

**PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA
MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH
MOHAMED BOUDIAF UNIVERSITY OF M'SILA**

**FACULTY OF TECHNOLOGY
ELECTRONICS DEPARTMENT**

N°d'ordre: 2026/ ING TLC



DOMAIN: SCIENCES AND TECHNOLOGY

FIELD: TELECOMMUNICATIONS

OPTION : ING TLC

**Dissertation submitted for the award of the
Academic Master's degree**

By: - *CHERIFI Nadjat*

- *BENTAHAR Aya*

Supervised by:

Pr. KHEDROUCHE Djamel

Project Title

**Design and Simulation of Microwave Power
Divider Based on Microstrip Technology**

Publicly defended on : / 06 / 2026

Before the examination committee composed of:

Dr. KEBAILI Farida	University of M'sila	Chairperson
Pr. KHEDROUCHE Djamel	University of M'sila	Rapporteur
Dr. KAHLOUCHE Ahmed	University of M'sila	Examiner

Academic Year :2025/2026

بسم الله الرحمن الرحيم

Acknowledgement

First and foremost, all praise is due to God, who granted us the strength and patience to complete this work.

We would like to express our sincere gratitude to our supervisor, **Pr. Djamel KHEDROUCHE**, for his continuous support, valuable guidance, and advice, which greatly contributed to the completion of this work.

We would also like to extend our sincere thanks to all our teachers, who generously shared their knowledge and contributed to our academic formation.

Our thanks also go to the members of the jury for their time and for evaluating this work.

We would like to express our deep appreciation to everyone who contributed, directly or indirectly, to the accomplishment of this work.

Finally, we thank our families and friends for their constant support and encouragement.

Dedication

We dedicate this modest work with great pride and gratitude :

To our beloved parents, who have always been our constant support, our source of strength and hope. Thanks to them, after God, we have reached where we are today. We owe them all our love, appreciation, and respect.

To our dear families, who stood by our sides throughout every stage of this journey and provided us with invaluable moral and emotional support.

To everyone who supported and encouraged us, even with a kind word.

To our friends, who shared with us moments of hardship and success, and were always a source of positive energy.

We dedicate this work to all of them, hoping that we have succeeded in accomplishing it.

CHRIFI Nadjat

BEN TAHAR Aya

List of figures

- Figure 1.1: Power division and combining. (a) Power division. (b) Power combining
- Figure 1.2: Two types of circulators and their scattering matrices. (a) Clockwise circulation. (b) Counterclockwise circulation. The phase references for the ports are arbitrary. combining
- Figure 1.3: A reciprocal lossless three-port network matched at ports 1 and 2.
- Figure 1.4: Various T-junction power dividers. (a) *E*-plane waveguide T. (b) *H*-plane waveguide T. (c) Microstrip line T-junction divider.
- Figure 1.5: Transmission line model of a lossless T-junction divider.
- Figure 1.6: An equal-split three-port resistive power divider.
- Figure 2.1: The Wilkinson power divider. (a) An equal-split Wilkinson power divider in microstrip line form. (b) Equivalent transmission line circuit.
- Figure 2.2: Operating Assumptions.
- Figure 2.3: The Wilkinson power divider circuit in normalized and symmetric form.
- Figure 2.4: Bisection of the circuit of Figure 2.3. (a) Even-mode excitation. (b) Odd-mode excitation.
- Figure 2.5: Analysis of the Wilkinson divider to find S_{11} . (a) The terminated Wilkinson divider (b) Bisection of the circuit.
- Figure 2.6: A Wilkinson power divider in microstrip form having unequal power division.
- Figure 2.7: An N-way, equal-split Wilkinson power divider.
- Figure 2.8: Photograph of a four-way corporate power divider network using three microstrip Wilkinson power dividers. Note the isolation chip resistors.
- Figure 2.9: Photograph of Wilkinson Power Divider with $Z_0 = 50 \Omega$
- Figure 2.10: Frequency response of an equal-split Wilkinson power divider. Port 1 is the input port; ports 2 and 3 are the output ports.
- Figure 3.1: Wilkinson Power Divider Structure at 1.8 GHz.
- Figure 3.2: S_{11} Parameter (Return Loss) for $f = 1.8$ GHz.
- Figure 3.3. S_{21} Parameter (Transmission Coefficient, Port 2), for $f = 1.8$ GHz.

- Figure 3.4 : S_{31} Parameter (Transmission Coefficient, Port 3) for $f = 1.8$ GHz.
- Figure 3.5: S_{23} Parameter (Isolation between Port 2 and Port 3) for $f = 1.8$ GHz.
- Figure 3.6: Wilkinson Power Divider Structure at 2.1 GHz.
- Figure 3.7: S_{11} Parameter (Return Loss) for $f = 2.1$ GHz.
- Figure 3.8 : S_{21} Parameter (Transmission Coefficient, Port 2), for $f = 2.1$ GHz.
- Figure 3.9 : S_{31} Parameter (Transmission Coefficient, Port 3) for $f = 2.1$ GHz.
- Figure 3.10: S_{23} Parameter (Isolation between Port 2 and Port 3) for $f = 2.1$ GHz.
- Figure 3.11: Wilkinson Power Divider Structure at 2.4 GHz.
- Figure 3.12: S_{11} Parameter (Return Loss) for $f = 2.4$ GHz.
- Figure 3.13 : S_{21} Parameter (Transmission Coefficient, Port 2), for $f = 2.4$ GHz.
- Figure 3.14 : S_{31} Parameter (Transmission Coefficient, Port 3) for $f = 2.4$ GHz.
- Figure 3.15: S_{23} Parameter (Isolation between Port 2 and Port 3) for $f = 2.4$ GHz.
- Figure 3.16: Wilkinson Power Divider Structure at 5 GHz.
- Figure 3.17: S_{11} Parameter (Return Loss) for $f = 5$ GHz.
- Figure 3.18 : S_{21} Parameter (Transmission Coefficient, Port 2), for $f = 5$ GHz.
- Figure 3.19 : S_{31} Parameter (Transmission Coefficient, Port 3) for $f = 5$ GHz.
- Figure 3.20: S_{23} Parameter (Isolation between Port 2 and Port 3) for $f = 5$ GHz.

List of Tables

- Table 1.1: Summary of Simulated S-Parameters for the Wilkinson Power Divider at 5 GHz.

Table of contents

Acknowledgement

Dedication

List of figures

List of tables

Table of contents.....	ii
Abstracts	iii
General Introduction	1
Chapter I: Generalities on Power Dividers and Theoretical Foundations	5
Introduction:	6
I.1. Basic properties of dividers	7
Three-Port Networks (T-Junctions).....	7
I.2. The T-junction power divider	10
Lossless Divider	10
Example of T-Junction power divider	12
Resistive Divider.....	13
Conclusion	15
Chapter II: Theoretical Analysis and Design of the Wilkinson Power Divider	16
Introduction.....	17
II.1 Wilkinson Divider Structure.....	17
II.2. Operating Assumptions	17
III. 3 Application de la méthode des moments pour deux milieux différents.....	Erreur ! Signet non défini.
II.2.1 The system is perfectly symmetrical.....	18
II.2.2 The loads connected to the ports are equal.....	18
II.2.3 The transmission lines are lossless.....	18
II.2.4 The operating frequency corresponds to the frequency for which the design was intended	18
II.3. Even-Odd Mode Analysis.....	19
Even mode	20
Odd mode	22
II.4. Unequal Power Division and N-Way Wilkinson Dividers	23
II.5. Example of Design and Performance of a Wilkinson Divider.....	25
Conclusion	29

Chapter III: Results and Discussion	30
Introduction.....	31
III.1. Simulation Tool.....	31
III.2. Application Examples	32
III.2.1. Example1 ($f_0 = 1.8$ Ghz).....	32
III.2.2. Example2 ($f_0 = 2.1$ Ghz).....	37
III.2.3. Example3 ($f_0 = 2.4$ Ghz).....	41
III.2.4. Example4 ($f_0 = 5$ Ghz).....	46
Conclusion	53
General Conclusion.....	54
References	57

ملخص

في هذا العمل، تم تقديم دراسة شاملة لمقسم القدرة لويلكينسون المستخدم في أنظمة الاتصالات اللاسلكية. يهدف هذا البحث إلى تحليل وتصميم ومحاكاة مقسم قدرة ويلكينسون ثنائي الاتجاه عند عدة ترددات تشغيل وهي: 1.8 جيجاهرتز، 2.1 جيجاهرتز، 2.4 جيجاهرتز، و5 جيجاهرتز، باستخدام صندوق أدوات الترددات الراديوية (RF Toolbox) في MATLAB Simulink. وقد تم اعتماد تحليل النمطين الزوجي والفردى لاشتقاق معادلات التصميم النظرية. تم تقييم أداء الدارة باستخدام معاملات التشتت الأساسية S_{11} ، S_{21} ، S_{31} و S_{23} . أظهرت نتائج المحاكاة توافقًا ممتازًا مع النظرية عند تردد التصميم، مع تحقيق مطابقة جيدة للممانعة، وتقسيم متساوٍ للقدرة، وعزل مرتفع بين منافذ الخرج. كما أظهرت النتائج أن الأداء يبقى مقبولًا حتى عند تردد 5 جيجاهرتز، مما يؤكد متانة وكفاءة هذا المقسم في التطبيقات العملية الحديثة، مثل معايير الاتصالات الخلوية وشبكات الاتصال اللاسلكية المحلية.

Résumé

Dans ce travail, une étude complète du diviseur de puissance de Wilkinson pour les systèmes de communication sans fil est présentée. Cette recherche vise à analyser, concevoir et simuler un diviseur de puissance de Wilkinson à deux voies à plusieurs fréquences de fonctionnement : 1,8 GHz, 2,1 GHz, 2,4 GHz et 5 GHz, en utilisant le module RF de MATLAB Simulink. L'analyse en modes pairs et impairs a été employée pour dériver les équations de conception théoriques. Les performances du circuit ont été évaluées à l'aide des paramètres de dispersion clés (S_{11} , S_{21} , S_{31} , S_{23}). Les résultats de simulation montrent un excellent accord avec la théorie à la fréquence de conception, réalisant un bon ajustement d'impédance, une division de puissance égale et un isolement élevé entre les ports de sortie. Les résultats montrent également que les performances restent acceptables même à 5 GHz, confirmant ainsi la robustesse et l'efficacité de ce diviseur pour des applications pratiques modernes, telles que les normes de communication cellulaire et les réseaux locaux sans fil.

Abstract

In this work, a comprehensive study of the Wilkinson power divider for wireless communication systems is presented. This research aims to analyze, design, and simulate a two-way Wilkinson power divider at multiple operating frequencies: 1.8 GHz, 2.1 GHz, 2.4 GHz, and 5 GHz, using the RF module of MATLAB Simulink. Even-odd mode analysis was employed to derive the theoretical design equations. The circuit performance was evaluated through the key scattering parameters (S_{11} , S_{21} , S_{31} , S_{23}). Simulation results show excellent agreement with theory at the design frequency, achieving good impedance matching, equal power splitting, and high isolation between output ports. The results also show that performance remains acceptable even at 5 GHz, confirming the robustness and effectiveness of this divider for modern practical applications, such as cellular communication standards and wireless local area networks.

GENERAL INTRODUCTION

General Introduction

Microwave power dividers constitute fundamental building blocks in modern radio frequency (RF) and wireless communication systems. These passive components are extensively employed in applications such as phased array antennas, power amplifiers, mixers, signal distribution networks, and feed networks for satellite and terrestrial communication systems. The primary function of a power divider is to split an input signal into two or more output signals with specific amplitude and phase relationships, or conversely, to combine multiple input signals into a single output.

Among the various types of power dividers available—including T-junctions, resistive dividers, directional couplers, and hybrid junctions—the Wilkinson power divider occupies a particularly prominent position. Proposed by Ernest Wilkinson in 1960, this three-port network offers a unique combination of desirable characteristics: it can be matched at all ports simultaneously, provides high isolation between output ports, and operates with low insertion loss under balanced conditions. These properties are achieved through the clever integration of quarter-wavelength transmission lines and an isolation resistor connected between the output ports. Unlike the simple lossless T-junction, which suffers from poor impedance matching and lack of isolation, or the resistive divider, which dissipates significant power, the Wilkinson divider represents an optimal compromise that has made it a standard choice in countless microwave circuits for over six decades.

The theoretical foundation of the Wilkinson power divider is well established, typically analyzed using even-odd mode decomposition. The equal-split version requires quarter-wave lines of characteristic impedance $Z = \sqrt{2}Z_0$ and an isolation resistor of value $R=2Z_0$ for a system impedance Z_0 . However, while the theory is mature, the practical frequency-dependent behavior of this divider when designed for different wireless communication bands remains an area of considerable practical interest. Modern communication systems operate across a wide spectrum, from the 1.8 GHz GSM band through the 2.1 GHz UMTS (3G) band, the 2.4 GHz ISM band used by Wi-Fi and Bluetooth, to the 5 GHz band employed by high-throughput WLAN standards (Wi-Fi 5 and Wi-Fi 6). Each of these frequencies imposes different design constraints in terms of physical dimensions, material properties, and loss mechanisms.

The present dissertation aims to bridge the gap between theoretical analysis and practical implementation by conducting a comprehensive numerical investigation of the Wilkinson power divider across these four representative frequencies. The study employs the RF module integrated within MATLAB Simulink, a powerful simulation environment that enables accurate circuit-level modeling based on transmission line theory and scattering parameter (S-parameter) analysis. The choice of MATLAB Simulink is motivated by its accessibility, its robust handling of microwave networks, and its ability to produce clear graphical representations of frequency-dependent behavior.

The dissertation is organized into three chapters. Chapter I presents generalities on power dividers and the theoretical foundations of three-port networks. It discusses the fundamental limitations of reciprocal lossless three-port junctions, introduces the scattering matrix formalism, and examines both lossless T-junction dividers and resistive dividers. The chapter establishes the theoretical context that motivates the need for the Wilkinson configuration. Chapter II is devoted to the theoretical analysis and design of the Wilkinson power divider. It presents the even-odd mode analysis technique in detail, derives the key design equations for equal-split operation, discusses unequal power division and N-way extensions, and provides a design example with simulated frequency responses. Chapter III presents the core simulation results of this work. The performance of the Wilkinson divider is evaluated at 1.8 GHz, 2.1 GHz, 2.4 GHz, and 5 GHz in terms of input return loss (S_{11}), transmission coefficients (S_{21} and S_{31}), and output isolation (S_{23}). Each case is accompanied by a discussion of the associated wireless standard, a description of the simulated structure on a Teflon substrate, and a detailed analysis of the S-parameter plots.

Through this systematic investigation, the dissertation seeks to answer several practical questions : How does the Wilkinson power divider perform when designed for different frequency bands ? What degradation can be expected as the operating frequency increases toward 5 GHz ? Does the divider maintain its theoretical properties—equal power division, excellent matching, and high isolation—across all these bands ? The answers to these questions have direct implications for engineers designing multi-band and dual-band wireless systems, where the same basic circuit topology may need to operate reliably across widely separated frequencies.

The main contribution of this work is a practical, simulation-based validation of the Wilkinson power divider's versatility across modern communication bands, accompanied by

quantitative performance metrics that can guide design decisions. The results confirm that while the divider operates optimally at its design frequency, it exhibits graceful degradation at higher frequencies, with performance remaining well within acceptable engineering tolerances even at 5 GHz. This finding underscores the enduring relevance of the Wilkinson power divider in contemporary RF engineering.

CHAPTER I

Generalities on Power Dividers and Theoretical Foundations

Introduction

Power dividers are typically three-port devices widely used in power amplifiers, mixers and phased arrays to split and combine RF signals, as illustrated in Figure 1.1. Ideally, a power divider divides the input signal into two output signals with equal amplitude and equal phase without additional insertion loss. All three ports are matched to the reference impedance [1]. In power division, an input signal is divided into two (or more) output signals of lesser power, while a power combiner accepts two or more input signals and combines them at an output port. The coupler or divider may have three ports, four ports, or more, and may be (ideally) lossless. Three-port networks take the form of T-junctions and other power dividers, while four-port networks take the form of directional couplers and hybrids. Power dividers usually provide in-phase output signals with an equal power division ratio (3 dB), but unequal power division ratios are also possible. Directional couplers can be designed for arbitrary power division, while hybrid junctions usually have equal power division. Hybrid junctions have either a 90° or a 180° phase shift between the output ports.

A wide variety of waveguide couplers and power dividers were invented and characterized at the MIT Radiation Laboratory in the 1940s. These included E- and H-plane waveguide T-junctions, the Bethe hole coupler, multihole directional couplers, the Schwinger coupler, the waveguide magic-T, and various types of couplers using coaxial probes. In the mid-1950s through the 1960s, many of these couplers were reinvented to use stripline or microstrip technology. The increasing use of planar lines also led to the development of new types of couplers and dividers, such as the Wilkinson divider, the branch line hybrid, and the coupled line directional coupler [2].

This chapter is devoted to presenting the fundamental concepts related to power dividers and directional couplers, including their classification, operating principles, and key performance parameters. It also examines the characteristics of power distribution, phase relationships, and bandwidth behavior, as well as the influence of structural and technological parameters on their performance. Furthermore, the chapter discusses wave propagation mechanisms in these microwave structures and highlights some of their most relevant practical applications in modern communication and microwave systems.

