Wilkinson Power Divider

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***Abstract*—This paper presents the design, simulation, and testing of a 2-way microstrip Wilkinson power divider optimized for 2.45 GHz. Utilizing Roger Corporation's RO4003C substrate for its superior high-frequency performance, the design process involved iterative schematic creation, layout design, and 3D electromagnetic simulation using Keysight's PathWave RF Synthesis (Genesys) and Ansys 3D High Frequency Simulation Software to predict and adjust electromagnetic behaviors within the planar structure accurately. Subsequent fabrication using LPKF milling and detailed testing highlighted slight deviations in expected performance attributed to construction variances and simulation settings, offering valuable insights for refinement. The findings underscore the power divider's potential in high-frequency RF applications, maintaining effective power distribution and performance across the intended bandwidth. The paper further discusses the power divider's enhanced power capabilities, extended bandwidth, and applicability to mmWave applications, illustrating its robust potential in high-frequency RF environments. The results confirm that the device maintains effective power distribution and stable performance across the targeted bandwidth, underpinning its suitability for advanced telecommunications and radar systems.**

***Index Terms*—Wilkinson power divider, microstrip design, electromagnetic simulation**

I. Introduction

Ernest J. Wilkinson's 1960 paper simply titled, An N-Way Power Hybrid Divider, has been cited well over 1000 times according to IEEE. Adding resistive loads between a common node and the end of quarter wavelength transmission lines results in a circuit geometry that is easy to simplify for calculation. The result is a power divider with any number of equi-phase equi-amplitude output ports that have a high degree of isolation. However, greater than a 2-way Wilkinson divider requires the dissipating resistors to cross over and therefore is not realizable in planar form. Modern RF circuits designed in microstrip can not implement N-Way designs, as first introduced, but the Wilkinson power divider lives on in many different variations.

II. Theory

A. Three-port Devices

The simplest form of a power divider is with a three-port network with one input port and two outputs. [1] The scattering matrix of an arbitrary 3-port network has the following nine elements:

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

A power divider that equally splits an input signal into two identical outputs while being matched at all ports, can not be entirely lossless. This is easily proven mathematically. A device with all matched ports has zeros along the main diagonal, and if the network is reciprocal, then the scattering matrix becomes:

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

Finally, if the network is lossless the following unitary properties must be satisfied:

$$\begin{aligned} |S_{12}|^2 + |S_{13}|^2 &= 1 \\ |S_{12}|^2 + |S_{23}|^2 &= 1 \\ |S_{13}|^2 + |S_{23}|^2 &= 1 \\ S_{13}^* S_{23} &= 0 \\ S_{23}^* S_{12} &= 0 \\ S_{12}^* S_{13} &= 0 \end{aligned}$$

In order for the latter half of the above equations to hold, at least two of the three variables must be zero, and that would result in at least one of the first half of the above equations not holding. Therefore, a three-port reciprocal, matched network can not be lossless.

III. Microstrip Design

The design of a Wilkinson power divider, particularly when moving beyond the fundamental 2-way configuration, can pose complexity. This is can be especially true if the goal is to maintain a planar structure and integrate it into a straightforward microstrip layout.

The internal resistive network used for isolation becomes more intricate for a Wilkinson power divider with more than two outputs, such as a 3-way or 4-way divider. A single resistor between the two output ports suffices in simple 2-way Wilkinson dividers. However, with more than two outputs, a fully interconnected resistive network is needed to ensure proper isolation between all output ports. This network generally involves multiple resistors connecting each pair of output ports.

This paper provides a comprehensive overview of the design process for a 2-way microstrip Wilkinson power divider. The design was targeted for resonance in return loss and transmission at 2.45 GHz. An iterative approach was employed before finalizing a microstrip design to be milled on a printed circuit board using a Leiterplatten-Kopierfräsen (LPKF). This approach involved the sequential creation of a schematic circuit design, a layout design, and a 3D simulation, with each step preceded by careful parameter tuning.

