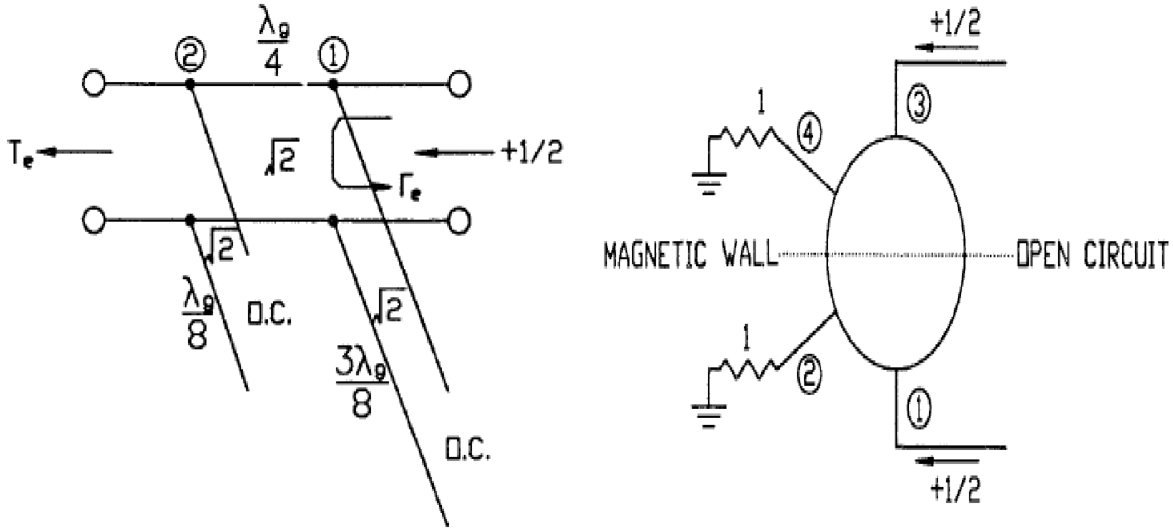
Based on two simpler circuits of the even–odd-mode, The amplitudes of the scattered waves will be:

$$B1=1/2(\Gamma e+\Gamma o) \quad (2.\ 1a)$$

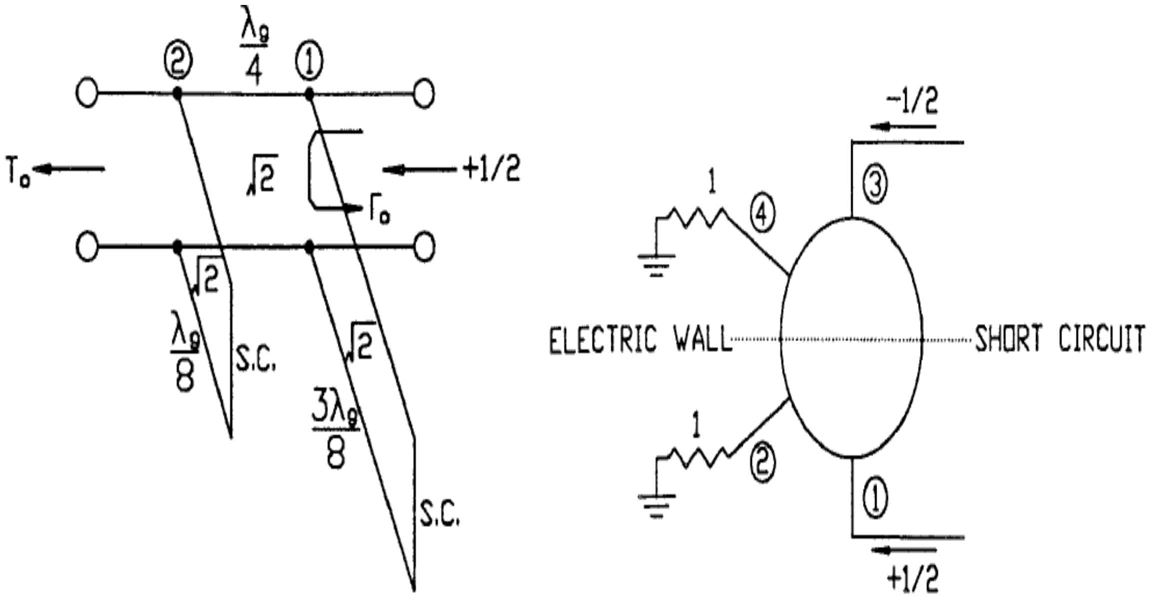
$$B2=1/2(\mathrm{T}e+\mathrm{T}o) \quad (2.\ 1b)$$

$$B3=1/2(\Gamma e\ -\Gamma o) \quad (2.\ 1c)$$

$$B4=1/2(\mathrm{T}e\ -\mathrm{T}o) \quad (2.\ 1d)$$



Figures II.2: Even-mode decomposition of the rat-race hybrid-ring divider when port 1 is excited with a unit amplitude incident wave.[12]



Figures II.3 Odd-mode decomposition of the rat-race hybrid-ring divider when port 1 is excited with a unit amplitude incident wave. [12]

where Γ*e*,*o* and *Te*,*o* are the even- and odd-mode reflection and transmission coefficients,

and *B*1, B2, *B*3, and *B*4 are the amplitudes of the scattered waves at ports 1, 2, 3, and 4, respectively.

To calculate the reflection and transmission coefficients, we choose the ABCD matrix

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} cos\beta l & jz0sin\beta l \\ jy0sin\beta l & cos\beta l \end{bmatrix}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} e = \begin{bmatrix} 1 & 0 \\ j & 1 \end{bmatrix} \begin{bmatrix} 0 & j\sqrt{2} \\ j/\sqrt{2} & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -j & 1 \end{bmatrix}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} e = \begin{bmatrix} 1 & j\sqrt{2} \\ j\sqrt{2} & -1 \end{bmatrix}$$

Calculate the reflection and transmission coefficients Γ*e* and *Te* of even-mode

$$\Gamma e = \frac{\mathrm{A+B-C-D}}{\mathrm{A+B+C+D}} = \frac{1+\mathrm{j}\sqrt{2}-\mathrm{j}\sqrt{2}+1}{1+\mathrm{j}\sqrt{2}+\mathrm{j}\sqrt{2}-1} = \frac{-j}{\sqrt{2}} \tag{2.2a}$$

$$Te = \frac{2}{A+B+C+D} = \frac{2}{1+j\sqrt{2}+j\sqrt{2}-1} = \frac{-j}{\sqrt{2}} \quad (2.2b)$$

Calculate the reflection and transmission coefficients Γo and To; of odd-mode

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} o = \begin{bmatrix} -1 & j\sqrt{2} \\ j\sqrt{2} & 1 \end{bmatrix}$$

$$\Gamma o = \frac{-1+j\sqrt{2}-j\sqrt{2}-1}{-1+j\sqrt{2}+j\sqrt{2}+1} = \frac{j}{\sqrt{2}} \quad (2.3a)$$

$$To = \frac{2}{-1+j\sqrt{2}+j\sqrt{2}+1} = \frac{-j}{\sqrt{2}} \quad (2.3b)$$

We have $\Gamma e = Te = To = \frac{-j}{\sqrt{2}}$ and $\Gamma o = \frac{j}{\sqrt{2}}$

Compensate these results in (2.1) , we obtain :

$$B1=1/2(-\frac{j}{\sqrt{2}}+\frac{j}{\sqrt{2}}) \quad (2.\ 4a)$$

$$B2=1/2(-\frac{j}{\sqrt{2}}-\frac{j}{\sqrt{2}}) \quad (2.\ 4b)$$

$$B3=1/2(-\frac{j}{\sqrt{2}}-\frac{j}{\sqrt{2}}) \quad (2.\ 4c)$$

$$B4=1/2(-\frac{j}{\sqrt{2}}+\frac{j}{\sqrt{2}}) \quad (2.\ 4d)$$

$$B1 = 0 \quad (2.5a)$$

$$B2 = \frac{-j}{\sqrt{2}} \quad (2.5b)$$

$$B3=\frac{-j}{\sqrt{2}} \quad (2.5c)$$

$$B4=0 \quad (2.5d)$$

The results obtained show that if the input signal is applied to input 1, the power will be evenly divided and in the same phase between outputs 2 and 3, in addition to input 4 being isolated and input 1 is matched

At this stage, we assume that the wave is entering input 4 and input 1 is isolated. By using the even–odd-mode analysis technique, this case can be decomposed into a superposition of two simpler circuits, as shown in Figures 2.4 and 2.5

