EE 502: Microwave Engineering

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Take-Home Exam 1
Broadband Stripline Directional Coupler

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Contents

1 Objective

The objective of this assignment was to design a broadband stripline directional coupler with the specifications listed in Table 1. ADS is to be used as a simulation tool and the paper "The Design of a Broadband Stripline Directional Coupler" by Yi Ge and Gaofeng Guo [1] can be used as a guide.

Table 1: Design Specifications

Parameter	**Value**	**Unit**
Topology	Stripline transmission line	-
Bandwidth	$3-22$	GHz
Coupling Ratio	10 ± 1	dB
VSWR	< 1.4	-
Directivity	> 15	dB
Insertion Loss	> -1.5	dB

NOTE: Reference Appendix A for design performance parameter definitions.

Additional requirements are noted below:

- Use a low-loss substrate manufactured by Rogers Corporation.
- Utilize the loss tangent and dimensions of the substrate material.
- Utilize the ADS Optimizer.
- At a minimum, produce the same design plots as shown on page 310 of [1].
- Document all steps taken in the design using a lab-notebook format. Document both failures and successes as iterations are performed towards the final design.
- Clearly document, compare, and analyze the final design and its performance.

2 Initial Design

Referencing "The Design of a Broadband Stripline Directional Coupler" and *RF and Microwave Coupled-Line Circuits* we can begin the initial design and modelling process.

The design process will begin with choosing a low-loss substrate manufactured by Rogers Corporation. RT/duroid 5880LZ substrate was chosen for it's low dielectric constant, low dissipation factor, and wide operational frequency [2]. Table 2 highlights the substrate performance specifications.

Table 2: RT/duroid 5880LZ Substrate Performance Specifications [2]

Parameter	**Value**	**Unit**
Dielectric Constant	2.00 ± 0.04	-
Dissipation Factor, tan	0.0021	-
Standard Thickness, b	1.270 ± 002	mm
Standard Panel Size	305×457	mm
Density	1.4	gm/cm^3
Thermal Conductivity	0.33	W/m/$^{\circ}$K
Surface Resistivity	2.08×10^6	$M\Omega \times cm$
Volume Resistivity	1.74×10^7	$M\Omega \times cm$
Standard Copper Cladding	1 / 18	oz / μm

The center frequency and wavelength can be computed via Equation 1.

$$f_o = \frac{f_1 + f_2}{2} = \frac{3\ GHz + 22\ GHz}{2} = \boxed{12.5\ GHz} \rightarrow \lambda_o = \frac{c}{f_o} = \frac{3.0E8\ m/s}{12.5\ GHz} = \boxed{24.0\ mm} \tag{1}$$

The guide wavelength, λ_g, can now be computed using the center wavelength and dielectric constant found in Table 2. Equation 3 solves for L, which is the initial length of each coupled lines length.

$$\lambda_g = \frac{\lambda_o}{\sqrt{\epsilon_r}} = \frac{0.024\ m}{\sqrt{2.00}} = \boxed{16.971\ mm} \tag{2}$$

$$L = \frac{\lambda_g}{4} = \frac{0.016971\ m}{4} = \boxed{4.243\ mm} \tag{3}$$

Equation 4 and 5, derive the fractional bandwidth, w, and bandwidth ratio, B, respectively.

$$w = \frac{f_2 - f_1}{f_o} = \frac{22\ GHz - 3\ GHz}{12.5\ GHz} = \boxed{1.52} \tag{4}$$

$$B = \frac{f_2}{f_1} = \frac{22\ GHz}{3\ GHz} = \boxed{7.333} \tag{5}$$

Referencing Table I in "The Design of a Broadband Stripline Directional Coupler" on Page 309 [1] as well as Table 6.1 on Page 182 of *RF and Microwave Coupled-Line Circuits* [3] we can observe and evaluate the the Even-Mode impedance of individual sections with a corresponding 10 dB coupling degree and various ripple factors. Table 3 highlights these values.

Table 3: Even-Mode Normalized Impedance at 10dB Coupling Degree

Section	**ripple**	$\mathbf{Z_{1e}}$	$\mathbf{Z_{2e}}$	$\mathbf{Z_{3e}}$	$\mathbf{Z_{4e}}$	$\mathbf{Z_{5e}}$
5	0.8	1.0714	1.2601	1.8194		
7	0.4	1.0360	1.0973	1.2384	1.8672	
9	0.2	1.0189	1.0516	1.1174	1.2639	1.9063
9	0.4	1.0304	1.0701	1.1431	1.2978	1.9607

A 9-section design will be chosen to achieve (relatively) the most constant coupling ratio over the effective bandwidth.

$$\boxed{Z_{0o}Z_{0e} = 1} \quad \propto \quad \boxed{Z_{0o}Z_{0e} = Z_0^2} \tag{6}$$

Equation 6 allows us to solve for the odd-mode normalized impedances highlighted in Table 4.

Table 4: Odd-Mode Normalized Impedance at 10dB Coupling Degree

Section	**ripple**	$\mathbf{Z_{1o}}$	$\mathbf{Z_{2o}}$	$\mathbf{Z_{3o}}$	$\mathbf{Z_{4o}}$	$\mathbf{Z_{5o}}$
9	0.2	0.9815	0.9509	0.8949	0.7912	0.5246
9	0.4	0.9705	0.9345	0.8748	0.7705	0.5100

The green highlighted rows in Tables 3 and 4 will be chosen due the minimized ripple factor of 0.2.

The LineCalc tool in Keysight's Advanced Design System can now be utilized to calculate the physical Line Width and offset (separation) dimensions observed in Table 5.

Table 5 also highlights the non-normalized even-odd mode section impedances found by scaling the normalized even-odd mode impedances seen in Tables 3 and 4 by the system characteristic impedance, $Z_0 = 50\Omega$.

Table 5: Section Even-Odd Mode Impedance and Physical Dimensions (L = 89.594 mil)

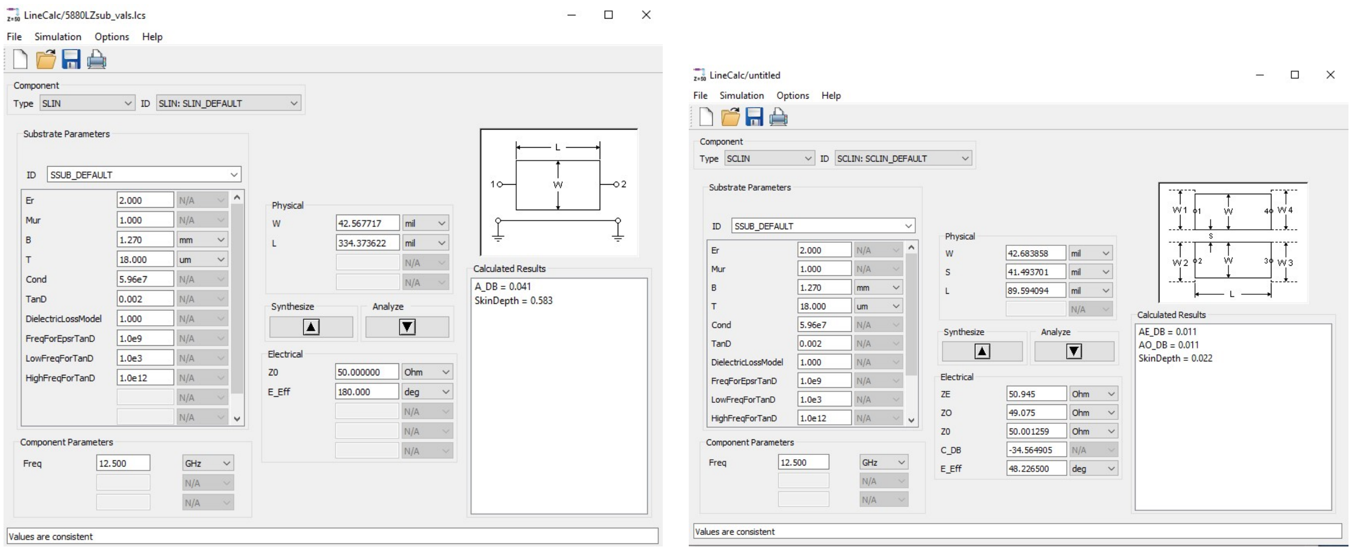
Section	$\mathbf{Z_e}$	$\mathbf{Z_o}$	**Line width (mil)**	**Offset (mil)**
1	50.9450	49.0750	42.684	41.494
2	52.5800	47.5450	42.476	25.907
3	55.8700	44.7450	41.567	14.063
4	63.1950	39.5600	38.131	4.957
5	95.3150	26.2300	22.906	0.136