The chosen substrate was Roger Corporation's RO4003C (32 mil, 1 oz). It is a widely used substrate known for its superior high-frequency performance, ease of manufacturing using standard epoxy/glass techniques, and cost-effectiveness. These qualities make it ideal for achieving the desired electrical properties and mechanical stability in complex RF applications. Its relatively higher dielectric constant of 3.55 and the ability to accommodate thinner trace width, thereby reducing the overall space required for the PCB design.

Rogers Corporation created the Microwave Impedance Calculator, a software tool that provides the predicted lengths of conductor widths and transmission line lengths at a provided substrate material, impedance, and aimed frequency. The software's predicted values provided the initial parameters in the circuit design implementation.

Keysight's PathWave RF Synthesis (Genesys) was used to create the circuit design. The design's main concern was ensuring sufficient length and widths in the quarter wavelength design and providing the best parameters to create a 2.45 GHz resonance. In the transition of the quarter wavelength to 50 ohms, there must be an avoidance of coupling of lines. Provided the initial ranges and context of the design, curved transmission line components for the quarter wavelength (70.7 ohms) and the characteristic impedance (50 ohms) sufficiently separated the lines to avoid coupling. A taper transmission line component was created to transition the line from the 70.7-ohm line to the 50-ohm line.

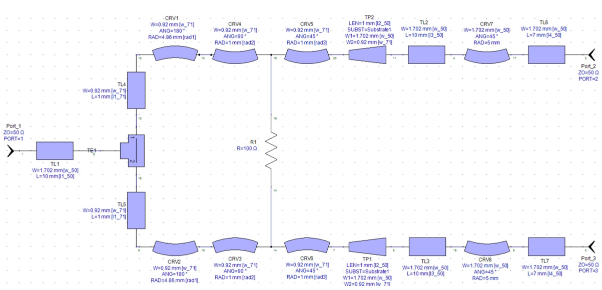

Fig. 1. Wilkinson power divider schematic circuit design

Taking the schematic circuit designed with the optimized tuning in Genesys, a layout simulation was operated using the Method of Moments (MoM) from Keysight's Momentum GXF. Momentum utilizes the Method of Moments, developed by R.F. Harrington, to solve Maxwell's equations for planar structures in multilayered substrates. This technique breaks down complex electromagnetic interactions into more straightforward elements for precise analysis. The software offers two simulation modes tailored for microwave and RF applications, each using variations of MoM to meet specific frequency requirements and ensure accurate simulations across a range of RF and microwave applications.

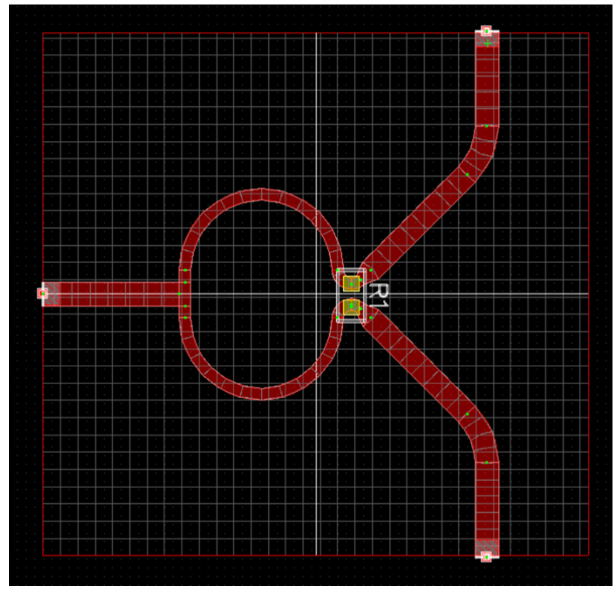

Fig. 2. Wilkinson power divider layout circuit design

Using the geometry of the traces in the layout, an Ansys HFSS model was created. The quarter wavelength parameters were tuned one final time to produce the most accurate result.