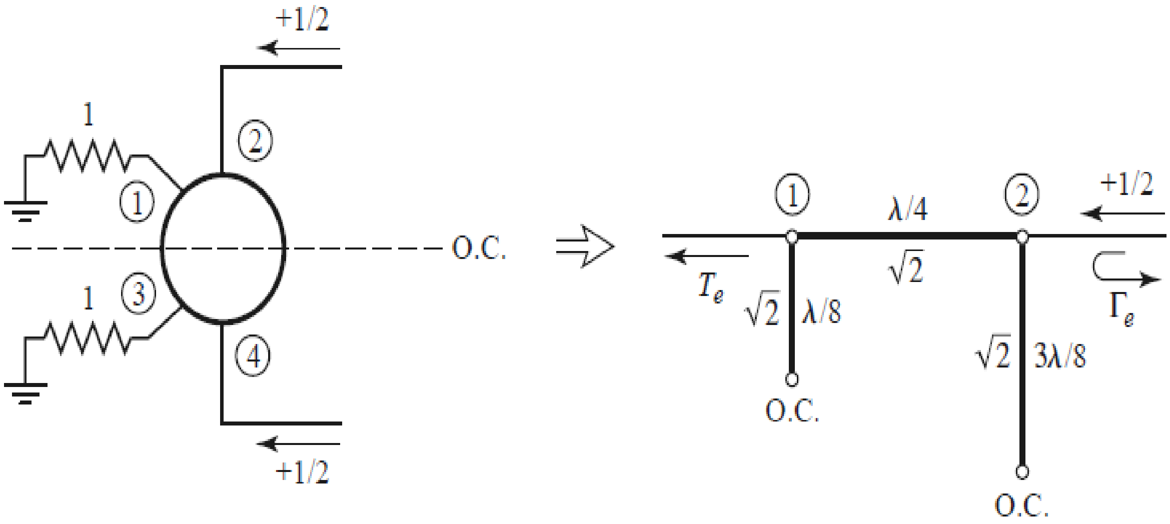
Through images 2.4 and 2.5, we can calculate the amplitudes of the scattered waves, which are as follows:

$$B1=1/2\ (\mathrm{T}e - \mathrm{T}o) \qquad (2.\ 6a)$$

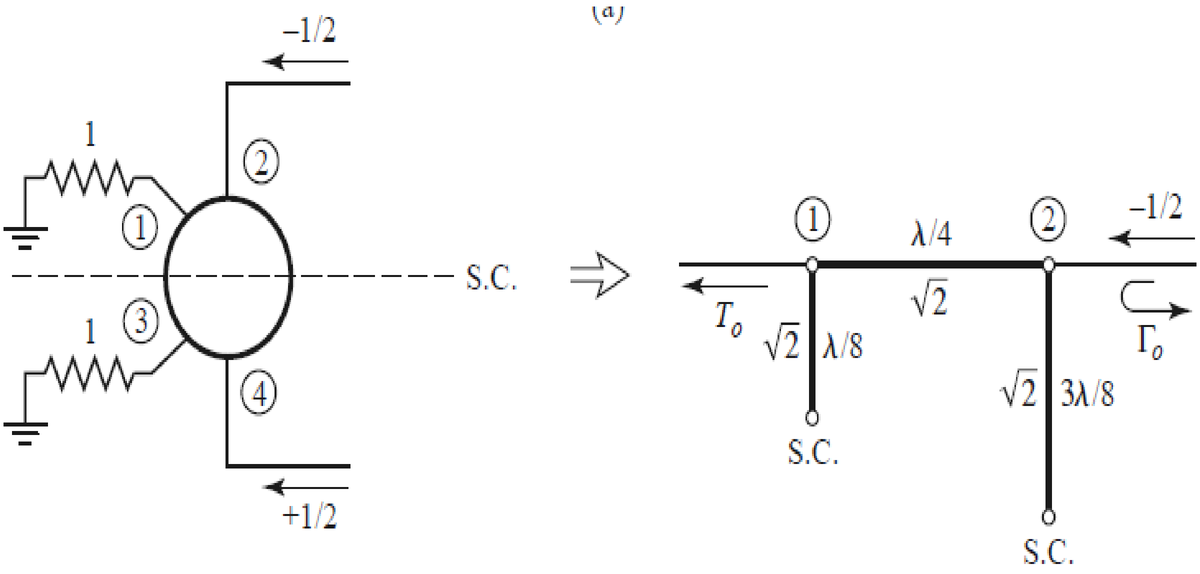
$$B2=1/2\ (\Gamma e - \Gamma o) \qquad (2.\ 6b)$$

$$B3=1/2\ (\mathrm{T}e+ \mathrm{T}o) \qquad (2.\ 6c)$$

$$B4=1/2\ (\Gamma e+ \Gamma o) \qquad (2.\ 6d)$$



Figures II.4: Rat-race even- mode analysis at port (4) excitation [13].



Figures II.5: Rat-race odd- mode analysis at port (4) excitation [13].

The *ABCD* matrices for the even-mode circuits :

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} e = \begin{bmatrix} -1 & j\sqrt{2} \\ j\sqrt{2} & 1 \end{bmatrix}$$

Calculate the reflection and transmission coefficients Γ*e* and *Te* of even-mode

$$\Gamma e = \frac{\mathrm{A+B-C-D}}{\mathrm{A+B+C+D}} = \frac{-1+\mathrm{j}\sqrt{2}-\mathrm{j}\sqrt{2}-1}{-1+\mathrm{j}\sqrt{2}+\mathrm{j}\sqrt{2}+1} = \frac{j}{\sqrt{2}} \quad (2.7a)$$

$$Te = \frac{2}{A+B+C+D} = \frac{2}{-1+\mathrm{j}\sqrt{2}+\mathrm{j}\sqrt{2}+1} = \frac{-j}{\sqrt{2}} \quad (2.7b)$$

Calculate the reflection and transmission coefficients Γo and To; of odd-mode

$$\begin{bmatrix} \mathrm{A} & \mathrm{B} \\ \mathrm{C} & \mathrm{D} \end{bmatrix} \mathrm{o} = \begin{bmatrix} 1 & \mathrm{j}\sqrt{2} \\ \mathrm{j}\sqrt{2} & -1 \end{bmatrix}$$

$$\Gamma \mathrm{o} = \frac{1+\mathrm{j}\sqrt{2}-\mathrm{j}\sqrt{2}+1}{1+\mathrm{j}\sqrt{2}+\mathrm{j}\sqrt{2}-1} = \frac{-j}{\sqrt{2}} \quad (2.8a)$$

$$\mathrm{To} = \frac{2}{1+\mathrm{j}\sqrt{2}+\mathrm{j}\sqrt{2}-1} = \frac{-j}{\sqrt{2}} \quad (2.8b)$$

We have $\Gamma o = Te = To = \frac{-j}{\sqrt{2}}$ and $\Gamma e = \frac{j}{\sqrt{2}}$

Compensate these results in (2.6) , we obtain :

$$B1=1/2(-\frac{j}{\sqrt{2}}+\frac{j}{\sqrt{2}}) \quad (2.\ 9a)$$

$$B2=1/2(\frac{j}{\sqrt{2}}+\frac{j}{\sqrt{2}}) \quad (2.\ 9b)$$

$$B3=1/2\ (-\frac{j}{\sqrt{2}}-\frac{j}{\sqrt{2}}) \quad (2.\ 9c)$$

$$B4=1/2\ (\frac{j}{\sqrt{2}}-\frac{j}{\sqrt{2}}) \quad (2.\ 9d)$$

$$B1 = 0 \quad (2.10a)$$

$$B2 = \frac{j}{\sqrt{2}} \quad (2.10b)$$

$$B3=\frac{-j}{\sqrt{2}} \quad (2.10c)$$

$$B4=0 \quad (2.10d)$$

The results obtained show that if the input signal is applied to input 4 the input power is evenly divided into ports 2 and 3 with a 180◦ phase difference, in addition to input 1 is isolated and input 4 is matched.

II..4 Applications and uses of even mode and odd mode in a rat-race divider

In the Rat-Race divider, the even mode and odd mode can be used in different ways to achieve different objectives:

II.4.1 Even Mode

- ✓ The even mode is used in the Rat-Race divider to evenly distribute power among different ports.
- ✓ The even mode can be used to achieve a balance in power distribution between inputs and outputs.
- ✓ The even mode can be used to achieve good isolation between different ports without interference.

II.4.2 Odd Mode

- ✓ In the single mode, the interfering current in the inputs and outputs is different
- ✓ The odd mode is used in the Rat-Race divider to achieve isolation between different ports.
- ✓ The odd mode can be used to improve the interaction between inputs and outputs.
- ✓ The odd mode can be used to improve dispersion efficiency and reduce interference between ports.

The single mode is characterized by its ability to generate unexpected effects, making it useful in some specific applications.

The even mode and odd mode in the Rat-Race divider can be integrated to achieve optimal performance in power distribution, improve dispersion efficiency, and enhance the interaction between inputs and outputs.

The even mode is used in the Rat-Race divider to achieve effective separation between the inputs and outputs and ensure good isolation between them, while the odd mode is used in some applications that require special effects. The appropriate mode should be selected according to the application requirements to ensure the optimal performance of the Rat-Race divider.

II.5 The impact of deviating from even mode and odd mode on the performance of a rat-race divider

When deviating from the even mode or odd mode in a Rat-Race divider, it can significantly affect its performance. Here are some effects that may occur when deviating from these modes:

II.5.1 Deviation from the Even Mode

- ✓ Deviating from the even mode in a Rat-Race divider may lead to uneven power distribution among the different ports.
- ✓ It can increase interference between inputs and outputs, resulting in degradation of the device's performance.
- ✓ Deviation may cause loss of isolation between ports, negatively impacting the Rat-Race divider's performance.

II.5.2. Deviation from the Odd Mode

- ✓ Deviating from the odd mode in a Rat-Race divider may result in loss of isolation between different ports.
- ✓ It can lead to increased dispersion and degradation in the interaction properties between inputs and outputs.
- ✓ Deviation may increase interference between ports and reduce the efficiency of the Rat-Race divider.

In general, it is advisable to avoid deviating from the even mode and odd mode in a Rat-Race divider to ensure optimal device performance and achieve design goals correctly. These factors should be considered during the design and manufacturing of a Rat-Race divider to ensure you get a reliable and efficient performance.

II.6 Conclusion

In conclusion, the rat-race divider, with its unique ability to divide signals into even and odd modes, plays a significant role in the operation of microwave devices. The even mode, characterized by synchronous signal movement, equal distance traveled by the signal in each arm, and equal time delay along each arm, allows for precise signal distribution. Conversely, the odd mode, with its asynchronous signal movement, unequal distance traveled by the signal in each arm, and different time delays along each arm, provides a different method of signal distribution. These distinct characteristics of the even and odd modes enable the rat-race divider to utilize different arms for achieving specific time delays and directing signals in a specific manner, thereby enhancing the functionality and efficiency of microwave devices.

