Microstrip Couplers

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Introduction:

Couplers are passive three or four port devices that are commonly used in RF and microwave design. In a coupler, a known percentage of power from a transmission line is coupled to another output. Furthermore, couplers have a phase shift between the transmitted and coupled port. This is one of the major differences between couplers and power splitters. The couplers designed and compared in this project are both four port couplers, known as directional couplers. The two couplers compared are the branch line and the rat-race couplers, both done with microstrip transmission lines. Each coupler has an input port, transmitted port, coupled port, and isolated port.

Types of Couplers:

There are dozens of different types of couplers used in just as many different applications. Couplers can be categorized in two main categories; waveguide couplers and microstrip couplers. Waveguide couplers usually have one or more holes between them for coupling. One simple waveguide coupler is the Bethe hole coupler, which uses one small hole to couple two waveguide transmission lines. Similarly, the multi-hole coupler is made of two waveguides coupled by two or more holes. Below are examples of these waveguide couplers. The Moreno crossed-guide coupler, Riblet short-slot coupler, Schwinger reversed-phase coupler, and others are variants of the waveguide couplers described above by varying the shapes and sizes of the holes as well as the angle of the waveguide transmission lines.

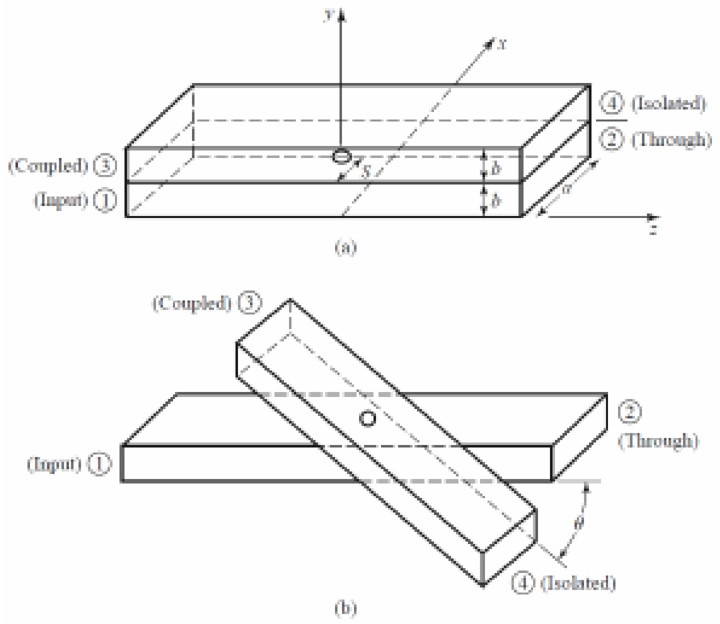


Figure 1: Bethe hole coupler (Pozar)

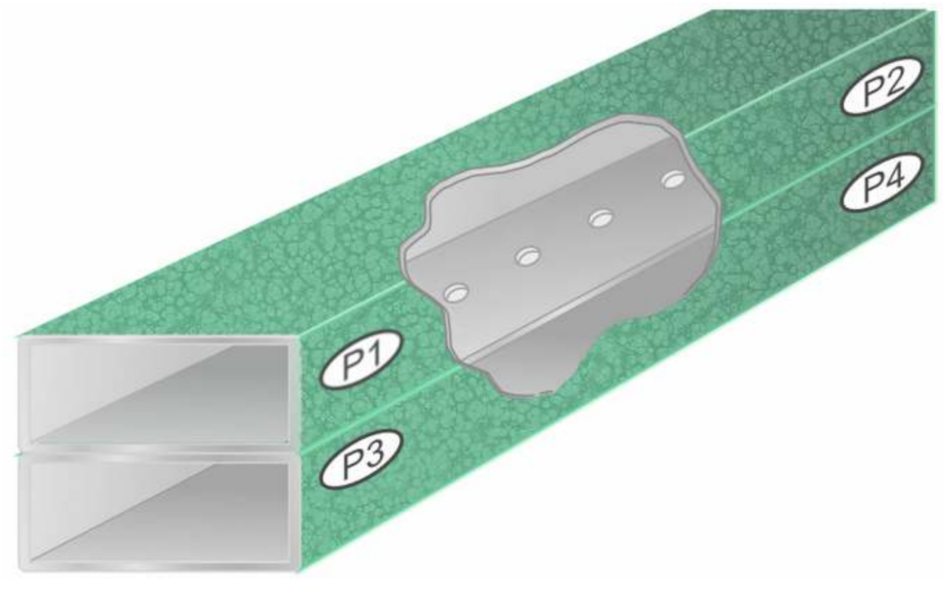


Figure 2: Multi-hole coupler (Ishii)