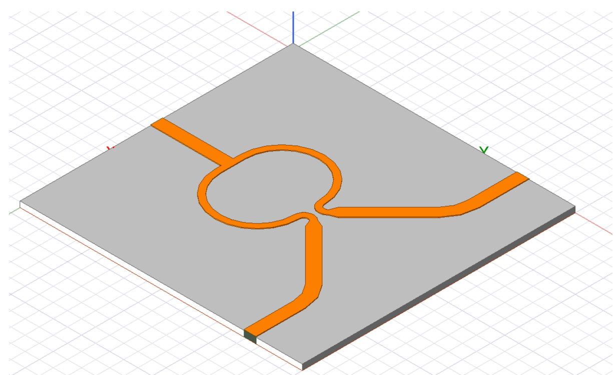

Fig. 3. Wilkinson power divider layout circuit design

Using the design in HFSS, the final design was milled onto an LPKF to be tested and measured. An added 100 ohm (twice the characteristic impedance) 0603 resistor (twice the characteristic impedance) was soldered along with three SMA Female ports to allow connection for testing with a Vector Network Analyzer (VNA).

IV. Results

The return loss, or the representation of the amount of signal power reflected from the input of the diver, shows resonance at 2.38 GHz with a magnitude of -36.891 dB. Analyzing the bandwidth of the return loss, at the aimed 2.45 GHz, the magnitude remains below -20 dB at -27.404 dB. This shift of resonance from the simulation to practice shows the quarter wavelength to be longer than it should be, as a short quarter wavelength provides a higher resonance frequency. The outputs' reflection remains under -20 dB across the 1 GHz and 3 GHz range.

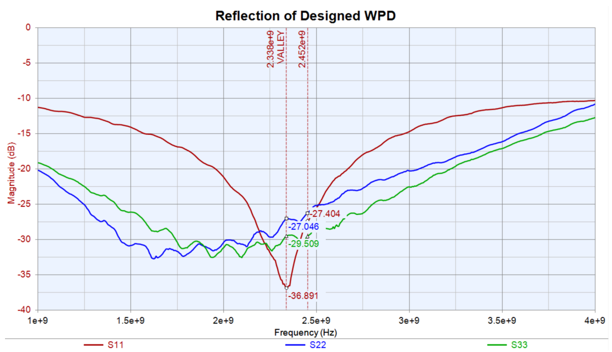

Fig. 4. Reflection S-parameters of designed Wilkinson power divider

The isolation loss, or the representation of the amount of signal power prevented from passing between the two output ports, shows a resonance of -2.38 GHz at a magnitude of -61.533 dB. The aimed 2.45 GHz resonance had a magnitude of -35.102 dB.

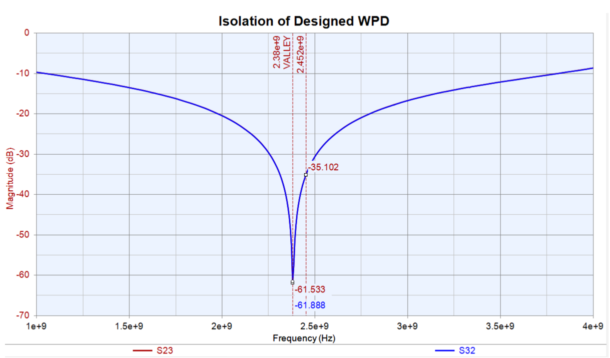

Fig. 5. Isolation S-parameters of designed Wilkinson power divider

Considering the Wilkinson power divider in this application design is a 2-port output device from a single input, the output across the two ports is half the power of the input (i.e., 3 dB power). The 2.38 GHz resonance in practice and the 2.45 GHz aimed resonance share a near-exact half-power value of around -3.1 dB.

The most accurate simulation in HFSS and the resulting milled board's frequency response are comparatively different. Notably, the resonance frequency targeted in the simulation is higher than the physical board designed. Factors from either physical construction or simulation methods could have contributed to the discrepancy.