Chapter III: Parametric study of rat-race divider

III.1 introduction

In this chapter, we will study some parameters of Rat Race divider in order to make changes in the settings such as dimensions, materials, and observe the impact of each change on the performance and effectiveness of the Rat Race divider in terms of coupling coefficient, return loss, insertion loss, isolation coefficient, as well as frequency and bandwidth using CST (Computer Simulation Technologies) software.

This study aims to understand how different parameter values in the Rat Race divider model affect the system behavior and performance. Studying parameters is an essential part of the system design process and improving its performance, helping in making the right decisions to adjust and enhance system performance.

III.2 Design Rat-Race Divider

III.2.1 Substrate

In the field of electronics design, the term "substrate" refers to the base on which electronic components are mounted. This substrate is usually made of an insulating material.

The substrate in electronics design plays a vital role in connecting electrical signals between components and ensuring the stability and performance of the electronic circuit. The type and properties of the material used in the substrate also affect factors such as electrical insulation, heat dissipation, and corrosion resistance.

Some type of substrate:

- ✓ **FR-4:** is an abbreviation for Flame Retardant, and Type "4" indicates woven glass reinforced epoxy resin.FR-4 is one of the most common types of substrates used in the fabrication of printed circuit boards (PCBs). FR-4 has several important properties that make it a popular choice in the electronics industry, including: Good electrical insulation, High mechanical strength, Heat resistance, Moisture resistance and Chemical resistance.

Glass transition temperature (T_g) 140 °C, dielectric constant $\varepsilon_r = 4.3$, loss tangent 0.025 poison's ratio 0.136. [14]

Table III.1: FR-4 Glass Epoxy Technical Product Information [14]

Property	**Units**	**Value**	**Conditions**
T_g *min* (DSC)	°C	135	
CTE x-axis	ppm/°C	14	Ambient to T_g
CTE y-axis	ppm/°C	13	Ambient to T_g
CTE z-axis	ppm/°C	175	Ambient to 288°C
Solder Float 288°C	seconds	>120	Condition A

Table III.2: Electrical Properties [14]

Property	**Units**	**Value**	**Conditions**
Permittivity (DK) max		4.7	C-24/23/50
@ 500 MHz		4.35	
@ 1 GHz (HP4291)		4.34	
Loss Tangent (DF), max. @			
1 MHz (2 Fluid Cell)		0.020	
500 Mhz		0.017	
1 GHz (2 Fluid Cell)		0.016	
Surface Resistivity,min.	megohms	$2\ x\ 10^{5}$	Condition F
		$1\ x\ 10^{8}$	E-24/125
Volume Resistivity,min.	min.	$8\ x\ 10^{7}$	Condition F
	megohm-cm	$2\ x\ 10^{7}$	E-24/125
Dielectric Breakdown, min	kV	55	D-48/50
Arc Resistance, min.	seconds	100	

- ✓ **Polycarbonate (PC):** is a type of plastic known for its transparency, hardness, and resistance to breakage. Polycarbonate is used in many applications and is considered a lightweight and strong material, making it a common choice in industries that require high-performance plastic materials. It is characterized by the following properties:

  Glass transition temperature (Tg) 147 °C, dielectric constant $\varepsilon_r = 2.9$, loss tangent 0.01 poison's ratio 0.37. [15]

Table III.3: Typical Properties of Polycarbonate [15]

Property	**Units**	**ASTM Test**	**Polycarbonate**	**Polycarbonate 20% Glass-Filled**
Tensile strength	psi	D638	9,500	16,000
Flexural modulus	psi	D790	345,000	800,00
Izod impact (notched)	ft-lbs/in of notch	D256	12.0 - 16.0	2.0

Heat deflection temperature @ 264 psi	°F		270	295
Maximum continuous service temperature in air	°F	D648	240	248
Water absorption (immersion 24 hours)	%	D570	0.15	0.16
Coefficient of linear thermal expansion	in/in/°F x 10^{-5}	D696	3.8	1.5

- ✓ **Aluminum:** is a chemical element with the symbol Al and atomic number 13. It has distinct physical and chemical properties: an atomic mass of 26.9815386 atomic mass units, a hardness (Mohs scale) of 1.5, and a melting point of 660.323 degrees Celsius. It is a silver, malleable metal that is corrosion-resistant and lightweight, with numerous applications in industry. Aluminum is commonly used as a base in the semiconductor and electronics industry, thanks to its lightweight, corrosion resistance, and ease of shaping. Dielectric constant ε_r = 8.6, loss tangent 0.0004, poison's ratio 0.22. [16]

Table III.4: Typical Properties of Aluminum [16]

Sr. No.	**Property/Description**	**Unit**	**Guaranteed Value / Details**
A	Diameter	mm	9.5 (+/- 0.51)
		mm	7.6 (+/- 0.40) (AS PER IS-5484 (1997)
B	Tensile Strength	Mpa	156.86 – 186.27
C	Resistivity (Max.)	Ohm mm2/m	0.033806
D	Conductivity (Min)	% IACS	51.00
E	Density at 20 Deg C	Kg/m3	2690
F	Surface		The Rod shall be clean, sound smooth and free from pipes, laps, cracks, kinks, twists, seams, damaged ends, excessive oil other injurious defects with in limit
G	Chemical Composition	%	Copper (Cu) Max 0.10 Iron (Fe) Max 0.50 Silicon (Si) 0.50-0.90 Manganese (Mn) Max 0.03 Magnesium 0.60-0.90 Zinc (Zn) Max 0.10 Chromium (Cr) Max 0.03 Boron (B) Max 0.06 Other Elements each (Max) 0.03 Elements Total (Max) 0.10 **Aluminium (Min) Remainder**

- ✓ **RO4003C:** is a type of high-frequency board material made from glass-saturated fiberglass and coated with copper. This material is known for its excellent electrical properties such as low loss, low dispersion, and high-frequency tolerance. It is used in the manufacturing of high-frequency electrical circuits and high-performance applications. the dielectric constant ε_r =3.55, loss tangent 0.0027. [17]

Table III.5: Electrical Properties of Rogers' RO4003C [17]

Property	Typical Value	Unit	Condition
	RO4003C™		
Dielectric Constant, ε_r (Process specification)	3.38 ± 0.05	--	10 GHz / 23 °C
Dielectric Constant, ε_r (Recommended for use in circuit design)	3.55 ± 0.05	--	FSR / 23°C
Dissipation Factor tan, δ	0.0027 0.0021	--	10 GHz / 23 °C 2.5 GHz / 23 °C
Thermal Coefficient of ε_r	+ 40	ppm/°C	-100 °C to 250 °C
Volume Resistivity	1.7 x 10^{10}	MΩ·cm	COND A
Surface Resistivity	4.2 x 10^{9}	MΩ	COND A
Electrical Strength	31.2 (780)	KV/mm (V/mil)	0.51 mm (0.020")
Tensile Modulus	26.889 (3900)	MPa (kpsi)	RT
Tensile Strength	141 (20.4)	MPa (kpsi)	RT
Flexural Strength	276 (40)	MPa (kpsi)	
Dimensional Stability	< 0.3	Mm/m (mils/inch)	After etch +E2 / 150 °C
Coefficient of Thermal Expansion	11 14 46	ppm/°C	-55 to 288 °C
Tg	>280	°C DSC	A
Td	425	°C TGA	
Thermal Conductivity	0.64	W/m/°k	100 °C
Moisture Absorption	0.04	%	48 hrs immersion 0.060" sample Temperature 50 °C
Density	1.79	gm/cm^3	23°C

Copper Peel Strength	1.05 (6.0)	N/mm (pli)	after solder float 1 oz. EDC Foil
Flammability	N/A		
Lead-Free Process Compatible	Yes		

III.2.2 COPPER

Copper is a red-colored metal that is considered one of the oldest metals used by humans. Copper is known for its good electrical and thermal conductivity, and it is a soft and malleable material. Copper is widely used in various industries such as electricity. Copper has many distinctive properties, including:

- ✓ High electrical conductivity.
- ✓ Good thermal conductivity.
- ✓ Corrosion resistance.
- ✓ Ease of shaping.
- ✓ Recyclability.
- ✓ Ability to expand.

The loss ratio in copper depends on several factors such as purity, shape, and size. Generally, the loss ratio in copper can range from around 1% to 10%. And The density of copper ranges from 8.5 to 8.96 g/cm³, which is considered moderate. The melting point of copper is approximately 1083 degrees Celsius. And The hardness of copper ranges from 2.5 to 3 on the Mohs hardness scale. [18]

Table III.6: Physical, Mechanical, and Electrical Properties of copper. [18]

Bare Copper Single Wire ASTM B3	**Conductor**
Conductor Size	14 AWG
Conductor Type	Solid Copper
Temper	Dead Soft Annealed (DSA)
Average Break Load	124 lbs.
Minimum Elongation	25%
Nominal Copper Weight	12.485
Nominal DC Resistance (ohms/1000 ft.)	2.5

Table III.7: Physical, Mechanical, and Electrical Properties of copper.[18]

High Density Polyethylene Insulator	Value
Density (ASTM D 792)	0.943 g/cc
Bulk Density (ASTM D 1895)	0.58 g/cc
Melt Index (ASTM D 1238/E)	0.70 dg/min
Tensile-Yield (ASTM D 638)	4300 psi
Tensile-Ultimate (ASTM D 638)	2900 psi
Tensile-Elongation (ASTM D 638)	850%
Flexural Modulus (ASTM D 790/1)	120,000 psi
Hardness (ASTM D 2240)	63 Shore D
Environmental Stress-Crack (ASTM D 1693/B)	F20> 48 h
Thermal Stress-Crack (ASTM D 2951)	F0> 1000 h
Brittleness Temperature (ASTM D 746)	< -95°F
Melting Point (DSC) (ASTM D 3417)	262 °F
Softening Point (Vicat) (ASTM D 1525)	250 °F
Oxidative Induction Time (ASTM D 3895)	> 50 min. @ 200 °C
Dielectric Constant (ASTM D 1531)	2.34 @ 1MHz
Dissipation Factor (ASTM D 1531)	0.00007 @ 1 MHz
Volume Resistivity (ASTM D 257)	$5\ x\ 10^{17}\ ohm - cm$
Dielectric Strength (ASTM D 3755)	1000 volts @ 20 mils

III.3 Parametric study of rat-race divider

III.3.1 Proposed Form

our choice is to use a split ring resonator designed in CST software with a length of 23mm and a width of 24mm, printed on a substrate with a height of 0.813mm of type FR-4 with a permittivity of ε_r =4.3. The chosen conductor is copper with a thickness of 0.035mm. The following table summarizes the selected dimensions for the split ring resonator.

