Faculty of Engineering – Cairo University

Electronics and Electrical Communication Department

Second Year – Mainstream

ELC2090 – Group 21 Project

Power Division Networks with Orthogonal phase relation between output signals

Submitted by:

Name	ID	Sec
شهد محمد محمد رامز محمد حسان	9210534	2
فتحى مصطفى فتحى عبد الحميد	9210808	3
مازن احمد عمر مصطفى عمر	9210887	3
مازن وائل ضياء الدين احمد رافت	9210892	3
محمود لطفى عبد الحميد عمرو	9211094	4
مصطفى مجدى ابراهيم محمد	9211191	4
يوسف معتزبالله احمد الصاوى	9211449	4

1. Introduction

Quadrature couplers are critical components in the transmission and modification of signals in telecommunications and signal processing. [1] These small and adaptable equipment have acquired popularity due to their extraordinary precision in splitting, combining, and controlling signals. A Quadrature coupler's basic function as a power splitter is to divide an input signal into two components that are 90 degrees out of phase with each other. Moreover, quadrature couplers have good balance and isolation properties. Balance indicates the equal splitting of input power between output ports, whereas isolation guarantees that these ports communicate or couple as little as possible. Quadrature couplers are used in a variety of applications, which incorporate wireless communication systems, radar systems, and instrumentation.

Lange couplers [2], branch line couplers, overlay couplers, edge couplers, and short-slot hybrid couplers are examples of quadrature couplers. We've chosen to design and test the Branch line coupler in this report because of the simplicity of its design as the circuit is entirely planar, its balanced power division, high isolation, good return loss and low excess insertion loss. It is commonly utilized in high-frequency and low-frequency transmission. The branch line coupler is used in the design of microwave devices such as mixers, balanced amplifiers, and phase shifters. It is also excellent for low-cost production.

Branch line couplers [3] can be implemented in a variety of ways. Waveguides, coaxial lines, microstrips, and straplines are examples of directional couplers. The microstrip line has the advantages of miniaturization, little weight, low production cost, [4] and simple circuit structure realization. Consequently, this report uses microstrip lines to construct a 3 dB directional Branch line coupler and then implements the lumped equivalent circuit to compare their performance.

Furthermore, due to the prevalence of the Wilkinson Power Divider among microwave circuits, a Wilkinson design modification will be introduced to achieve the same functionality as that of a quadrature coupler.

The designs are simulated using the ADS tool. The S-parameters simulation on the schematic view and the EM simulations are carried out, testing the performance of each proposed design and see whether they match the required specs in the [S] matrix or not.

An application of our chosen design could be its usage in communication satellites. We set out to cover the band concerned with wireless communication systems (2-3) GHz, focusing on serving the range from 2.4 GHz to 3 GHz. We'll only study a somewhat larger band in our work (1-4.5) GHz.

In the next section, our work will discuss the theory of operation of the networks we mentioned in our introduction. We'll also briefly discuss the lumped derivation and implementation of our networks.

In Section 3, we'll discuss our proposed designs for the Branch Line Couplers and Wilkinson Power Divider networks. We'll touch upon our usage of the multi-section design of the Branch Line Coupler in order to expand the band of operation. We also discuss the modification needed for the WPD in order to achieve an orthogonal phase relation between the output signals. We finally discuss our design process.

In Section 4, we'll show the results of our work and engage in some discussion about these results. We'll compare the success of each design in terms of specification achievement at the center frequency 2.4 GHz and over a band of frequencies.

In Section 5, we'll conclude with some takeaways about our body of work.

2. Theory of Operation

A. Quadrature Methodology

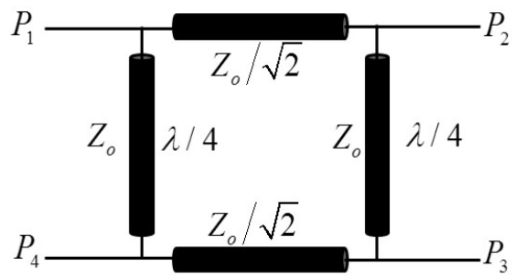

Fig. (1.1): Branch line coupler design

A branch line coupler, illustrated in **Fig. (2.1),** is a design that can be used as a power splitter. [5] It consists of 4 ports as shown in figure (2): Input (*P1*), Output 1 (*P2*) and Output 2 (*P3*). The fourth port (*P4*) is terminated at Z_o (the characteristic impedance of the port) for the signal splitter and is isolated from the input, so no power flows through it. Output signals are of the same magnitude with a 90-degree phase shift between them with the fact that the lower output port (port 3) has the most negative transmission phase since it travels the farthest.

The branch line coupler exhibits a notable level of symmetry, allowing any of its four ports to function as the input port. The output ports are positioned on the opposite side of the input port, while the isolated port is situated on the same side as the input port. This symmetry is reflected in the S matrix, where each row is a transposed version of the first row.

On doing even and odd mode analysis, the ideal branch line coupler's [S] matrix at the design frequency is evaluated to be:

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

B. Wilkinson Power Divider

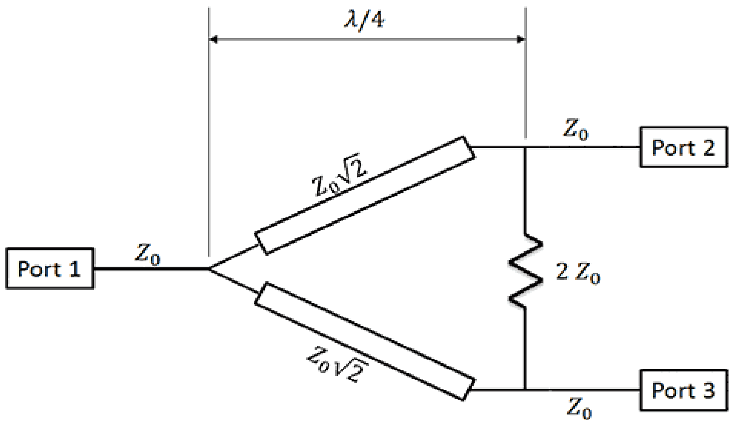

Fig. (2.2): Wilkinson power splitter design

As a power divider, the Wilkinson splitter which is depicted in **Fig. (2.2)** operates as follows: when a signal enters port 1, it is split into equal amplitude, equal-phase output signals at ports 2 and 3. Because the resistor used to isolate between ports 2 and 3 has the same potential at both ends, no current flows through it, and so the resistor is isolated from the input.

The two output port terminations will add in parallel at the input, therefore they must be changed to $2Z_o$ each at the input port before combining to Z_o. Without the quarter-wave transformers, the overall impedance of the two outputs at port 1 would be $Z_o/2$. The characteristic impedance of the quarter-wave lines must be $\sqrt{2}Z_o$ for the input to be matched when ports 2 and 3 are terminated in Z_o.

In an ideal situation, when all ports are matched, there will be no load-resistor dissipation. If the output ports observe the same exact mismatch, there will be no dissipation and the reflected power will be returned to the input. Dissipation happens when the reflection coefficients of the two output ports vary.

When a signal is applied to port 2, it is evenly split between port 1 and the resistor R, while no power is delivered to port 3. This arrangement enables the resistor to play a crucial role in isolating ports 2 and 3, thus achieving the necessary condition for isolation between the outputs. The same analysis applies for port 3.

On doing even and odd mode analysis, the [S] matrix of Wilkinson power divider at the design frequency is evaluated to be:

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

C. Lumped Equivalent Model

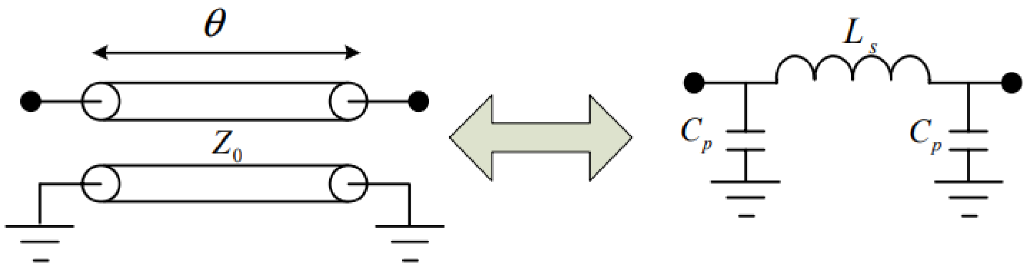

Fig. (2.3): Lumped-element π-circuit equivalent of a transmission line with electrical length θ.

A commonly used representation for a transmission line segment is through the use of lumped-element networks, [6] which can take the form of either a "T" or a "π" network. Specifically, a quarter-wave line operating at a frequency f_o and possessing a characteristic impedance Z_o can be substituted with a "π" circuit equivalent network, as depicted in **Fig. (2.3).**

The element values are:

$$L_S = \frac{Z_o}{2\pi f_o}\sin(\theta) \quad \text{and} \quad C_p = \frac{1-\cos(\theta)}{2\pi f_o Z_o \sin(\theta)}$$

If the electrical length (θ) is equivalent to $\frac{\lambda}{4}$, then the equations can be simplified to:

$$L_S = \frac{Z_o}{2\pi f_o} \quad \text{and} \quad C_p = \frac{1}{2\pi f_o Z_o}$$

In theory, the π-circuit is expected to closely approximate the behavior of the transmission line specifically at the center frequency f_o. However, this approximation remains valid within the vicinity of the center frequency, encompassing the bandwidth of interest should it be chosen well.

3. Proposed designs

A. Wider band branch line coupler

Cascading branch line couplers are a technology used to increase the system bandwidth. By connecting multiple branch line couplers in series, their separate bandwidths combine to create a wider operational frequency range. The cascade method includes connecting the output port of one branch line coupler to the input port of the next coupler, essentially extending the signal channel. As a result, the specific bandwidth constraints of each coupler are reduced, allowing for a wider frequency response.

In this report, both double and triple cascaded section branch line couplers are proposed to obtain bandwidths larger than that of a single section branch line coupler.

A. (I) Double section branch line coupler

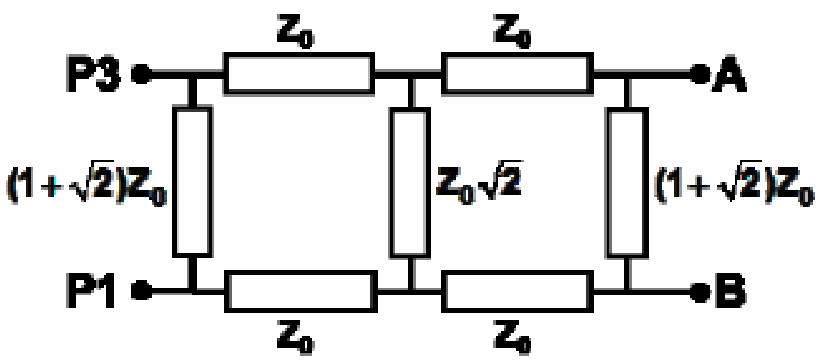

Fig. (3.1): Double section branch line coupler

In **Fig. (3.1),** the double section branch line coupler design is proposed. [4] As mentioned, it is expected by cascading that bandwidth will get wider. But it is noticed that by cascading, the impedances values of the design increases. This introduces a fabrication challenge, where these lines typically require narrower tracks. As the number of sections in the coupler increases, the ratio of impedances between the branch lines also increases. In planar formats, this constraint often limits the design to three sections due to manufacturing limitations. Therefore, the number of sections in a coupler design is influenced by the impedance requirements and the practical considerations of manufacturing processes.

A. (II) Triple section branch line coupler

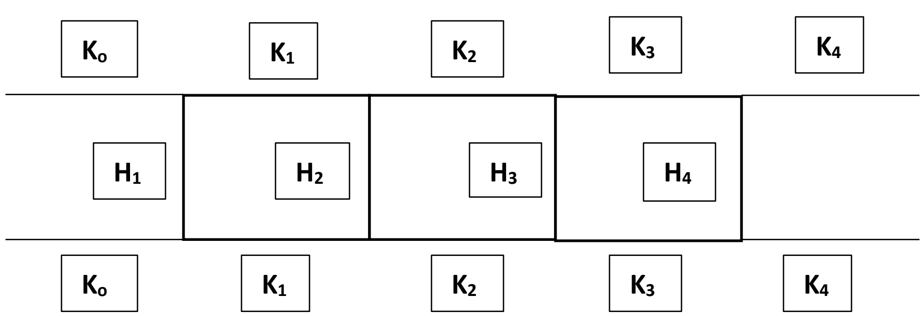

Fig. (3.2): Triple section branch line coupler before numerical analysis

Using the notation present in [7], we've managed to construct a model of the Triple section BLC (illustrated in **Fig. (3.2)**). The inverse of each of K and H represents a coefficient for the horizontal and vertical transmission lines respectively, that is multiplied by Z_o to obtain the impedance of each line. All lengths are assumed to be $\lambda/4$.

The coupler is assumed to have end-to-end symmetry, so that $H_{n+1}=H_1$, $K_{n+1}= K_o=1$, $H_2=H_3$ and $K_1=K_n$. Where n represents the number of sections (3 for our purposes).