Note: Since the 9-section design is *symmetrical* about the fifth section, the following relations can be made:

$$Z_e^6 = Z_e^4, Z_o^6 = Z_o^4 \quad \therefore \quad W_6 = W_4, S_6 = S_4$$
$$Z_e^7 = Z_e^3, Z_o^7 = Z_o^3 \quad \therefore \quad W_7 = W_3, S_7 = S_3$$
$$Z_e^8 = Z_e^2, Z_o^8 = Z_o^2 \quad \therefore \quad W_8 = W_2, S_8 = S_2$$
$$Z_e^9 = Z_e^1, Z_o^9 = Z_o^1 \quad \therefore \quad W_9 = W_1, S_9 = S_1$$

where, W is the Line Width and S is the offset separation, both in units mils.

Figure 1(a) and (b) below highlight the LinCalc tool in ADS used to find the physical dimensions of each coupled line and the series lines used to interconnect the coupled sections to each distinct port.



(a) Series Line Computations

(b) Coupled Section Line Computations

Figure 1: ADS LinCalc Tool

2.1 First Iteration

Utilizing the physical dimensions noted in Table 5, an initial model of the stripline directional coupler was designed in Keysight ADS.

Figure 2 shows the initial design with a stripline substrate definition aligning with Table 2.

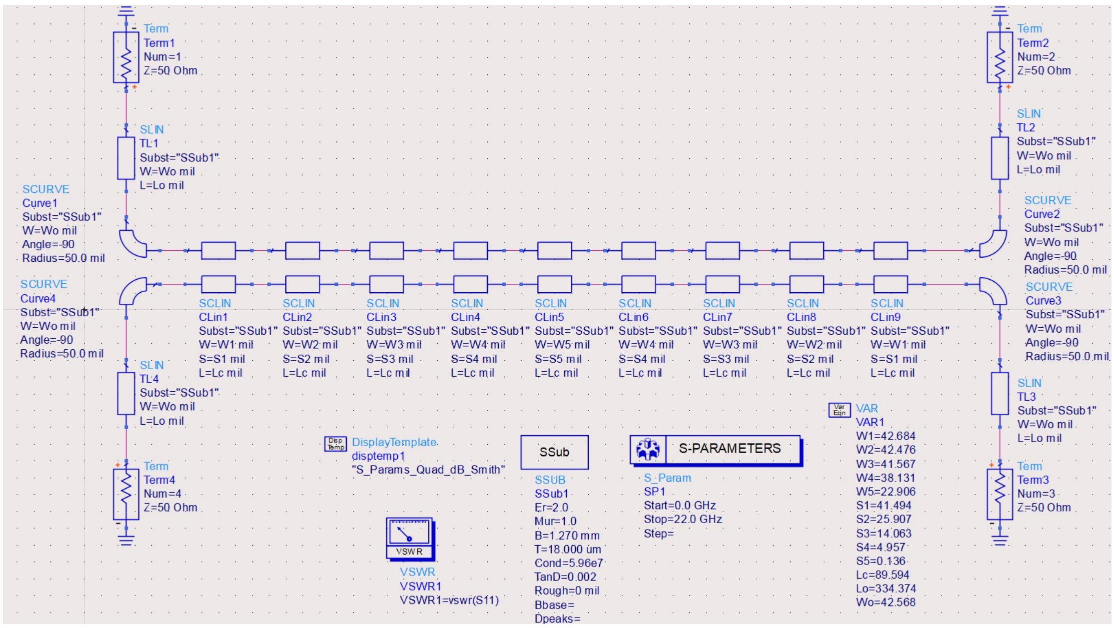


Figure 2: First (Initial) Iteration Design Schematic

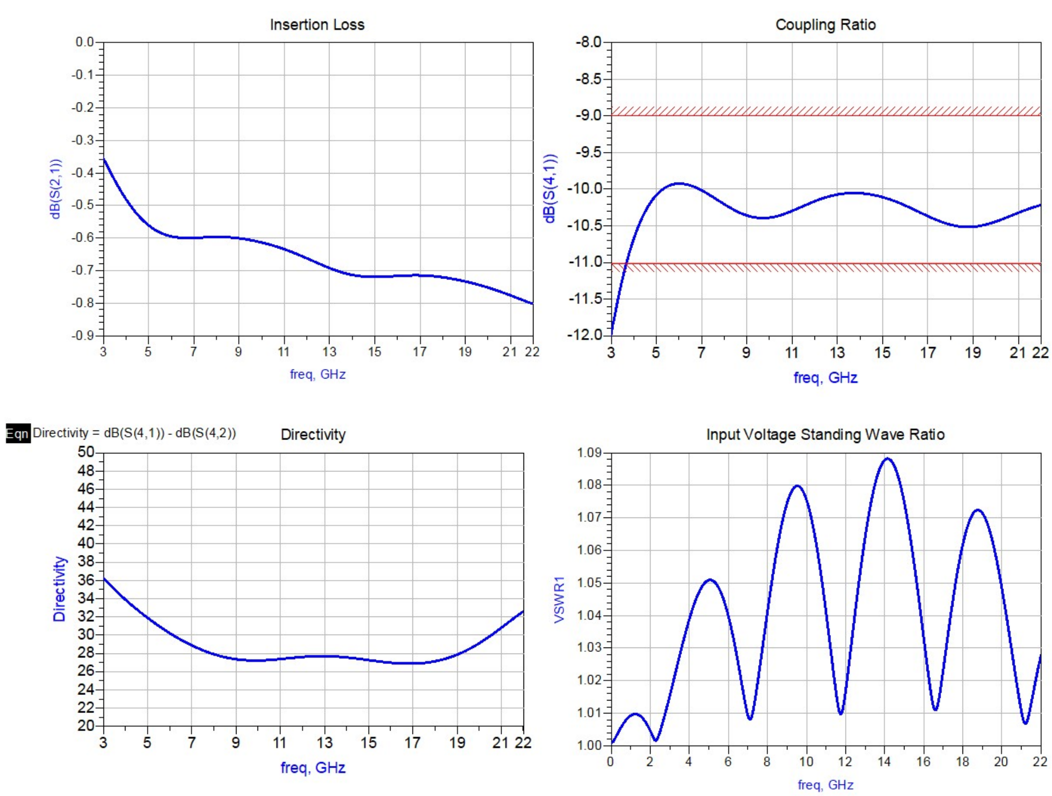


Figure 3: First (Initial) Iteration Design Simulation Results

Figure 3 shows the corresponding four design parameters under considerations, insertion loss, coupling ratio, directivity, and VSWR over the effective bandwidth, 3-22 GHz.

It can be observed that three of the four design parameters are satisfied from this first iteration. To obtain a coupling ratio that is within the design specs, design optimization can be performed.