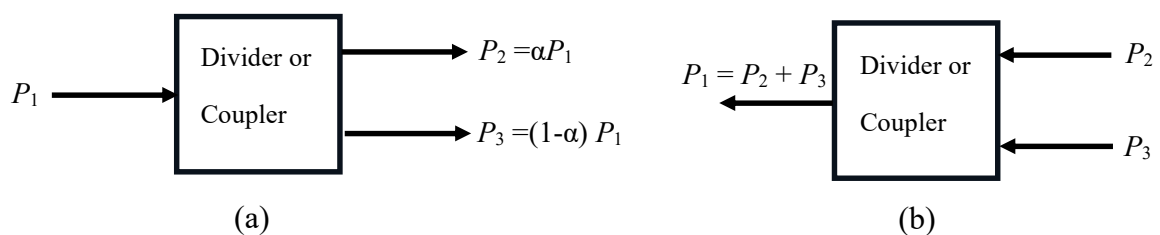


Figure 1.1 Power division and combining. (a) Power division. (b) Power combining [2].

I.1. Basic properties of dividers

Three-Port Networks (T-Junctions)

The simplest type of power divider is a *T-junction*, which is a three-port network with two inputs and one output. The scattering matrix of an arbitrary three-port network has nine independent elements [2]:

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \quad (1.1)$$

If the device is passive and contains no anisotropic materials, then it must be reciprocal and its scattering matrix will be symmetric ($S_{ij} = S_{ji}$). Usually, to avoid power loss, we would like to have a junction that is lossless and matched at all ports. We can easily show, however, that it is impossible to construct such a three-port lossless reciprocal network that is matched at all ports. If all ports are matched, then $S_{ii} = 0$, and if the network is reciprocal, the scattering matrix of (1.1) reduces to

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & 0 \end{bmatrix} \quad (1.2)$$

If the network is also lossless, then energy conservation requires that the scattering matrix satisfy the unitary properties of, which leads to the following conditions [3, 4]:

$$|S_{12}|^2 + |S_{13}|^2 = 1, \quad (1.3a)$$

$$|S_{12}|^2 + |S_{23}|^2 = 1, \quad (1.3b)$$

$$|S_{13}|^2 + |S_{23}|^2 = 1, \quad (1.3c)$$

$$S_{13}^* S_{23} = 0 \quad (1.3d)$$

$$S_{23}^* S_{12} = 0 \quad (1.3e)$$

$$S_{12}^* S_{13} = 0 \quad (1.3f)$$

Equations (1.3d) – (1.3f) show that at least two of the three parameters (S_{12} , S_{13} , S_{23}) must be zero. However, this condition will always be inconsistent with one of equations (1.3a)– (1.3c), implying that a three-port network cannot be simultaneously lossless, reciprocal, and matched at all ports. If any one of these three conditions is relaxed, then a physically realizable device is possible. If the three-port network is nonreciprocal, then $S_{ij} \neq S_{ji}$, and the conditions of input matching at all ports and energy conservation can be satisfied. Such a device is known as a *circulator*, and generally relies on an anisotropic material, such as ferrite, to achieve nonreciprocal behavior., but we can demonstrate here that any matched lossless three-port network must be nonreciprocal and, thus, a circulator. The scattering matrix of a matched three-port network has the following form:

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{21} & 0 & S_{23} \\ S_{31} & S_{32} & 0 \end{bmatrix} \quad (1.4)$$

If the network is lossless, $[S]$ must be unitary, which implies the following conditions:

$$S_{31}^* S_{32} = 0 \quad (1.5a)$$

$$S_{21}^* S_{23} = 0 \quad (1.5b)$$

$$S_{12}^* S_{13} = 0 \quad (1.5c)$$

$$|S_{12}|^2 + |S_{13}|^2 = 1, \quad (1.5d)$$

$$|S_{21}|^2 + |S_{23}|^2 = 1, \quad (1.5e)$$

$$|S_{13}|^2 + |S_{32}|^2 = 1, \quad (1.5f)$$

These equations can be satisfied in one of two ways. Either

$$S_{12} = S_{23} = S_{31} = 0, \quad |S_{21}| = |S_{32}| = |S_{13}| = 1, \quad (1.6a)$$

or

$$S_{21} = S_{32} = S_{13} = 0, \quad |S_{12}| = |S_{23}| = |S_{31}| = 1. \quad (1.6b)$$

These results show that $S_{ij} \neq S_{ji}$ for $i \neq j$, which implies that the device must be nonreciprocal. The scattering matrices for the two solutions of (7.6) are shown in Figure 1.2, together with the symbols for the two possible types of circulators. The only difference between the two cases is in the direction of power flow between the ports: solution (1.6a) corresponds to a circulator that allows power flow only from port 1 to 2, or port 2 to 3, or port 3 to 1, while solution (1.6b) corresponds to a circulator with the opposite direction of power flow. Alternatively, a lossless and reciprocal three-port network can be physically realized if only two of its ports are matched [3]. If ports 1 and 2 are the matched ports, then the scattering matrix can be written as

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & S_{33} \end{bmatrix} \quad (1.7)$$

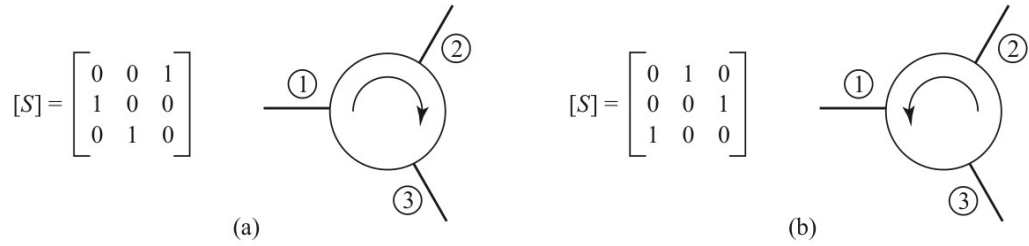


Figure 1.2 Two types of circulators and their scattering matrices. (a) Clockwise circulation. (b) Counterclockwise circulation. The phase references for the ports are arbitrary.

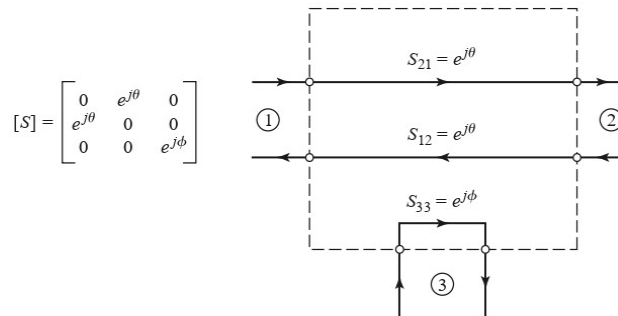


Figure 1.3 A reciprocal lossless three-port network matched at ports 1 and 2.

To be lossless, the following unitarity conditions must be satisfied:

$$S_{13}^* S_{23} = 0 \quad (1.8a)$$

$$S_{12}^* S_{13} + S_{23}^* S_{33} = 0 \quad (1.8b)$$

$$S_{23}^* S_{12} + S_{33}^* S_{13} = 0 \quad (1.8c)$$

$$|S_{12}|^2 + |S_{13}|^2 = 1, \quad (1.8d)$$

$$|S_{12}|^2 + |S_{23}|^2 = 1, \quad (1.8e)$$

$$|S_{13}|^2 + |S_{23}|^2 + |S_{33}|^2 = 1, \quad (1.8f)$$

Equations (1.8d) and (1.8e) show that $|S_{13}| = |S_{23}|$, so (1.8a) leads to the result that $S_{13} = S_{23} = 0$. Then, $|S_{12}| = |S_{33}| = 1$. The scattering matrix and corresponding signal flow graph for this network are shown in Figure 1.3, where it is seen that the network actually degenerates into two separate components—one a matched two-port line and the other a totally mismatched one-port. Finally, if the three-port network is allowed to be lossy, it can be reciprocal and matched at all ports; this is the case of the *resistive divider*, which will be discussed in Section 1.2. In addition, a lossy three-port network can be made to have isolation between its output ports (e.g., $S_{23} = S_{32} = 0$).

1.2. The T-junction power divider

The T-junction power divider is a simple three-port network that can be used for power division or power combining, and it can be implemented in virtually any type of transmission line medium. Figure 1.4 shows some commonly used T-junctions in waveguide and microstrip line or stripline form. The junctions shown here are, in the absence of transmission line loss, lossless junctions. Thus, as discussed in the preceding section, such junctions cannot be matched simultaneously at all ports. We will analyze the T-junction divider below, followed by a discussion of the resistive power divider, which can be matched at all ports but is not lossless.

Lossless Divider

The lossless T-junction dividers of Figure 1.4 can all be modeled as a junction of three transmission lines. In general, there may be fringing fields and higher order modes associated with the discontinuity at such a junction, leading to stored energy that can be accounted for by

a lumped susceptance, B . In order for the divider to be matched to the input line of characteristic impedance Z_0 , we must have [5]

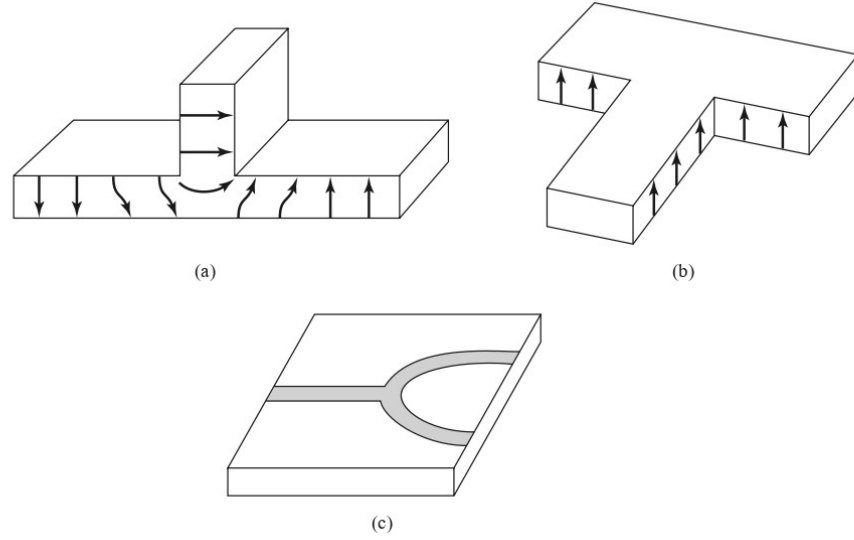


Figure 1.4 Various T-junction power dividers. (a) *E*-plane waveguide T. (b) *H*-plane waveguide T. (c) Microstrip line T-junction divider. [5]

$$Y_{in} = jB + \frac{1}{Z_1} + \frac{1}{Z_2} = \frac{1}{Z_0} \quad (1.9)$$

If the transmission lines are assumed to be lossless (or of low loss), then the characteristic impedances are real. If we also assume $B = 0$, then (1.9) reduces to

$$\frac{1}{Z_1} + \frac{1}{Z_2} = \frac{1}{Z_0} \quad (1.10)$$

In practice, if B is not negligible, some type of discontinuity compensation or a reactive tuning element can usually be used to cancel this susceptance, at least over a narrow frequency range.

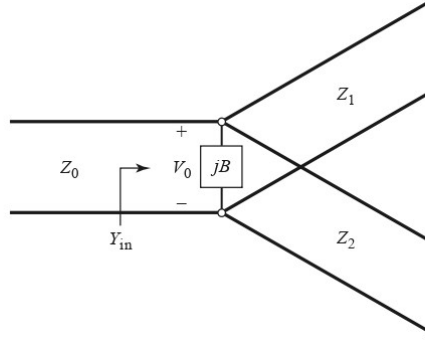


Figure 1.5 Transmission line model of a lossless T-junction divider.

The output line impedances, Z_1 and Z_2 , can be selected to provide various power division ratios. Thus, for a $50\ \Omega$ input line, a 3 dB (equal split) power divider can be made by using two $100\ \Omega$ output lines. If necessary, quarter-wave transformers can be used to bring the output line impedances back to the desired levels. If the output lines are matched, then the input line will be matched. There will be no isolation between the two output ports, however, and there will be a mismatch looking into the output ports.

Example of T-Junction power divider

A lossless T-junction power divider has a source impedance of $50\ \Omega$. We seek to find the output characteristic impedances so that the output powers are in a 2:1 ratio. We also need to compute the reflection coefficients seen looking into the output ports

If the voltage at the junction is V_0 , as shown in Figure 1.5, the input power to the matched divider is

$$P_{in} = \frac{1}{2} \frac{V_0^2}{Z_0}$$

while the output powers are

$$P_1 = \frac{1}{2} \frac{V_0^2}{Z_1} = \frac{1}{3} P_{in}$$

$$P_2 = \frac{1}{2} \frac{V_0^2}{Z_2} = \frac{2}{3} P_{in}$$

These results yield the characteristic impedances as

$$Z_1 = 3Z_0 = 150 \Omega$$

$$Z_2 = \frac{3Z_0}{2} = 75 \Omega$$

The input impedance to the junction is

$$Z_{in} = 75 \text{ parallel } 150 = 50 \Omega.$$

so that the input is matched to the 50Ω source.

Looking into the 150Ω output line, we see an impedance of $50 \parallel 75 = 30 \Omega$, while at the 75Ω output line we see an impedance of $50 \parallel 150 = 37.5 \Omega$. The reflection coefficients seen looking into these ports are

$$\Gamma_1 = \frac{30 - 150}{30 + 150} = -0.666,$$

$$\Gamma_2 = \frac{37.5 - 75}{37.5 + 75} = -0.333.$$

- Resistive Divider

If a three-port divider contains lossy components, it can be made to be matched at all ports, although the two output ports may not be isolated [5]. The circuit for such a divider is illustrated in Figure 1.6, using lumped-element resistors. An equal-split (-3 dB) divider is shown, but unequal power division ratios are also possible.

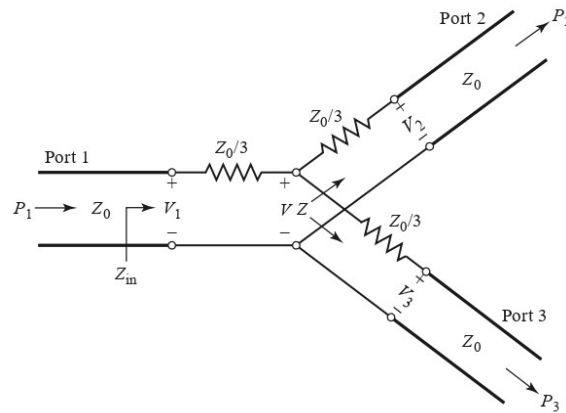


Figure 1.6 An equal-split three-port resistive power divider.

The resistive divider of Figure 1.6 can easily be analyzed using circuit theory. Assuming that all ports are terminated in the characteristic impedance Z_0 , the impedance Z , seen looking into the $Z_0/3$ resistor followed by a terminated output line, is

$$Z = \frac{Z_0}{3} + Z_0 = \frac{4Z_0}{3} \quad (1.11)$$

Then the input impedance of the divider is

$$Z_{in} = \frac{Z_0}{3} + \frac{2Z_0}{3} = Z_0 \quad (1.12)$$

which shows that the input is matched to the feed line. Because the network is symmetric from all three ports, the output ports are also matched. Thus, $S_{11} = S_{22} = S_{33} = 0$. If the voltage at port 1 is V_1 , then by voltage division the voltage V at the center of the junction is

$$V = V_1 \frac{2Z_0/3}{Z_0/3 + 2Z_0/3} = \frac{2}{3}V_1 \quad (1.13)$$

and the output voltages are, again by voltage division,

$$V_2 = V_3 = V \frac{Z_0}{Z_0 + Z_0/3} = \frac{3}{4}V = \frac{1}{2}V_1 \quad (1.14)$$

Thus, $S_{21} = S_{31} = S_{23} = 1/2$, so the output powers are 6 dB below the input power level. The network is reciprocal, so the scattering matrix is symmetric, and it can be written as

$$[S] = \frac{1}{2} \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix} \quad (1.15)$$

We can verify that this is not a unitary matrix.

The power delivered to the input of the divider is

$$P_{in} = \frac{1}{2} \frac{V_1^2}{Z_0} \quad (1.16)$$

while the output powers are

$$P_2 = P_3 = \frac{1}{2} \frac{(1/2 V_1)^2}{Z_0} = \frac{1}{8} \frac{V_1^2}{Z_0} = \frac{1}{4} P_{in} \quad (1.17)$$

which shows that half of the supplied power is dissipated in the resistors.

Conclusion

This chapter presented the fundamental concepts and theoretical foundations related to power dividers and microwave junctions. The basic operating principles of three-port networks were introduced, with particular emphasis on the scattering matrix formulation and the conditions of reciprocity, matching, and losslessness. Through theoretical analysis, it was demonstrated that a three-port network cannot simultaneously satisfy these three properties, which explains the practical limitations encountered in the design of passive microwave dividers. The chapter also highlighted the role of circulators as nonreciprocal matched three-port devices and discussed the implications of relaxing one or more of the ideal conditions.

Furthermore, the T-junction power divider was studied as one of the simplest and most widely used microwave power distribution structures. Both lossless and resistive configurations were analyzed in terms of characteristic impedances, power division ratios, matching conditions, and reflection coefficients. The presented example illustrated how unequal power division can be achieved by properly selecting the output impedances, while also revealing the mismatch observed at the output ports in lossless configurations. In contrast, the resistive divider demonstrated the possibility of obtaining matched ports at the expense of power dissipation and reduced efficiency.