We assume that $H_1= \sqrt{2}-1$, $K_1=1$ (where $H_1^{-1}= (\sqrt{2}+1)$, obtaining the same vertical impedance present in the double section BLC) and substitute in the design equations present in [7]:

$$\mathrm{H}_2 = \frac{K_1^2(1-H_1)}{1+2H_1-H_1^2} = \frac{\sqrt{2}}{4}$$

$$\mathrm{K}_2 = \frac{H_2\ \sqrt{2}}{1-H_1} = \frac{2+\sqrt{2}}{4}$$

So, the impedances obtained are illustrated in the following figure:

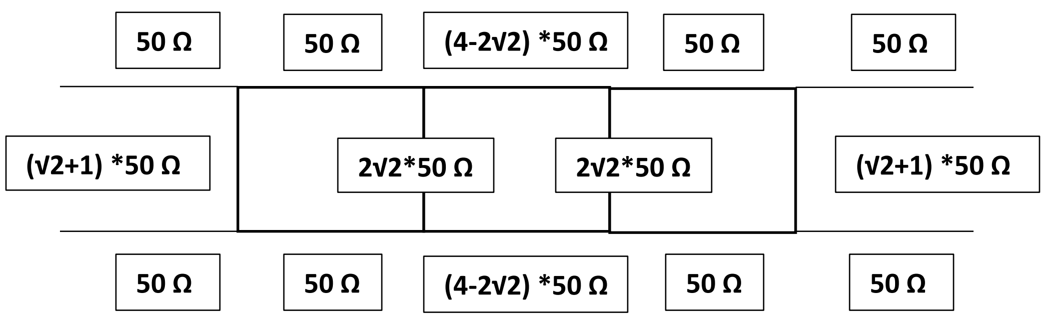

Fig. (3.3): Triple section branch line coupler after numerical analysis

The bandwidth improvement achieved by this design, shown in **Fig. (3.3),** will be discussed in the results section.

B. Equal power splitting with orthogonal phase relation using Wilkinson power divider.

In this paper, we propose a modification to the Wilkinson power divider that was previously depicted in Fig (3). Our objective is to achieve equal power division of the input signal between two isolated output ports while introducing a 90-degree phase shift between the output signals. The conventional Wilkinson power divider without any modification already provides two isolated output signals with equal magnitude and in phase with each other. To achieve the desired phase shift, our modification involves adding an additional transmission line at port (2) with an electrical length equivalent to $\lambda/4$. This additional transmission line introduces a delay that shifts the phase of the output signal at port (2) by 90 degrees. By incorporating this modification, we can achieve the desired equal power division with the required phase shift between the output signals. We will discuss the advantages and disadvantages of this design compared to the Branch Line Coupler (BLC) later on.

Before we move on to the next section discussing the results of the simulation, we'll discuss our design process illustrated by **Fig. (3.4).** It started by the derivation and calculation of the values of the impedances then we used the LineCalc tool, present in ADS software, in order to calculate the dimensions corresponding to these impedances at the center operating frequency of 2.4 GHz. We then simulated the outputs provided in the schematic and EM simulation views, after generating a layout, and studied the values. We then used the tuning and Optimization tools, also present in ADS software, in order to recalculate the physical length of the transmission lines to provide a better response and so on. We'll now show and discuss our results.

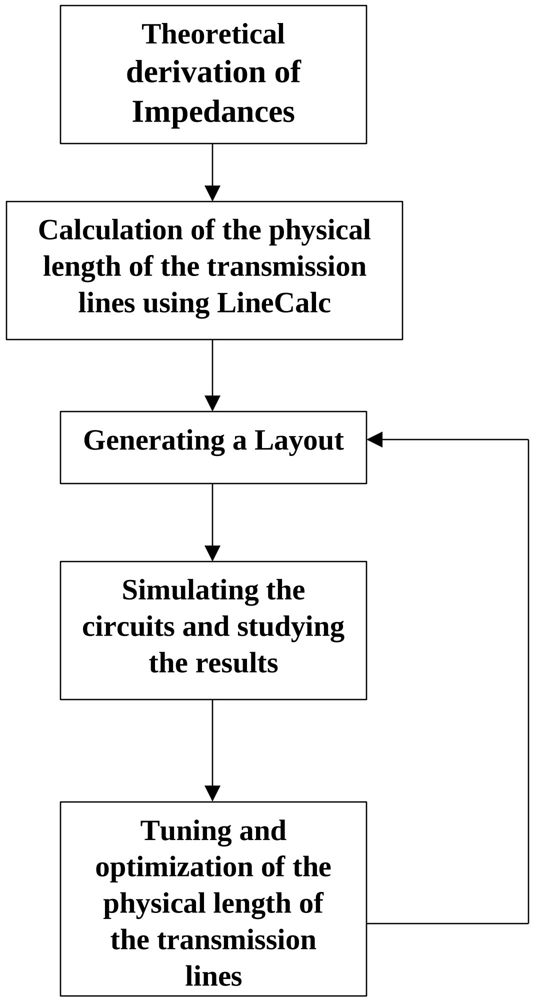

Fig. (3.4): Block diagram for our design process

4. Results & Discussion

A. Single Section Branch Line Coupler

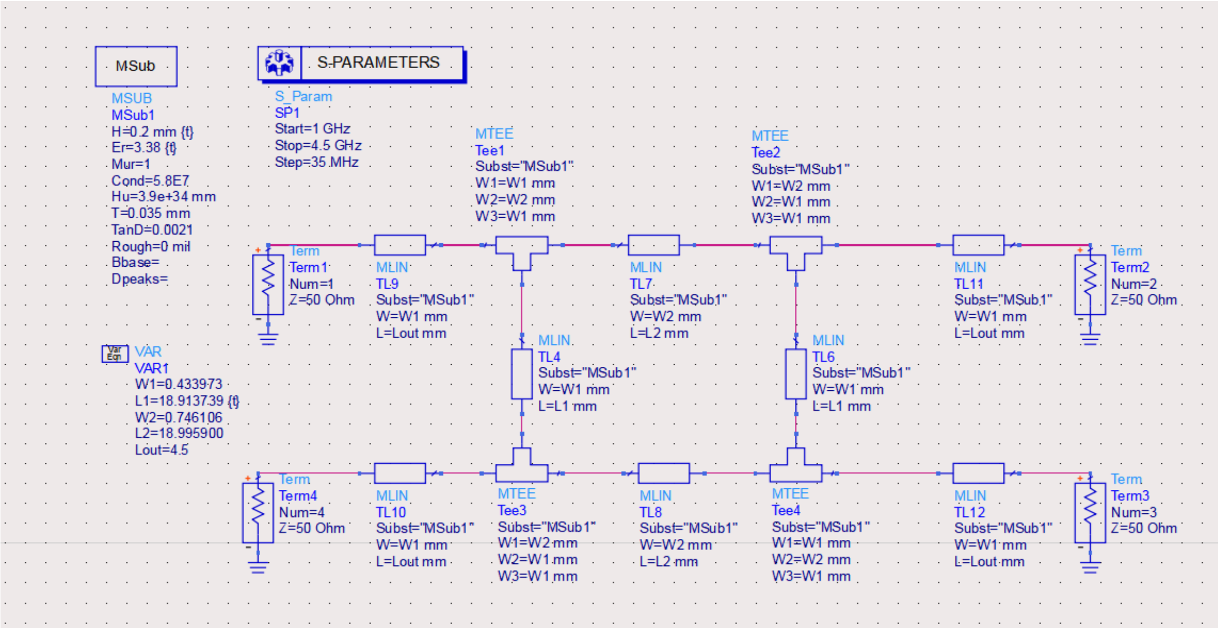

Fig (4.1): Single section branch line coupler design using microstrip lines.

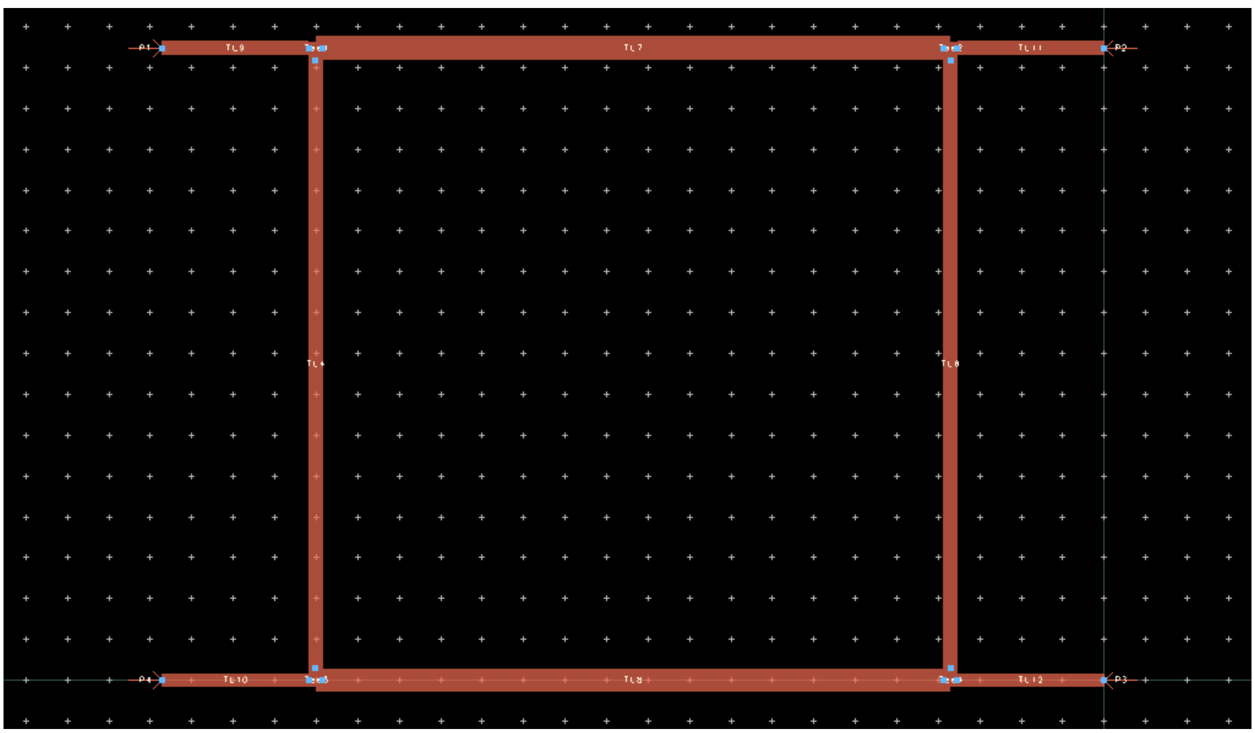

Fig (4.2): Layout of single section branch line coupler.

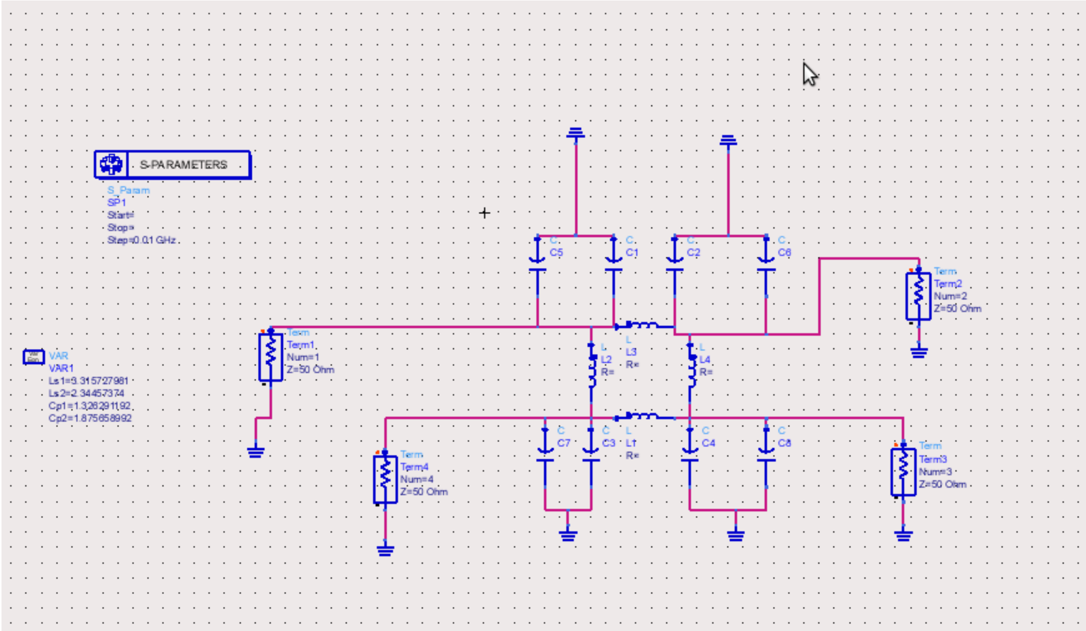

Fig (4.3): Schematic of lumped single section branch line coupler.