Section 3 will explore several additional iterations and optimization techniques to strengthen this design.

NOTE: Reference Appendix A for design performance parameter definitions.

3 Design Optimization

Several optimization techniques were performed to arrive at a design that not only satisfied but surpassed the four performances specifications.

Utilizing the Optimization tool in ADS, several goals were set and select parameters were varied to try and satisfy all the goals. Each coupled line section width, separation offset, and length were varied as well as the respective curved and series lines' width, radius, and length.

3.1 Second Iteration

<u>Optimization Types Used:</u> Random, Gradient

<u>Number of Iterations:</u> 1000, 1000

Table 6: Second Iteration Optimization Goals

Goal	Limit	Unit	Weight
VSWR	< 1.4	-	1.0
Coupling Ratio	$[-11, -9]$	dB	1.0
Insertion Loss	> -1.5	dB	1.0
Directivity	> 15	dB	1.0

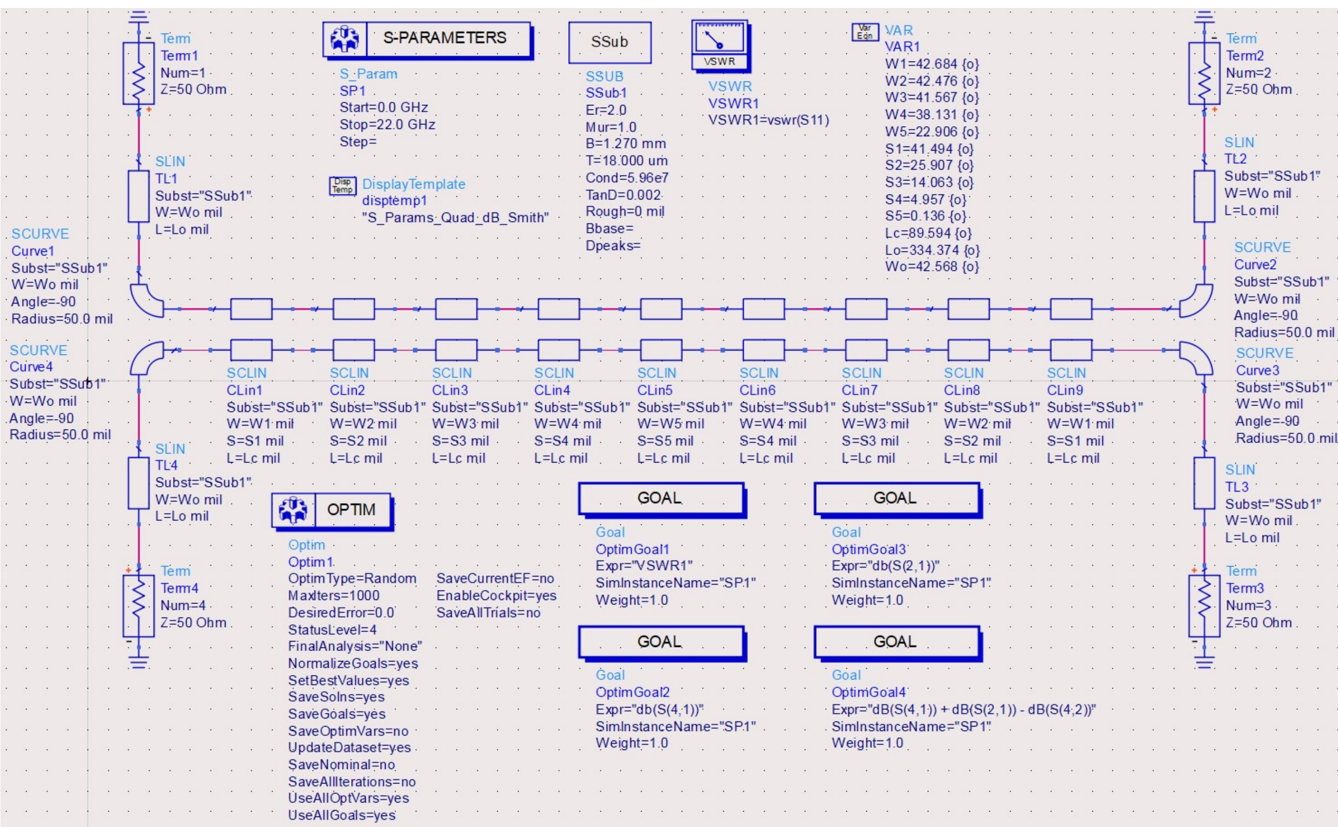


Figure 4: Second Iteration Design Schematic

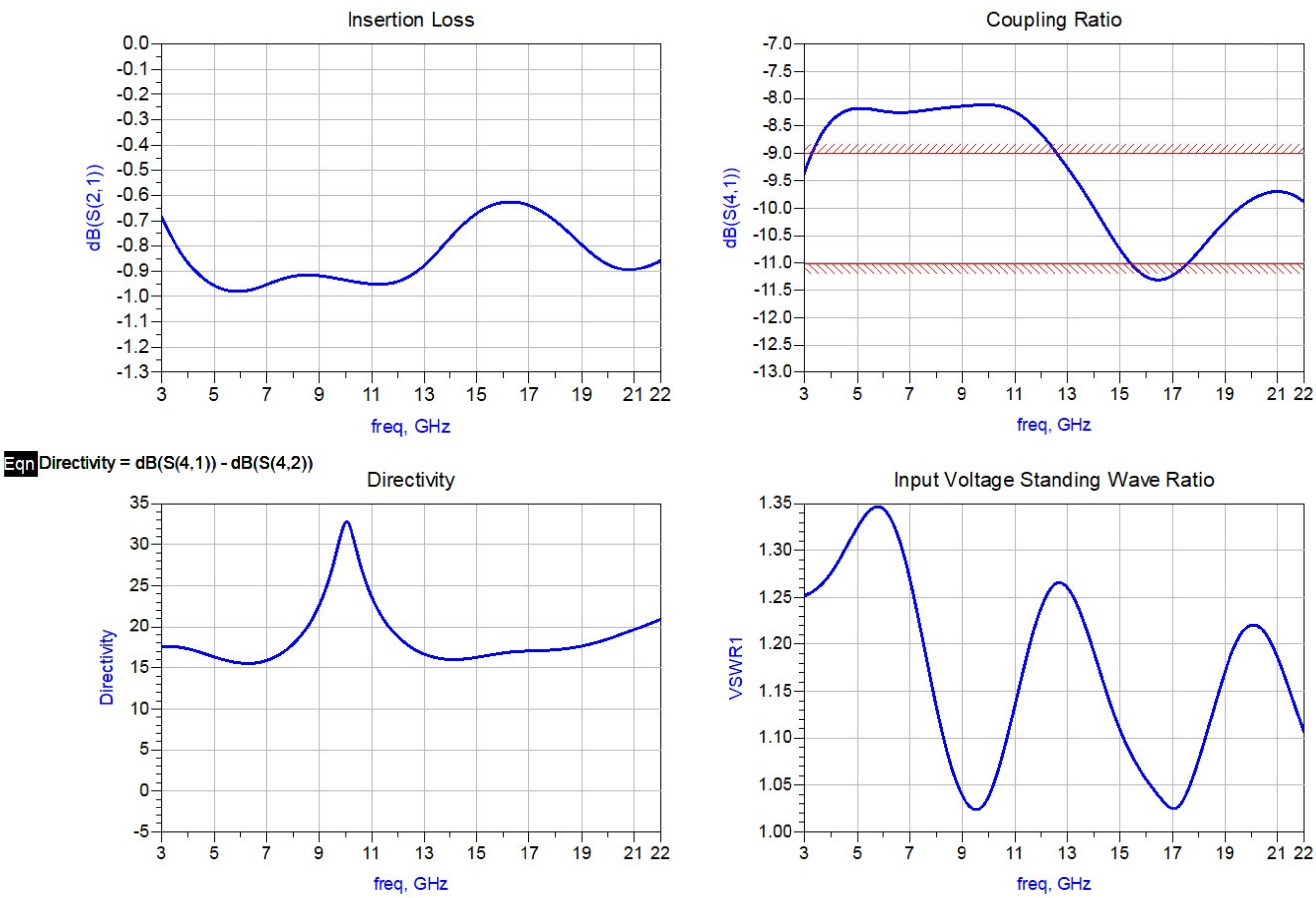


Figure 5: Second Iteration Design Simulation Results

Figure 5 above shows that although the coupling ratio from 3-4 GHz was brought closer to the design specifications, the parameter fell out of the targeted range from 3.5 to approximately 12.5 GHz and 15.5 to 17.5 GHz.