CHAPTER II

Theoretical Analysis and Design of the Wilkinson Power Divider

Introduction

The lossless T-junction divider suffers from the disadvantage of not being matched at all ports, and it does not have isolation between output ports. The resistive divider can be matched at all ports, but even though it is not lossless, isolation is still not achieved. From the discussion in Chapter 1, however, we know that a lossy three-port network can be made having all ports matched, with isolation between output ports. The *Wilkinson power divider* [6] is such a network, with the useful property of appearing lossless when the output ports are matched; that is, only reflected power from the output ports is dissipated. The Wilkinson power divider can be made with arbitrary power division, but we will first consider the equal-split (3 dB) case. This divider is often made in microstrip line or stripline form, as depicted in Figure 2.1a; the corresponding transmission line circuit is given in Figure 2.1b. We will analyze this circuit by reducing it to two simpler circuits driven by symmetric and antisymmetric sources at the output ports. This “even-odd” mode analysis technique [7] will also be useful for other networks that we will encounter in other analysis.

I.1. Wilkinson Divider Structure

The Wilkinson power divider, proposed by Ernest Wilkinson in 1960, provides isolation between the output ports, is capable of being matched at all ports, and becomes lossless when the output ports are matched. Figure 2.1b shows the equivalent transmission line circuit for a Wilkinson power divider, where the power delivered to the two output ports is equal.

The design of the Wilkinson divider is composed of a transmission line (typically microstrip or stripline) that has been split into a specific number of transmission lines, each one quarter-wavelength long. In Wilkinson’s original proposal, a shorting plate is used at the input to connect each of the transmission lines. Resistors are connected between each output transmission line and a common junction. When the outputs are connected to matched loads for an equal split Wilkinson, the voltages along each output transmission line are of the same magnitude and phase. This causes the connecting resistors to have no voltage drop across them, and consequently, dissipate no power [2].

II.2. Operating Assumptions

The theoretical analysis of the Wilkinson power divider relies on several assumptions that simplify the mathematical process and yield accurate results under ideal conditions [8]:

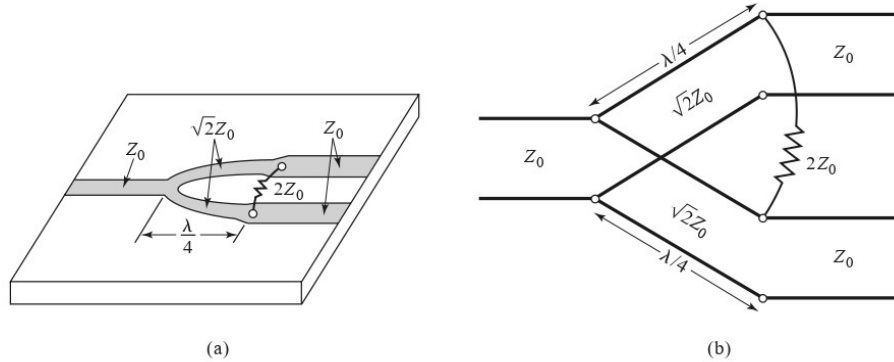


Figure 2.1 The Wilkinson power divider. (a) An equal-split Wilkinson power divider in microstrip line form. (b) Equivalent transmission line circuit.

II.2.1 The system is perfectly symmetrical:

This means that all transmission lines and the circuits connected to them are identical in their properties. In other words, there is no variation between the components of the system, ensuring that the power is divided evenly between the output ports, and each part behaves in the same way

II.2.2 The loads connected to the ports are equal:

This assumption ensures that all output ports are connected to resistive loads of equal value. With matched loads, the power divider splits the input power equally between the output ports, which is crucial for achieving balanced performance. Equal loads also minimize reflection and ensure efficient power distribution

II.2.3 The transmission lines are lossless:

This assumption states that there is no power loss within the transmission lines. In reality, transmission lines have losses due to resistance and other factors, but for the sake of ideal analysis, we assume the lines are lossless.

This assumption ensures that the total power entering the system is equal to the total power output, with no energy dissipated within the transmission lines.

II.2.4 The operating frequency corresponds to the frequency for which the design was intended:

The transmission lines are designed to have a physical length of one-quarter wavelength at the operating frequency. This quarter-wave length is crucial because it defines the impedance transformation properties of the lines, allowing the Wilkinson divider to function optimally at

this frequency. Deviations from the designed frequency can cause the divider's performance to degrade, especially in terms of impedance matching and power distribution.

Based on these assumptions, the Wilkinson power divider behaves ideally in its applications. The system is designed to divide power symmetrically, provide isolation between the output ports, and maintain a match at all ports when the loads are correctly matched.

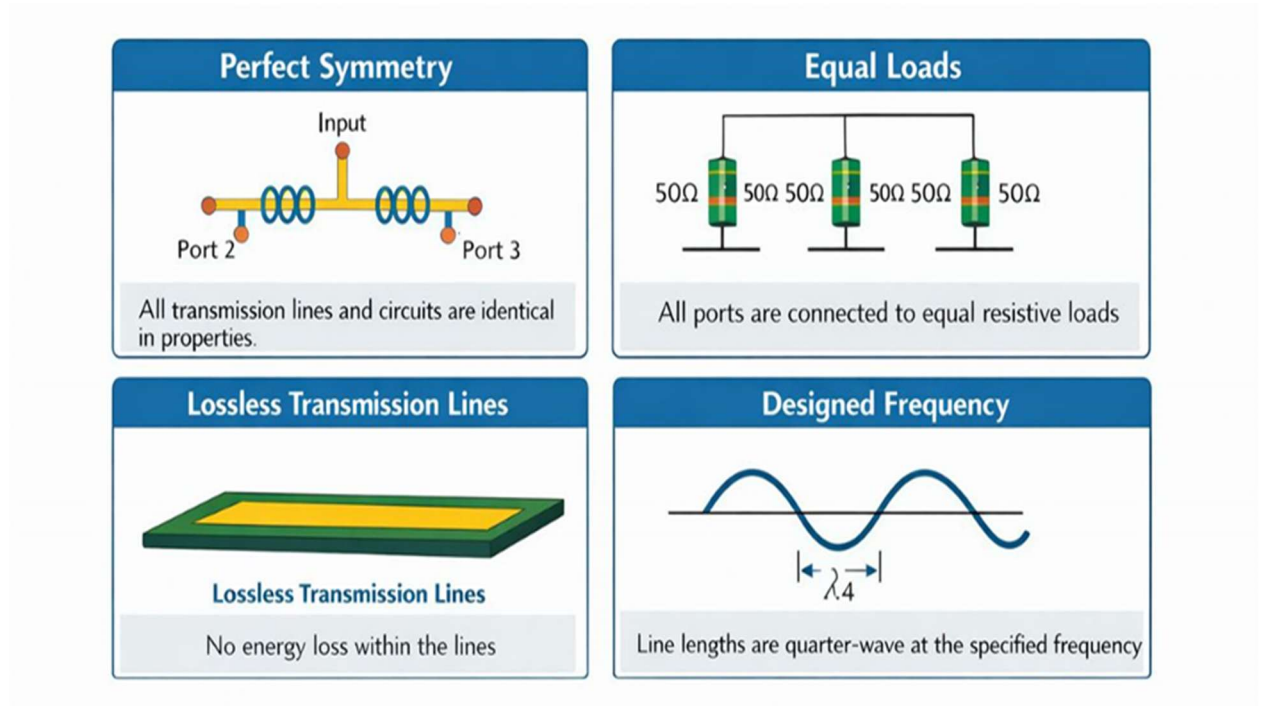


Figure 2.2 Operating Assumptions.

II.3. Even-Odd Mode Analysis [2]

The Wilkinson power divider's design and functionality can be analyzed by performing an even-odd mode analysis. This analysis utilizes superposition and circuit symmetry to solve for incident and reflected voltages. Once these voltages are obtained, the scattering matrix of the Wilkinson can be derived. Initially, a Wilkinson featuring a source of value V_s at port two is considered, while ports one and three are terminated with loads of impedance Z_0 .

For simplicity, we can normalize all impedances to the characteristic impedance Z_0 , and redraw the circuit of Figure 2.1b with voltage generators at the output ports as shown in Figure 2.3. This network has been drawn in a form that is symmetric across the midplane; the two source resistors of normalized value 2 combine in parallel to give a resistor of normalized value 1, representing the impedance of a matched source. The quarter-wave lines have a

normalized characteristic impedance Z , and the shunt resistor has a normalized value of r ; we shall show that, for the equal-split power divider, these values should be $Z = \sqrt{2}$ and $r = 2$, as given in Figure 2.1.

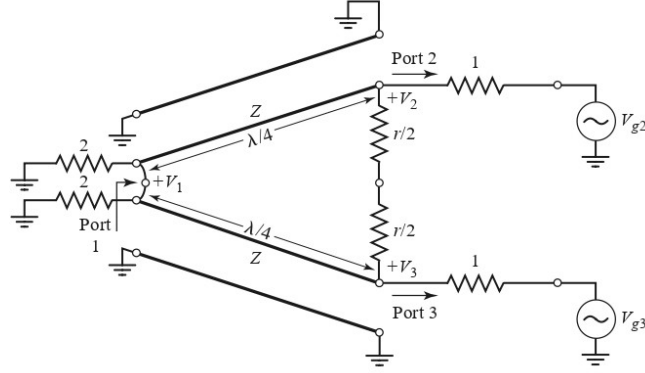


Figure 2.3 The Wilkinson power divider circuit in normalized and symmetric form.

Now define two separate modes of excitation for the circuit of Figure 2.3: the *even mode*, where $V_{g2} = V_{g3} = 2V_0$, and the *odd mode*, where $V_{g2} = -V_{g3} = 2V_0$. Superposition of these two modes effectively produces an excitation of $V_{g2} = 4V_0$ and $V_{g3} = 0$, from which we can find the scattering parameters of the network. We now treat these two modes separately.

Even mode :

For even-mode excitation, $V_{g2} = V_{g3} = 2V_0$, so $V_{2e} = V_{3e}$, and therefore no current flows through the $r/2$ resistors or the short circuit between the inputs of the two transmission lines at port 1. We can then bisect the network of Figure 2.3 with open circuits at these points to obtain the network of Figure 2.4a (the grounded side of the $\lambda/4$ line is not shown). Then, looking into port 2, we see an impedance

$$Z_{in}^e = \frac{Z^2}{2} \quad (2.1)$$

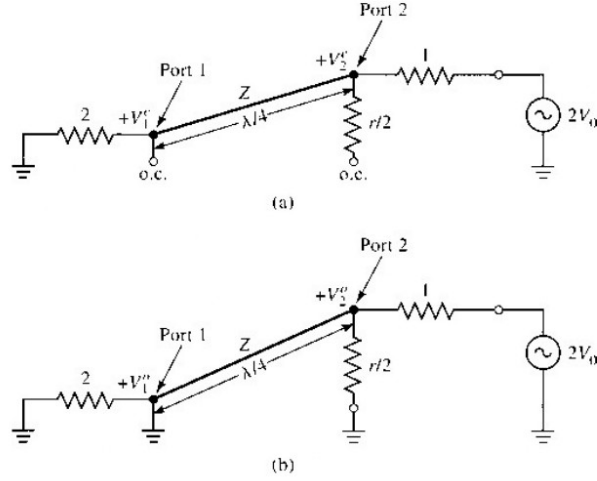


Figure 2.4 Bisection of the circuit of Figure 2.3. (a) Even-mode excitation. (b) Odd-mode excitation.

since the transmission line looks like a quarter-wave transformer. Thus, if $Z = \sqrt{2}$, port 2 will be matched for even-mode excitation ; then $V_2^e = V_0$ since $Z_{in}^e = 1$. The $r/2$ resistor is superfluous in this case since one end is open-circuited. Next, we find V_1^e from the transmission line equations. If we let $x = 0$ at port 1 and $x = -\lambda/4$ at port 2, we can write the voltage on the transmission line section as

$$V(x) = V^+(e^{-j\beta x} + \Gamma e^{j\beta x}).$$

Then

$$V_2^e = V(-\lambda/4) = jV^+(1 - \Gamma) = V_0, \quad (2.2a)$$

$$V_1^e = V(0) = V^+(1 + \Gamma) = jV_0 \frac{\Gamma + 1}{\Gamma - 1}. \quad (2.2b)$$

The reflection coefficient Γ is that seen at port 1 looking toward the resistor of normalized value 2, so

$$\Gamma = \frac{2 - \sqrt{2}}{2 + \sqrt{2}},$$

and

$$V_1^e = -jV_0\sqrt{2}. \quad (2.3)$$

Odd mode :

For odd-mode excitation, $V_{g2} = -V_{g3} = 2V_0$, and so $V_2^0 = -V_3^0 V_{2e}$, and there is a voltage null along the middle of the circuit in Figure 2.3. We can then bisect this circuit by grounding it at two points on its midplane to give the network of Figure 2.4b. Looking into port 2, we see an impedance of $r/2$ since the parallel-connected transmission line is $\lambda/4$ long and shorted at port 1, and so looks like an open circuit at port 2. Thus, port 2 will be matched for odd-mode excitation if we select $r = 2$. Then $V_2^0 = V_0$ and $V_1^0 = 0$; for this mode of excitation all power is delivered to the $r/2$ resistors, with none going to port 1.

Finally, we must find the input impedance at port 1 of the Wilkinson divider when ports 2 and 3 are terminated in matched loads. The resulting circuit is shown in Figure 2.5a, where it is seen that this is similar to an even mode of excitation since $V_2 = V_3$.

No current flows through the resistor of normalized value 2, so it can be removed, leaving the circuit of Figure 7.5b. We then have the parallel connection of two quarter-wave transformers terminated in loads of unity (normalized). The input impedance is

$$Z_{in} = \frac{1}{2}(\sqrt{2})^2 = 1. \quad (2.4)$$

In summary, we can establish the following scattering parameters for the Wilkinson divider:

$$\begin{array}{ll} S_{11} = 0 & (Z_{in} = 1 \text{ at port 1}) \\ S_{22} = S_{33} = 0 & (\text{ports 2 and 3 matched for even and odd modes}) \\ S_{12} = S_{21} = \frac{V_1^e + V_1^o}{V_2^e + V_2^o} = -j/\sqrt{2} & (\text{symmetry due to reciprocity}) \\ S_{13} = S_{31} = -j/\sqrt{2} & (\text{symmetry of ports 2 and 3}) \\ S_{23} = S_{32} = 0 & (\text{due to short or open at bisection}) \end{array}$$

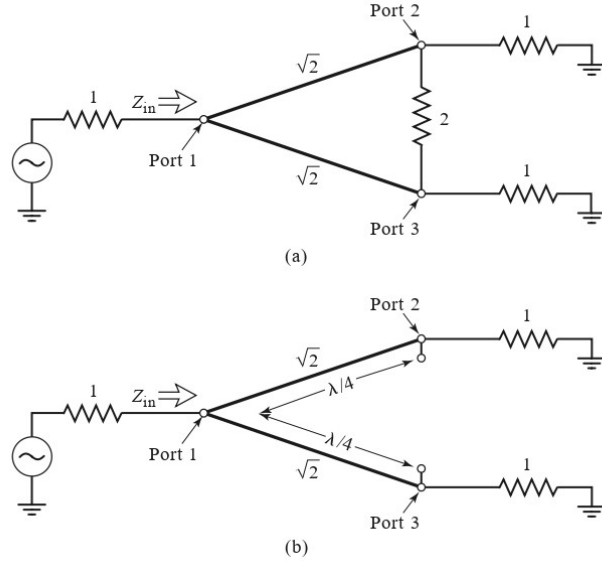


Figure 2.5 Analysis of the Wilkinson divider to find S_{11} . (a) The terminated Wilkinson divider. (b) Bisection of the circuit.

The preceding formula for S_{12} applies because all ports are matched when terminated with matched loads. Note that when the divider is driven at port 1 and the outputs are matched, no power is dissipated in the resistor. Thus the divider is lossless when the outputs are matched; only reflected power from ports 2 or 3 is dissipated in the resistor. Because $S_{23} = S_{32} = 0$, ports 2 and 3 are isolated.

II.4. Unequal Power Division and N-Way Wilkinson Dividers

Wilkinson-type power dividers can also be made with unequal power splits; a microstrip line version is shown in Figure 2.6. If the power ratio between ports 2 and 3 is $K^2 = P_3/P_2$, then the following design equations apply:

$$Z_{03} = Z_0 \sqrt{\frac{1 + K^2}{K^3}} \quad (2.5a)$$

$$Z_{02} = K^2 Z_{03} = Z_0 \sqrt{K(1 + K^2)}, \quad (2.5b)$$

$$R = Z_0 \left(K + \frac{1}{K} \right). \quad (2.5c)$$

Note that the above results reduce to the equal-split case for $K = 1$. Also observe that the output lines are matched to the impedances $R_2 = Z_0 K$ and $R_3 = Z_0 / K$, as opposed to the impedance Z_0 ; matching transformers can be used to transform these output impedances. The Wilkinson divider can also be generalized to an N -way divider or combiner [9], as shown in Figure 2.7. This circuit can be matched at all ports, with isolation between all ports. A disadvantage, however, is the fact that the divider requires crossovers for the resistors for $N \geq 3$, which makes fabrication difficult in planar form. The Wilkinson divider can also be made with stepped multiple sections, for increased bandwidth. A photograph of a four-way Wilkinson divider network is shown in Figure 2.8.

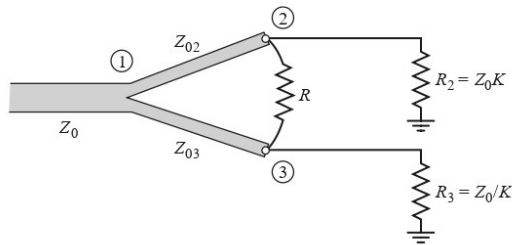


Figure 2.6 A Wilkinson power divider in microstrip form having unequal power division.