Microstrip schematics: simulation output graphs

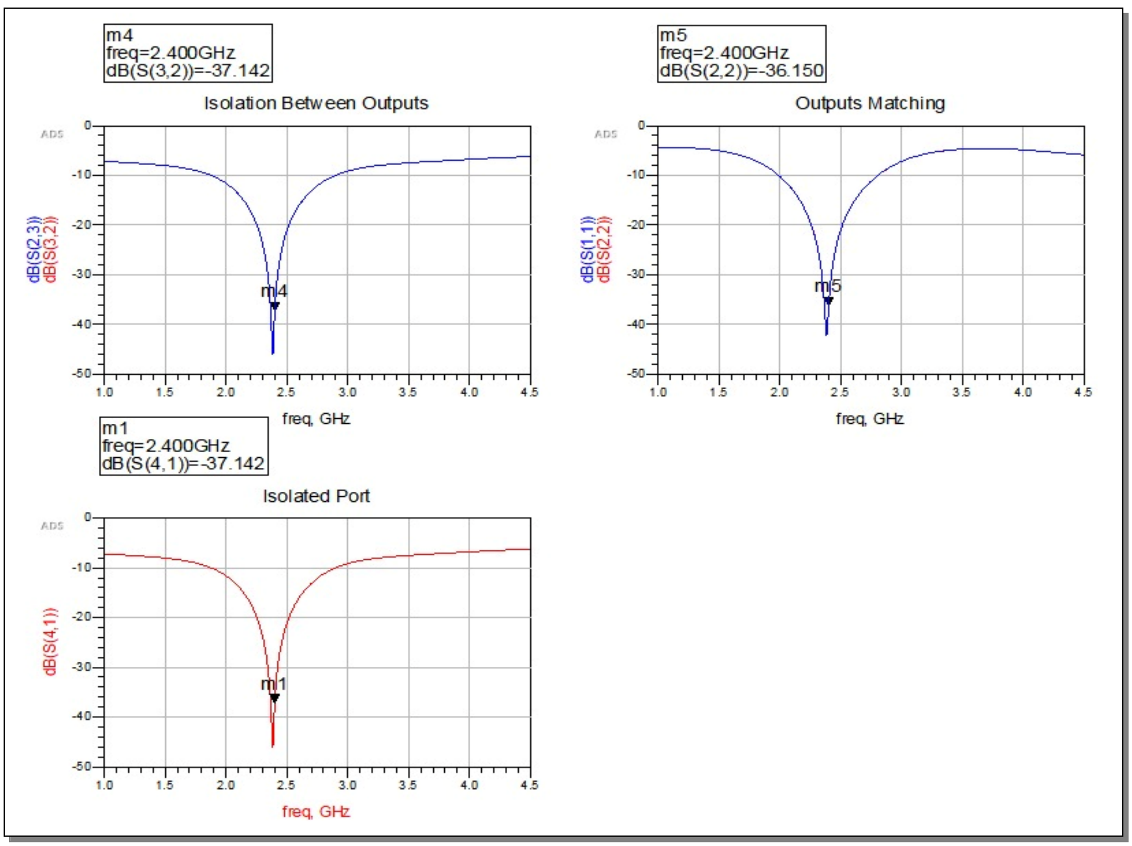

Figure (4.4): S-parameter graphs that depict the isolation between output ports 2 and 3, the isolation of port 4, and the matching of the outputs for a single branch line coupler using microstrip lines.

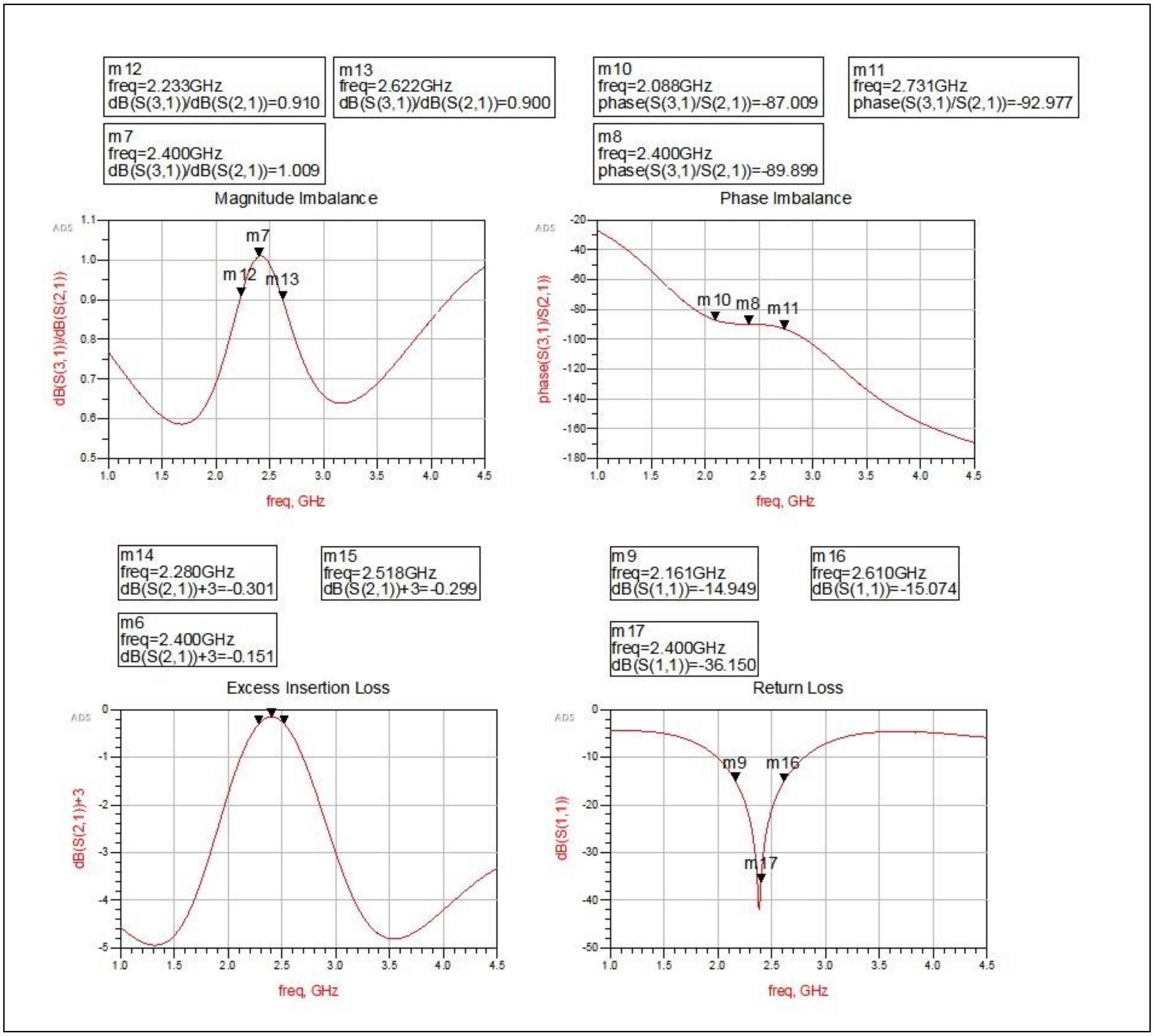

Fig (4.5): Graphical representation of a microstrip-based single branch line coupler's performance, showcasing bandwidth for IL, RL, phase imbalance, and magnitude imbalance. Additionally, illustrating matching at the input and output ports, as well as the isolation between the output ports.

Lumped schematics: simulation output graphs

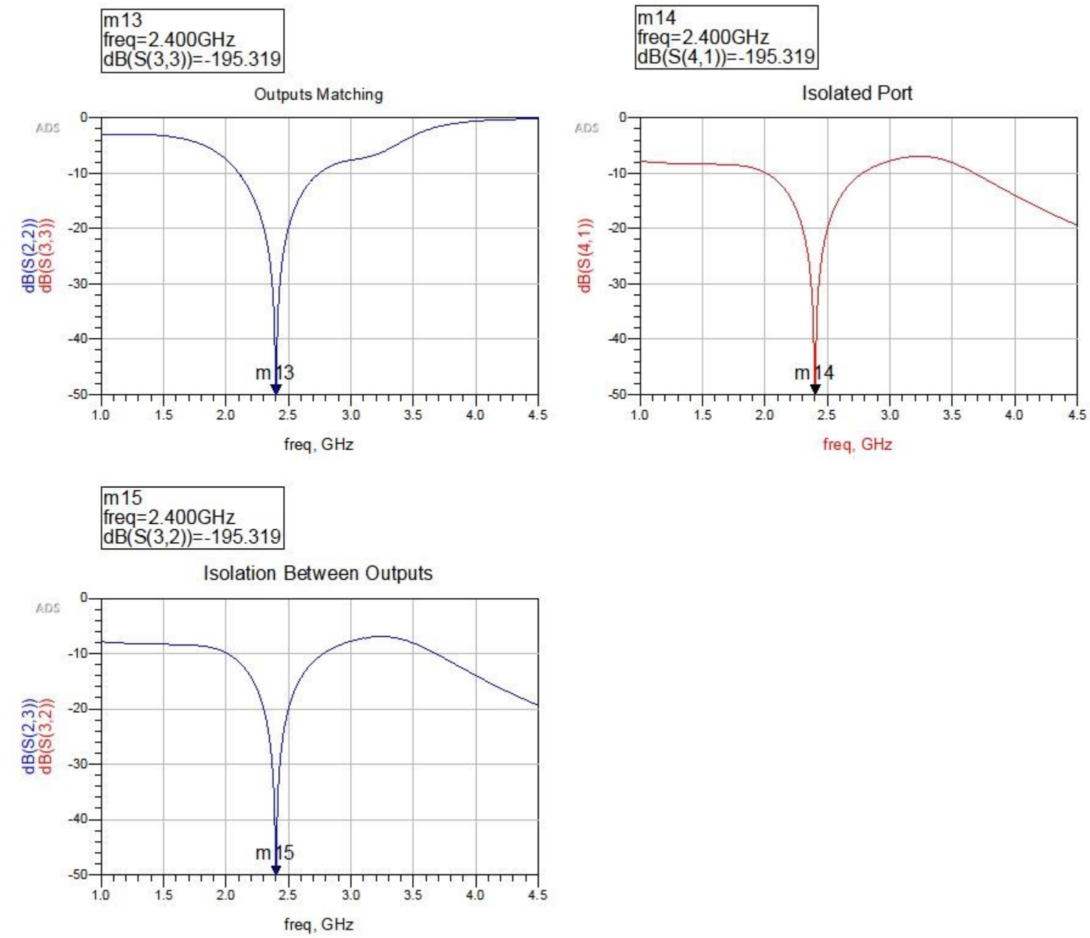

Figure (4.6): S-parameter graphs that depict the isolation between output ports 2 and 3, the isolation of port 4, and the matching of the outputs for a single branch line coupler using Lumped components.

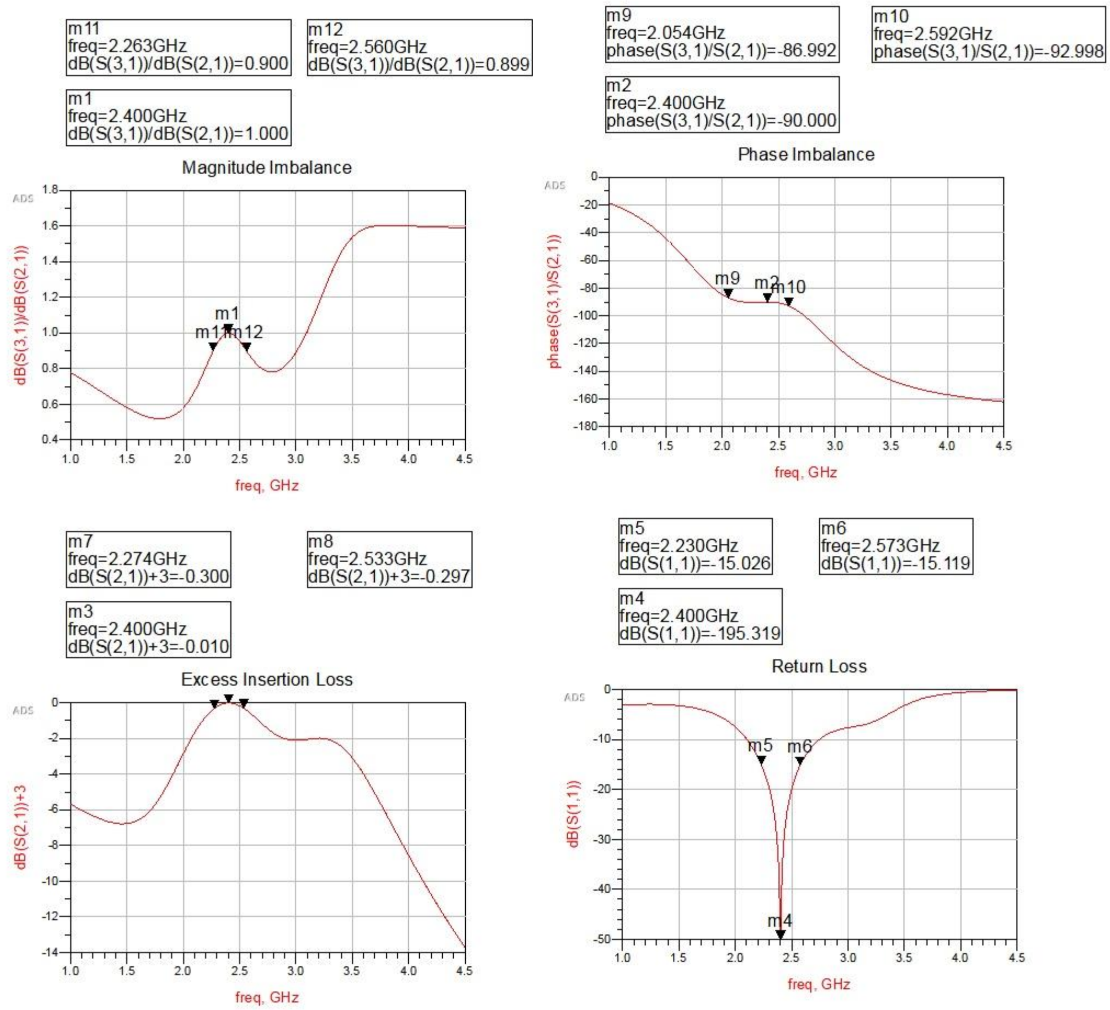

Fig (4.7): Graphical representation of a single branch line coupler's performance using Lumped components, showcasing bandwidth for IL, RL, phase imbalance, and magnitude imbalance. Additionally, illustrating matching at the input and output ports, as well as the isolation between output ports.