The remaining three design parameters still stayed within their specifications.

The next iteration will attempt to use higher performance Optimization types.

3.2 Third Iteration

Optimization Type(s) Used: Gradient Minimax, Quasi-Newton

Number of Iterations: 1000, 1000

Table 7: Third Iteration Optimization Goals

Goal	Limit	Unit	Weight
VSWR	< 1.4	-	1.0
Coupling Ratio	$[-11, -9]$	dB	1.0
Insertion Loss	> -1.5	dB	1.0
Directivity	> 15	dB	1.0

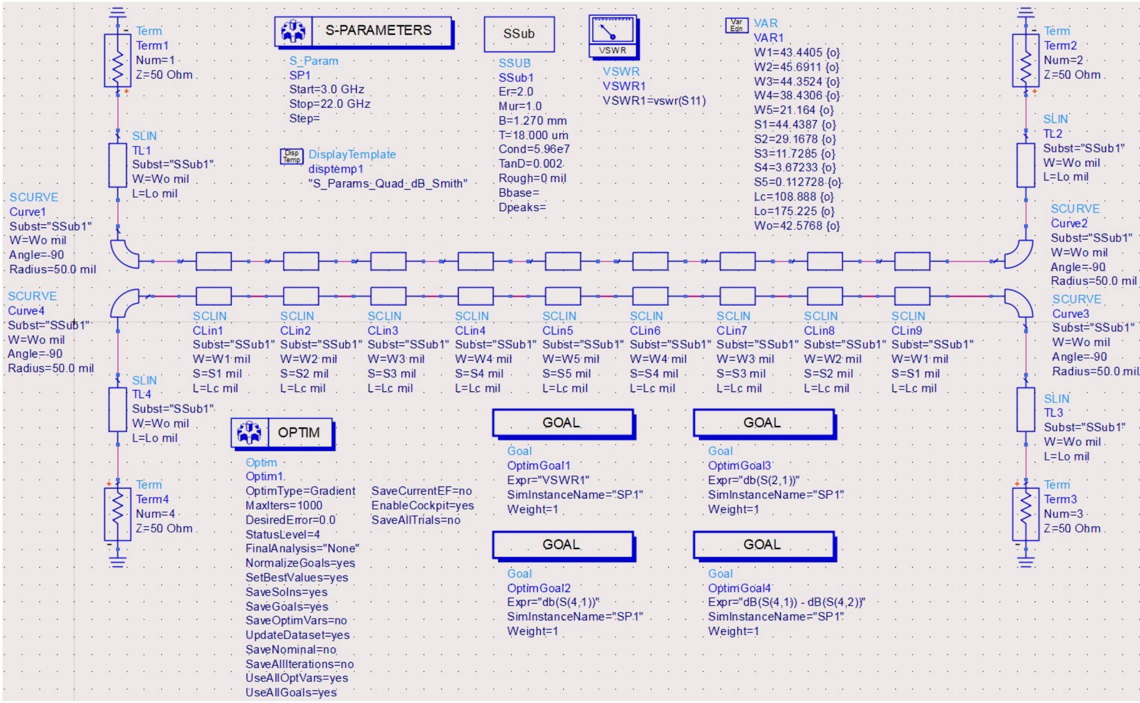


Figure 6: Third Iteration Design Schematic

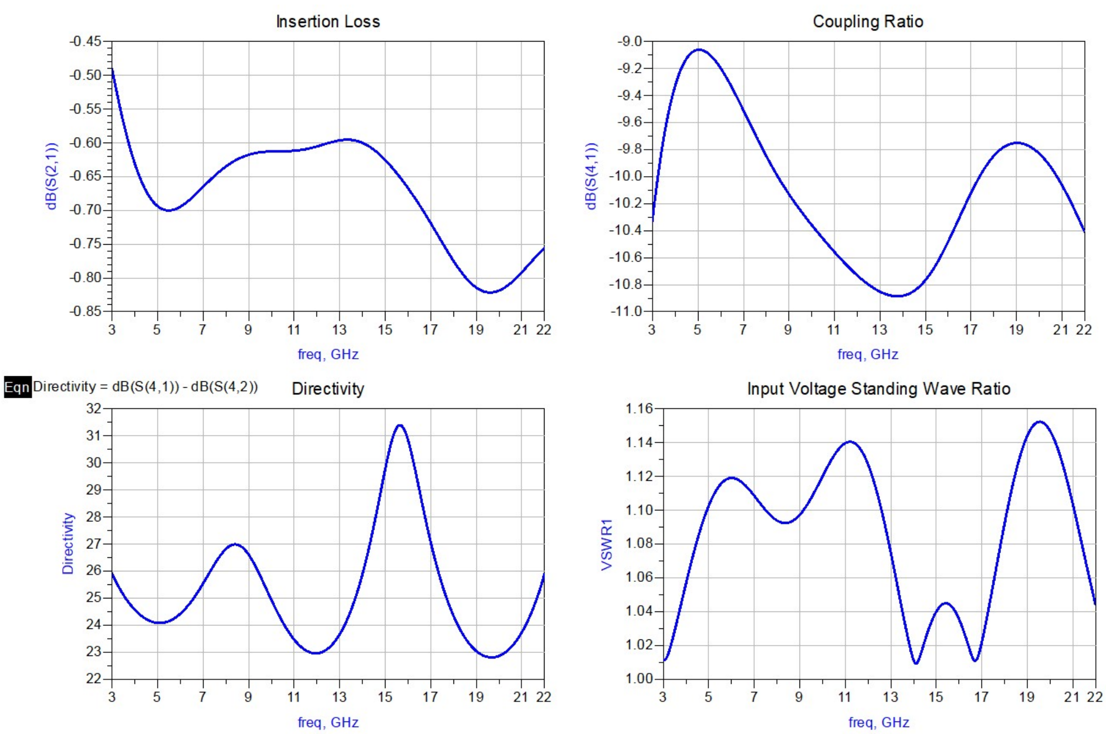


Figure 7: Third Iteration Design Simulation Results

Figure 7 shows that the Quasi-Newton Optimizer combined with the Gradient Minimax Optimizer was able to optimize the variable design parameters such that all four design specifications were satisfied.

Although all of the initial design specifications have been met, further optimization will be performed to try and achieve the best possible results for this 9-section stripline directional coupler design.

3.3 Fourth (Final) Iteration

Optimization Type(s) Used: Least Pth, Genetic, Hybrid

Number of Iterations: 100, 100, 100

Table 8: Fourth (Final) Iteration Optimization Goals

Goal	Limit	Unit	Weight
VSWR	< 1.12	-	1.0
Coupling Ratio	$[-10.5, -9.5]$	dB	1.0
Insertion Loss	> -0.8	dB	1.0
Directivity	> 25	dB	1.0

Observe from Table 8 that the goal limits for this final iteration optimization were improved to try and achieve a higher performing design.