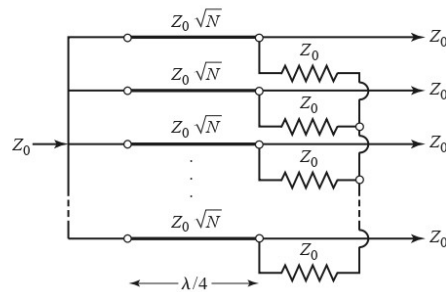


Figure 2.7 An N -way, equal-split Wilkinson power divider.

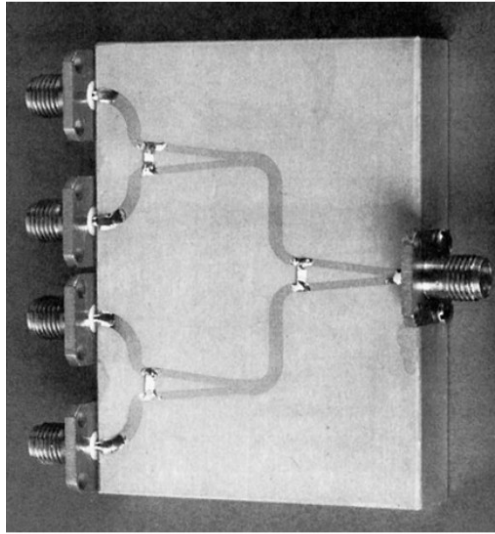


Figure 2.8 Photograph of a four-way corporate power divider network using three microstrip Wilkinson power dividers. Note the isolation chip resistors [2].

II.5. Example of Design and Performance of a Wilkinson Divider [2]

We want to design an equal-split Wilkinson power divider, as shown in Figure 2.9, for a $50\ \Omega$ system impedance at the frequency f_0 , and plot the return loss (S_{11}), insertion loss ($S_{21} = S_{31}$), and isolation ($S_{23} = S_{32}$) versus frequency over the range from $0.5 f_0$ to $1.5 f_0$.



Figure 2.9 Photograph of Wilkinson Power Divider with $Z_0 = 50 \Omega$.

From Figure 2.1 and the above derivation, we have that the quarter-wave transmission lines in the divider should have a characteristic impedance

$$Z = \sqrt{2}Z_0 = 70.7 \Omega,$$

and the shunt resistor a value of

$$R = 2Z_0 = 100 \Omega.$$

The transmission lines are $\lambda/4$ long at the frequency f_0 .

Using a computer-aided design tool for the analysis of microwave circuits, the scattering parameter magnitudes were calculated and plotted in Figure 2.10.

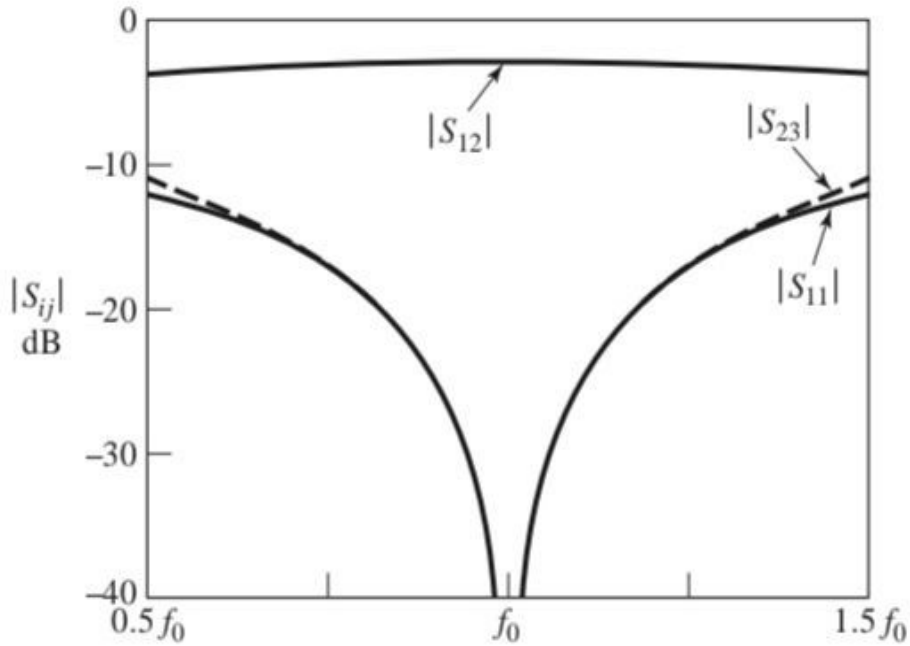


Figure 2.10 Frequency response of an equal-split Wilkinson power divider. Port 1 is the input port; ports 2 and 3 are the output ports.

A. Return Loss (S_{11})

The input reflection coefficient S_{11} characterizes the impedance matching at the input port of the Wilkinson power divider.

At the design frequency f_0 , S_{11} exhibits a pronounced minimum (highly negative value in dB), indicating excellent matching conditions and minimal reflected power. Under this condition, nearly all the incident power is efficiently transferred to the output ports.

A return loss better than -20 dB confirms a high-quality impedance match at f_0 . However, as the frequency deviates from the center frequency, S_{11} increases, indicating degraded matching, increased reflections, and reduced power transfer efficiency.

B. Insertion Loss ($S_{21} = S_{31}$)

The transmission coefficients S_{21} and S_{31} describe the power divider from the input port to each output port.

For an ideal lossless and perfectly symmetric Wilkinson divider, the expected value is:

$$S_{21} = S_{31} = -3 \text{ dB}$$

This correspond to an equal power split between the two output ports.

Simulation results show that around f_0 , both S_{21} and S_{31} closely follow -3 dB, confirming:

- equal power division,
- proper symmetry of the structure,
- good agreement with theoretical behavior.

Outside the design frequency, deviations appear due to phase imbalance and the frequency-dependent behavior of the quarter-wave transmission lines, resulting in increased insertion loss and non-ideal power splitting.

C. Isolation ($S_{23} = S_{32}$)

The isolation parameters S_{23} and S_{32} quantify the level of coupling between the two output ports.

In an ideal Wilkinson power divider, high isolation is achieved through the presence of an isolation resistor, which absorbs any imbalance between the output branches.

At the design frequency f_0 , S_{23} reaches a minimum (strongly negative value), indicating excellent isolation and negligible power leakage between output ports.

As the frequency deviates from f_0 , isolation degrades due to:

- imperfect phase conditions,
- reduced effectiveness of quarter-wave sections,
- increased parasitic coupling.

Following the above discussion, the obtained results confirm that the Wilkinson power divider operates optimally at the design frequency f_0 . At this frequency, the device simultaneously achieves:

- excellent input matching (low S_{11}),
- equal power division ($S_{21} = S_{31} \approx -3$ dB),
- high isolation between output ports (low S_{23}).

However, performance degradation is observed outside the design frequency, which is inherent to narrowband quarter-wave structures.

Conclusion

In this chapter, we presented a comprehensive theoretical analysis and design methodology of the Wilkinson power divider. The study began by highlighting the limitations of conventional power dividers such as the T-junction and resistive splitters. While the T-junction suffers from poor impedance matching and lack of isolation, the resistive divider, although matched and isolated, introduces significant power loss. In contrast, the Wilkinson power divider overcomes these limitations by ensuring simultaneous impedance matching at all ports, equal (or controlled) power division, and high isolation between output ports, while remaining lossless under ideal balanced conditions.

The theoretical analysis was based on key assumptions, including perfect symmetry, equal load conditions, lossless transmission lines, and operation at the design frequency corresponding to the quarter-wavelength condition. These assumptions define the ideal operating environment of the divider and also explain its limitations in practical applications, particularly its frequency sensitivity.

An even–odd mode analysis was used to rigorously derive the operation of the divider. This method simplified the three-port network into two equivalent excitation modes, enabling the derivation of key design parameters.

Finally, a practical design example for a $50\ \Omega$ system validated the theoretical results through simulation. The results confirmed excellent matching, accurate $-3\ \text{dB}$ power splitting, and high isolation at the design frequency.

CHAPTER III

Results and Discussion

Introduction

In this section, we present and analyze the simulation results of a Wilkinson power divider using the RF module integrated in MATLAB Simulink. The study focuses on the key S-parameters that characterize the performance of the device, namely the return loss (S_{11}), the transmission coefficients (S_{21} and S_{31}), and the isolation between the output ports (S_{23}). These parameters are essential for evaluating the impedance matching, power division efficiency, and port-to-port isolation of the circuit.

The simulations are carried out for four practical operating frequencies: 1.8 GHz, 2.1 GHz, 2.4 GHz, and 5 GHz. These frequencies are selected to cover commonly used wireless communication bands, ranging from cellular applications to Wi-Fi systems.

For each case, the behavior of S_{11} is examined to assess the quality of input matching at the design frequency. The parameters S_{21} and S_{31} are analyzed to verify the equal power splitting characteristic of the Wilkinson divider, ideally close to -3 dB in a lossless and perfectly symmetric configuration. In addition, S_{23} is studied to evaluate the isolation between the output ports, which should ideally be very high (strongly negative in dB) due to the presence of the isolation resistor.

The comparison across different frequencies allows us to observe how the performance of the divider evolves when operating away from its optimal design frequency. All simulations are performed using MATLAB Simulink RF toolbox, which provides accurate circuit-level modeling in the frequency domain.

Overall, this study provides a comprehensive insight into the frequency-dependent behavior of the Wilkinson power divider under realistic operating conditions.

III.1. Simulation Tool

To validate and complement the theoretical analysis of the Wilkinson power divider, numerical simulations were carried out using the RF module integrated within MATLAB Simulink. This tool provides a powerful environment for modeling and analyzing high-frequency circuits based on transmission line theory and scattering parameters. The RF Simulink toolbox allows the construction of microwave networks using ideal and practical components such as transmission lines, resistors, and ports, while enabling direct computation of S-parameters over a specified frequency range. In this chapter, it was used to evaluate the frequency-dependent behavior of the Wilkinson power divider, particularly in terms of return loss (S_{11}), transmission coefficients (S_{21} and S_{31}), and isolation (S_{23} and S_{32}). This simulation

approach bridges the gap between theoretical derivations and practical performance, offering a clear visualization of how the divider behaves under real operating conditions and confirming the validity of the analytical design.

III.2. Application Examples

In order to illustrate the practical relevance of the Wilkinson power divider, four application cases are considered at commonly used wireless communication frequencies: 1.8 GHz, 2.1 GHz, 2.4 GHz, and 5 GHz. These frequencies correspond to key standards in modern RF systems, including cellular networks and Wi-Fi applications. The performance of the divider is evaluated at each frequency in terms of its scattering parameters, namely S_{11} , S_{21} , S_{31} , and S_{23} , in order to assess impedance matching, power division accuracy, and output port isolation. This comparative study highlights how the behavior of the Wilkinson divider varies with frequency and demonstrates its effectiveness across different real-world communication bands.

III.2.1 Example1 ($f_0 = 1.8 \text{ GHz}$)

The frequency of 1.8 GHz (1800 MHz) is historically associated with the GSM mobile communication system, more specifically with the DCS 1800 band (*Digital Cellular System 1800*). It played a major role in the expansion of second-generation mobile networks (2G) around the world, especially in Europe and densely populated urban areas.

The original GSM system mainly operated at 900 MHz. While GSM 900 provided excellent coverage over large areas, it eventually became insufficient in cities where the number of mobile users increased rapidly. Network operators needed a solution capable of supporting more simultaneous users and higher traffic density.

To solve this problem, the 1800 MHz band was introduced during the early 1990s. This new band became known as DCS 1800.

The idea was simple:

- use a higher frequency,
- create smaller cells,
- increase frequency reuse,
- and improve network capacity.

Structure and Design Description

The simulated structure is a two-way Wilkinson power divider implemented using microstrip technology. The circuit consists of:

- One input port (Port 1)
- Two output ports (Port 2 and Port 3)
- Two quarter-wavelength transmission lines
- One isolation resistor connected between the output ports

The substrate used is Teflon, which is characterized by:

- Low dielectric losses
- Stable permittivity

This choice improves the overall RF performance, especially at microwave frequencies.

Figure III.1 shows the design of a Wilkinson power divider fabricated on a Teflon substrate. The conductive lines (PEC), input/output feeds, and load are illustrated. This structure is used to equally divide the input signal into two output signals while ensuring good impedance matching and minimal reflections at 1.8 GHz.

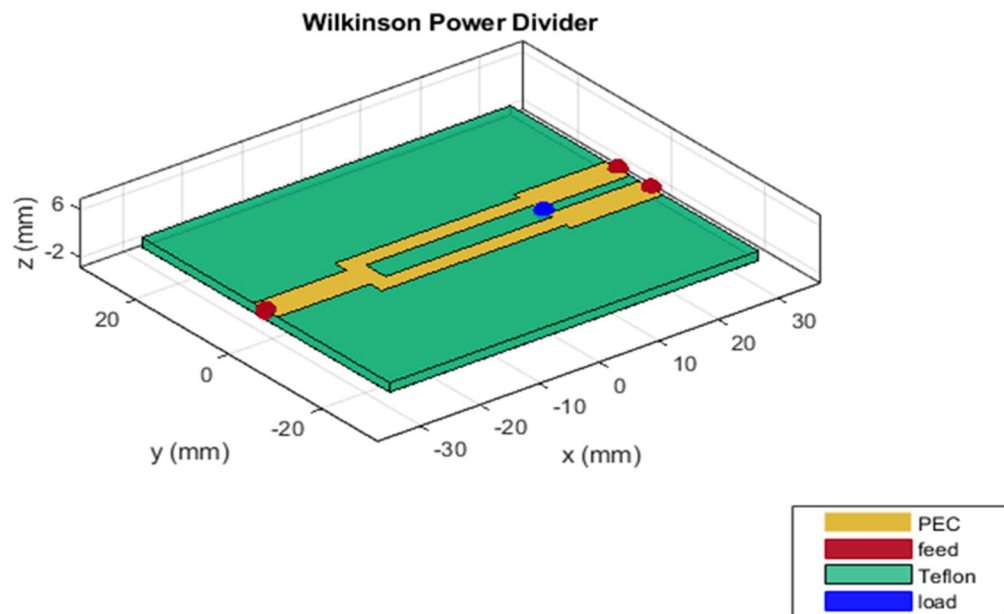


Figure 3.1. Wilkinson Power Divider Structure at 1.8 GHz.

S-Parameters Analysis

Figure 3.2 shows the S_{11} parameter, representing the input return loss of the Wilkinson power divider, and evaluates the impedance matching at the input port.

At the operating frequency of 1.8 GHz, the simulated S_{11} value reaches a very low level (highly negative in dB), indicating excellent impedance matching between the source and the divider input. This means that most of the incident power is transmitted toward the output ports, while only a very small portion is reflected back to the source.

The obtained results confirm that the designed structure provides efficient power transfer with minimal reflection losses at the design frequency. As the frequency moves away from 1.8 GHz, the return loss gradually increases, which indicates a degradation of the matching performance outside the operating band.

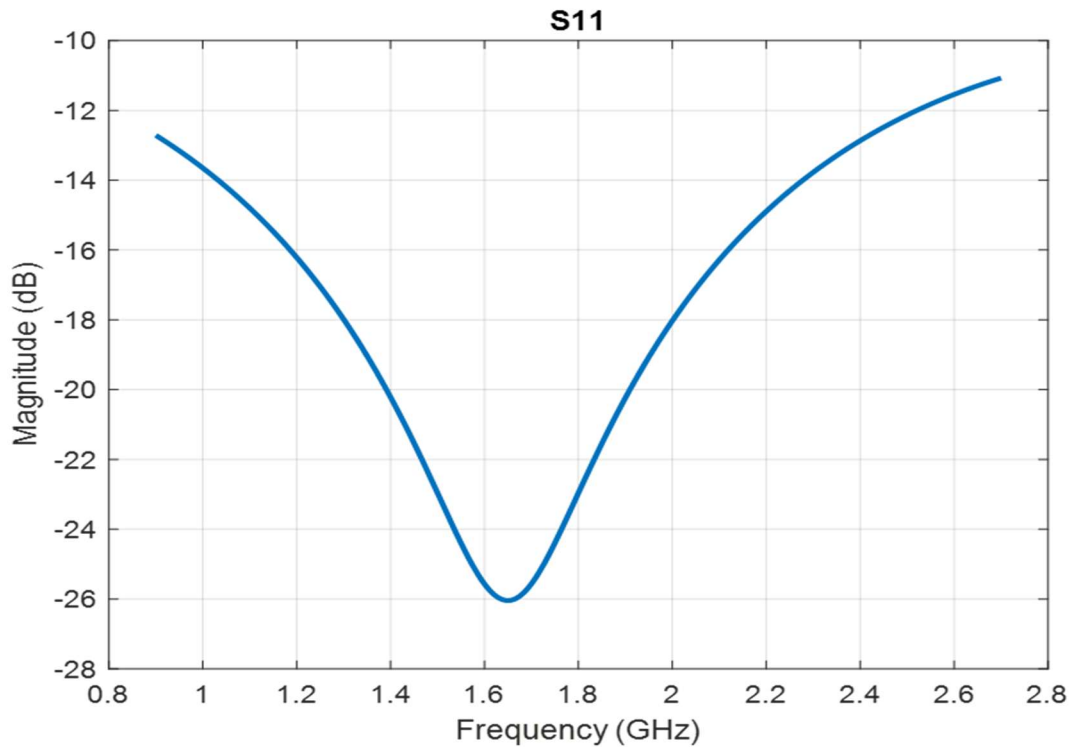


Figure 3.2. S_{11} Parameter (Return Loss) for $f = 1.8$ GHz.