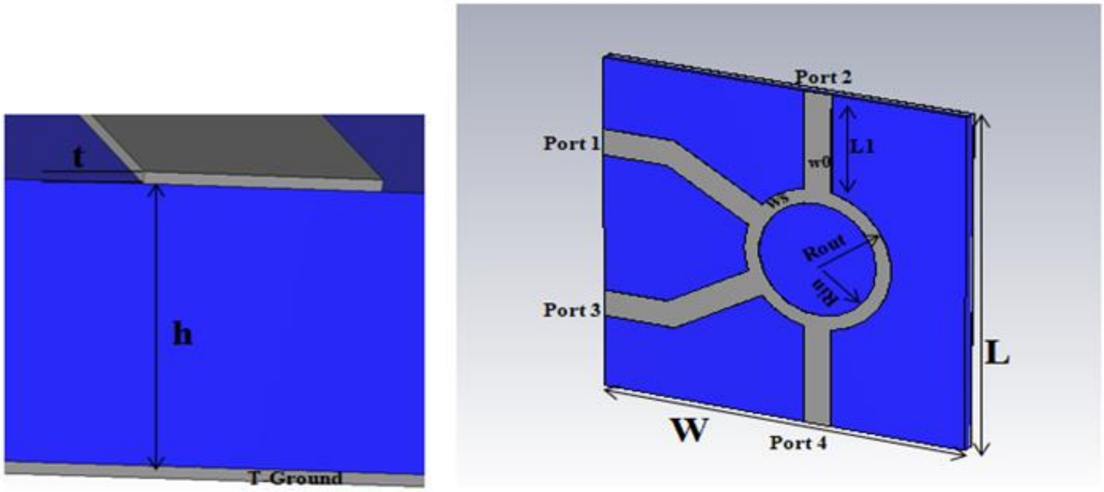


Figure III.1: Dimensions of our rat-race divider

Table III.8: Lengths of our initial rat-race divider

Parameters	**values (mm)**
W	24
L	23
h	0.813
t	0.035
T-Ground	0.035
R_{out}	4.85
R_{in}	3.88
W_0	1.8
W_s	0.97
L_1	7.15

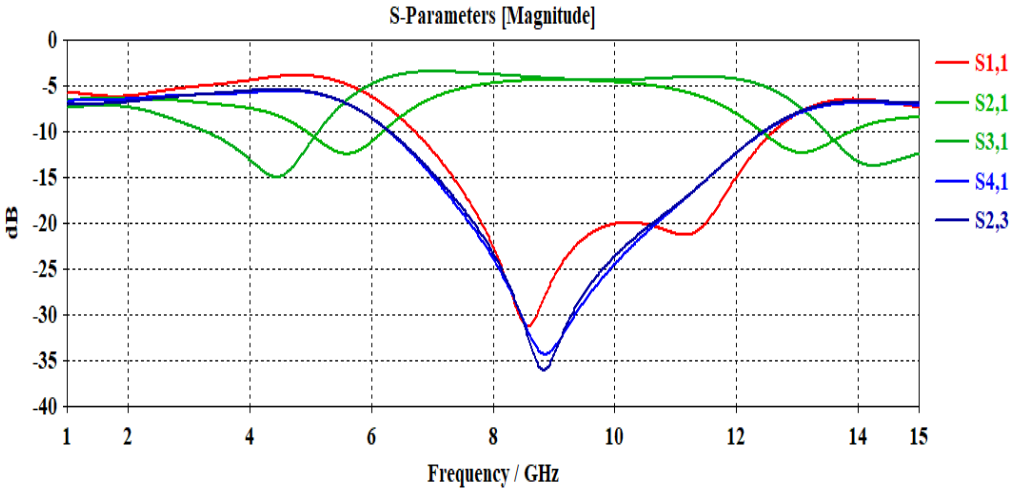


Figure III.2: S-parameters of the proposed rat-race divider for FR-4 substrate

Through these curves, we can see that the resonance frequency is 8.6 GHz with a bandwidth of 6.5 to 12.5 GHz at -10 dB, and the return loss at the input S_{11} is -31dB, insertion loss S_{21}/S_{31}= -3dB, and S_{41}/S_{23} port isolation -33 dB.

III.3.2 The effect of Polycarbonate substrate

We maintain all variables while changing the substrate material to Polycarbonate with ε_r= 2.9 and changing the width of line (W_o=2.04) and the width of ring (W_s=1.11) to maintain the matching condition (Z0=50;$\sqrt{2}$ Z0 =70.71) and observe its impact.

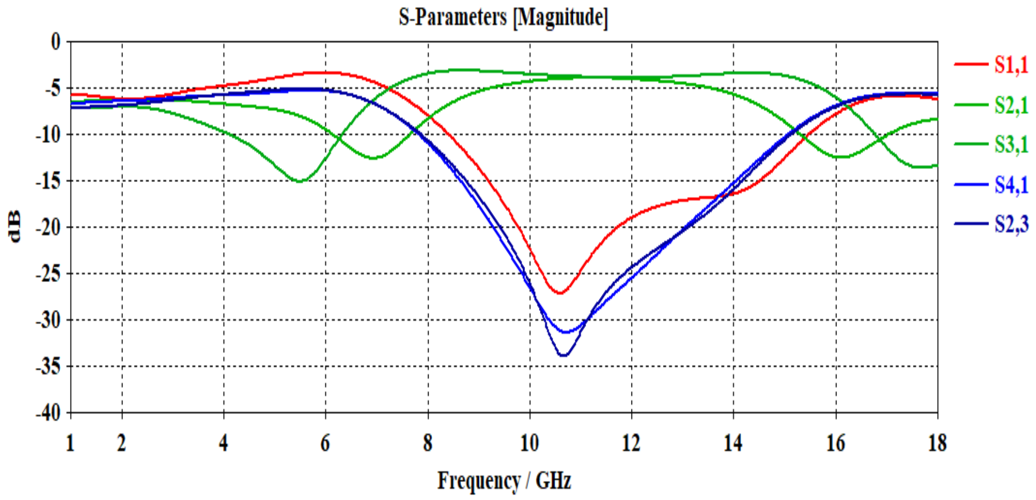


Figure III.3: S-parameters of the proposed rat-race divider for Polycarbonate substrate.

according to Figure III.3.3 the resonance frequency is 10.5 GHz with a bandwidth between 8.4 to 15.5 GHz at -10 dB, a reflection coefficient S_{11} equal to -27dB, a transmission coefficient (insertion loss) S_{21}/S_{31} of -3db, in addition to an isolation coefficient (port isolation.) S_{41}/S_{23} of -31dB.

III.3.3 The effect of Rogers' RO4003C substrate

We maintain all variables while changing the substrate material to Rogers' RO4003C (ε_r=3.55) and changing the width of line (W_0=1.77) and the width of ring (W_s=0.94) to maintain the matching condition (Z0=50;$\sqrt{2}$ Z0 =70.71) and observe its impact.

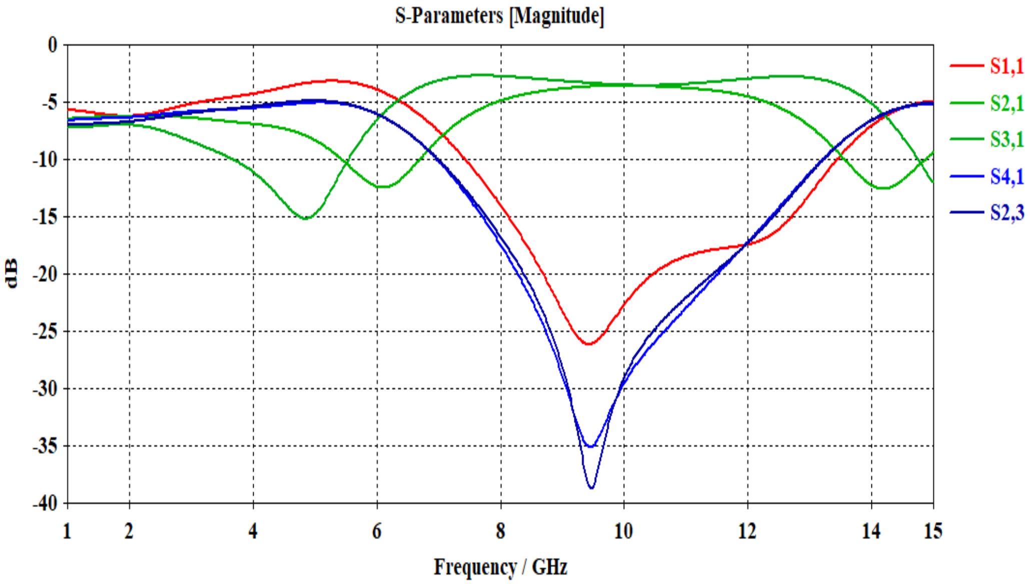


Figure III.4: S-parameters of the proposed rat-race divider for Rogers' RO4003C substrate.