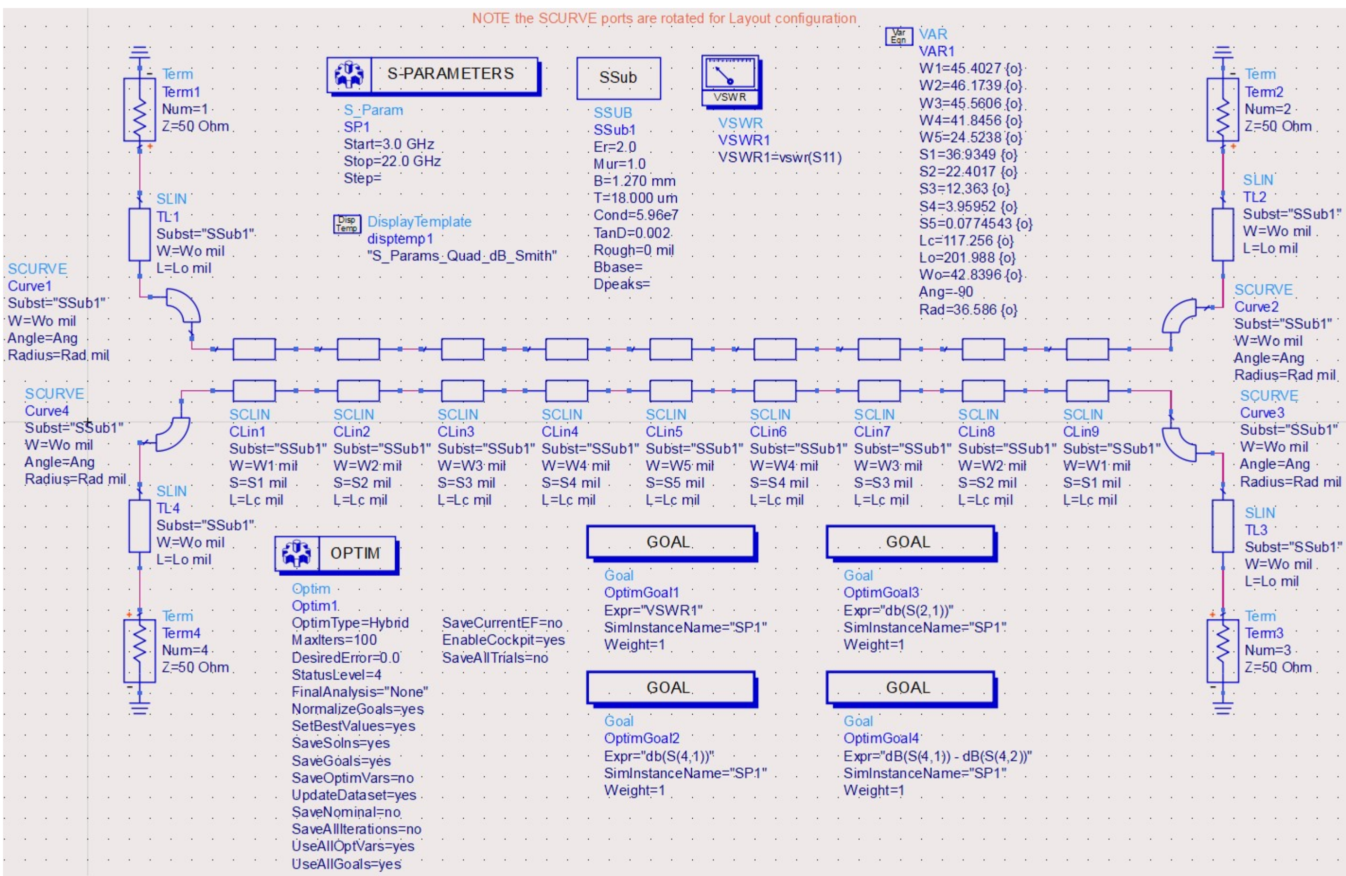


Figure 8: Fourth (Final) Iteration Design Schematic

Note that the orientation of the four SCURVE lines at each end of the coupler observed in Figure 8 above were rotated to satisfy the proper layout orientation (reference Section 4.1, Figure 10).

Figure 9, displays the simulated results of the final, fourth iteration.

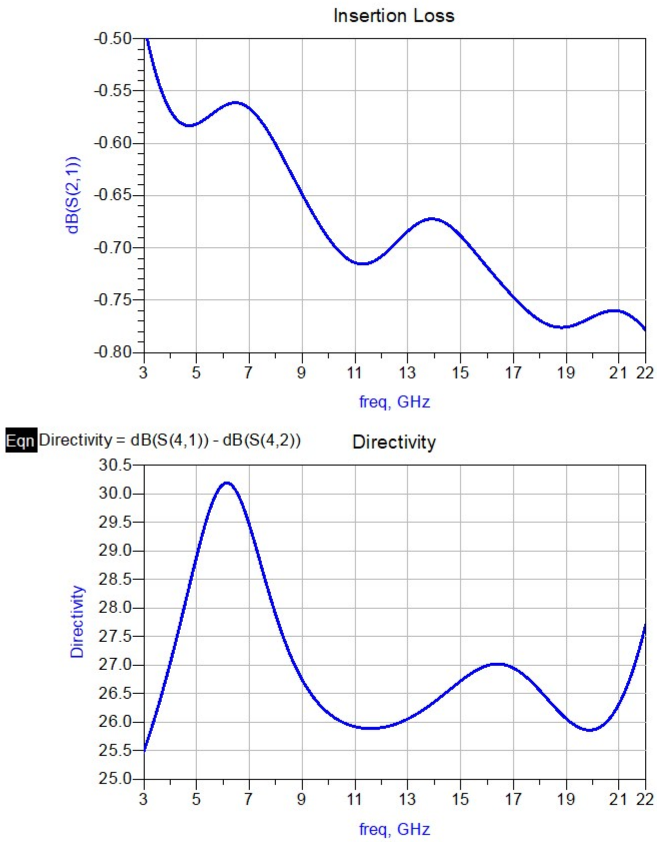


Figure 9: Fourth (Final) Iteration Simulation Results

The Insertion Loss of this final design performs very well, staying above -0.8 dB for all frequencies from 3 to 22 GHz. The Coupling Ratio remains centered around -10 dB with only a slight ripple of less than ±0.5 dB for all frequencies within the band of interest. The Directivity peaks to 30.19 dB at 6.14 GHz and stays more than 10 dB *above* the initial design specifications for all operational frequencies. Furthermore, the Voltage Standing Wave Ratio observed at the input port does not rise above 1.1 for all frequencies within the band of interest.

Table 9 below summarizes the final design performance, relative to the initial design specifications.

Table 9: Initial Design Specifications vs. Final Design Performance (3 – 22 GHz)

Parameter	**Initial Specification**	**Final Result**	**Unit**
Coupling Ratio	10 ± 1	10 ± 0.5	dB
VSWR	< 1.4	< 1.11	-
Directivity	> 15	> 25	dB
Insertion Loss	> -1.5	> -0.8	dB

Table 10 summarizes the final design physical dimensions for each coupled line section, the curved lines, and the series in-lines.

Table 10: Final Design Physical Dimensions

Parameter	**Line Width (mils)**	**Offset (mils)**	**Line Length (mils)**	**Angle (°)**	**Radius (mils)**
Sections 1,9	45.40	36.94	117.26	-	-
Sections 2,8	46.17	22.40	117.26	-	-
Sections 3,7	45.56	12.36	117.26	-	-
Sections 4,6	41.85	3.96	117.26	-	-
Section 5	24.52	0.08	117.26	-	-
Series In-Lines	42.84	-	201.99	-	-
Curved Lines	42.84	-	-	-90	36.59

4 Layout and Momentum Simulation

To further explore this broadband stripline directional coupler a layout was generated from the final design schematic shown in Figure 8.