Figure 3.3 shows the S_{21} parameter, which represents the transmission coefficient between Port 1 and Port 2.

At the center frequency of 1.8 GHz, the simulated value of S_{21} is close to -3 dB, which corresponds to the theoretical behavior of an ideal equal-split Wilkinson power divider. This result indicates that approximately half of the input power is transmitted to Port 2.

The low insertion loss observed around the operating frequency demonstrates the effectiveness of the quarter-wavelength transmission lines in achieving efficient power division. The response also confirms that the divider operates correctly within the intended frequency range.

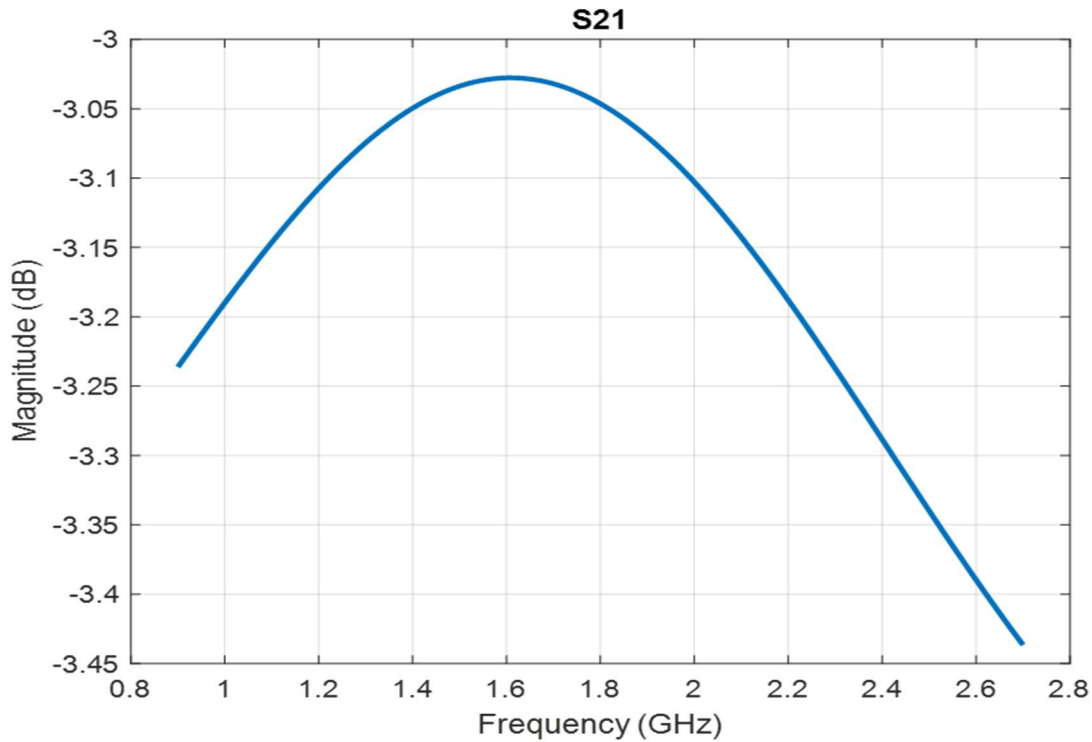


Figure 3.3. S_{21} Parameter (Transmission Coefficient, Port 2), for $f = 1.8$ GHz.

Figure 3.4 shows the S_{31} parameter, which represents the transmission coefficient between Port 1 and Port 3.

The simulated curve of S_{31} exhibits nearly the same behavior as S_{21} , with a value close to -3 at 1.8 GHz. This confirms that the input power is equally divided between the two output ports.

The symmetry between the S_{21} and S_{31} responses demonstrates that the two branches of the divider possess identical electrical characteristics. Therefore, the Wilkinson divider achieves balanced power distribution with good transmission efficiency.

Figure 3.5 shows the S_{23} parameter, which represents the isolation between the two output ports of the Wilkinson power divider.

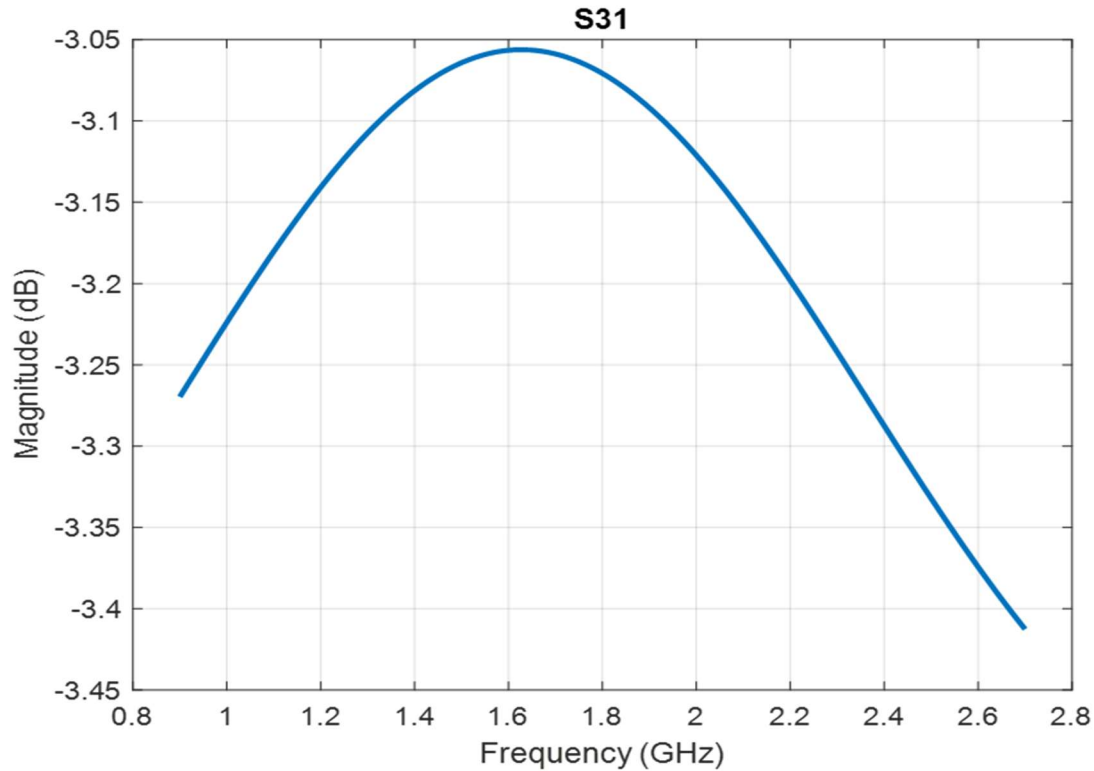


Figure 3.4. S_{31} Parameter (Transmission Coefficient, Port 3) for $f = 1.8$ GHz.

At the operating frequency of 1.8 GHz, the S_{23} value becomes very low (highly negative in dB), indicating excellent isolation between Ports 2 and 3. This means that the signal transmitted to one output port has minimal influence on the other output port. The high isolation performance is mainly achieved by the isolation resistor connected between the output ports. This characteristic is particularly important in RF and microwave systems, where unwanted coupling between ports can degrade the overall system performance.

The above simulated results demonstrate that the designed Wilkinson power divider operating at 1.8 GHz achieves satisfactory RF and microwave performance. The structure provides:

- excellent input impedance matching,
- equal power division between the output ports,
- low insertion losses,
- and high isolation between outputs.

In addition, the use of a Teflon substrate contributes to improved performance due to its low dielectric losses and stable electrical properties at microwave frequencies.

Therefore, the proposed Wilkinson power divider is suitable for GSM/DCS 1800 and other microwave communication applications operating around 1.8GHz.

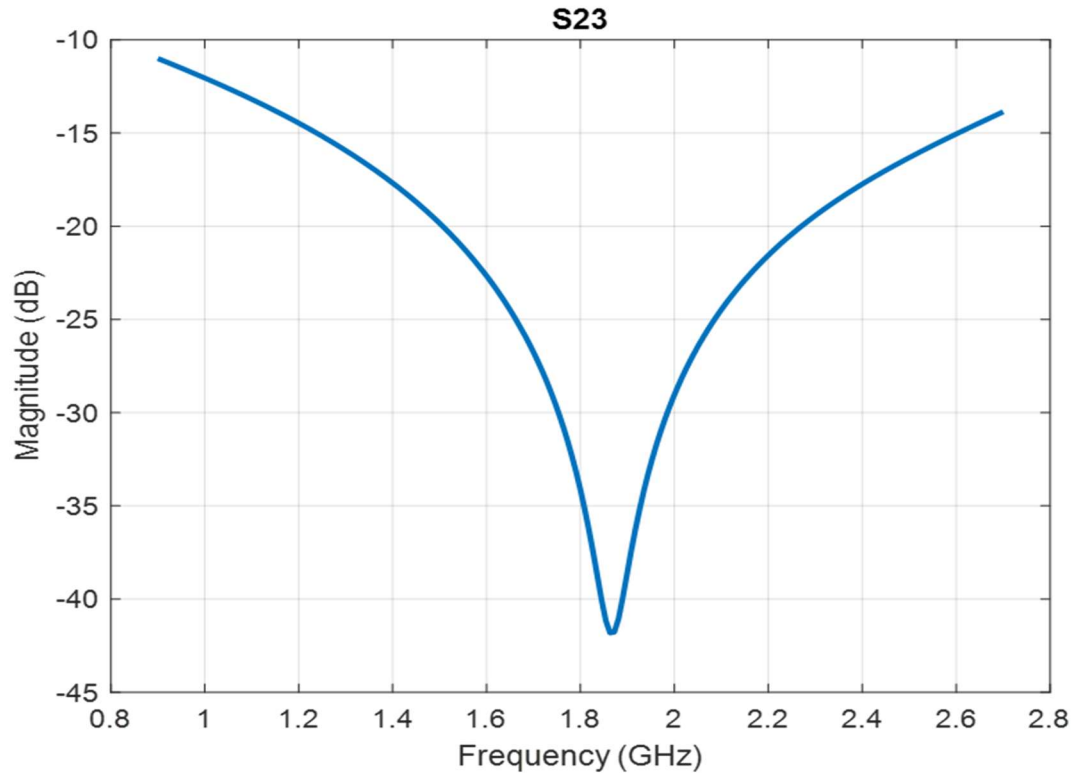


Figure 3.5. S_{23} Parameter (Isolation between Port 2 and Port 3) for $f = 1.8$ GHz.

III.2.2 Example2 ($f_0 = 2.1$ Ghz)

The frequency of 2.1 GHz (2100 MHz) is strongly associated with third-generation mobile communication systems (3G), particularly the UMTS (Universal Mobile Telecommunications System) standard. This band marked a major step forward compared to 2G systems, enabling higher data rates and supporting services such as video calls, mobile internet browsing, and multimedia transmission.

The 2100 MHz band was widely adopted in Europe, Asia, and many other regions as the primary spectrum for UMTS deployment. Unlike GSM systems that were mainly designed for voice communication and low-rate data services, UMTS introduced a more advanced air interface capable of handling significantly larger bandwidth and improved spectral efficiency.

The motivation behind using the 2.1 GHz band can be summarized as follows:

- to provide higher data transmission rates,
- to support emerging multimedia mobile applications,
- to improve network capacity for increasing user demand,
- and to enable more flexible and efficient spectrum usage.

However, similar to other higher-frequency bands, the 2.1 GHz system also comes with trade-offs, such as slightly reduced coverage range compared to lower-frequency GSM bands, requiring a denser network of base stations in urban environments.

Structure and Design Description

For $f = 2.1$ GHz, a two-way Wilkinson power divider is implemented using microstrip technology, similar to the case of $f = 1.8$ GHz. It consists of one input port, two output ports, two quarter-wavelength lines, and an isolation resistor between the outputs to ensure proper isolation and equal power splitting.

A Teflon substrate is used due to its low losses and stable permittivity, improving RF performance at microwave frequencies.

Figure 3.6 illustrates the layout of the Wilkinson power divider on Teflon, showing the PEC transmission lines and port configuration. The structure is used to equally split the input signal into two outputs at 2.1 GHz while maintaining good impedance matching and reducing reflections.

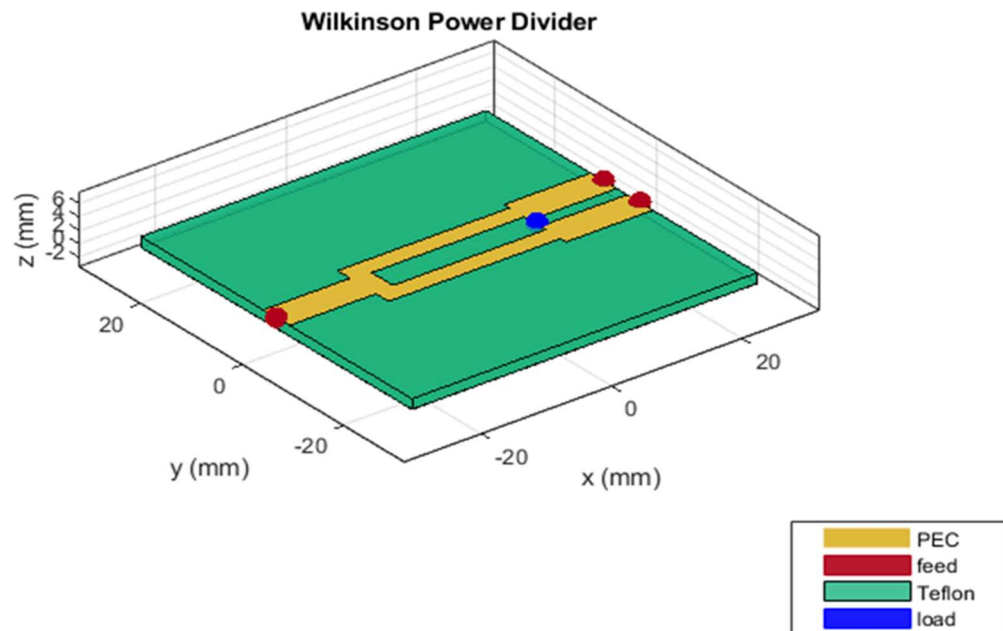


Figure 3.6. Wilkinson Power Divider Structure at 2.1 GHz.

S-Parameters Analysis

The simulated Wilkinson power divider operating at 2.1 GHz demonstrates the expected theoretical behavior of an ideal equal-split network implemented in microstrip technology.

The layout shown in Figure 3.6 confirms a standard two-way Wilkinson configuration on a Teflon substrate. The structure clearly defines the input/output ports and conductive microstrip lines, ensuring a symmetric geometry that is essential for balanced power division and stable RF performance at the target frequency.

The S_{11} response (Figure 3.7) exhibits a pronounced dip around 2.1 GHz, indicating strong impedance matching at the design frequency. This low reflection level confirms that the input signal is efficiently transferred into the network with minimal return loss, which reflects a well-optimized design.

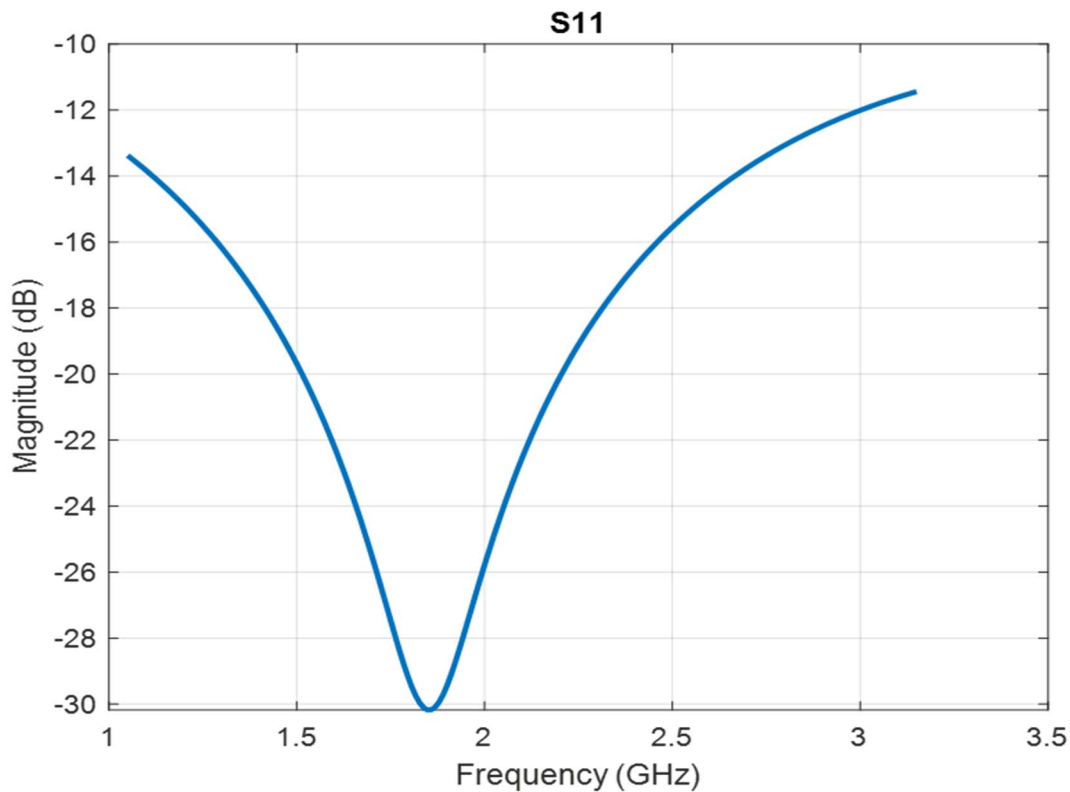


Figure 3.7. S_{11} Parameter (Return Loss) for $f = 2.1$ GHz.