The second classification of commonly used RF couplers is the microstrip coupler group. Two of the most common couplers that use microstrip transmission lines are the branch line and rat-race couplers. The significance of these couplers is that they have 90 degree and 180 degree phase shifts, respectively, between the transmitted port and coupled port. The branch line and rat-race couplers are the couplers designed and compared in this project. Their ease of fabrication and useful phase shifts made them ideal choices. Both are 3 dB couplers, meaning that half of the power should be output at the transmitted and the coupled port each. For wider bandwidths and lower coupling, coupled line couplers are common. Examples of these are the single-section coupled line coupler or the Lange coupler. These couplers use the proximity of the microstrip transmission lines to achieve the coupling.

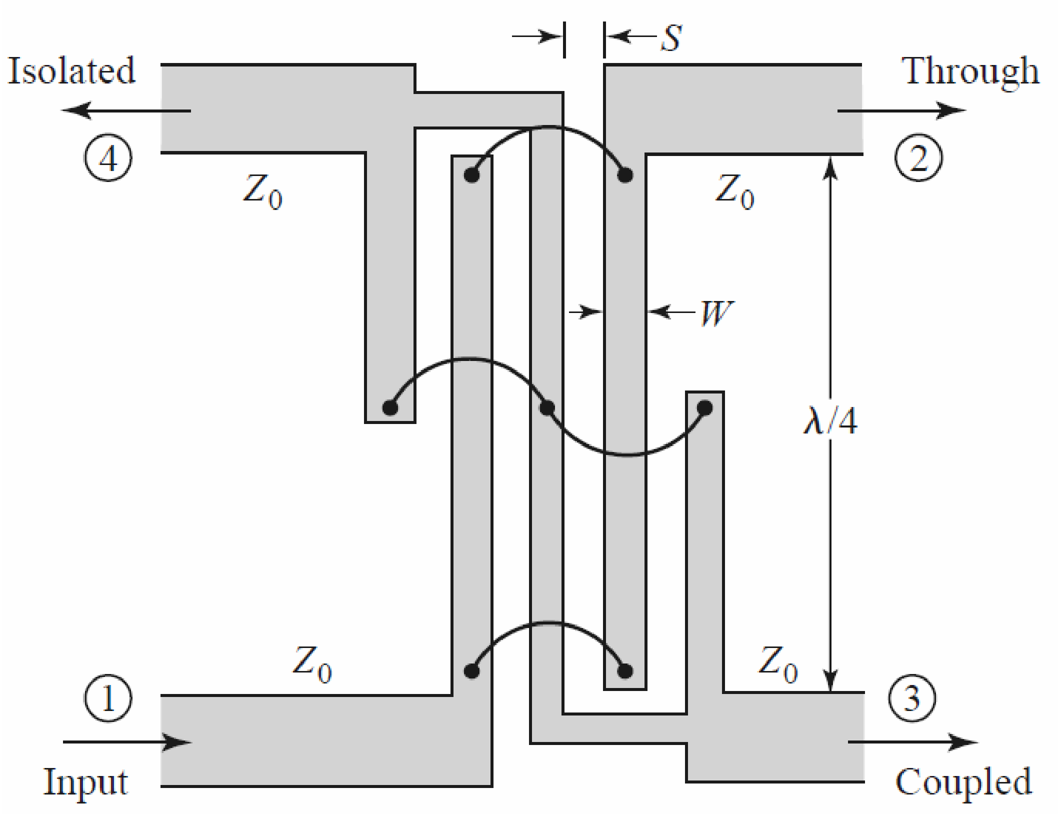


Figure 3: Lange Coupler (Pozar)

Initial Design & Simulation:

The assignment, as it was given to me, was to compare the branch line and rat-race microstrip couplers. I knew I would use Express PCB to design and print the circuits, so my only set specifications were the manufacturing specifications from Express PCB. Since the lengths of both couplers are based on wavelength, I wanted to design the couplers for a frequency high enough to minimize my PCB area, but low enough to be able to test with a 3 GHz network analyzer. I chose 2.4 GHz. Below are the initial set specifications I had to work with:

Cu Thickness	0.0017"

FR-4 Height	0.062"
Dielectric Constant	4.3 to 4.9
Char Impedance	50 ohm

Table 1: Set Specifications

Fifty ohms was used for the characteristic impedance, Z_O, so that no impedance matching circuits were needed between the ports and the measurement equipment. Due to the range of the dielectric constant, ε_r, I assumed the value to be 4.6 for my future calculations.