Performance Metric	Schematic		Layout		Lumped	
S11 in dB (Return Loss)	-36.15		-44.911		-195.319	
S22 in dB	-36.15		-44.907		-195.319	
S33 in dB	-36.15		-44.886		-195.319	
S44 in dB	-36.15		-44.887		-195.319	
S21 in dB (Insertion Loss)	-3.174		-3.161		-3.010	
S31 in dB (Coupling Coefficient)	-3.197		-3.212		-3.010	
S23 in dB (Isolation between output ports)	-36.607		-40.065		-195.319	
S41 in dB (Isolation Loss)	-37.142		-40.058		-195.319	
Excess Insertion Loss	-0.151		-0.161		-0.010	
Phase Imbalance	-0.101		-0.11		$-4.554*10^{-8} \approx 0$	
BW	Start	End	Start	End	Start	End
Min. RL of 15 dB	2.161	2.610	2.178	2.640	2.230	2.573
Max. EIL of -0.3 dB	2.280	2.518	2.305	2.543	2.274	2.533
Magnitude Imbalance of 0.1	2.233	2.622	2.233	2.670	2.263	2.560
Phase Imbalance of ± 3◦	2.088	2.731	2.116	2.760	2.054	2.592
Phase Imbalance of ± 3◦	2.087	2.730	2.116	2.760	2.054	2.592

Table (1): illustrating performance of single branch line coupler from its simulation outputs for each of the Microstrip, Lumped and Layout simulation.

A surprising takeaway from the results present in **Table (1) and illustrated in figures (4.3-4.6)** is the noticeable advantage the microstrip Layout Simulation (LS) values have over the Schematic Simulation (SS) values in some performance metrics. That's due to the fact the values of the dimensions were specifically tuned with the layout in mind as previously explained. At the center frequency of 2.4 GHz, the LS exhibits a 26.83% increase in Return Loss (RL), a 9.427% increase in Isolation Loss, a 9.446% increase in isolation between output ports and a slight improvement in Excess Insertion Loss (EIL). Over the band of interest, the LS values satisfy all of our specs in bandwidths very similar to the SL values. The Lumped Implementation Simulation (LIS) values show an immense advantage at the center frequency in practically every performance metric, a 334.9% increase in RL, a 387.6% increase in Isolation Loss and isolation between output ports, a perfectly orthogonal relation between the outputs. But, these major advantages hold for bandwidths noticeably shorter than the microstrip layout and schematic values (They're also aperiodic).

B. Double Section Branch Line Coupler

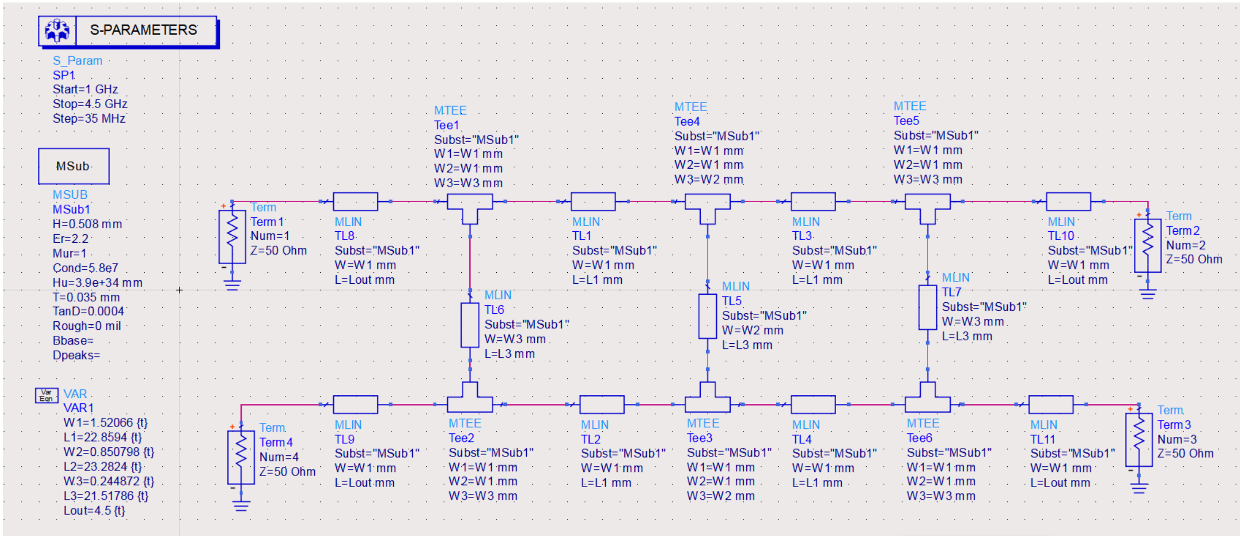

Fig (4.8): Double section branch line coupler design using microstrip lines.

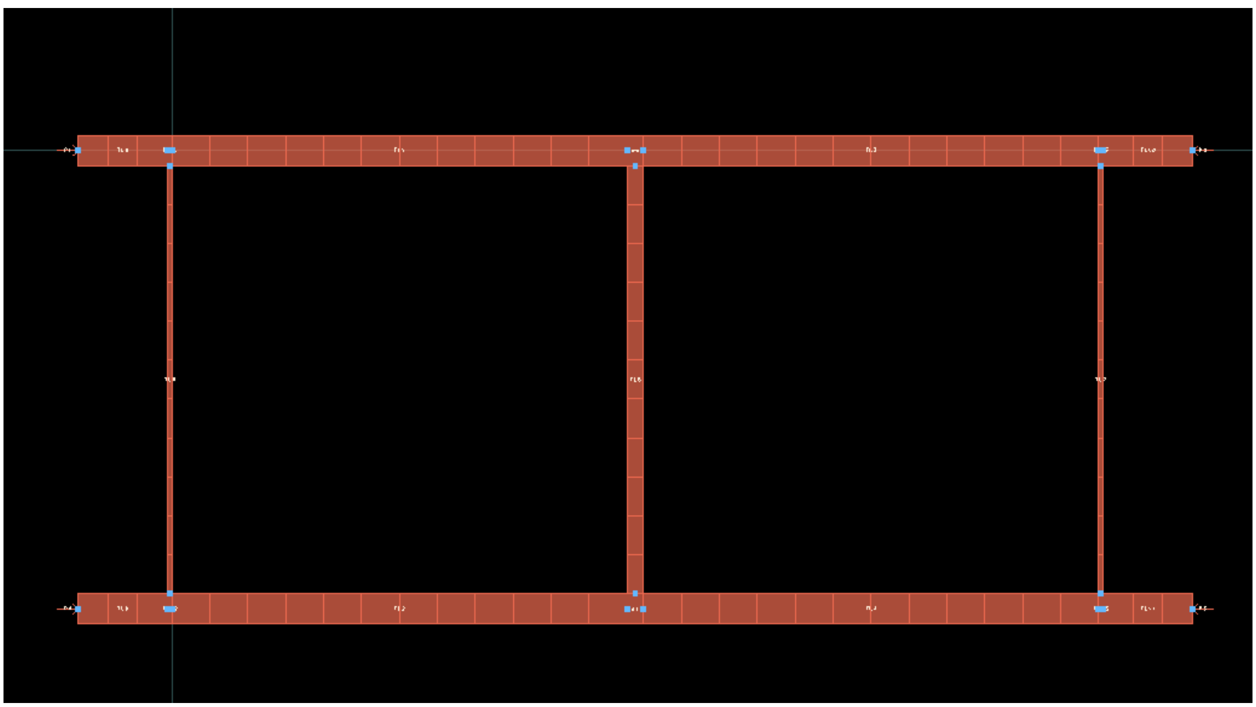

Fig (4.9): Layout of double section branch line coupler.

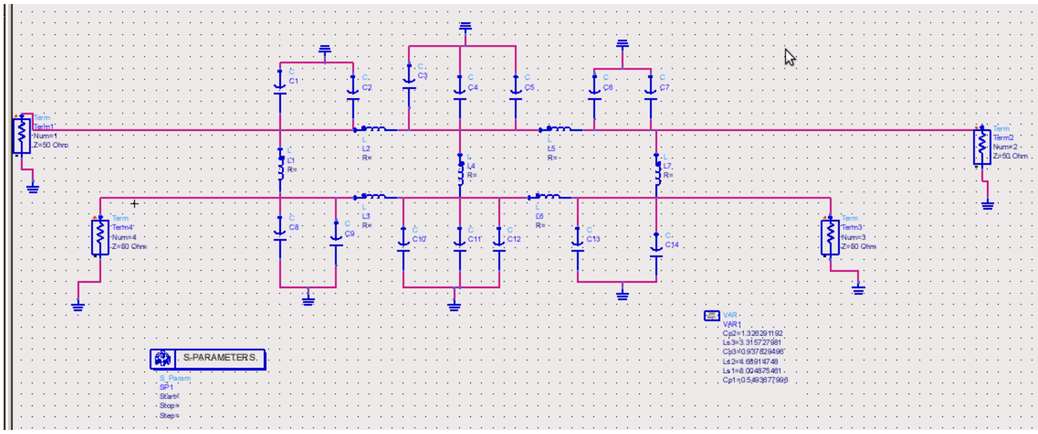

Fig (4.10): Schematic of lumped double section branch line coupler.

<u>**Microstrip schematics: simulation output graphs**</u>

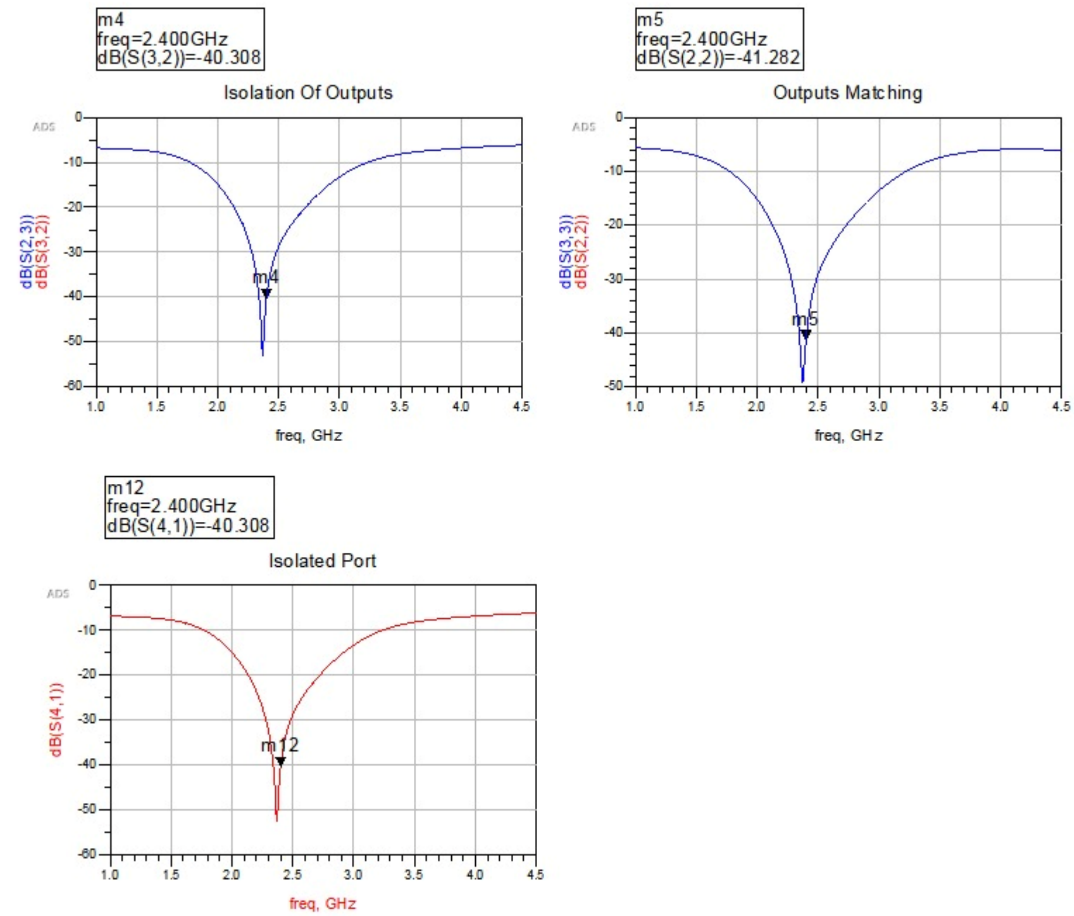

Fig (4.11): S-parameter graphs that depict the isolation between output ports 2 and 3, the isolation of port 4, and the matching of the outputs for a double branch line coupler using microstrip lines.