Regarding the transmission characteristics, both S_{21} (Figure 3.8) and S_{31} (Figure 3.9) remain close to -3 dB at 2.1 GHz, which validates the equal power split between the two output ports. The symmetry between these two curves also confirms that the structure is well balanced, with negligible amplitude imbalance or design asymmetry.

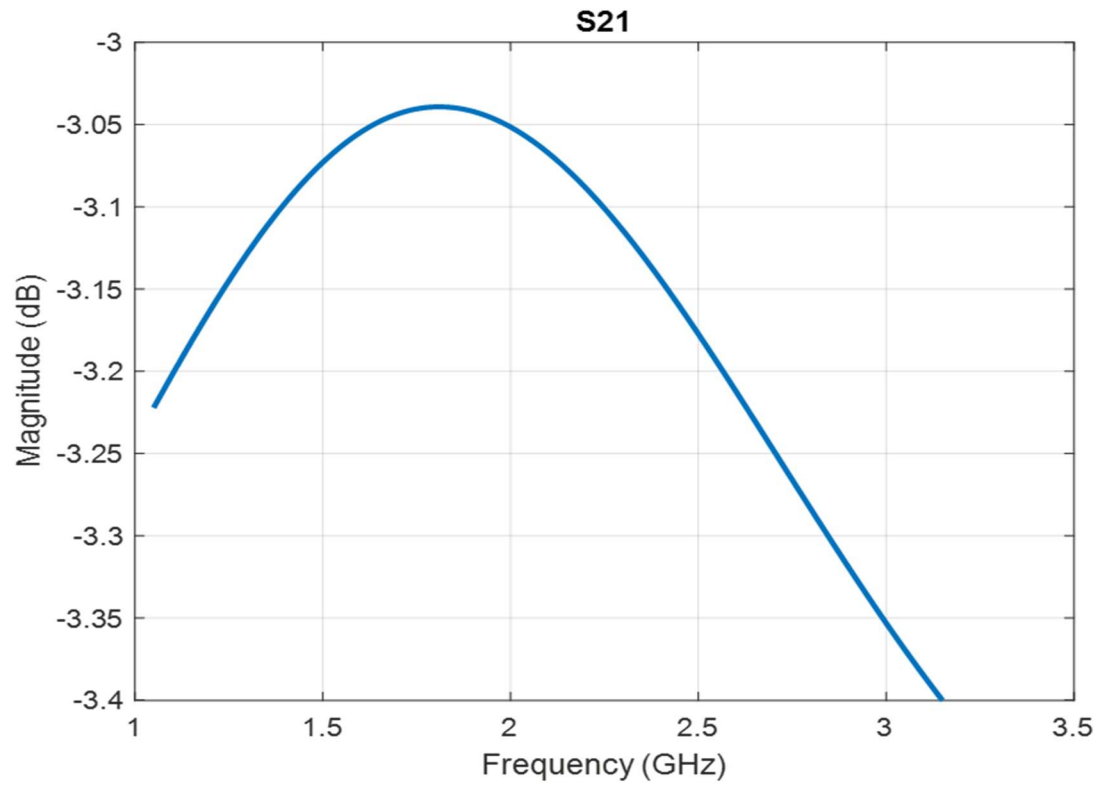


Figure 3.8. S_{21} Parameter (Transmission Coefficient, Port 2), for $f = 2.1$ GHz.

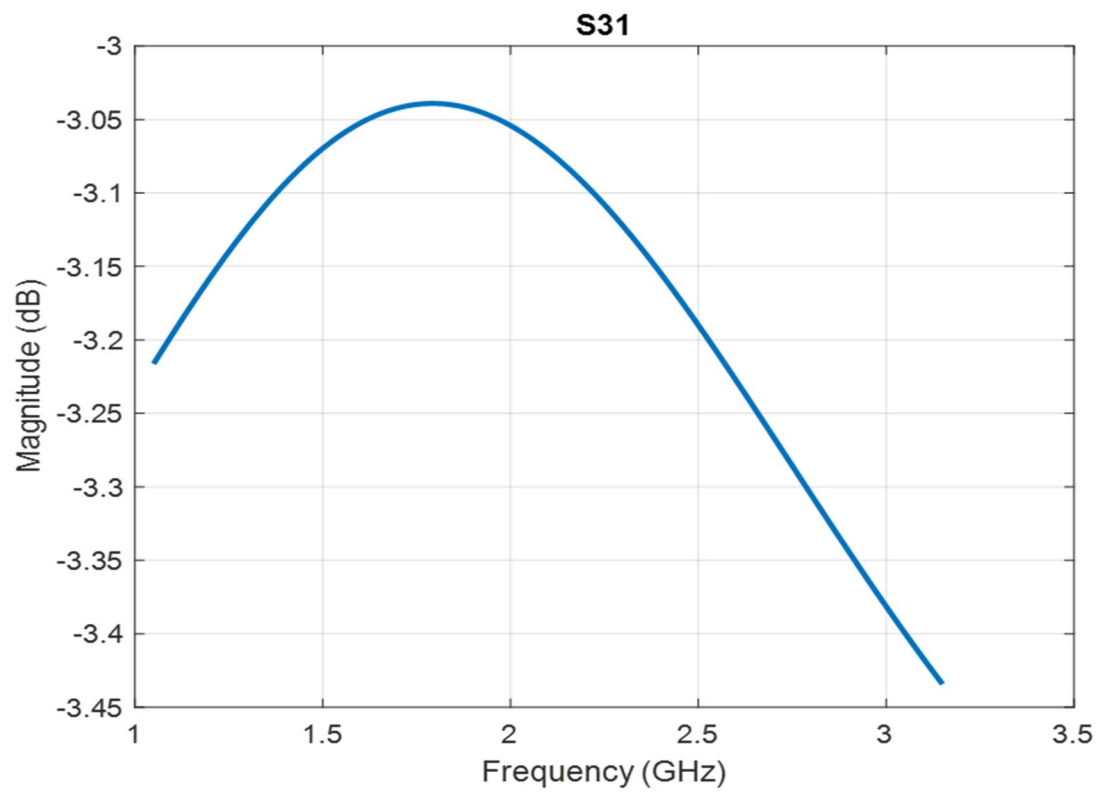


Figure 3.9. S_{31} Parameter (Transmission Coefficient, Port 3) for $f = 2.1$ GHz.

The isolation parameter S_{23} (Figure 3.10) shows a very low value around -30 dB to -33 dB at the operating frequency, demonstrating strong isolation between the output ports. This performance is a direct result of the isolation resistor, which effectively suppresses undesired coupling and ensures independent operation of the output channels.

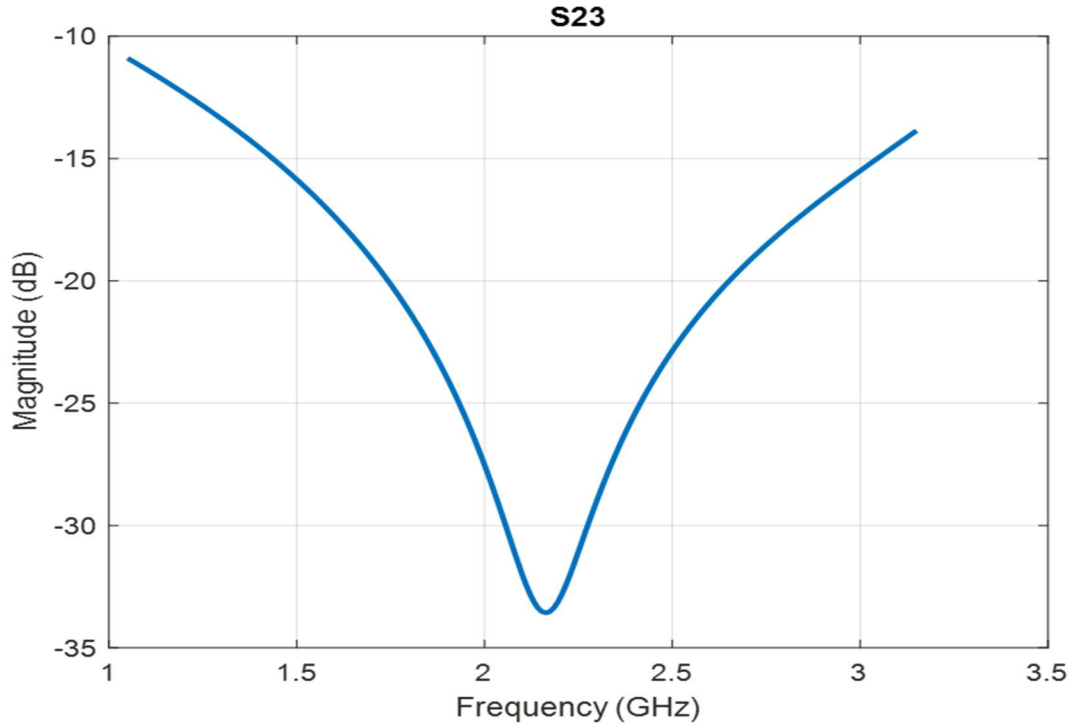


Figure 3.10. S_{23} Parameter (Isolation between Port 2 and Port 3) for $f = 2.1$ GHz.

Overall, the results at 2.1 GHz confirm that the Wilkinson power divider operates efficiently, providing good matching, accurate equal power division, and high isolation, all of which are key requirements for microwave communication systems.

III.2.3 Example3 ($f_0 = 2.4$ Ghz)

The operating frequency of 2.4 GHz is widely recognized as a cornerstone of modern short-range wireless communications. It serves as the foundation for the Industrial, Scientific, and Medical (ISM) band, which hosts a multitude of consumer and industrial applications. Among the most prominent standards operating in this band are Wi-Fi (IEEE 802.11b/g/n/ax), Bluetooth, Zigbee, and various cordless phone systems.

The choice of 2.4 GHz offers a practical trade-off between wavelength, antenna size, and propagation characteristics, enabling compact device designs while maintaining reasonable indoor coverage. Unlike the cellular-centric frequencies of 1.8 GHz and 2.1 GHz, the 2.4 GHz

band is license-free, which has fueled the proliferation of countless wireless devices in home, office, and industrial environments. However, this popularity also brings challenges, such as increased interference from coexisting systems, making good isolation and impedance matching even more critical.

- **Structure and Design Description**

For the 2.4 GHz case, the Wilkinson power divider is again realized using microstrip technology on a Teflon substrate. Teflon is retained for its favorable microwave properties, including a stable relative permittivity and low dissipation factor, which help maintain consistent performance at higher frequencies.

The circuit topology remains classic and unchanged from the previous examples:

- Port 1: Input port.
- Ports 2 and 3: Two symmetrical output ports.
- Two quarter-wavelength transmission lines: These are dimensioned to be exactly $\lambda/4$ at 2.4 GHz, transforming the impedance from 100 Ω (at the outputs) to 50 Ω at the input.
- One isolation resistor: Connected directly between Port 2 and Port 3, whose value is typically 100 Ω for a 50 Ω system, ensuring that any reflected or coupled power between the output arms is dissipated rather than reaching the opposite port.

The layout, depicted in Figure 3.11, shows a symmetric three-dimensional view of the conductive microstrip lines (modeled as perfect electric conductors — PEC) over the Teflon dielectric substrate. The input and output feeds, along with the terminations, are clearly indicated. This symmetrical geometry is essential to guarantee equal electrical path lengths for both branches, which in turn ensures that the two output signals have identical amplitude and phase.

S-Parameters Analysis

Input Return Loss (S_{11})

The reflection coefficient at the input port, S_{11} , is plotted across a frequency span around the design target (Figure 3.11). A pronounced null is observed very close to 2.41 GHz, with a magnitude of approximately –22 dB. In practical terms, a value below –20 dB is considered excellent matching, indicating that over 99% of the incident power is transferred into the divider, while less than 1% is reflected back toward the source. The narrow and deep nature of this dip confirms that the quarter-wave transformers have been precisely dimensioned for the 2.4 GHz center frequency.

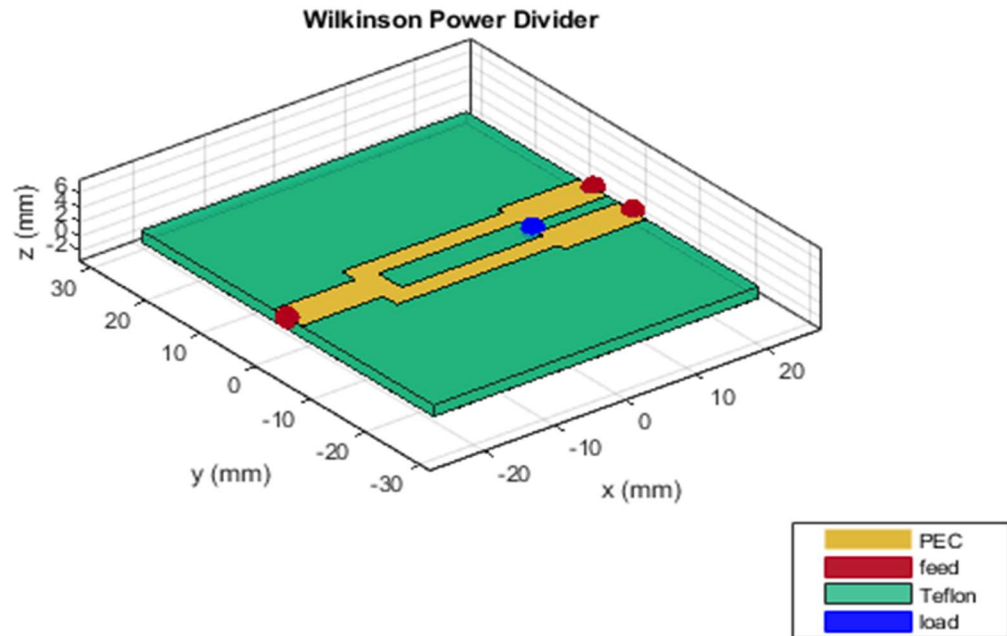


Figure 3.11. Wilkinson Power Divider Structure at 2.4 GHz.

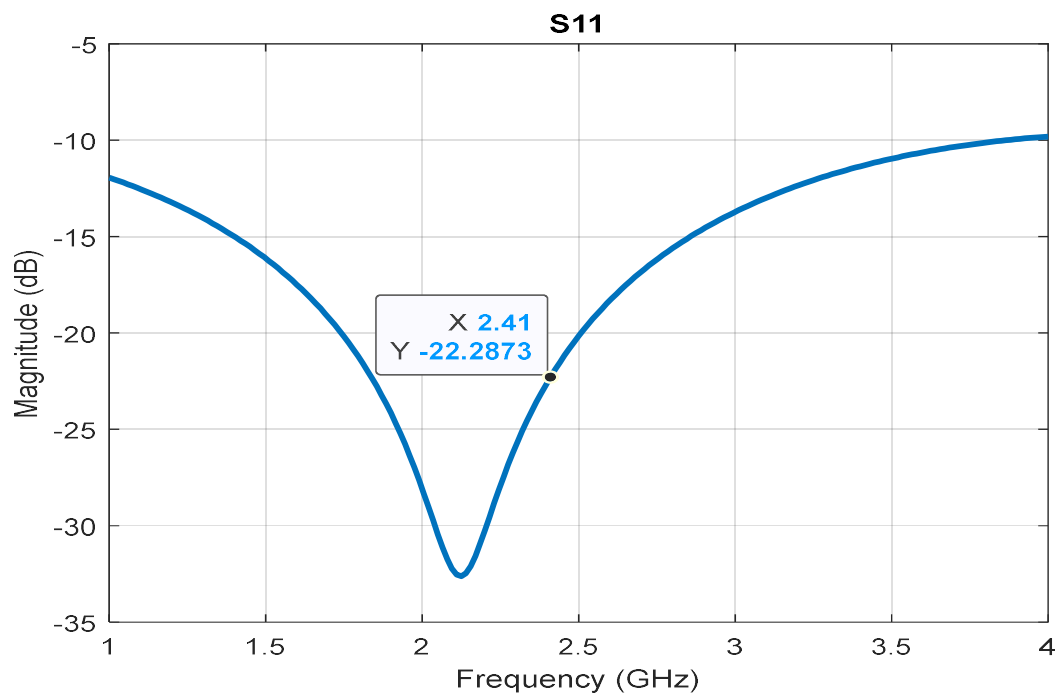


Figure 3.12. S₁₁ Parameter (Return Loss) for f = 2.4 GHz.

Transmission Coefficients (S_{21} and S_{31})

Both forward transmission parameters are analyzed together, as they jointly characterize the power splitting capability of the divider.

- At 2.41 GHz, S_{21} (Figure 3.13) reaches approximately -3.07 dB.
- S_{31} (Figure 3.14) shows a nearly identical value of around -3.08 dB at the same frequency.