Next, I calculated microstrip trace widths for the values needed in the two couplers; .707 Z_O, Z_O, and 1.414 Z_O. There are numerous approximation equations for microstrip impedance calculations. I based my choices off of Equation (1), but all the equations yielded very similar answers.

$$Zo = \frac{87}{\sqrt{\varepsilon r + 1.41}} \ln\left(\frac{5.98 \times H}{.8 \times W + T}\right)$$

where ε_r is the dielectric constant, Zo is the characteristic impedance, W is the trace width, T is the copper thickness, and H is the substrate height between the ground plane and the microstrip transmission line. Solving this equation for the impedances needed in the two coupler designs give the following widths:

Specified	**Resistance (Ω)**	**W (in)**
.707 Zo	35.35	0.17
Zo	50	0.11

1.414 Zo	70.7	0.061

Table 2: Width Calculations

To determine the length of each branch of the couplers, the equations below are used:

$$\lambda = \frac{c}{f\sqrt{\varepsilon\mathrm{eff}}}$$

where λ is the wavelength, c is the speed of light, f is the frequency, and $\varepsilon_{\mathrm{eff}}$ is the effective dielectric constant, and

$$\varepsilon\mathrm{eff} = \frac{\varepsilon\mathrm{r} + 1}{2} + \frac{\varepsilon\mathrm{r} - 1}{2\sqrt{1 + 12(\frac{H}{W})}}$$

when $\frac{W}{H} \geq 1$. Unfortunately, during my initial design, I overlooked the $\varepsilon_{\mathrm{eff}}$ factor in the wavelength equation. Therefore, I incorrectly calculated the wavelength of a 2.4 GHz signal on a microstrip transmission like to be 4.92 inches. I will elaborate and correct my errors later in the paper.

Below are schematics of the couplers to be compared:

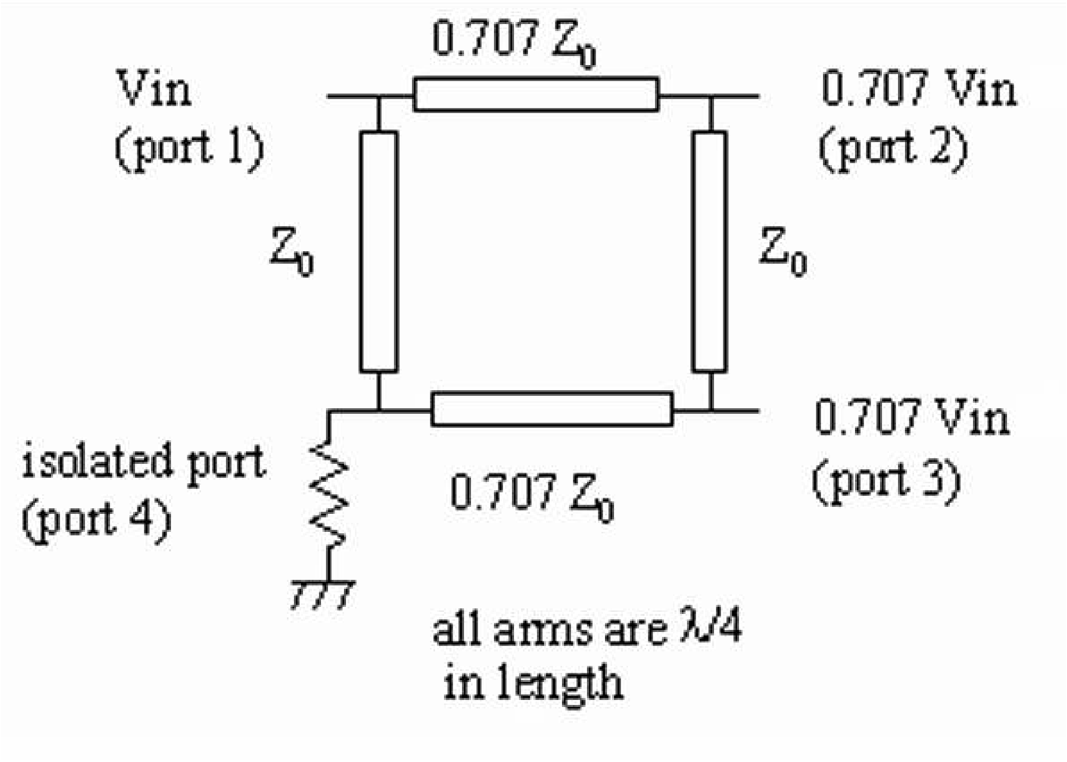


Figure 4: Branch line coupler (Microwaves 101)