Furthermore, Momentum was used on the layout to perform 3D full-wave planar EM simulations on the design.

4.1 Layout

Figure 10 below shows the layout for the broadband stripline directional coupler design. Pins were places at the four respective ports and each coupled line was interconnected to perform EM simulations.

Note that the fragmented appearance of the lines is due to the Momentum simulator. There also appears to be no separation offset for the fifth center section, but this is due to the display of the figure – the separation gap can be observed if the figure was zoomed in on the central, fifth section.

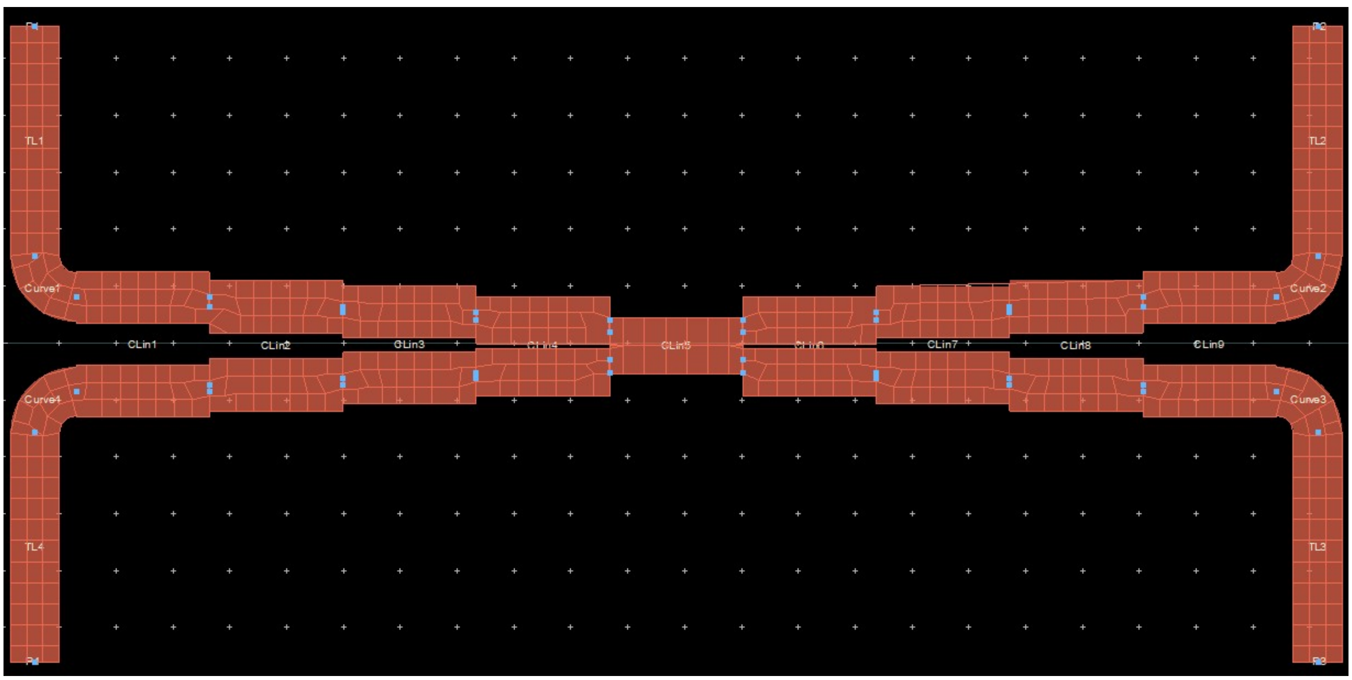


Figure 10: Final Design ADS Layout

4.2 Momentum Simulation

Momentum simulations were performed on the layout shown in Figure 10. Figure 11 shows the 3D substrate model defined for the RT/Duroid 5880LZ material. Figure 12 displays the Momentum simulated results from the design layout.