These results are extremely close to the theoretical -3 dB target for an ideal lossless equal-split divider. The slight deviation (approximately 0.07 to 0.08 dB) can be attributed to minor resistive losses in the microstrip lines and the isolation resistor, as well as numerical precision in the simulation. The near-perfect overlap between the S_{21} and S_{31} curves across the entire displayed frequency range demonstrates excellent structural symmetry. Therefore, the divider successfully delivers half the input power to each output port with negligible amplitude imbalance.

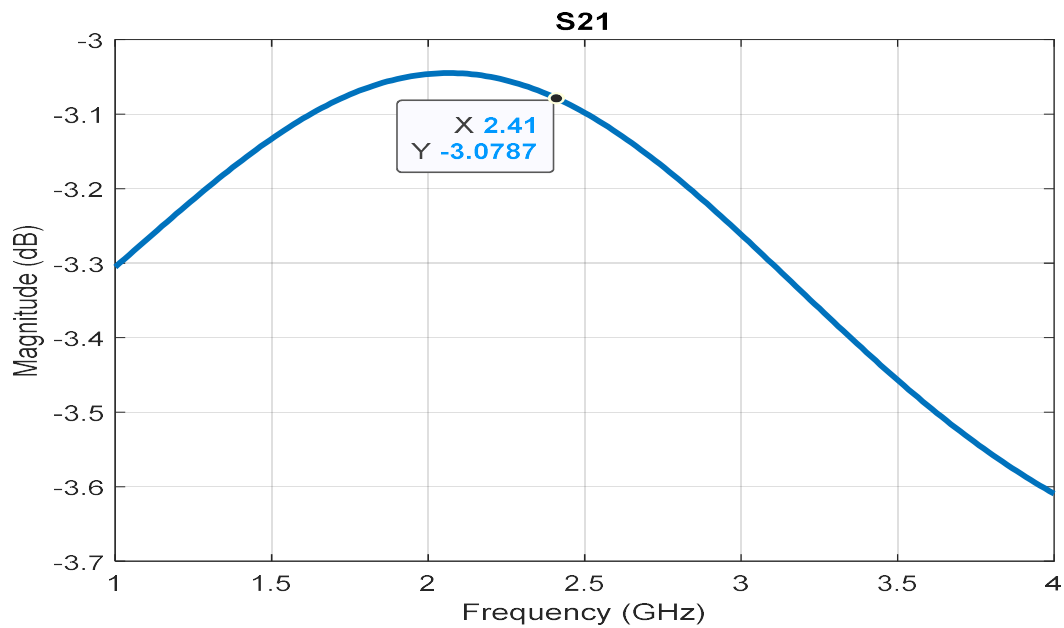


Figure 3.13. S_{21} Parameter (Transmission Coefficient, Port 2), for $f = 2.4$ GHz.

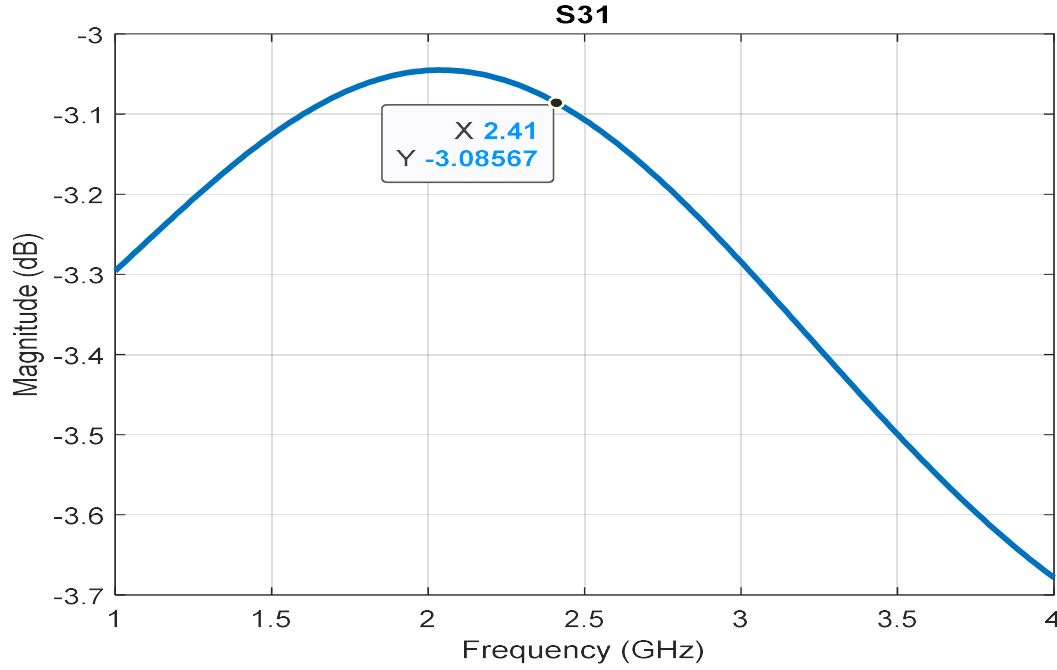


Figure 3.14. S_{31} Parameter (Transmission Coefficient, Port 3) for $f = 2.4$ GHz.

Output Isolation (S_{23})

The isolation between the two output ports is captured by the S_{23} (Figure 3.15) parameter. At the design frequency of 2.41 GHz, the curve drops to a minimum of approximately -30 dB. This level of isolation is highly satisfactory for most RF applications, as it means that any signal attempting to travel from Port 2 to Port 3 (or vice versa) is attenuated by a factor of 1000 in power. This performance is primarily enabled by the $100\ \Omega$ isolation resistor, which dissipates out-of-phase energy that would otherwise couple between the two branches. Good isolation is particularly beneficial in 2.4 GHz systems, where antenna crosstalk or reflected signals from mismatched loads could otherwise degrade receiver sensitivity.

The simulated results at 2.4 GHz confirm that the designed Wilkinson power divider meets the key performance criteria for practical wireless applications :

- Excellent input matching ($S_{11} \approx -22$ dB),
- Accurate equal power division ($S_{21} \approx S_{31} \approx -3.07$ dB),
- High output port isolation ($S_{23} \approx -30$ dB).

These characteristics make the proposed divider well suited for use in Wi-Fi access points, Bluetooth repeaters, and other 2.4 GHz ISM-band systems where reliable power distribution and port decoupling are required.

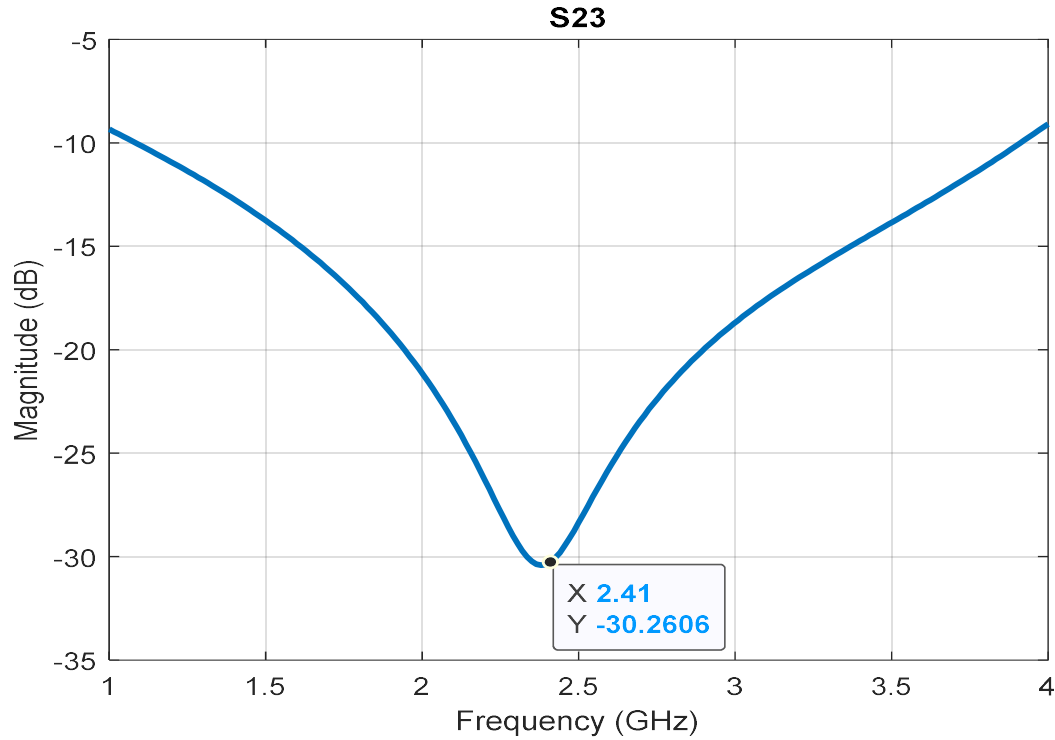


Figure 3.15. S_{23} Parameter (Isolation between Port 2 and Port 3) for $f = 2.4$ GHz.

III.2.4 Example4 ($f_0 = 5$ GHz)

The frequency of 5 GHz represents a significant step into the higher echelons of microwave communications. It is most notably associated with the 5 GHz ISM band, which serves as the primary operating spectrum for modern high-throughput wireless local area networks (WLANs), including IEEE 802.11ac and 802.11ax (Wi-Fi 5 and Wi-Fi 6), as well as radar systems, satellite communications, and emerging 5G sub-6 GHz deployments.

Unlike the lower frequencies discussed previously (1.8 GHz, 2.1 GHz, and 2.4 GHz), the 5 GHz band offers substantially wider channel bandwidths (up to 160 MHz or more) and reduced congestion compared to the heavily populated 2.4 GHz band. This enables higher data rates, lower latency, and more reliable connections in dense urban or office environments. However, operating at 5 GHz introduces new challenges : increased free-space path loss, greater sensitivity to manufacturing tolerances, and higher dielectric and conductor losses in microstrip circuits. Therefore, the performance of the Wilkinson power divider at this frequency provides a valuable stress test of its design robustness.

- **Structure and Design Description**

For the 5 GHz operating point, the Wilkinson power divider is once again implemented using microstrip technology on a Teflon substrate. Teflon remains the substrate of choice due to its

stable relative permittivity and low dissipation factor, which become even more critical at higher frequencies where material losses can otherwise degrade performance.

The circuit topology adheres strictly to the classical two-way Wilkinson configuration :

- Port 1: Input port.
- Ports 2 and 3: Two symmetric output ports.
- Two quarter-wavelength transmission lines: At 5 GHz, the physical length of these lines is considerably shorter than in the previous examples, since the guided wavelength (λ) is inversely proportional to frequency. The quarter-wave segments are precisely calculated to transform the impedance from $100\ \Omega$ (at the output nodes) to $50\ \Omega$ at the input.
- One isolation resistor (typically $100\ \Omega$): Connected between Port 2 and Port 3 to dissipate any out-of-phase energy and ensure high isolation.

Figure 3.16 illustrates the three-dimensional layout of the 5 GHz Wilkinson power divider on the Teflon substrate.

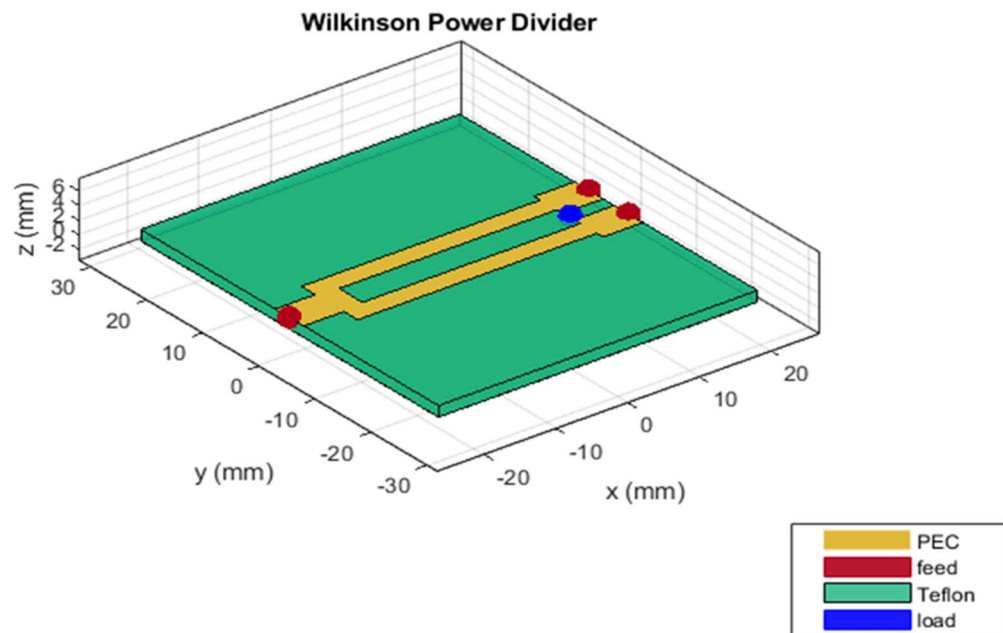


Figure 3.16. Wilkinson Power Divider Structure at 5 GHz.

The conductive microstrip lines (modeled as perfect electric conductors — PEC) are shown, along with the clearly identified input/output ports and termination loads. A notable observation from the figure is the reduced physical footprint compared to lower-frequency designs ; the inter-stage distances and line lengths are visibly shorter, which is an expected consequence of operating at a higher frequency with a correspondingly smaller wavelength. Despite these dimensional changes, the structure maintains perfect symmetry, which is essential for achieving equal amplitude and phase at both output ports.

S-Parameters Analysis

Input Return Loss (S_{11})

The reflection coefficient at the input port, S_{11} (Figure 3.17), is plotted over a frequency sweep centered around 5 GHz. A distinct and well-defined minimum is observed in the vicinity of 5 GHz, with a magnitude falling between approximately -25 dB and -27 dB.

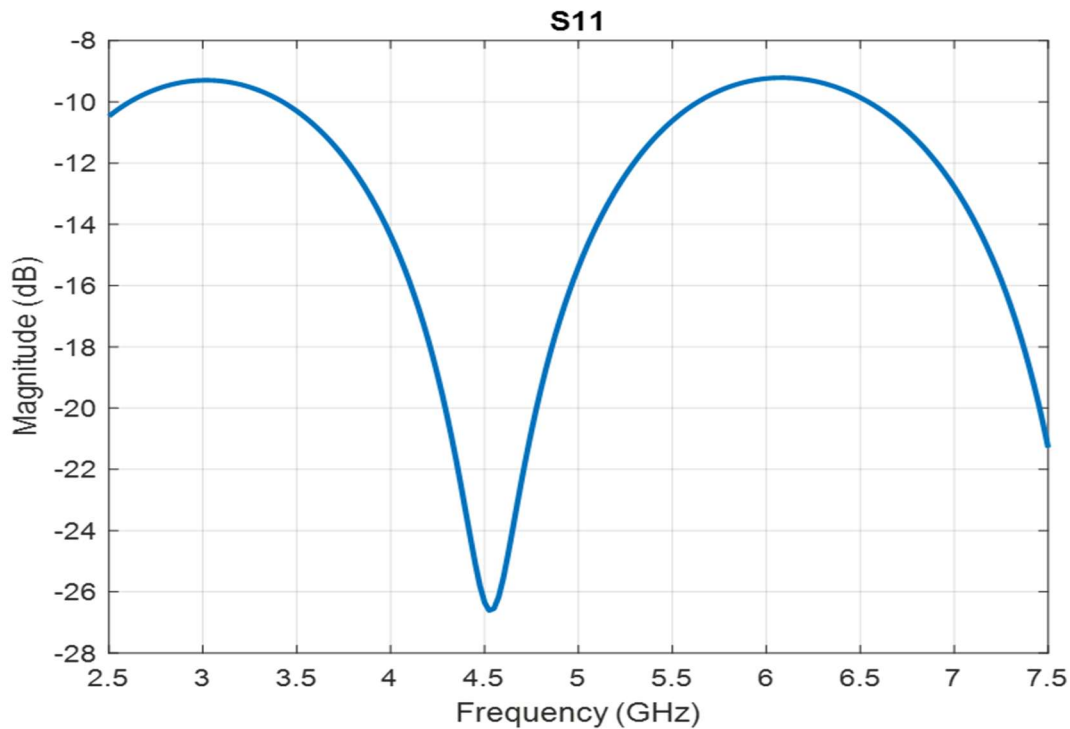


Figure 3.17. S_{11} Parameter (Return Loss) for $f = 5$ GHz.

This level of return loss is considered excellent in microwave engineering, as it indicates that more than 99.7% of the incident power is successfully coupled into the divider, while less than 0.3% is reflected back toward the source. Compared to the lower-frequency cases (1.8 GHz, 2.1 GHz, 2.4 GHz), the 5 GHz result remains fully within acceptable limits, although the dip appears slightly broader and marginally less deep. This minor difference can be attributed to increased frequency-dependent losses and the inherent challenges of maintaining perfect matching as the electrical length becomes more sensitive to small geometric variations. Nevertheless, the result confirms that the quarter-wave transformers have been accurately dimensioned for the 5 GHz target frequency.

Transmission Coefficients (S_{21} and S_{31})

The forward transmission parameters, which together characterize the power splitting accuracy of the divider, are examined jointly.

- S_{21} (Port 1 to Port 2), shown in Figure 3.18, reaches approximately -3.2 dB near the center frequency of 5 GHz.
- S_{31} (Port 1 to Port 3), depicted in Figure 3.19, exhibits a nearly identical value of around -3.2 dB at the same frequency.