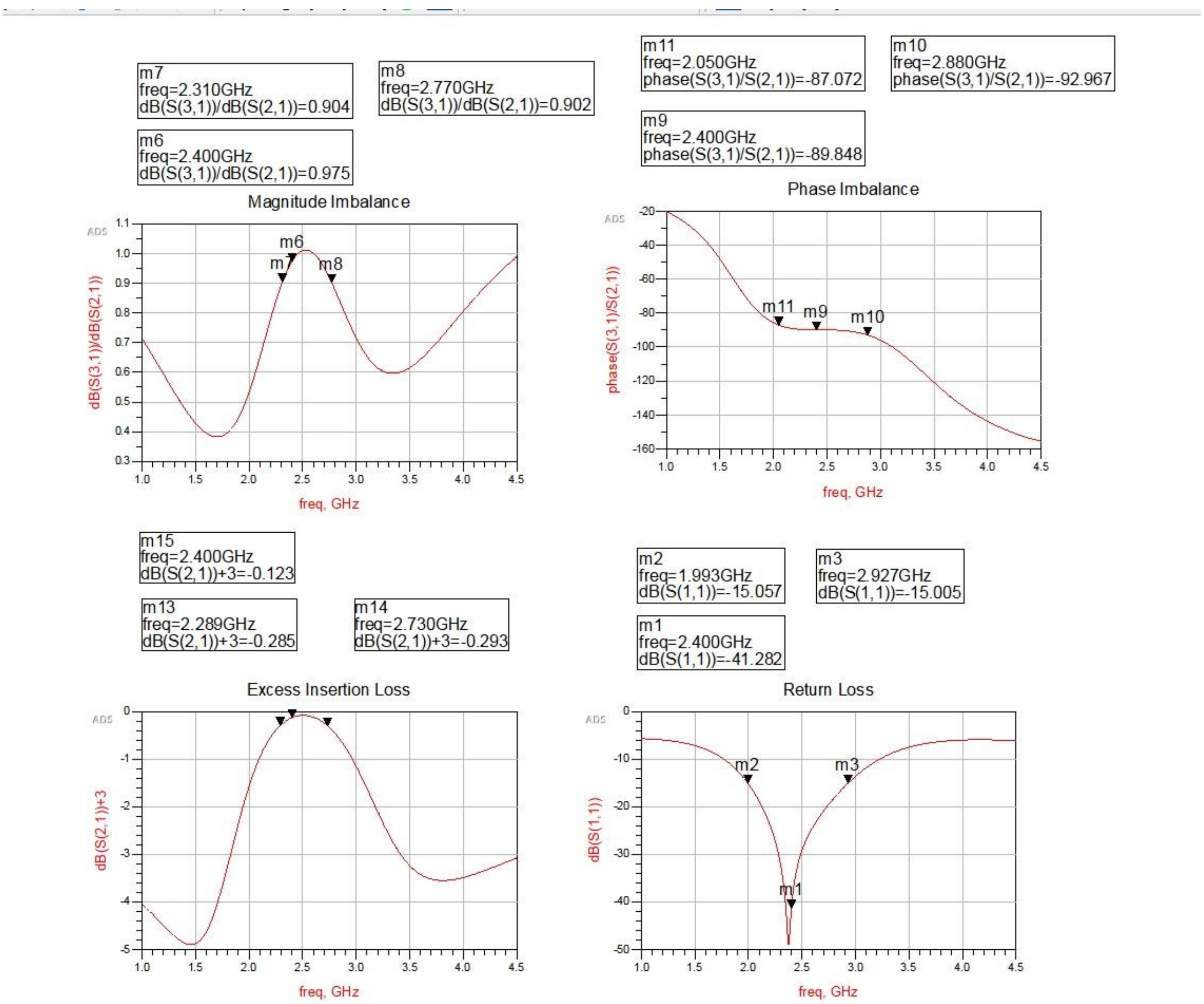

Fig (4.12): Graphical representation of a microstrip-based double branch line coupler's performance, showcasing bandwidth for IL, RL, phase imbalance, and magnitude imbalance. Additionally, illustrating matching at the input and output ports, as well as the isolation between output ports.

Lumped schematics: simulation output graphs

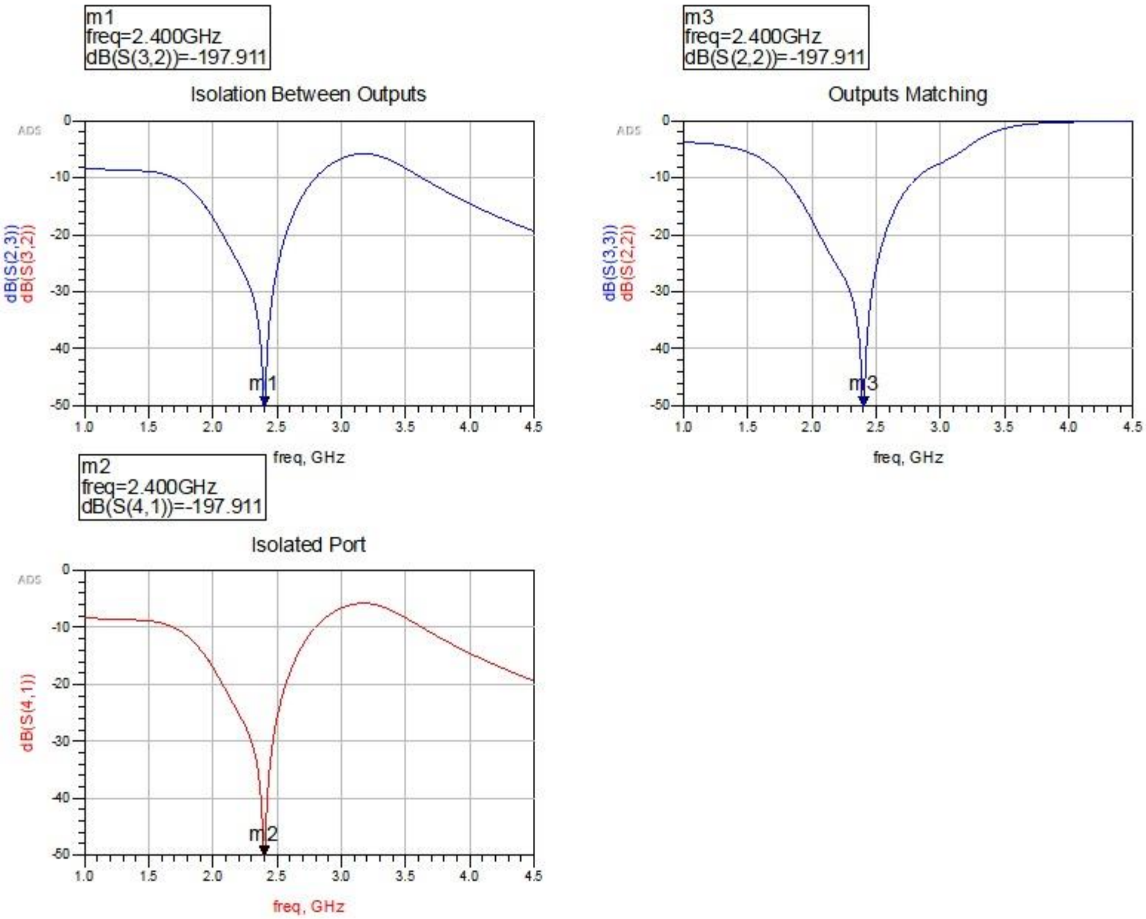

Fig (4.13): S-parameter graphs that depict the isolation between output ports 2 and 3, the isolation of port 4, and the matching of the outputs for a double branch line coupler using Lumped components.

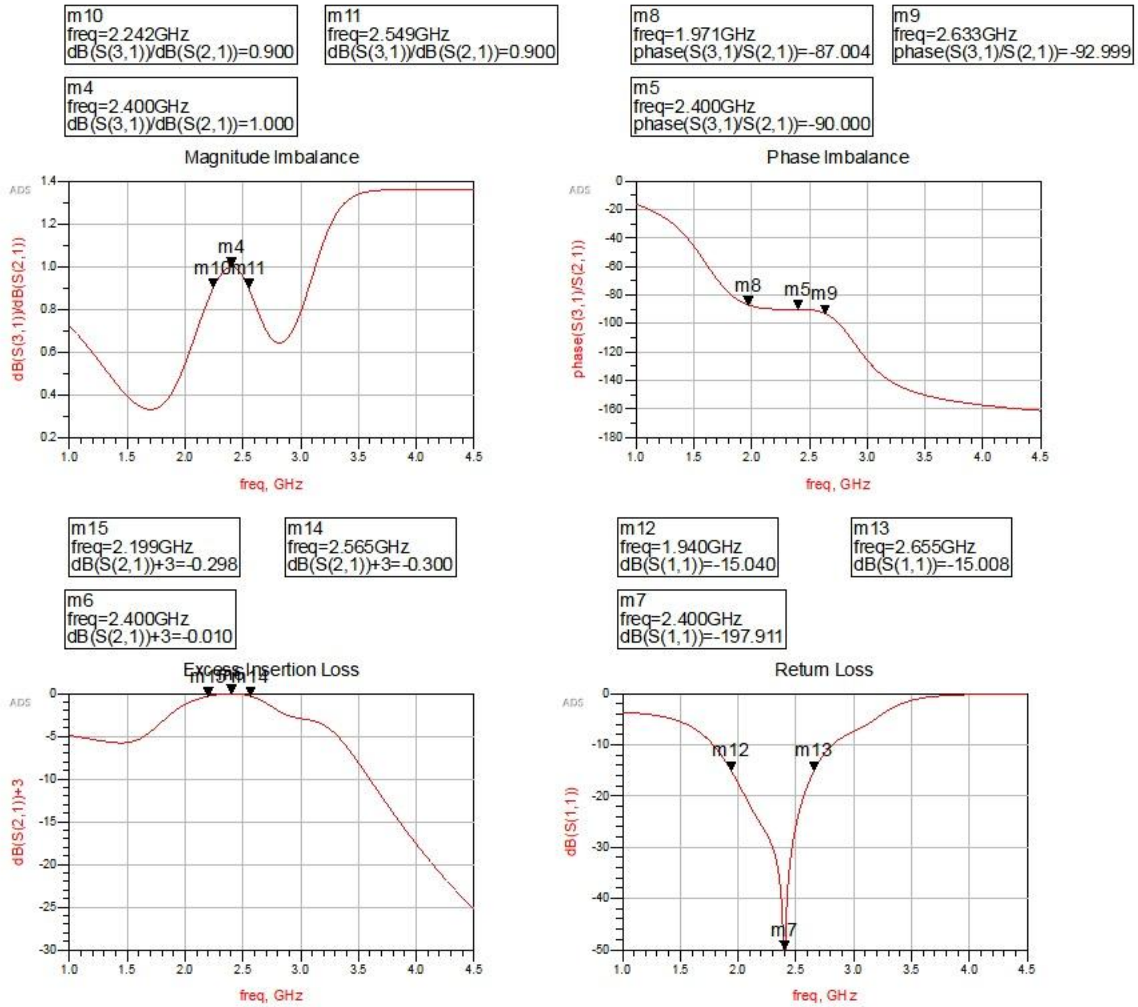

Fig (4.14): Graphical representation of a double branch line coupler's performance using Lumped components, showcasing bandwidth for IL, RL, phase imbalance, and magnitude imbalance. Additionally, illustrating matching at the input and output ports, as well as the isolation between output ports.

Performance Metric	Schematic	Layout	Lumped
S11 in dB (Return Loss)	-41.282	-39.148	-197.911
S22 in dB	-41.282	-39.263	-197.911
S33 in dB	-41.282	-39.266	-197.911
S44 in dB	-41.282	-39.152	-197.911
S21 in dB (Insertion Loss)	-3.136	-3.161	-3.010

S31 in dB (Coupling Coefficient)	-3.049		-3.071		-3.010	
S23 in dB (Isolation between output ports)	-40.308		-39.664		-197.911	
S41 in dB (Isolation Loss)	-40.308		-39.748		-197.911	
Excess Insertion Loss	-0.123		-0.161		-0.010	
Phase Imbalance	-0.152		-0.137		$-4.554*10^{-8} \approx 0$	
BW (GHz)	Start	End	Start	End	Start	End
Min. RL of 15 dB	1.993	2.927	2.008	2.940	1.940	2.655
Max. EIL of -0.3 dB	2.289	2.730	2.309	2.739	2.199	2.565
Magnitude Imbalance of 0.1	2.310	2.770	2.320	2.810	2.242	2.549
Phase Imbalance of ± 3◦	2.050	2.880	2.060	2.895	1.971	2.633

Table (2): illustrating performance of double branch line coupler from its simulation outputs for each of the Microstrip, Lumped and Layout simulation.