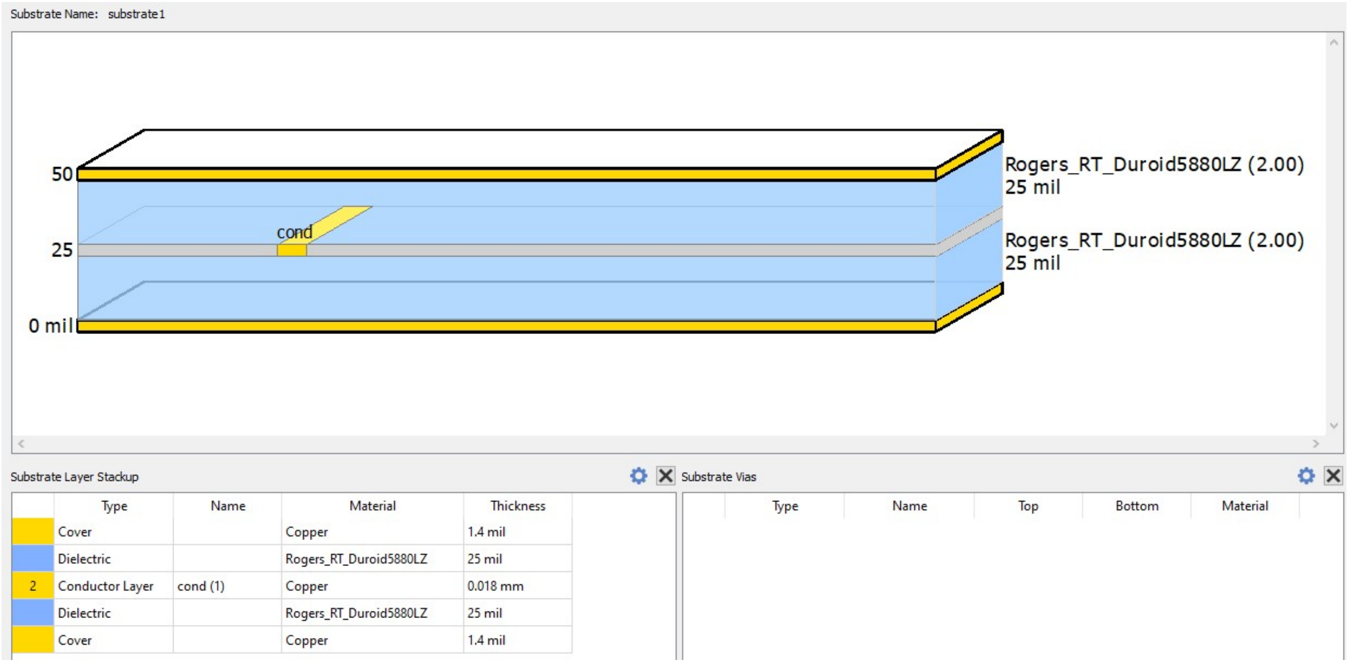


Figure 11: Momentum Substrate Definition

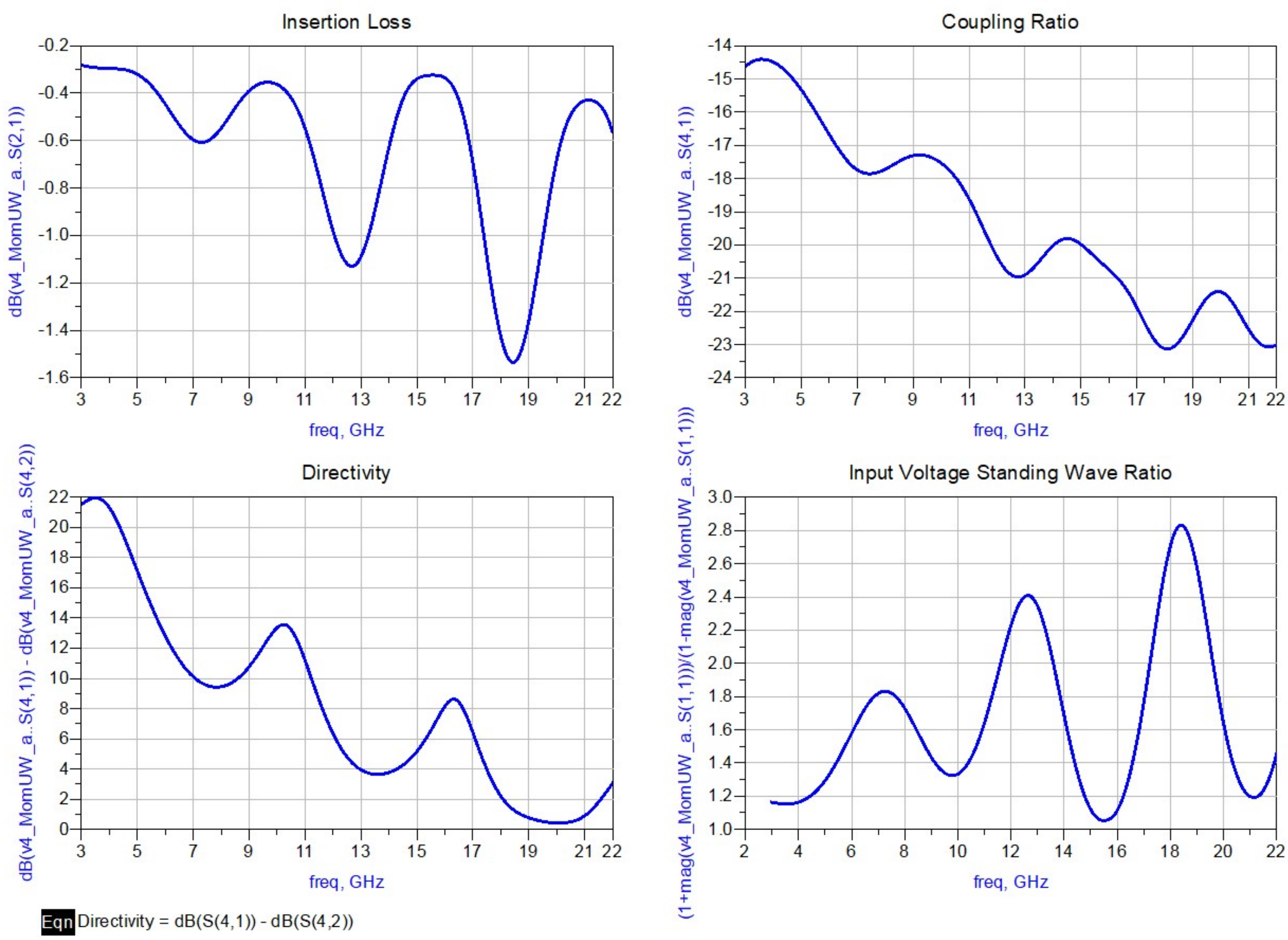


Figure 12: Momentum Layout Simulated Results

4.3 Layout vs. Schematic Results

Figure 13 below overlays the schematic simulated results of Figure 8 with the Momentum layout simulated results of Figure 12 on the same plots to better visualize the comparison. Table 11 summarizes these findings.

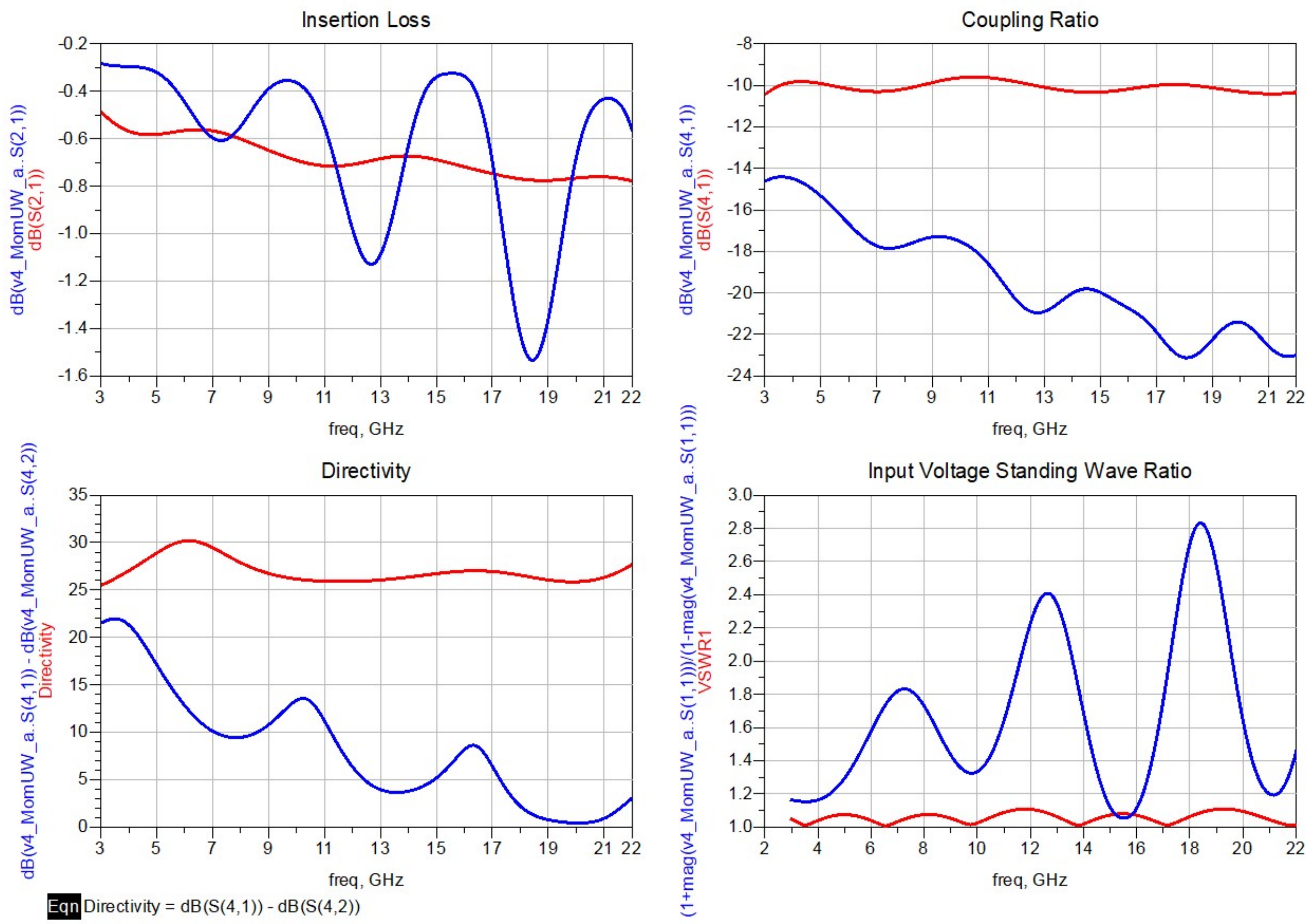


Figure 13: Final Design Schematic vs. Layout Results

It's apparent that the physical layout Momentum simulations do not perform nearly as well as the schematic simulations. This could be due to several factors including unwanted coupling, parasitics, the skin effect, and the substrate effect.

Due to the scope of this project, further optimization of the design to improve the physical layout and Momentum simulated results will not be performed.