These results deviate slightly from the theoretical ideal of -3 dB for a perfectly lossless equal-split divider. The additional 0.2 dB of loss (beyond the inherent 3 dB splitting loss) can be explained by several factors that become more pronounced at higher frequencies:

- Dielectric losses within the Teflon substrate, which increase with frequency.
- Conductor losses in the microstrip lines due to the skin effect, which reduces the effective cross-section of the copper traces at 5 GHz.
- Radiation losses, which, while typically small in microstrip, can become non-negligible at higher frequencies.
- Numerical precision in the simulation environment.

Despite this minor deviation, the excellent symmetry between the S_{21} and S_{31} curves is preserved across the entire frequency range, confirming that the two branches of the divider are electrically identical. Therefore, the input power is still divided almost equally between the two output ports, with only a slight increase in insertion loss compared to lower-frequency operation. For most practical 5 GHz WLAN applications, a transmission coefficient of -3.2 dB is entirely acceptable.

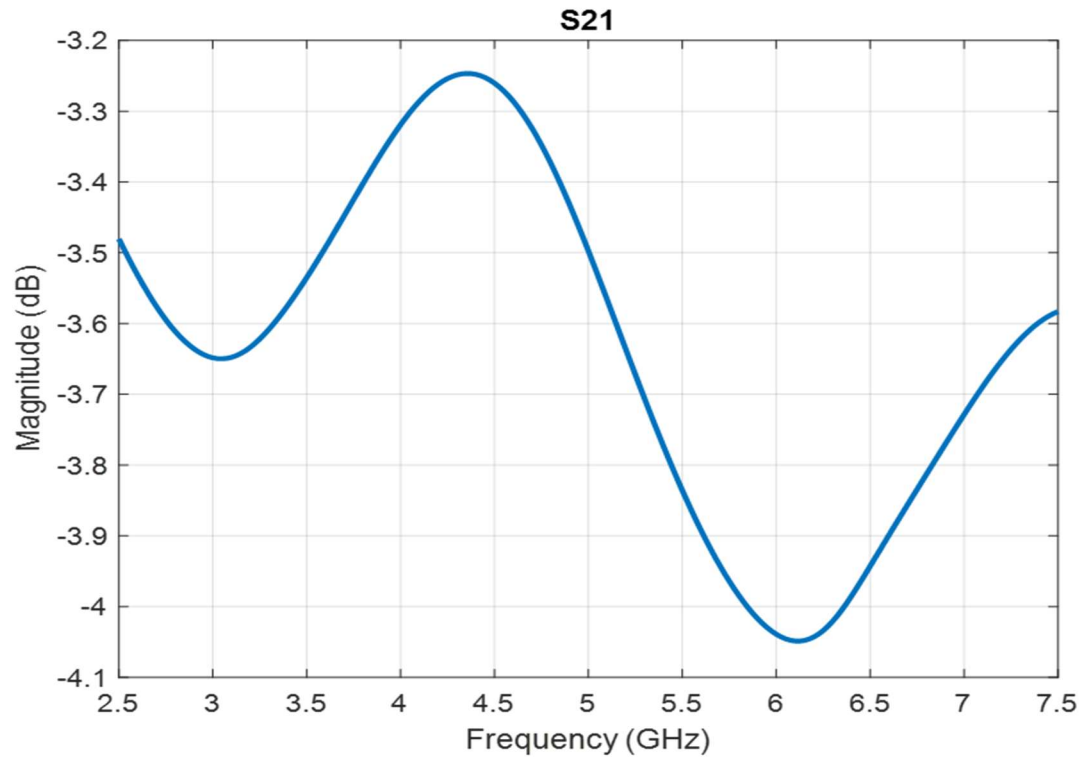


Figure 3.18. S₂₁ Parameter (Transmission Coefficient, Port 2), for f = 5 GHz.

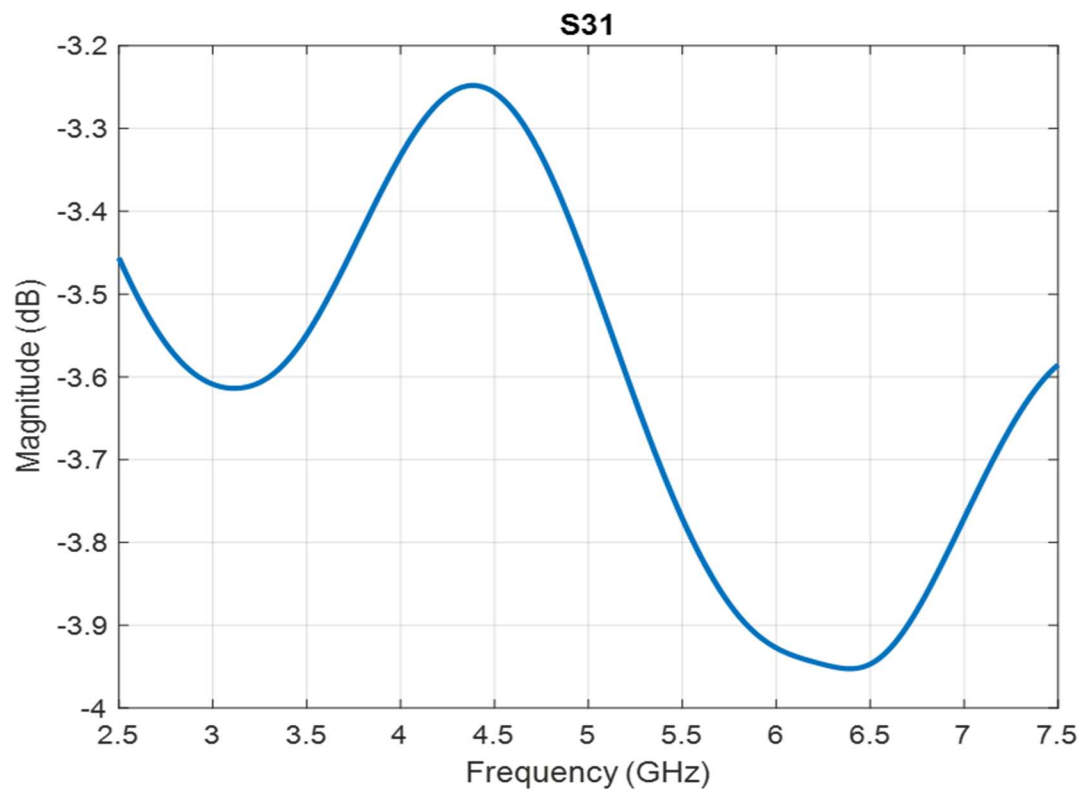


Figure 3.19. S₃₁ Parameter (Transmission Coefficient, Port 3) for f = 5 GHz.

Output Isolation (S_{23})

The isolation between the two output ports is characterized by the S_{23} parameter, plotted in Figure 3.20. At the design frequency of 5 GHz, the curve reaches a minimum value of approximately -27 dB.

This level of isolation, while slightly reduced compared to the 2.1 GHz case (which achieved around -30 dB to -33 dB), remains very good for most RF and microwave systems. An isolation of -27 dB means that any unwanted signal leaking from Port 2 to Port 3 (or vice versa) is attenuated by a factor of nearly 500 in power. The slight degradation relative to lower frequencies can be attributed to :

- Parasitic effects in the isolation resistor at higher frequencies (e.g., stray capacitance and inductance).
- Slight phase imbalances due to fabrication tolerances becoming more critical at shorter wavelengths.
- Increased coupling between closely spaced microstrip lines as the electrical separation becomes smaller relative to the wavelength.

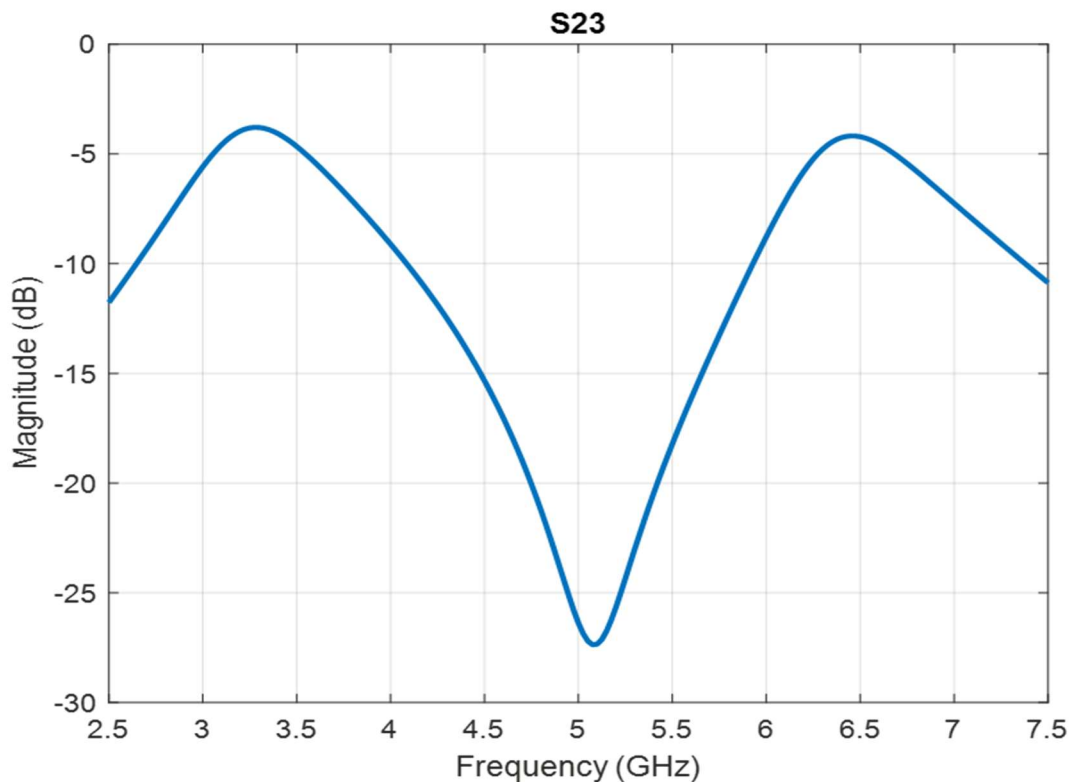


Figure 3.20. S_{23} Parameter (Isolation between Port 2 and Port 3) for $f = 5$ GHz.

Nevertheless, a value of -27 dB confirms that the isolation resistor continues to function effectively, dissipating out-of-phase energy and preventing cross-talk between the output channels. This performance is more than sufficient for most 5 GHz applications, including multi-antenna Wi-Fi systems and beamforming networks.

The simulated results at 5 GHz demonstrate that the Wilkinson power divider remains a viable and effective solution even as the operating frequency moves into the higher microwave range. The key performance metrics can be summarized as follows:

Table 3.1 – Summary of Simulated S-Parameters for the Wilkinson Power Divider at 5 GHz

Parameter	Simulated Value at 5 GHz	Theoretical Ideal	Assessment
S_{11} (Transmission to Port)	≈ -3.2 dB	-3.0 dB	Very good (slight loss)
S_{31} (Transmission to Port 3)	≈ -3.2 dB	-3.0 dB	Very good (slight loss)
S_{23} (Isolation)	≈ -27 dB	$-\infty$ dB	Good to very good
S_{21} (Transmission to Port 2)	≈ -3.2 dB	-3.0 dB	Very good (slight loss)

Despite a marginal increase in insertion loss (approximately 0.2 dB above the theoretical 3 dB splitting loss) and a slight reduction in isolation (from -30 dB down to -27 dB), the overall performance remains well within acceptable engineering tolerances for most wireless communication systems. The divider continues to provide:

- Excellent input impedance matching,
- Nearly equal power division between the two outputs,
- Good output port isolation.

These characteristics make the proposed Wilkinson power divider suitable for deployment in 5 GHz WLAN access points, dual-band routers (2.4 GHz / 5 GHz), radar front-ends, and other high-frequency microwave applications where compact size and reliable performance are essential. The 5 GHz case also illustrates an important practical insight : while the Wilkinson divider is theoretically frequency-limited by its quarter-wave design, it still performs admirably at frequencies significantly higher than the original GSM-oriented designs, confirming its versatility across a wide range of modern communication bands.

Conclusion

In this chapter, the performance of a Wilkinson power divider was numerically simulated at four practical frequencies—1.8 GHz, 2.1 GHz, 2.4 GHz, and 5 GHz—using MATLAB Simulink RF module. The analysis focused on the key S-parameters: input return loss (S_{11}), transmission coefficients (S_{21} and S_{31}), and output isolation (S_{23}).

At 1.8 GHz, 2.1 GHz, and 2.4 GHz, the divider exhibited excellent performance, with S_{11} reaching values below -22 dB, S_{21} and S_{31} remaining very close to the theoretical -3 dB, and isolation exceeding -30 dB in most cases. At 5 GHz, a slight degradation was observed, with transmission coefficients around -3.2 dB and isolation around -27 dB. These minor deviations are attributed to increased dielectric and conductor losses, skin effect, and parasitic phenomena at higher frequencies.

Despite these marginal differences, the divider maintained excellent input matching, nearly equal power division, and good isolation across all frequencies. The results confirm that the Wilkinson power divider is a robust and versatile component, well suited for GSM, UMTS, Wi-Fi, and 5 GHz WLAN applications. The use of a Teflon substrate further enhanced performance due to its low losses and stable permittivity. Overall, this study validates the theoretical design and demonstrates the divider's effectiveness across modern wireless communication bands.

GENERAL CONCLUSION

General Conclusion

This dissertation has presented a comprehensive investigation of the Wilkinson power divider, from theoretical foundations to numerical simulation results across four practical wireless communication frequencies: 1.8 GHz, 2.1 GHz, 2.4 GHz, and 5 GHz. The work aimed to validate the analytical design of this fundamental microwave component and assess its frequency-dependent performance under realistic operating conditions.

Chapter I established the theoretical context by examining the general properties of three-port networks. Using scattering matrix formalism, it was demonstrated that a reciprocal lossless three-port network cannot be matched at all ports simultaneously. This limitation was illustrated through the analysis of lossless T-junction dividers (which suffer from poor matching and no isolation) and resistive dividers (which are matchable but dissipate half the input power). These shortcomings provided the motivation for the Wilkinson configuration.

Chapter II presented a rigorous theoretical analysis of the Wilkinson power divider using even-odd mode decomposition. The key design parameters were derived: for an equal-split 50 Ω system, the quarter-wave transmission lines require a characteristic impedance of $Z = \sqrt{2}Z_0 = 70.7 \Omega$, and the isolation resistor must be $R=2Z_0=100 \Omega$. The analysis revealed the elegant behavior whereby the resistor carries no current under even-mode excitation (making the divider lossless) but dissipates all power under odd-mode excitation (providing isolation).

Chapter III formed the core contribution of this work. Using MATLAB Simulink RF module, the Wilkinson divider was simulated at four frequencies of practical importance. At 1.8 GHz, 2.1 GHz, and 2.4 GHz, the divider exhibited excellent performance : S_{11} values below -22 dB, S_{21} and S_{31} within 0.08 dB of the ideal -3 dB, and isolation exceeding -30 dB. At 5 GHz, slight degradation was observed—transmission coefficients around -3.2 dB and isolation around -27 dB—attributed to increased dielectric and conductor losses, skin effect, and parasitic phenomena. Despite these minor deviations, performance remained well within acceptable engineering tolerances.

Several key conclusions emerge from this study:

1. **Theoretical validation** : The simulation results strongly confirm the analytical design derived from even-odd mode analysis.
2. **Frequency versatility**: The Wilkinson divider performs admirably across all four investigated bands, from 1.8 GHz to 5 GHz, making it suitable for GSM, UMTS, Wi-Fi, Bluetooth, and modern WLAN applications.
3. **Graceful degradation**: While optimal at its design frequency, the divider exhibits graceful rather than catastrophic degradation at higher frequencies, with performance remaining acceptable even at 5 GHz.
4. **Material importance** : The use of a Teflon substrate, with its low dielectric losses and stable permittivity, contributed significantly to maintaining performance at higher frequencies.

The primary limitation of this study is its reliance on idealized circuit-level simulations. Future work should include full-wave electromagnetic simulations using tools such as HFSS or CST, experimental validation through fabrication and measurement, and the development of multi-section broadband dividers for extended frequency ranges.

REFERENCES

References

- [1] B. Sütbaşı, “Improved Wilkinson Power Divider Structures,” Master’s thesis, Dept. of Electrical and Electronics Engineering, Bilkent University, Ankara, Turkey, Jan. 2019.
- [2] Microwave engineering. Pozar, D. M. Wiley, Hoboken, NJ, 4th ed edition, 2012. OCLC: ocn714728044.
- [3] L. E. Larson, *RF and Microwave Circuit Design for Wireless Communications*, Artech House, Norwood, Mass., 1996.
- [4] J. R. Smith, *Modern Communication Circuits*, 2nd edition, McGraw-Hill, New York, 1998.
- [5] U. L. Rohde, *Microwave and Wireless Synthesizers: Theory and Design*, Wiley-Interscience, New York, 1997.
- [6] G. D. Vendelin, A. M. Pavio, and U. L. Rohde, *Microwave Circuit Design Using Linear and Nonlinear Techniques*, John Wiley & Sons, New York, 1990.
- [7] S. A. Maas, *Nonlinear Microwave and RF Circuits*, 2nd edition, Artech House, Norwood, Mass., 2003.
- [8] David K. Cheng, *Field and Wave Electromagnetics*, 2nd ed. Reading, MA, USA: Addison-Wesley, 1989.
- [9] G. D. Vendelin, A. M. Pavio, and U. L. Rohde, *Microwave Circuit Design Using Linear and Nonlinear Techniques*, John Wiley & Sons, New York, 1990.