Significant changes exist in the physical construction between the simulation and the actual design. One impactful

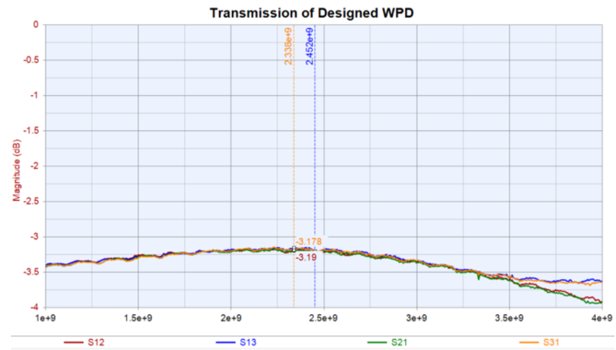

Fig. 6. Transmission S-parameters of designed Wilkinson power divider

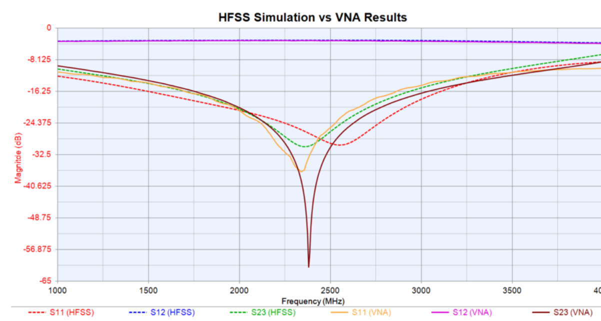

Fig. 7. HFSS simulation against experimental S-parameters of Wilkinson power divider

difference can be the capacitance added to parts of the board from the solder applied to adhere the resistor and the female SMA ports. In addition, the placement of the resistor may have needed alignment with its placement in the simulations.

As for the simulation methods that influenced the difference in actual output, the analysis setting and plotting in the simulations required a more refined mesh to closely match physical results. Ansys' HFSS has default automatic adaptive meshing. HFSS automatically generates a tetrahedral mesh with a set number of tetrahedral that covers the geometry of a design. It automates to below 100,000 tetrahedra, which can be undesirable as it does not accurately match the geometry of the designed 3D model. With more tetrahedra, the meshing algorithm can have a more refined mesh to cover the S-parameters for a defined frequency range.

Additionally, more adaptive passes for the mesh would have made the simulation results even more accurate. With every pass, HFSS adds more to the mesh, which makes it more precise. Lastly, the original HFSS models use a lumped port instead of a wave port. Wave ports can provide one with a reading of the characteristic impedance. Allowing for more proper tuning of the characteristic impendence width, a matched result is guaranteed to be reached.

To conclude the results garnered, the designed Wilkinson Power divider had a center frequency of 2.38 GHz. Still, it maintained a magnitude below -20 dB for transmission and return loss at the intended center frequency of 2.45 GHz, which can still achieve half the power at each of the two output ports. Refinement of the simulation analysis settings would yield a more precise emulation of the actual result.

V. Further Considerations

As stated previously, there have been numerous papers which built upon the power divider first presented by Wilkinson in *An N-Way Hybrid Power Divider*. Modifications made to Wilkinson's original design making it suitable for high-power applications will be discussed. Followed a way to greatly increase the bandwidth, and finally how the circuit can be changed to allow for significantly higher input signal frequencies.

A. High-Power Capabilities [8]

The N-Way divider has significant disadvantages in the resistive star is difficult to realize, and the power-handling of said resistors. Ulrich H. Gysel proposed an extension of this design by using external isolation loads, which can have variable power capabilities and can be realized in microstrip lines easily. Below is the design, where all transmission lines are quarter-wavelength at midband.