In **Table (2)** and **figures (4.9-4.12)**, the microstrip schematic and layout values for the double section branch line coupler are almost identical at the center frequency and they maintain our specs over bandwidths very similar in length. The major takeaway is the improvement in bandwidth over the values obtained in **Table (1)** for the single section branch line coupler, satisfying the RL spec for a band that's 108.2% longer in length and a similar improvement is achieved for the EIL spec. The bandwidths obtained for the magnitude and phase imbalance specs are quite similar for the single and double microstrip branch line couplers. The discrepancy in spec achievement over the bandwidth between the microstrip and lumped implementations for the double branch line couplers, is more apparent than the single section implementation except for the phase imbalance spec.

C. Triple Section Branch Line Coupler

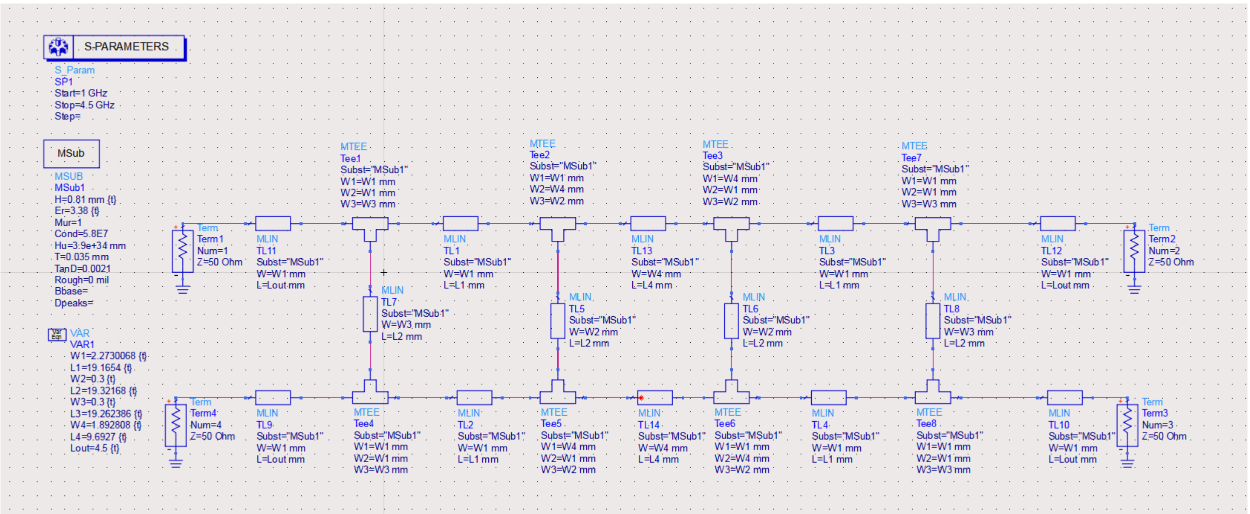

Fig (4.15): Triple section branch line coupler design using microstrip lines.

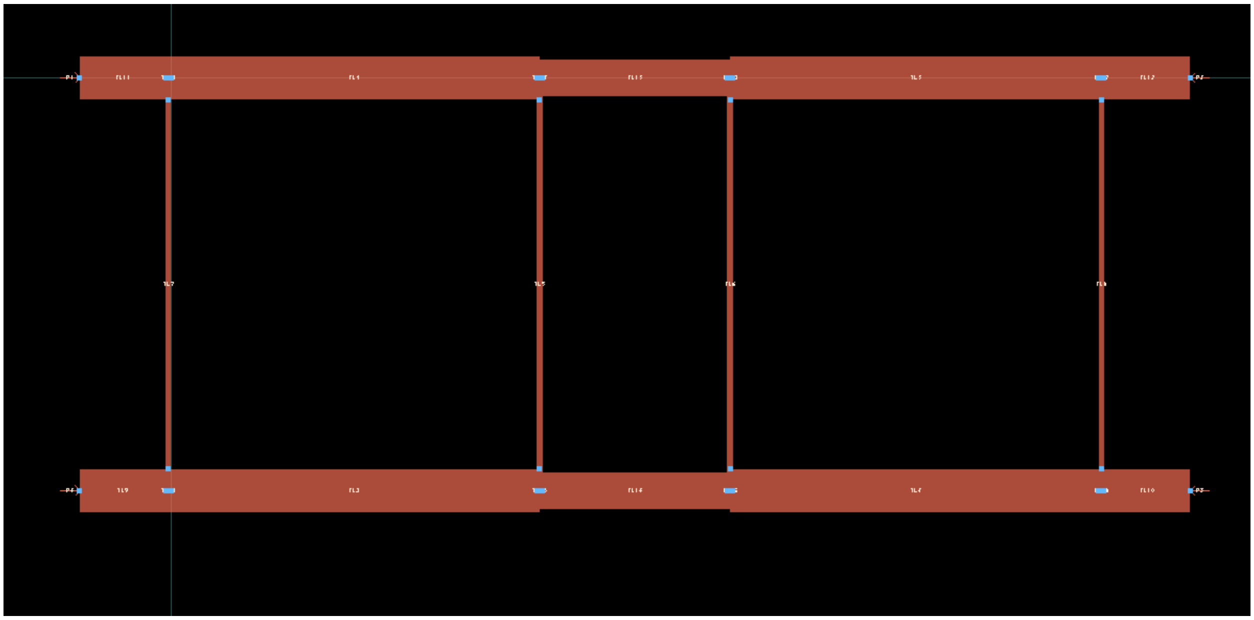

Fig (4.16): Layout of triple section branch line coupler.

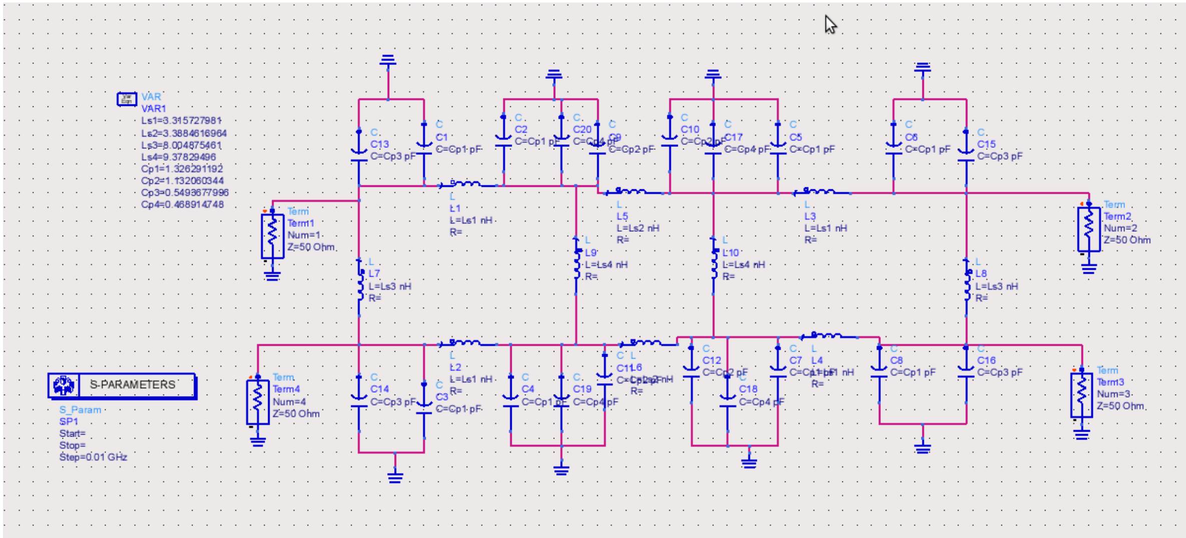

Fig (4.17): Schematic of lumped triple section branch line coupler.

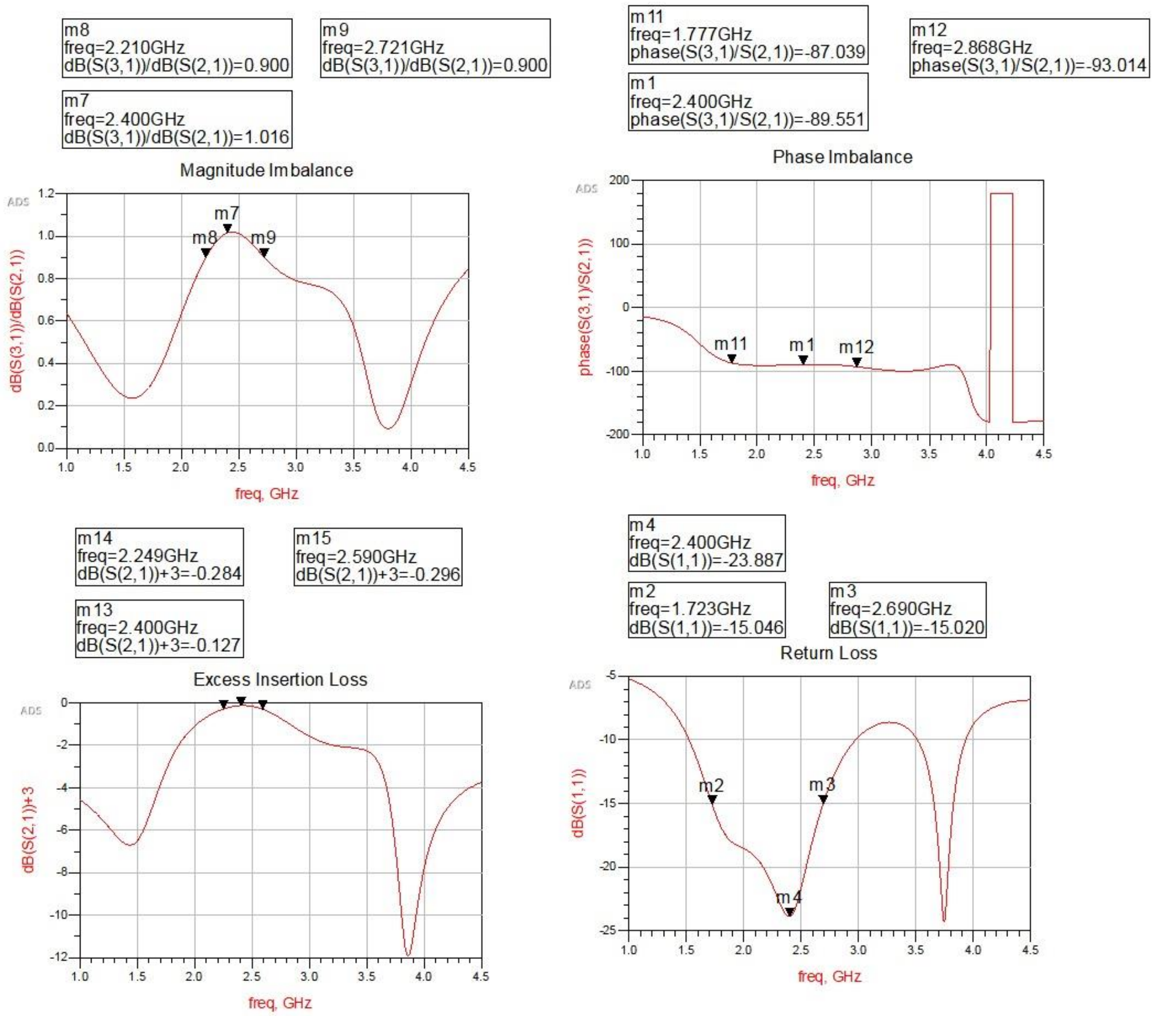

Fig (4.18): Graphical representation of a microstrip-based triple branch line coupler's performance, showcasing bandwidth for IL, RL, phase imbalance, and magnitude imbalance. Additionally, illustrating matching at the input and output ports, as well as the isolation between output ports.