Through figure III 3.4, the resonance frequency is 9.46 GHz with a bandwidth between 7.4 to 13.4 GHz at -10 dB, a reflection coefficient S_{11} equal to -26 dB, a transmission coefficient (insertion loss) S_{21}/S_{31} of -3db, in addition an isolation coefficient (port isolation.) S_{41}/S_{23} of -35 dB.

III.3.4 The effect of Aluminum's substrate

We change the substrate material to Aluminum with Dielectric constant ε_r =8.6, W_o=0.83mm, W_s= 0.34mm

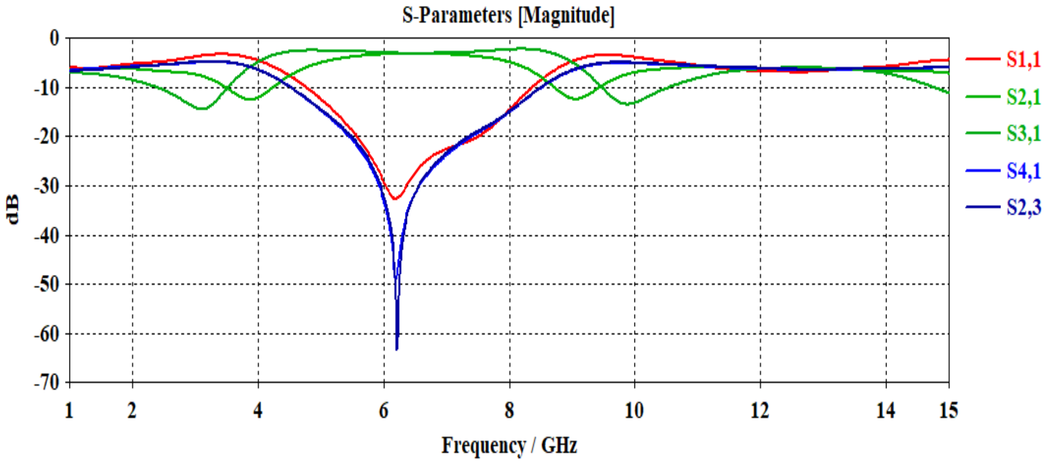


Figure III.5: S-parameters of the proposed rat-race divider for Aluminum's substrate.

The previous figure displays the S-parameters of a rat-race coupler on an aluminum substrate. The main frequency has a value of 6.2 GHz with a bandwidth ranging from 4.7 to 8.3 GHz at -10 dB. The reflection coefficient S_{11} is -32 dB, and the transmission coefficient (insertion loss) S_{21}/S_{31} is -3 dB. Additionally, the isolation coefficient (port isolation) S_{41}/S_{23} is -50 dB.

III.3.5 The effect of radius (R_{out})

we make a change in the width of the circle **(W_s)** while keeping all other variables constant. The subsequent figure shows the effectiveness of this change on the performance of Rat Race divider.

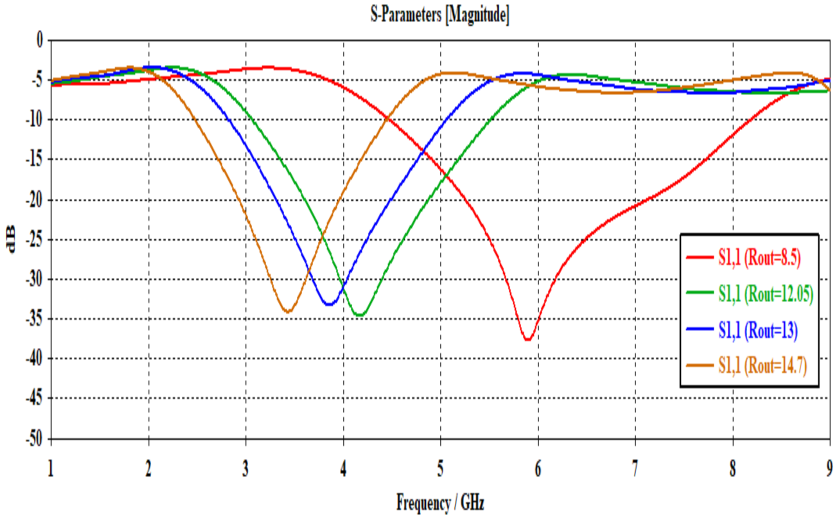


Figure III.6: Evolution of the Input returns loss S_{11} of the rat-race divider with Polycarbonate substrate for different values of (R_{out})

Through these curves, we can say that as the value of the radius changes, the main frequency changes. We see that at the value (r_{out}=8.5), the main frequency is 5.9 GHz, and at the value (R_{out}=12.05), the frequency is 4.2 GHz. At the value (r_{out} =13), the frequency is 3.9 GHz, and at the value (R_{out}=14.7), the frequency is 3.5 GHz.

III.4 Conclusion:

This chapter delves into a thorough examination of the Rat Race divider's parameters, focusing on alterations in dimensions and materials to assess their effects on performance. Key parameters such as, return loss, isolation coefficient, frequency, and bandwidth were scrutinized using CST software. The study aimed to elucidate how varying parameter values influence the Rat Race divider's behavior and performance, crucial for system design and enhancement. By testing three materials with different ε_r values, the study provides insights into the divider's behavior under diverse conditions, emphasizing the significance of parameter studies in optimizing system performance.

Chapter IV: Optimization of a rat race divider

IV.1 introduction

After an extensive parametric study detailed in the previous chapter, we will now embark on an optimization process utilizing CST Studio Suite, a robust electromagnetic simulation software. Throughout this optimization phase, a meticulous fine-tuning of numerous critical parameters will be conducted using an integrated algorithm. Among the array of optimization techniques available, the Particle Swarm Optimization (PSO) method has been thoughtfully chosen for our specific application.

The rat race divider, a fundamental element in microwave engineering, holds a crucial role in achieving balanced power distribution and phase control. Our design efforts have been significantly focused on optimizing this divider for medium-band 5G applications. Specifically tailored to operate within the 3.5 GHz frequency band, aligning with the requirements of modern 5G networks, the corresponding bandwidth and performance characteristics are depicted in the forthcoming figure:

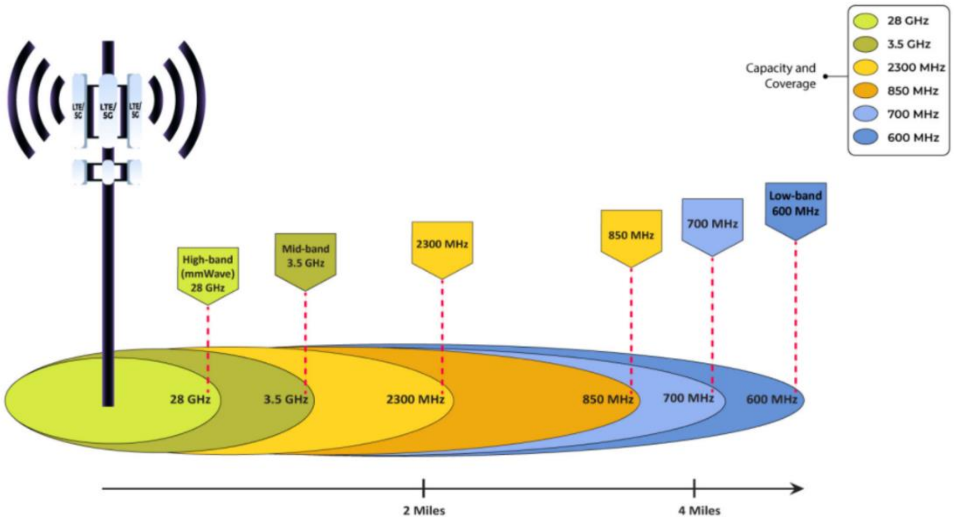


Figure IV.1: Optimized Rat Race Divider Performance at 3.5 GHz [19]

Our work not only aims at achieving optimal performance but also takes into account practical considerations such as manufacturability, cost-effectiveness, and seamless integration into 5G base stations. By harnessing the PSO algorithm, our goal is to strike a balance between performance metrics and real-world constraints.

In essence, this chapter delves into the complexities of optimizing the rat race divider for 5G applications, highlighting the significance of rigorous electromagnetic analysis and the selection of appropriate algorithms. Our commitment to advancing microwave engineering contributes significantly to the evolution of wireless communication systems.