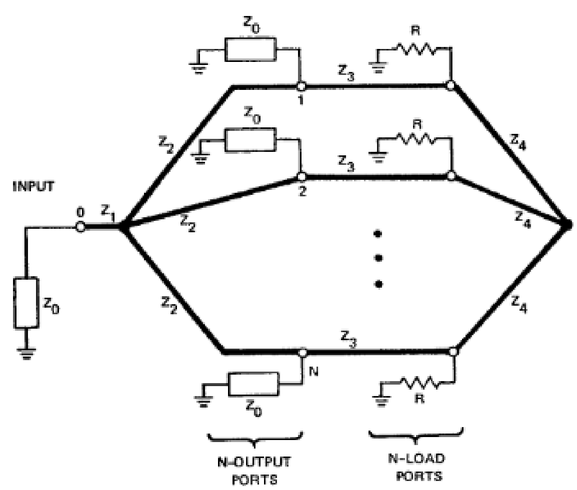

Fig. 8. Gysel N-Way

This divider replaces the resistive star in the original design with a combination of TLs and shunt-connected resistors. This schematic can be simplified for analysis, to is equivalent four-port network. The four-port network can then be separated using even and odd modes.

Gysel states that there is no closed-form solution for the design parameters, line impedance's, and he instead used CAD to obtain minimum VSWR at the ports and maximum isolation between output ports. Below is the experimental design created (1.15 GHz, 20% band)

Each side of the design represents one arm of the N-Way divider, where the port pair is the output port and connection for the changeable load. And the center post is the single input port.

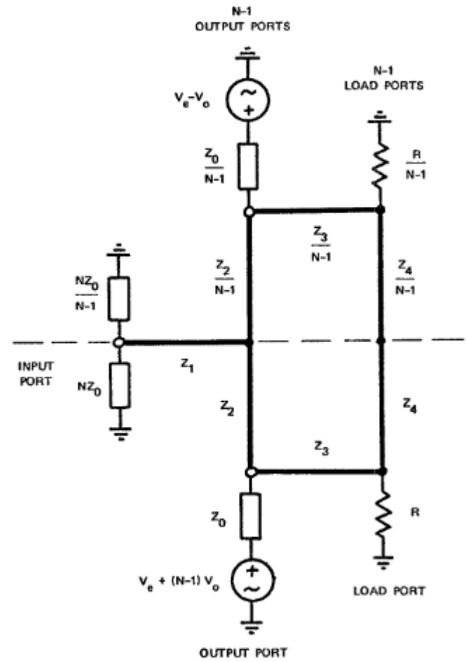

Fig. 9. Gysel Equivalent Four Port Design

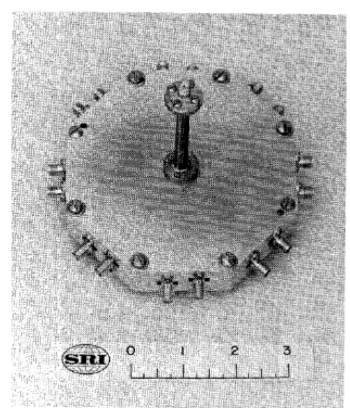

Fig. 10. Experimental 8-Way Divider/Combiner

B. Ultra-wideband and Increased Isolation [6]

In both Wilkinson's original design and Gysel's High-Power capable variant, the bandwidth of the device was approximately 20%. For many applications, a wider band may be desired. One way of accomplishing this is to use a binomial multi-section matching transformer. By gradually stepping between transmission line impedances, we can take advantage of the theory of small reflections to improve the S parameters across a wider frequency range. Figure 11 shows the experimental designs.

The following four plots contain all of the relevant S parameter data to be able to conclude that the proposed design works as stated. First, fig.12 shows the reflection coefficient at the input to the 2-way dividers shown in fig. 11

It can be seen that adding additional sections to the divider

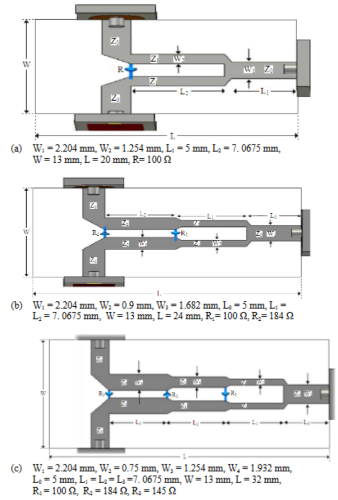

Fig. 11. Geometry of the microstrip WPD using (a) one (b) two and (c) three sections