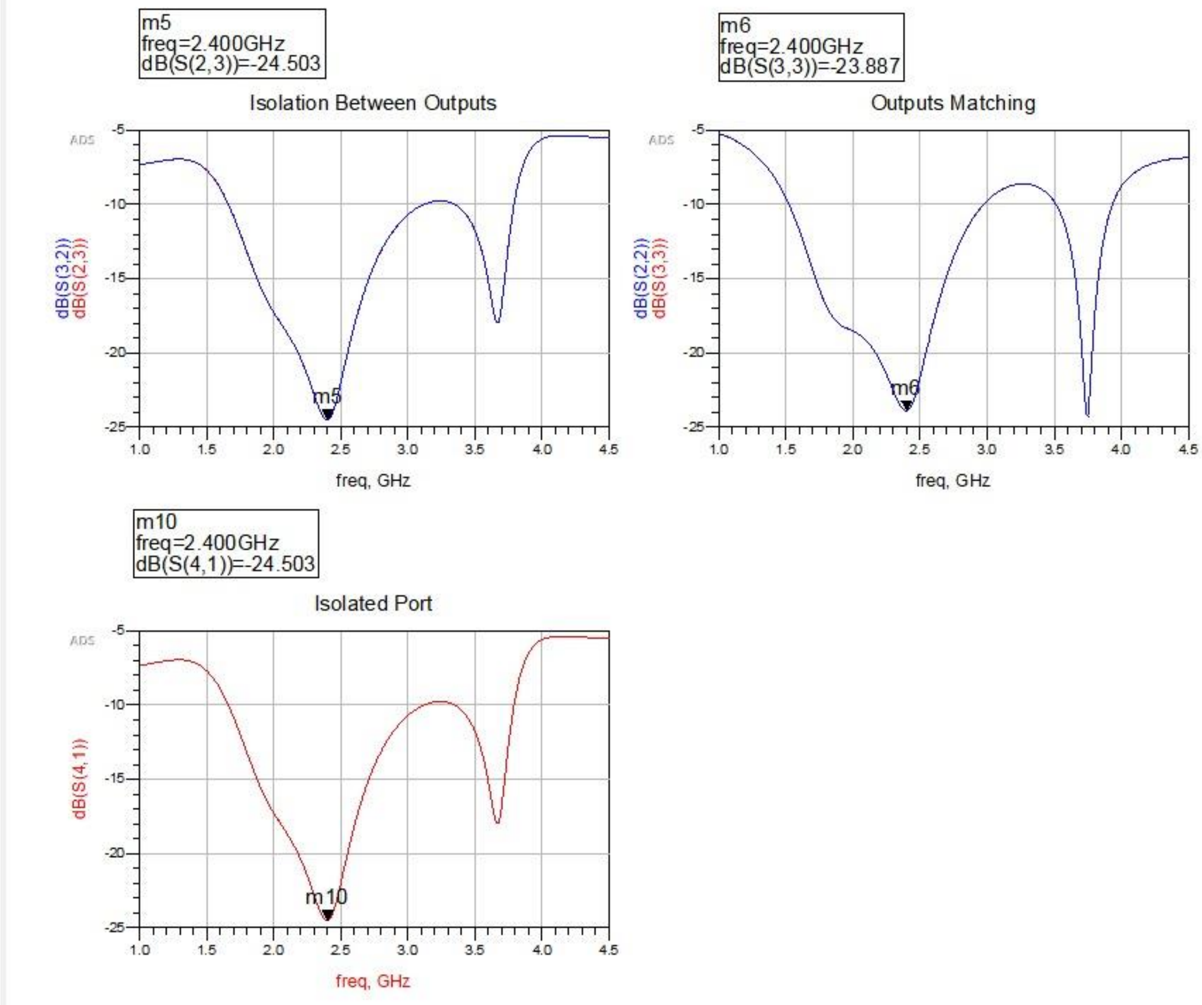

Fig (4.19): S-parameter graphs that depict the isolation between output ports 2 and 3, the isolation of port 4, and the matching of the outputs for a triple branch line coupler using microstrip lines.

Lumped schematics: simulation output graphs

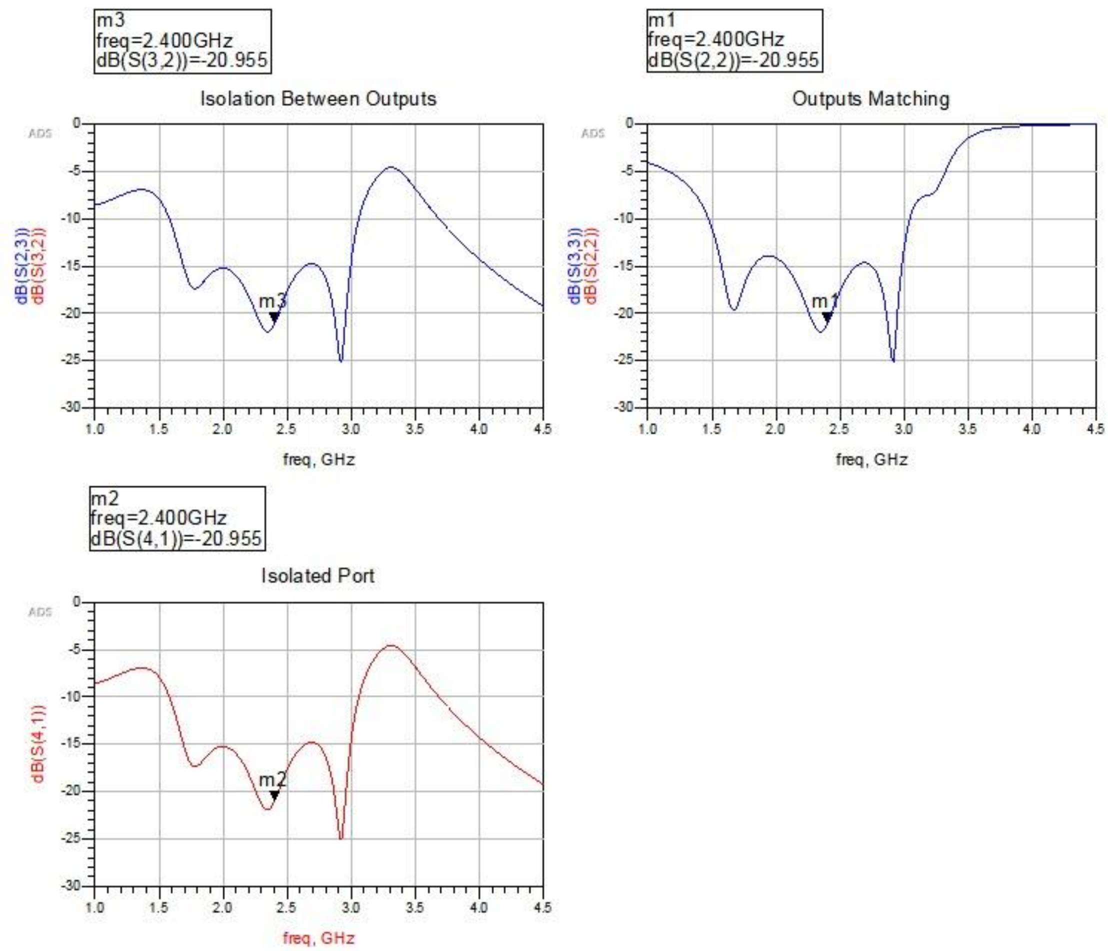

Fig (4.20): S-parameter graphs that depict the isolation between output ports 2 and 3, the isolation of port 4, and the matching of the outputs for a triple branch line coupler using Lumped components.

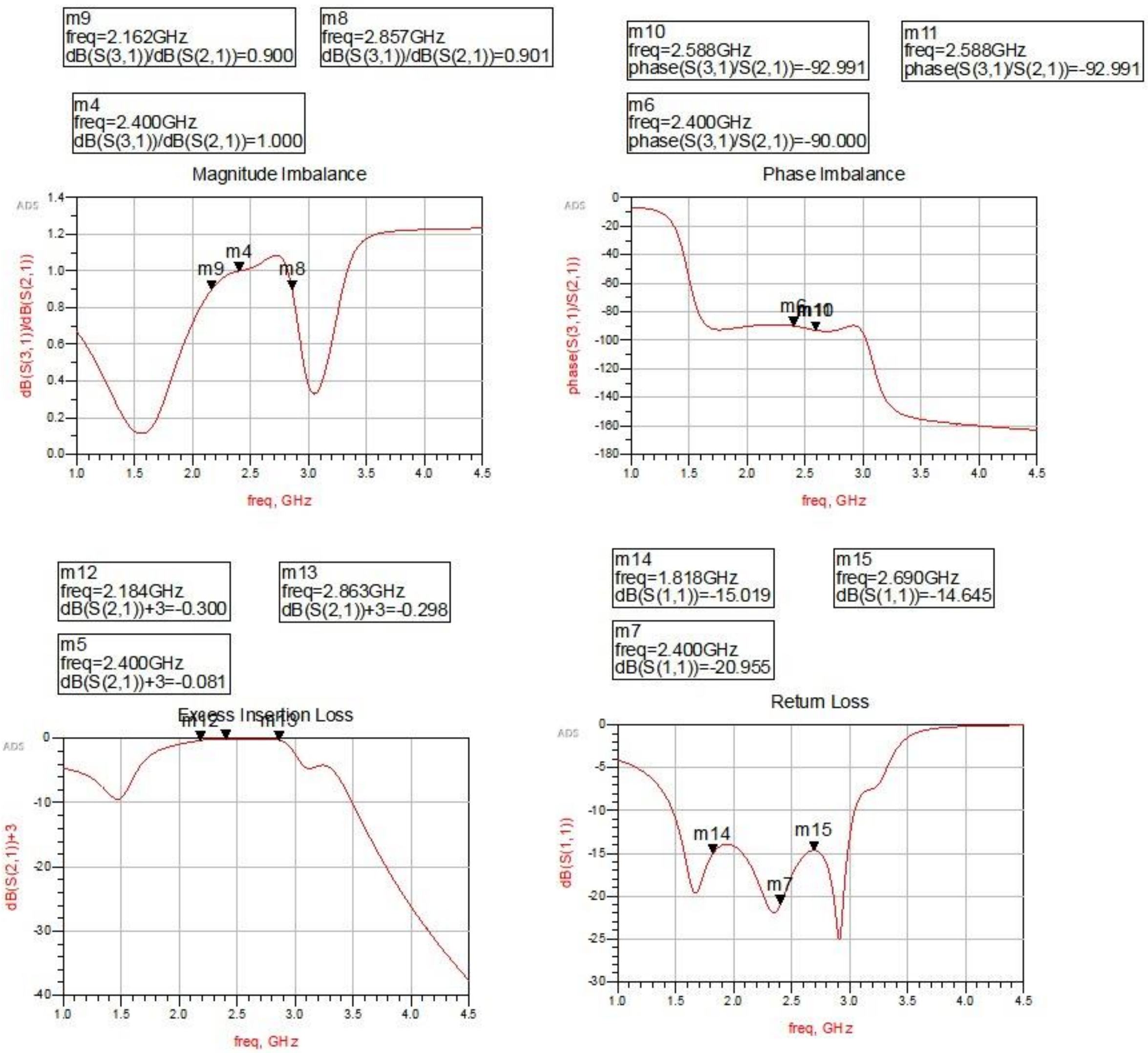

Fig (4.21): Graphical representation of a triple branch line coupler's performance using Lumped components, showcasing bandwidth for IL, RL, phase imbalance, and magnitude imbalance. Additionally, illustrating matching at the input and output ports, as well as the isolation between output ports.

Performance Metric	Schematic		Layout		Lumped	
S11 in dB (Return Loss)	-23.887		-24.035		-20.955	
S22 in dB	-23.887		-24.058		-20.955	
S33 in dB	-23.887		-24.030		-20.955	
S44 in dB	-23.887		-24.026		-20.955	
S21 in dB (Insertion Loss)	-3.137		-3.147		-3.081	
S31 in dB (Coupling Coefficient)	-3.173		-3.219		-3.081	
S23 in dB (Isolation between output ports)	-24.503		-24.881		-20.955	
S41 in dB (Isolation Loss)	-24.503		-24.893		-20.955	
Excess Insertion Loss	-0.127		-0.219		-0.081	
Phase Imbalance	-0.45		-0.317		$4.219*10^{-8} \approx 0$	
BW	Start	End	Start	End	Start	End
Min. RL of 15 dB	1.723	2.690	1.738	2.720	1.818	2.69
Max. EIL of -0.3 dB	2.249	2.590	2.266	2.619	2.184	2.863
Magnitude Imbalance of 0.1	2.210	2.721	2.220	2.780	2.162	2.857
Phase Imbalance of ± 3◦	1.777	2.86	1.793	2.870	1.621	2.588

Table (3): illustrating performance of triple branch line coupler from its simulation outputs for each of the Microstrip, Lumped and Layout simulation.

Significant drops in RL and Isolation loss mark the start of **Table (3) and figures (4.15-4.18)**, exhibiting values 38.6% and 37.4% less than the corresponding double section values at the center frequency. That drop is offset by the notable improvements in bandwidth, especially in the phase balance department. As, the bandwidth increases by 28.98% and 67.24% compared to the single and double section designs.