IV.2 Optimization tool in CST

We optimize with the CST Studio Suite, and as it is known, the CST Studio Suite is a high-performance 3D electromagnetic analysis (EM) software package designed for the design, analysis and optimization of electromagnetic components and systems. It provides electromagnetic field solvers that cover electromagnetic spectrum applications, including antennas, waveguides, filters and RF dividers. Engineers and researchers use CST Studio Suite to study the behavior of these components in the high frequency range. The software integrates seamlessly into the overall design process, helping to make informed decisions to improve system performance. In addition, CST Studio Suite combines a user-friendly interface with powerful simulation performance, offering a variety of solvers for high-frequency simulations, all grouped under the specific high-frequency module known as CST Microwave Studio®.[20]

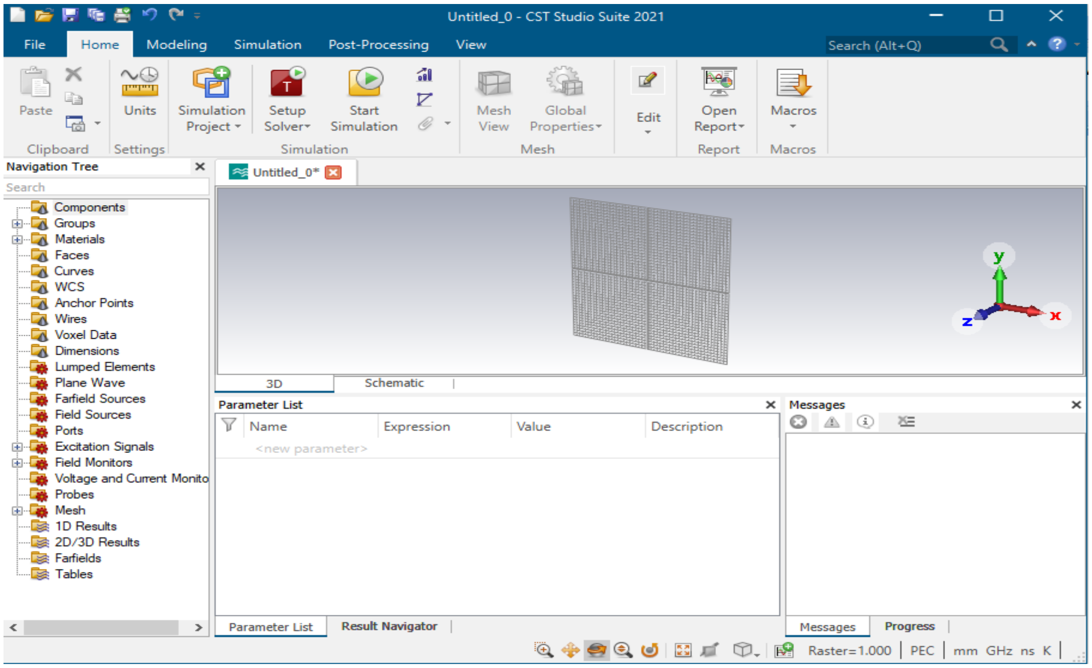
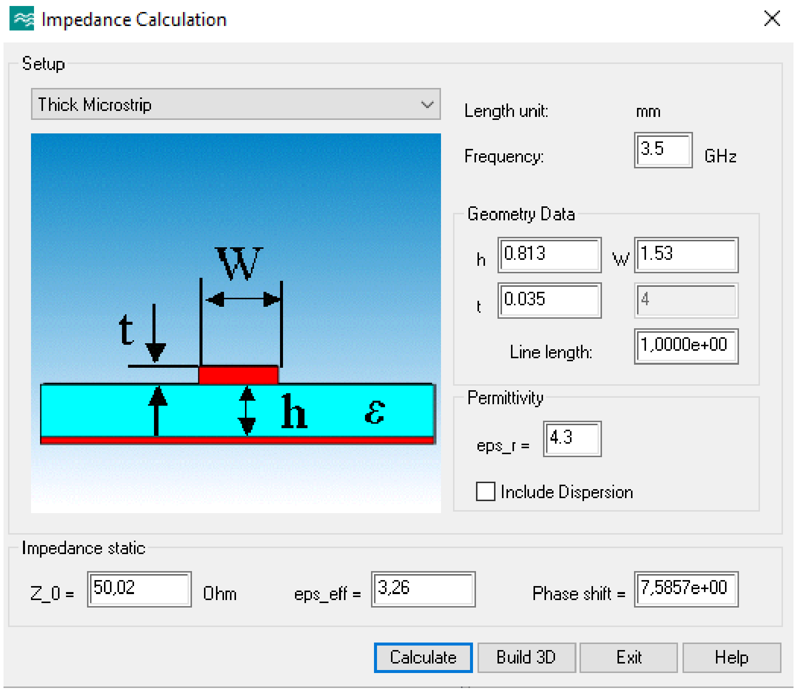


Figure IV.2: Graphical interface of the CST Studio simulator

IV.3 Design of a rat race divider

The proposed divider is designed on a low-cost substrate (FR-4 with losses) with dimensions of 50 × 50 mm2 (length × width). This part has a relative permittivity of ε_r = 4.3, with a loss tangent tan δ of 0.025 and a thickness h of 0.813 mm. The copper thickness t is approximately 0.035 mm. The ground line dimensions are the same as the part dimensions (length × width). The divider is directly connected to a feed line with characteristic impedance Zc = 50Ω.

For the preservation of adaptation, we choose values for w (Z= 50) and W_s (√2*50=70.71) using the impedance calculation within the CST program for a thickness substrate h =0.813 and a relative permittivity of ε_r = 4.3.



Thick Microstrip

Length unit: mm

Frequency: 3.5 GHz

h 0.813

w 1.53

t 0.035

4

Line length: 1,0000e+00

eps_r = 4.3

☐ Include Dispersion

Z_0 = 50,02 Ohm

eps_eff = 3,26

Phase shift = 7,5857e+00

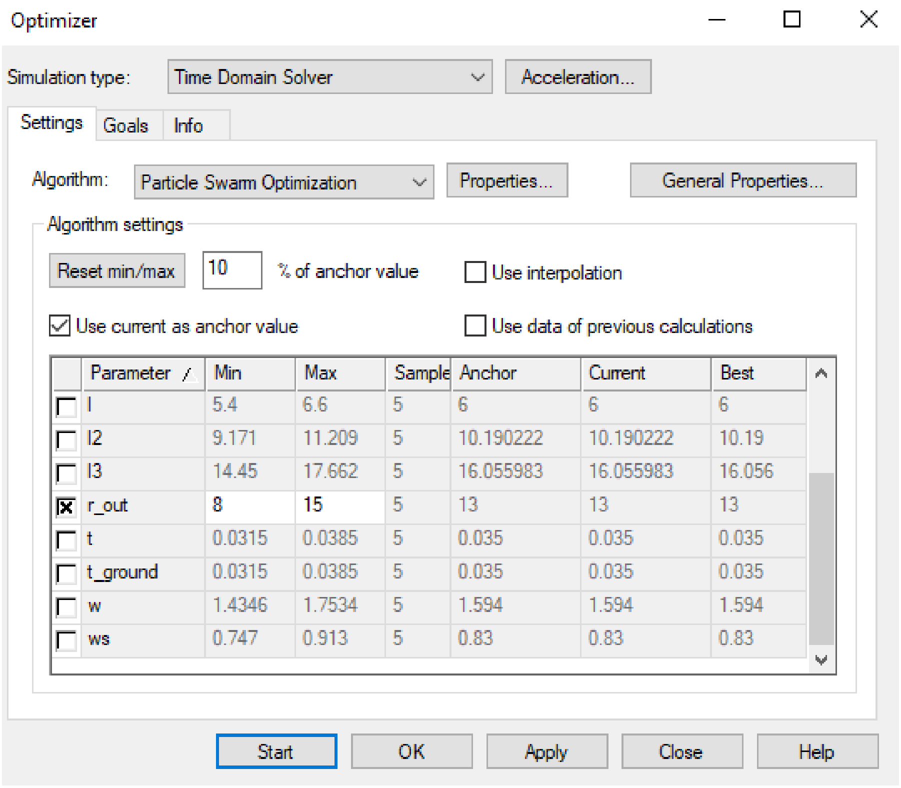
Figure IV.3: Determination of the characteristic impedance Zo for w

The initial dimensions of this divider are tabulated in the following table.

Table VI.1: Dimensions of Rate-Race divider

parameters	A	B	h_s	t	w	w_s	R_{out}	L	r_{in}
Values(mm)	50	50	0.813	0.035	1.35	0.76	12.05	10	11.29

To achieve the desired results, by clicking on the Optimizer icon in the simulation menu, we will choose the parameters to optimize; in our case, we chose one parameter to optimize: R_{out}



Simulation type: Time Domain Solver

Algorithm: Particle Swarm Optimization

Algorithm settings

10 % of anchor value

☐ Use interpolation

☑ Use current as anchor value

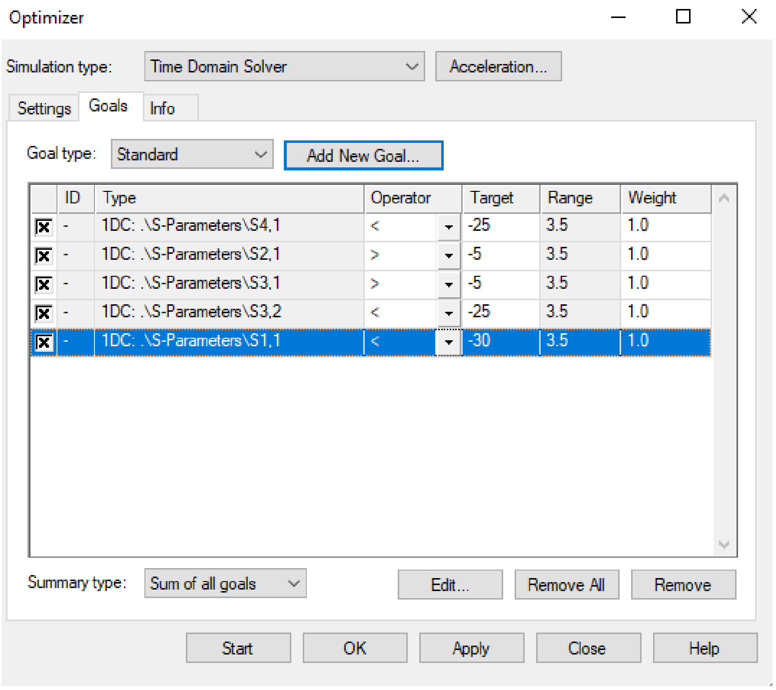
☐ Use data of previous calculations

	Parameter	Min	Max	Sample	Anchor	Current	Best
☐	l	5.4	6.6	5	6	6	6
☐	l2	9.171	11.209	5	10.190222	10.190222	10.19
☐	l3	14.45	17.662	5	16.055983	16.055983	16.056
☒	r_out	8	15	5	13	13	13
☐	t	0.0315	0.0385	5	0.035	0.035	0.035
☐	t_ground	0.0315	0.0385	5	0.035	0.035	0.035
☐	w	1.4346	1.7534	5	1.594	1.594	1.594
☐	ws	0.747	0.913	5	0.83	0.83	0.83

Figure IV.4: Choice of parameters to be optimized

As we mentioned earlier, we use PSO algorithm. Particle Swarm Optimization is an optimization algorithm used within CST Studio Suite to find the optimum design parameters that meet product requirements. It chosen within CST Studio Suite for its robustness, efficient handling of many parameters, global search capabilities, and ease of implementation. It complements other optimization methods, making it valuable for engineers seeking optimal designs in the high-frequency range.