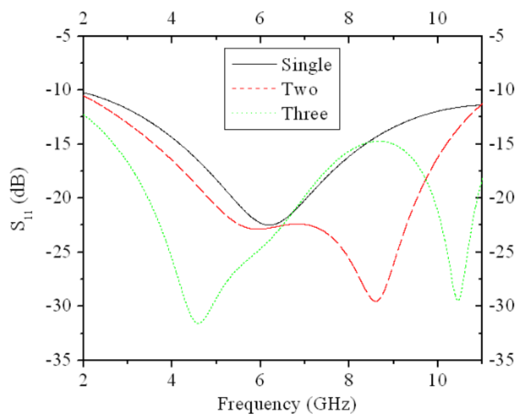

Fig. 12. Ultrawide S_{11} (Input Reflection)

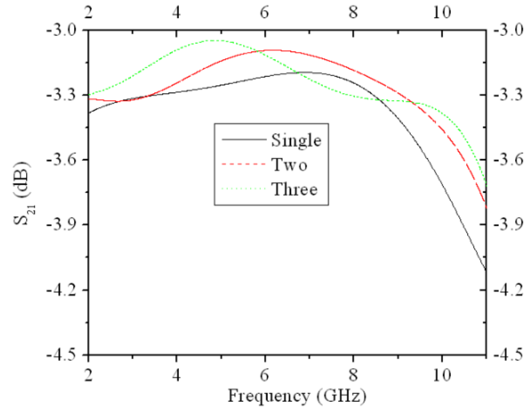

Fig. 13. Ultrawide S_{21} (Transmission)

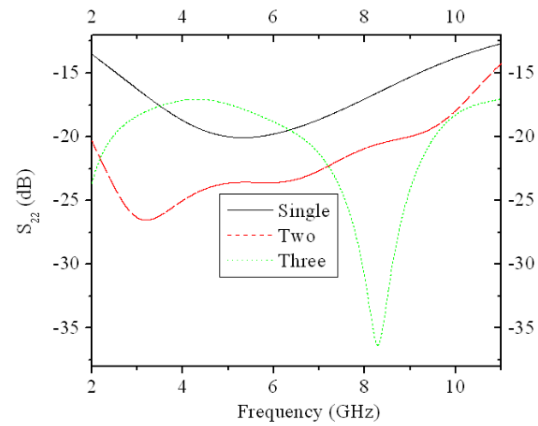

Fig. 14. Ultrawide S_{22} (Output Reflection)

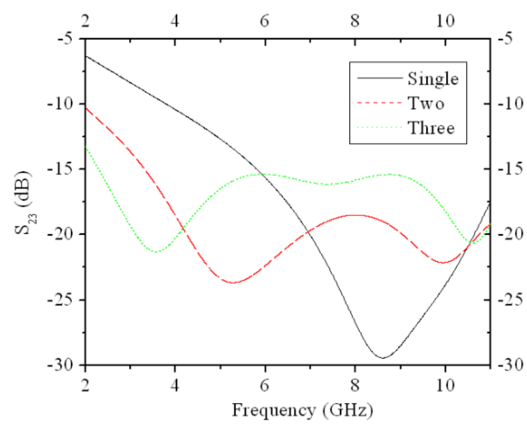

Fig. 15. Ultrawide S_{23} (Output Isolation)

only improves the reflection at the input of the device. Fig. 13 then shows the transmission coefficient between the input and one of the outputs, by symmetry, this is approximately the same for the other output port. This value stays about consistent throughout the designs with a more significant improvement visible around the extremities of the frequency range.

Additionally, it can be seen (fig. 14) that the output reflection coefficient is approximately below -15dB for the entire frequency range in the two- and three-section designs, which is exceptional. Finally, fig 15 shows the isolation between the output ports. This does not improve across the entire frequency range is more than adequate. Since the designs with added sections are approximately as good or better across all metrics this is a possible improvement.