Table 11: Schematic vs. Momentum Layout Simulated Results (3 – 22 GHz)

Parameter	**Layout**	**Schematic**	**Unit**
Coupling Ratio	$[-13.8, -23.3]$	$[-10.5, -9.5]$	dB
VSWR	< 2.85	< 1.11	-
Directivity	> 0.98	> 25	dB
Insertion Loss	> -1.55	> -0.8	dB

5 Conclusion

This project resulted in the successful design of a 9-section, stripline broadband directional coupler. Several iterations and optimization processes were required to arrive at this final design, but it ultimately performed extremely well compared to initial specifications. Reviewing Table 9 shows how the final design outperformed the initial design specifications.

Reviewing the optimization process revealed that the highest performing Optimization Types were the Hybrid, Least Pth, and Genetic Optimizers. Additionally, Momentum allowed for the successful simulation and comparison of the physical layout results with those of the final schematic design simulation. This revealed the discrepancies between 2D schematic based simulation and 3D full-wave planar EM layout based simulations.

Lastly, Figure 14 below shows an exported Gerber file view of the directional coupler design. The final design dimensions are 580 mils $\times$ 1185 mils.

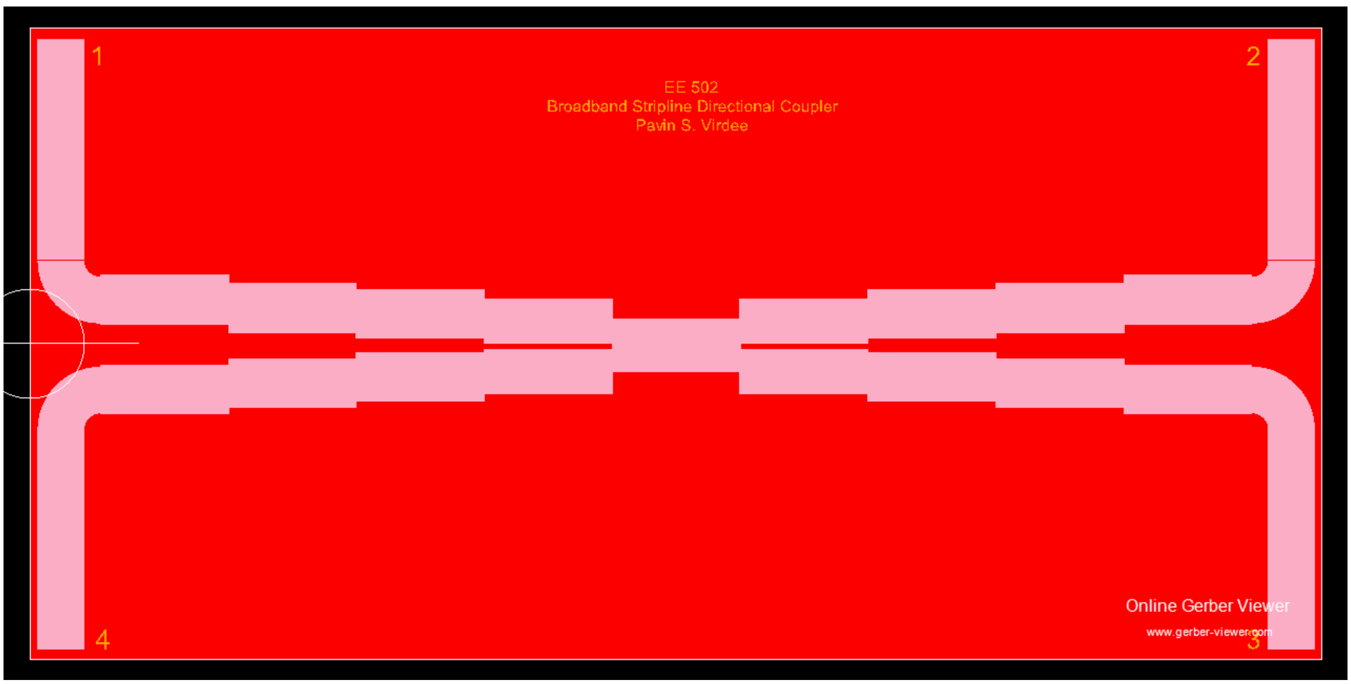


Figure 14: Final Design Gerber File View

References

[1] Y. Ge and G. Guo, "The design of broadband stripline directional coupler," in Proceedings of 2012 5th Global Symposium on Millimeter-Waves, pp. 307–311, 2012.

[2] Rogers Corporation, "RT/duroid 5880LZ High Frequency Laminates." https://rogerscorp.com/-/media/project/rogerscorp/documents/advanced-connectivity-solutions/english/data-sheets/rt-duroid-5880lz-high-frequency-laminates.pdf, 2019.

[3] B. H. Mongia, Bahl, RF and Microwave Coupled-Line Circuits. Artech House, 2007.

[4] Marki Microwave, "Directivity and VSWR Measurements." https://www.markimicrowave.com/Assets/appnotes/directivity_and_vswr_measurements.pdf, 2012.

[5] D. M. Pozar, Microwave Engineering. Wiley, 2012.

A Stripline Directional Coupler Performance Definitions

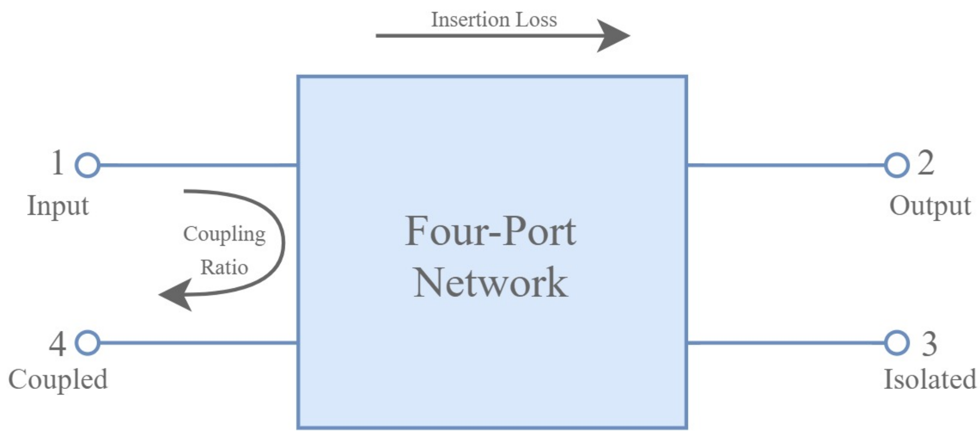


Figure 15: Directional Coupler Block Model

Insertion Loss is defined as the forward transmission coefficient for a passive network. From Figure 15, it can be observed that it's equivalent to the ratio of the output power at port 2 and the input power at port 1. This relation is denoted in S-Parameter form below in Equation 7.

$$\boxed{Insertion\ Loss = S_{21}(dB)} \tag{7}$$

Coupling Ratio is the ratio of coupled power to incident power. Figure 15 provides a visual representation of this term, which is defined in Equation 8.

$$\boxed{Coupling\ Ratio = S_{41}(dB)} \tag{8}$$

Directivity defines how well a coupler discriminates between forward and reverse waves [4]. It is the ratio between the input and reflected signals at the coupled port and is defined below in Equation 9.

$$\boxed{Directivity = S_{41}(dB) - S_{42}(dB)} \tag{9}$$

Voltage Standing Wave Ratio (VSWR) is defined as the ratio between the maximum and minimum standing waves present on a transmission line or terminal. It is a function of reflection coefficient and is a measure of how efficiently power can be transmitted. The best case achievable VSWR, equal to 1, represents zero reflections and 100% power transmission.

$$\boxed{VSWR = \frac{1 + |S_{11}|}{1 - |S_{11}|}} \tag{10}$$