We choose the goals that we want to achieve with an input return loss $S_{11} < -30$, an insertion loss $S_{21}/S_{31} > -5$, and a port isolation $S_{41}/S_{23} < -25$.



Simulation type: Time Domain Solver

Goal type: Standard

	ID	Type	Operator	Target	Range	Weight
☒	-	1DC: .\S-Parameters\S4,1	<	-25	3.5	1.0
☒	-	1DC: .\S-Parameters\S2,1	>	-5	3.5	1.0
☒	-	1DC: .\S-Parameters\S3,1	>	-5	3.5	1.0
☒	-	1DC: .\S-Parameters\S3,2	<	-25	3.5	1.0
☒	-	1DC: .\S-Parameters\S1,1	<	-30	3.5	1.0

Summary type: Sum of all goals

Figure IV.5: Goals of rat-race divider

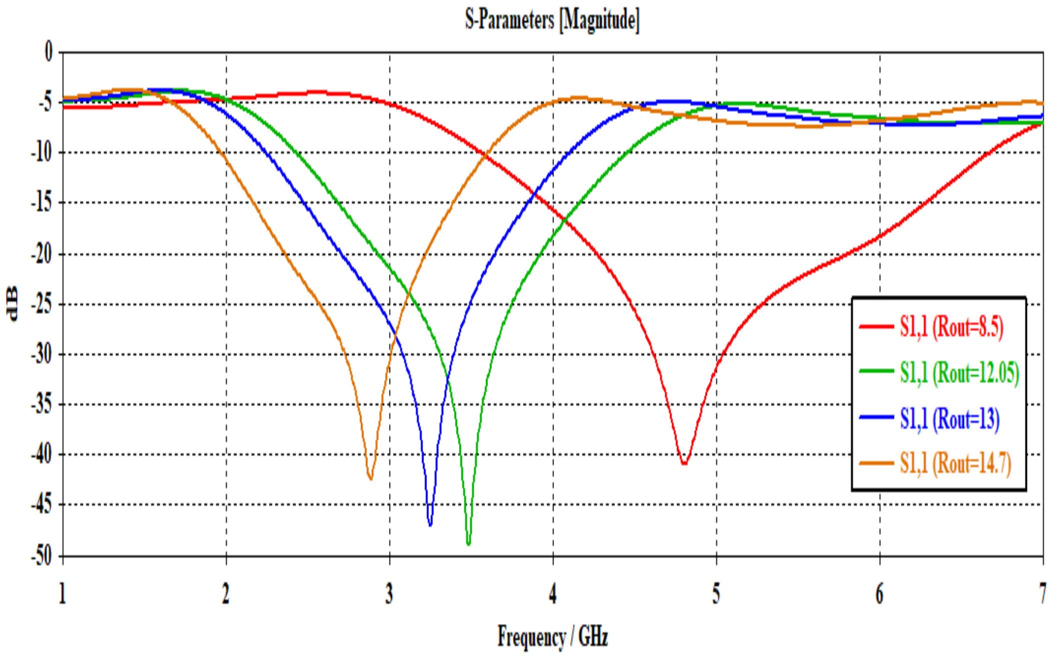


Figure IV.6: Evolution of the Input returns loss S₁₁ of the rat-race divider with FR-4 substrate for different values of R_{out}

The image 4.6 illustrates different values of reflection coefficients S_{11} with varying values of the radius, where the value achieved for us at 3.5 GHz is (R_{out} = 12.05).

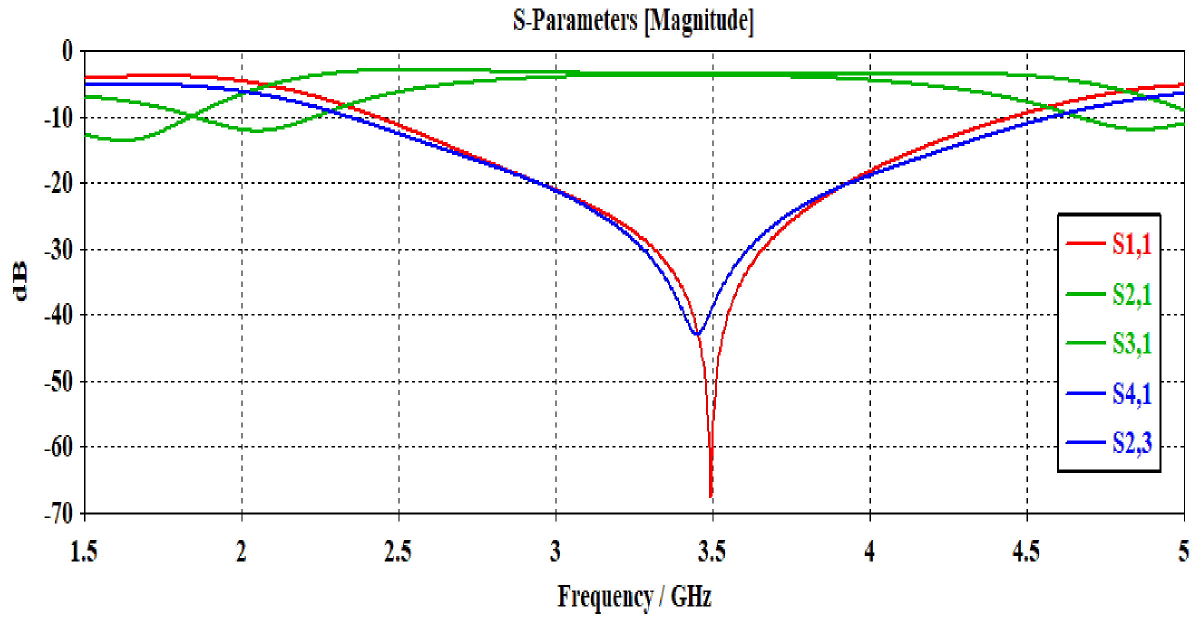
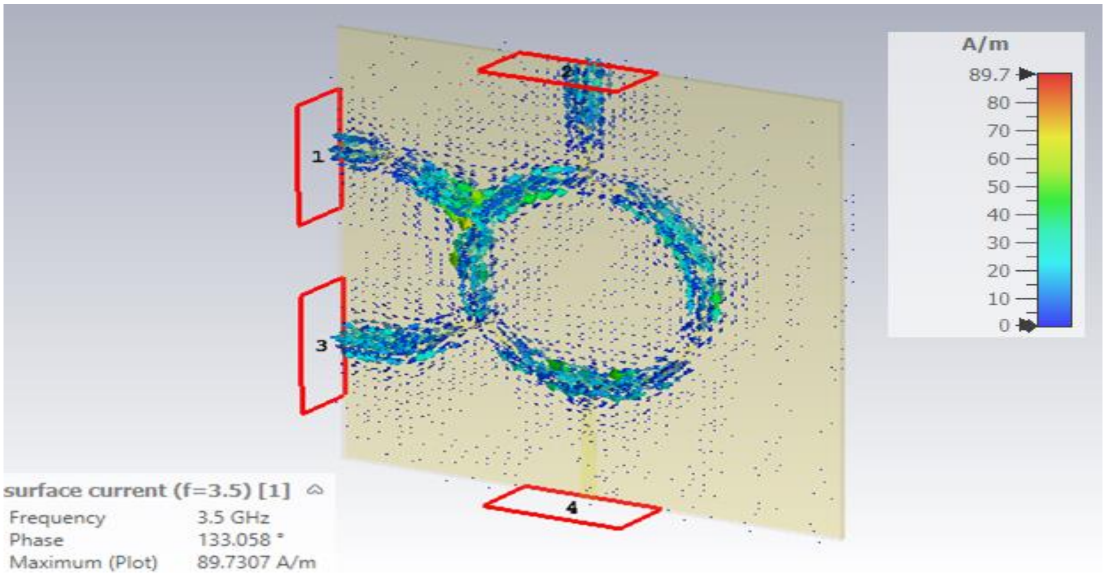


Figure IV.7: S-parameters of rat-race divider

Through figure 4.7, it is evident to us that the S_{11} Input return loss, is -68 dB, the S_{21}/S_{31} insertion loss is -3 dB, and the isolation value between the outputs S_{23} and S_{41} is -42 dB. The resonance frequency is 3.5 GHZ with a bandwidth between 2.5 to 4.5 GHz at -10dB.



surface current (f=3.5) [1]
Frequency 3.5 GHz
Phase 133.058 °
Maximum (Plot) 89.7307 A/m

Figure IV.8: Surface Current Distribution of rat-race divider

IV.4 Conclusion

In summary, our thorough optimization process, guided by CST Studio Suite and utilizing the Particle Swarm optimization (PSO) method, has successfully customized the rat race divider for medium-band 5G applications. Achieving balanced power distribution and precise phase control within the 3.5 GHz frequency band.