C. mmWave Modifications [7]

Modern technology has moved toward using higher frequency signals to increase data transmission rates among many other uses. Since the circuit designs discussed here are all relative to the wavelength of the signal, and this value changes inversely with frequency, microstrip designs need to be more precise or risk greater residual losses due to geometric inconsistencies. One of the difficulties faced with this project is the quarter wavelength transmission lines must be separated from each other to avoid line coupling, but the thin film resistor (0603 in our case) is very short compared to this distance.

Therefore the lines must travel away from each other before coming back together for the resistor connection, then going to separate outputs. Additionally, these integrated resistors (Fig.18) have an equivalent high-frequency model of an ideal resistor with some length of transmission line on either end. This design also relies on the symmetry of the design and uses odd- and even-mode analysis to reduce complexity.

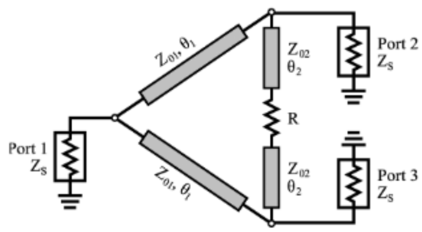

Fig. 16. Modified Wilkinson Design for HF

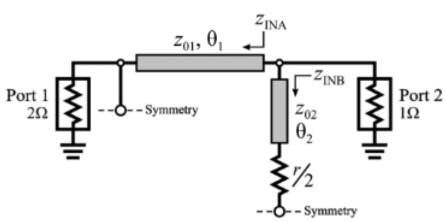

Fig. 17. Normalized Equivalent Circuit

In even mode analysis, the line of symmetry represents a virtual open circuit since the outputs are exited with currents of equal magnitude and phase. In the odd mode, the phases are not opposite and a virtual short is created along the line of symmetry. The following four normalized equations are the result of this analysis:

$$z_{O1} = Z_{O2}$$
$$r = z_{O2}^2$$
$$\theta_2 = tan^{-1}\left(\sqrt{1 - \frac{r}{2}}\right)$$
$$\theta_1 = \frac{\pi}{2} + \theta_2$$

There are five unknowns and four equations, leaving an under-determined system of equations that meet the requirements of being matched, reciprocal, with isolated outputs. It is also easy to see that as θ_2 goes to 0, the system reduces to Wilkinson's original design. The simulation results then show how the modification reduces insertion loss and isolation between the output ports.

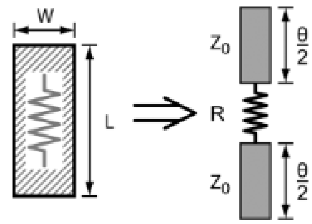

Fig. 18. Equivalent High Frequency Model of Thin Film Resistor

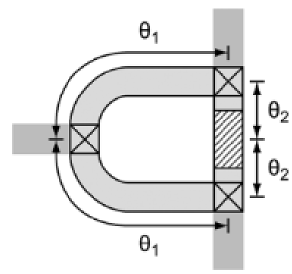

Fig. 19. Proposed Layout

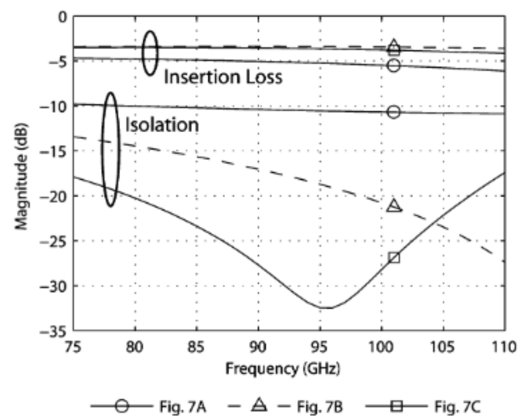

Fig. 20. Simulation Results

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