D. Modified Wilkinson Power Divider (M-WPD)

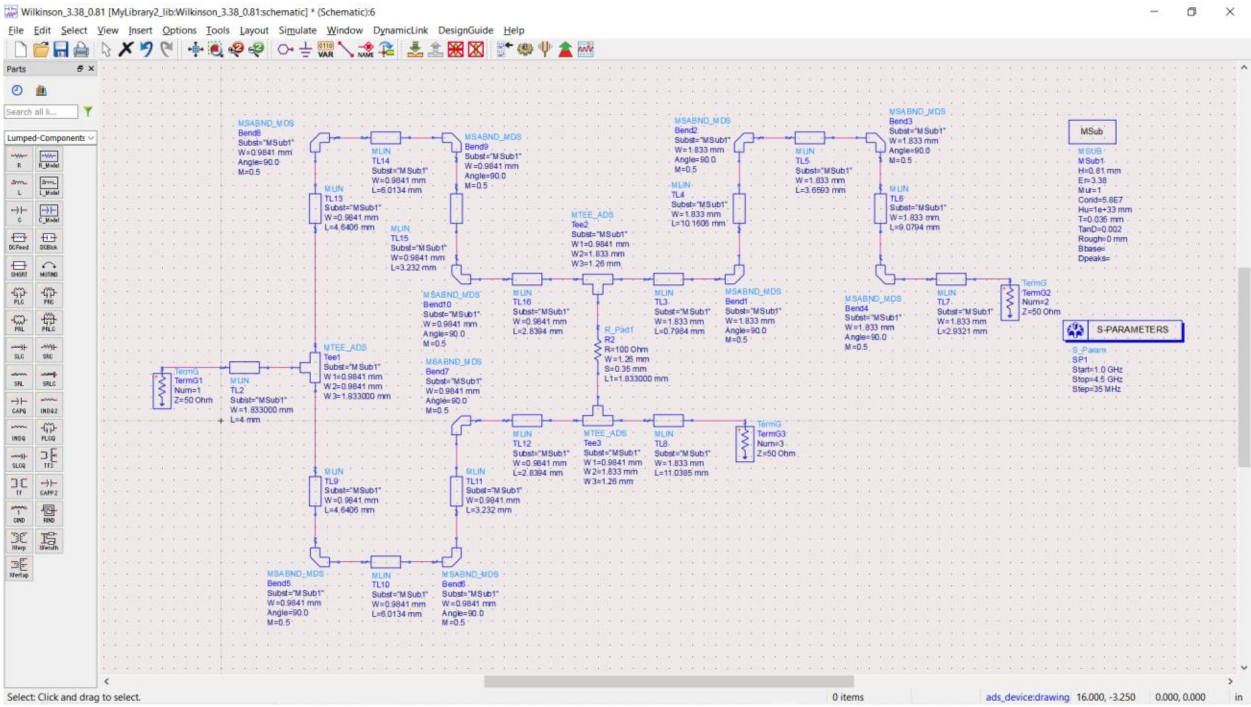

Figure (4.22): Wilkinson design using microstrip lines.

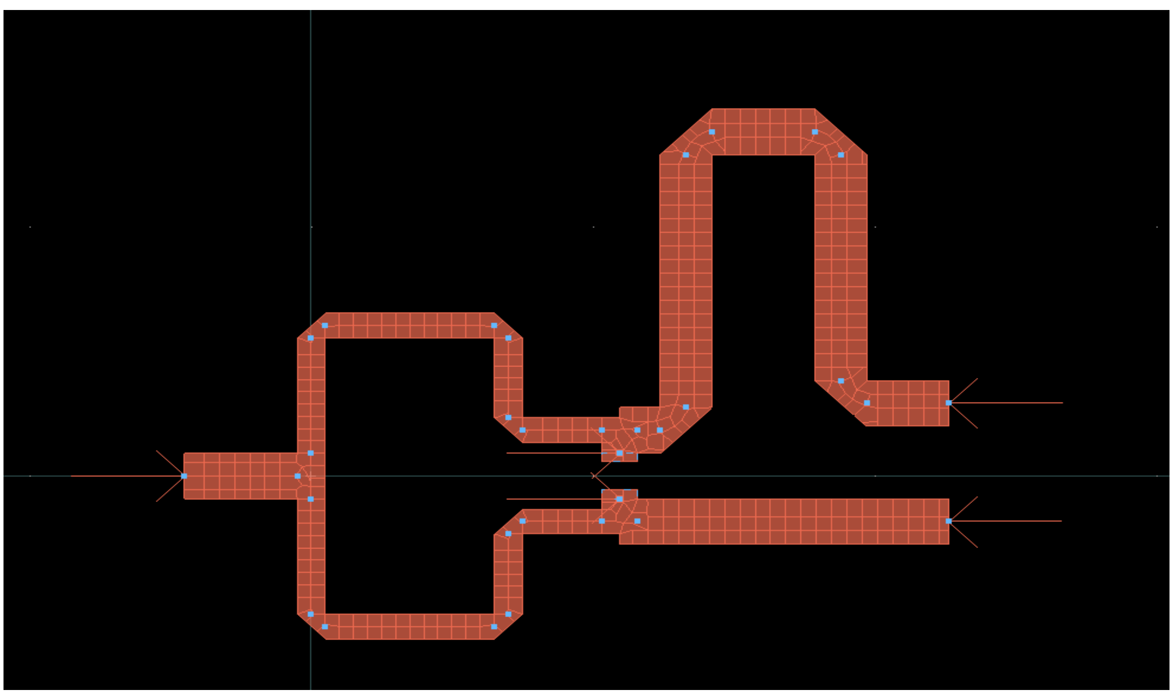

Figure (4.23): Layout of Wilkinson power divider.

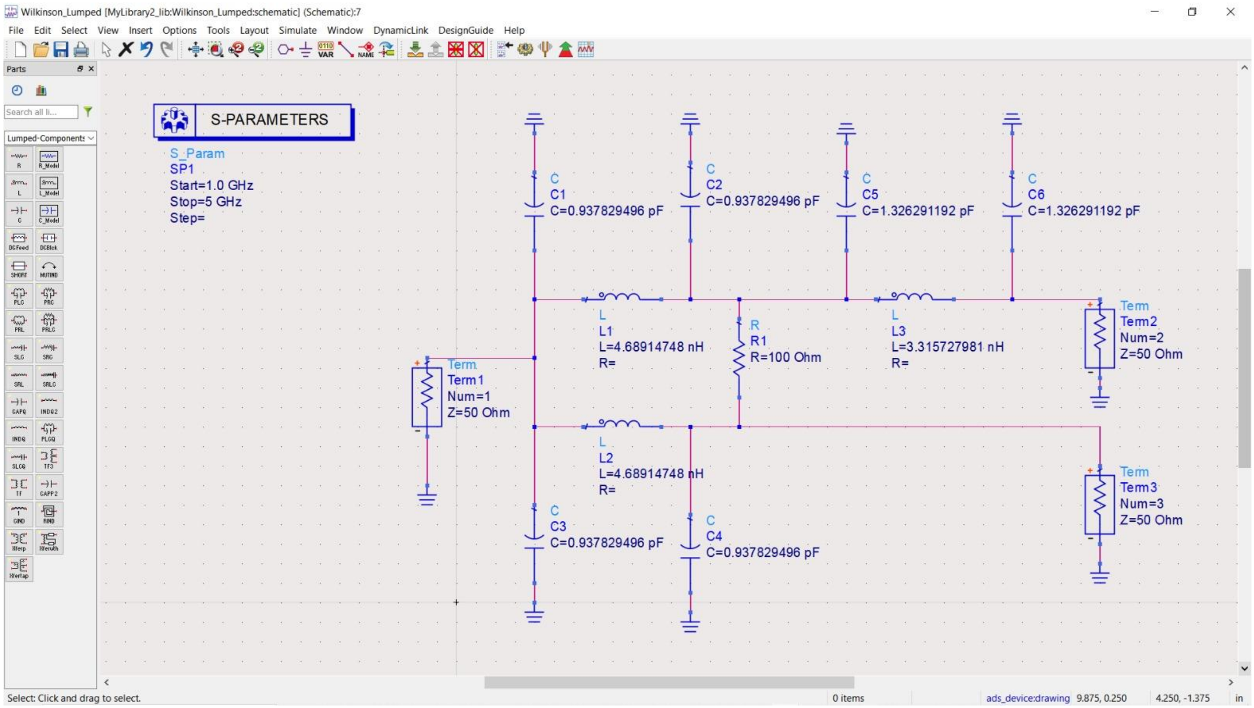

Figure (4.24): Lumped design of Wilkinson power divider.

Performance Metric	Schematic		Layout		Lumped	
S11 in dB (Return Loss)	-32.126		-27.372		-216.128	
S22 in dB	-41.103		-39.206		-211.673	
S33 in dB	-41.941		-27.879		-235.878	
S21 in dB (Insertion Loss)	-3.073		-3.096		-3.010	
S31 in dB (Coupling Coefficient)	-3.055		-3.066		-3.010	
S23 in dB (Isolation between output ports)	-32.846		-30.145		-231.108	
Excess Insertion Loss	-0.091		-0.096		-0.010	
Phase Imbalance	0.352		0.654		$6.563*10^{-8}\approx 0$	
BW	Start	End	Start	End	Start	End
Min. RL of 15 dB	1.616	3.303	1.430	3.153	1.962	2.862
Max. EIL of -0.3 dB	1.268	3.536	1.143	3.154	1.75	2.806
Magnitude Imbalance of ± 0.1	1.000	4.500	1.000	4.500	1.446	2.829
Phase Imbalance of $\pm 3^\circ$	2.331	2.488	2.338	2.497	2.336	2.461

Table (4): illustrating performance of Wilkinson power divider from its simulation outputs for each of the Microstrip, Lumped and Layout simulation.

Analyzing the results illustrated in **Table (4)**, we find that our modified microstrip WPD achieves a RL that's significantly less than that obtained by the single and double section BLC designs (about 30.1%), but it's quite similar to that of the triple section design. The isolation between the output ports at the center frequency is also 24.75% less than that of the single and double section topologies. Its EIL is quite close to the corresponding values present in all BLC designs. In terms of bandwidth, the modified WPD truly shines in terms of magnitude balance as it covers the entire band of interest. In, fact it covers the entire range of our analysis! However, its phase balance bandwidth is a fraction of that obtained by the triple section, coming in at about 14.76% of it. It even pales in comparison to the corresponding single section value, equaling 24.69% of it. That leads us to an important takeaway, that if a large bandwidth of phase balance is required then a multi section BLC would do the trick. However, if a large bandwidth of magnitude balance is required then the M-WPD would be ideal. That confirms our intuition about both devices' purpose.

5. Conclusion

To conclude, our work studies power division networks with an orthogonal phase relation between its two loads. We've discussed two main topologies which are the Branch Line Coupler (BLC) and the modified Wilkinson Power Divider. We've gone over their theory of operation, choosing to explore how to expand their bandwidth of operation in order to cover our band of interest, which is (). We've managed to do so through the use of multi section BLC. We set out to achieve the following in that band:

- Input and output matching

We've achieved values as high as -200 dB for Return Loss in the ideal lumped implementation in both networks and as high as -40 dB in the microstrip double section BLC at the center frequency. We've managed to cover bands as large as 1.723 GHz in the M-WPD design. We've also managed to cover bands as large as 0.982 GHz in the triple section BLC design. That marks the start of a trend where the lumped implementation achieves much 'sharper' results. As, it produces very efficient results but in a bandwidth much shorter than that of the microstrip implementation.

- Isolation between output ports

We've achieved values as high as -230 dB for Isolation between output ports in the ideal lumped implementation of the M-WPD and as high as -40 dB in the single section BLC at the center frequency.

- Equal power division ratio

We've achieved values for Excess Insertion Loss (EIL) as small as 0.01 dB in the ideal lumped implementation in both networks and as small as 0.096 dB for the microstrip M-WPD at the center frequency. We succeeded in covering bands as large as 3.5 GHz of magnitude balance in the M-WPD design. We've also covered bands as large as 0.56 GHz of magnitude balance in triple section BLC design.

- Orthogonal phase relation between output signals

We’ve achieved values of phase imbalance as small as 0.11^{o} at the center frequency using the microstrip single section BLC design. The lumped implementation also achieved a perfectly orthogonal phase relation between the output signals at the center frequency. We’ve managed to cover bands as large as 0.982 GHz using the microstrip triple section BLC design.

We finally choose the microstrip double section BLC to serve our application, as it achieves a respectable balance between the specifications we’ve set out to meet in terms of performance and bandwidth.

References

[1] S. Sharma, "Design and Simulation of Quadrature Branch-line Coupler for S Band Applications," in *2nd International Conference on Micro-Electronics and Telecommunication Engineering*, 2018.

[2] "Microwaves101," March 2014. [Online]. Available: https://www.microwaves101.com/encyclopedias/quadrature-couplers. [Accessed April 2020].

[3] "Microwaves101," February 2023. [Online]. Available: https://www.microwaves101.com/encyclopedias/branchline-couplers. [Accessed April 2023].

[4] A. R. Shirley Helen Judith, "Two-Section Branch-Line Coupler for Wireless Application," *Journal of Network Communications and Emerging Technologies (JNCET) ,* vol. 9, no. 4, 2019.

[5] D. S. Ricketts, "Rickettslab," 2015. [Online]. Available: https://rickettslab.org/bits2waves/design/branchline-coupler/branchline-coupler-theory/. [Accessed May 2023].

[6] "Microwaves101," 2022. [Online]. Available: https://www.microwaves101.com/encyclopedias/wilkinson-power-splitters#:~:text=Here%20is%20how%20the%20Wilkinson%20splitter%20works%20as,therefore%20the%20resistor%20is%20decoupled%20from%20the%20input.. [Accessed April 2023].

[7] G. L. MATTHAEI, MICROWAVE FILTERS, IMPEDANCE-MATCHING NETWORKS, AND COUPLING STRUCTURES, 1995.

[8] Y. C. Yonggang Zhou, "Lumped-Element Equivalent Circuit Models for Distributed Microwave Directional Couplers," 2008.