Conclusion

This work contributes to the field's knowledge base, laying a foundation for further advancements in Rat Race divider design and optimization. The study underscores the importance of material selection in achieving desired performance characteristics and offers valuable implications for the divider's application across various technological domains.

In this work, we were trying to make an improvement to enhance the rat race divider for 5G applications.

We began by positioning the proposed work by presenting a state of the art on the rate race dividers, then we exposed the main theoretical notions concerning these dividers.

Then, we carried out exhaustive research on the theoretical and applied parts on a rate race divider, in addition to their applications. In the third simulation part, we performed a parametric study of a rate race divider which showed us the effect of different physical dimensions of a divider on its important characteristics in terms of reflection coefficient in each port, isolation between the output ports and the others.

In the fourth chapter which is the optimization part, we have made several changes on the rate race divider to achieve the desired frequency of 3.5 GHz for 5G applications.

References

1. H. Xu, G. Wang, and K. Lu, “Microstrip Rat-Race Couplers,” IEEE Microwave Magazine, vol. 12, no. 4, pp. 117–129, Jun. 2011, doi: 10.1109/mmm.2011.940600.

2. I. Hickman, “Couplers, hybrids and directional couplers,” Practical RF Handbook, pp. 49–57, 2006, doi: 10.1016/b978-075068039-4/50006-8.

3. David M. Pozer, “Microwave engineering”, John Willey and Sons Inc. Publication, third ed., 2005.

4. F. ZHANG, “RF RAT-RACE COUPLERS WITH U-TYPE DGS MICROSTRIP ELECTROMAGNETIC BAND GAP ELEMENT,” Modern Physics Letters B, vol. 23, no. 13, pp. 1611–1617, May 2009, doi: 10.1142/s0217984909019776.

5. S. Khanmohamadi and A. Eskandari, “A compact and wideband rat-race coupler using two-section ring and artificial transmission lines,” Analog Integrated Circuits and Signal Processing, vol. 108, no. 1, pp. 1–6, Nov. 2020, doi: 10.1007/s10470-020-01743-5.

6. W. Wang, Y. Zheng, and Y. Wu, “A generalized broadband coupled-line based rat-race coupler with arbitrary power division ratios and free terminated impedances,” AEU - International Journal of Electronics and Communications, vol. 125, p. 153388, Oct. 2020, doi: 10.1016/j.aeue.2020.153388.

7. M. Moubadir, H. Aziz, I. Badaoui, N. A. Touhami, and A. Mohamed, “Miniaturized design of rat-race coupler by utilizing T-shape stubs,” Procedia Manufacturing, vol. 22, pp. 79–84, 2018, doi: 10.1016/j.promfg.2018.03.013.

8. A. Kumari, P. Bhowmik, and T. Moyra, “Design and validation of miniaturize Rat Race Coupler based microstrip Balun,” AEU - International Journal of Electronics and Communications, vol. 95, pp. 155–161, Oct. 2018, doi: 10.1016/j.aeue.2018.08.013.

9. G. Bhargava and S. Majumdar, “Design of Novel Rat-Race Coupler Based Analog Pre-Distortion Circuit for 5G Applications,” 2022 International Conference for Advancement in Technology (ICONAT), Jan. 2022, doi: 10.1109/iconat53423.2022.9725857.

10. B. Dwivedy and S. K. Behera, “Modelling, analysis and testing of an active element based wide-band frequency tunable compact rat-race hybrid,” AEU - International Journal of Electronics and Communications, vol. 103, pp. 24–31, May 2019, doi: 10.1016/j.aeue.2019.02.009.

11. POZAR, David M. Microwave engineering. Fourth Editions, University of Massachusetts at Amherst, John Wiley & Sons, Inc, 2012, p. 26-30.

12. Chang, Kai, and Lung-Hwa Hsieh. Microwave ring circuits and related structures. Vol. 156. John Wiley & Sons, 2004.

13. Salvador Vasques Seabra Águas, “Design, Manufacture and Testing of Microstrip Directional Couplers”, Thesis to obtain the Master of Science degree in Electrical and Computer Engineering at The Instituto Superior Técnico is the school of engineering and technology of the University of Lisbon, June 2019.

14. FR-4 data sheet: https://laminatedplastics.com/fr-4.pdf

15. Polycarbonate data sheet: https://laminatedplastics.com/polycarbonate.pdf

16. “Aluminum data sheet,” Metal Finishing, vol. 101, no. 6, p. 139, Jun. 2003, doi: 10.1016/s0026-0576(03)80481-6.

17. RO4003C data sheet: https://integratedtest.com/wp-content/uploads/2021/08/Rogers4003-4350.pdf

18. Copper data sheet: https://copperheadwire.com/wp-content/uploads/2022/11/SC1445-Data-Sheet.pdf

19. website: https://nybsys.com/5g-bands; Visited Date: May 05,2024.

20. CST Studio Suite High Frequency Simulation, Version 2020.0 - 8/16/2019

Abbreviation:

VSWR: Voltage Sanding-Wave Ratio

RF: Radiofrequency

HC: Hybrid Coupler

ADS: Advance Design System

IDC: Interdigital Capacitor

RRD: Rat Race Divider

TL: Transmission Line

FBW: Fractional Bandwidth

WPD: Wilkinson Power Dividers

PS: Phase Shifters

HB-1 tone: a Tone Simulation

PA: Power Amplifier

PCBs: Printed Circuit Boards

PSO: Particle Swarm Optimization

CST: Computer Simulation Technologies

EM: Electromagnetic

Abstract:

The spectacular development in the field of wired and wireless communications has led to the emergence of many technologies, such as fourth and fifth generation networks, or even the sixth generation that is under development. This evolution has also created the need to reduce the size of devices used in this field while preserving their performance and services. All active and passive microwave circuits must align with the trend towards service integration.

These include the rat race coupler, which is one of the important negative microwave circuits and is a key element of our research. The latter is used in several fields such as communications, surveillance, radar systems, and other applications. Among the most important and outstanding couplers are the rat race coupler, which is one of the types of power couplers with narrow bandwidth.

The objective of this work is to optimize the parameters of the rat race coupler for ideal performance in 5G applications, using CST Studio simulation software. We also performed an analysis of this coupler to assess the impact of geometric dimensions on its physical properties, such as operating frequency and bandwidth. After the parameter improvements, we reached a frequency of 3.5 GHz, which is ideal for 5G applications.

ملخص:

أدى التطور الرهيب الذي يجري في مجال الاتصالات السلكية واللاسلكية الى ظهور العديد من الخدمات كشبكات الجيل الرابع والجيل الخامس وحتى الجيل السادس الذي هو محل تطوير، هذا التطور أدى بدوره للحاجة الى العمل على تصغير الأجهزة المستعملة في هذا المجال الى أصغر حجم ممكن مع الحفاظ على نفس الأداء والخدمات، كل دارات الميكرويف النشطة وغير النشطة يجب ان تتماشى مع ظاهرة ادماج الخدمات، من بين هذه الأجهزة نذكر مقسم الطاقة الذي يعتبر من الدوائر الميكرويفية السلبية الهامة محورا اساسيا في بحثنا هذا. يستعمل هذا الاخير في عدة مجالات كالاتصالات، المراقبة، أنظمة الرادار وغيرها من التطبيقات. من بين اهم و أبرز المقسمات يأتي ذكر Rate race الذي يعتبر من ضمن أنواع المقسمات الطاقوية التي لها نطاق ترددي ضيق. يهدف هذا العمل إلى محاولة إجراء تحسينات على اعدادات Rate race لأداء مثالي لتطبيقات 5G وذلك باستعمال برنامج محاكاة من نوع CST Studio كما قمنا بدراسة تحليلية لهذا المقسم من أجل معاينة تأثير الابعاد الهندسية للمقسم على خصائصه الفيزيائية كذبذبة العمل وعرض النطاق. بعد التحسينات التي قمنا بإجرائها على الاعدادات وصلنا الى تردد 3.5 GHz وهو تردد مثالي لتطبيقات 5G.

Abstract:

Le développement spectaculaire dans le domaine des communications filaires et sans fil a conduit à l’émergence de nombreuses technologies, telles que les réseaux de quatrième et cinquième génération, voire même de la sixième génération qui est en cours de développement. Cette évolution a également créé la nécessité de réduire la taille des dispositifs utilisés dans ce domaine tout en préservant leurs performances et services. Toutes les circuits micro-ondes actives et passives doivent s’aligner sur la tendance à l’intégration des services.

Parmi ces dispositifs, mentionnons le coupleur rat race, qui est l’un des circuits micro-ondes négatifs importants et constitue un élément clé de notre recherche. Ce dernier est utilisé dans plusieurs domaines tels que les communications, la surveillance, les systèmes radar, et d’autres applications. Parmi les coupleurs les plus importants et les plus remarquables, citons le coupleur rat race, qui fait partie des types de coupleurs de puissance ayant une bande passante étroite.

L’objectif de ce travail est d’optimiser les paramètres du coupleur rat race pour des performances idéales dans les applications 5G, en utilisant un logiciel de simulation de type CST Studio. Nous avons également effectué une analyse de ce coupleur afin d’évaluer l’impact des dimensions géométriques sur ses propriétés physiques, telles que la fréquence de fonctionnement et la largeur de bande. Après les améliorations apportées aux paramètres, nous avons atteint une fréquence de 3,5 GHz, qui est idéale pour les applications 5G.