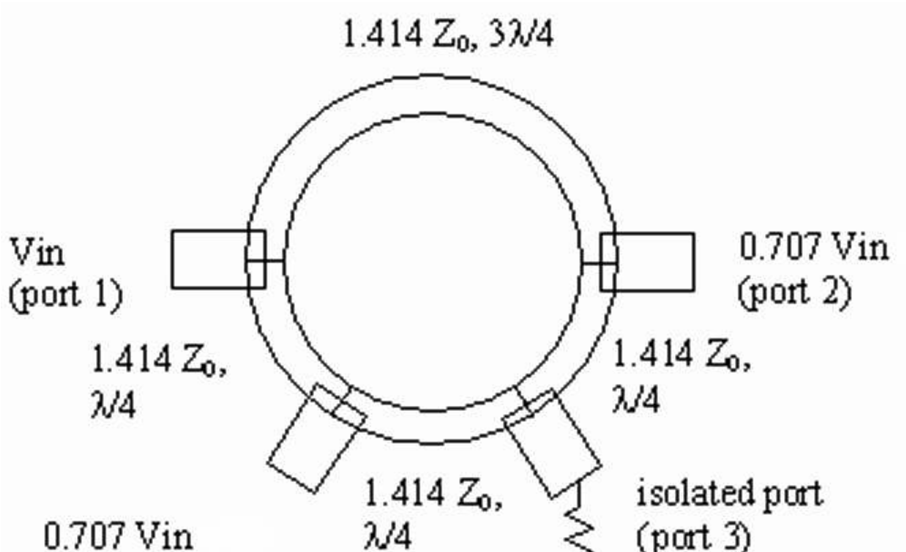


Figure 5: Rat-race coupler (Microwaves 101)

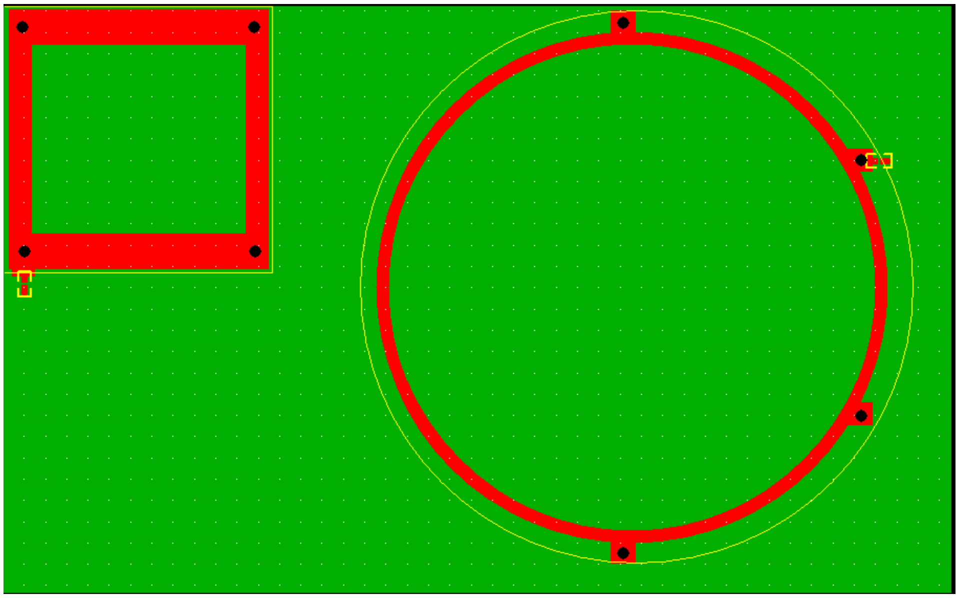


Figure 6: Couplers on Express PCB

Figure 6 shows the design of the branch line coupler (left) and rat-race coupler (right). I also performed a simulation on AWR Microwave Office of the two coupler types using generic transmission line blocks to confirm that my design was correct. The simulations are in the appendix at the end of the paper.

Analysis

The easiest way to analyze couplers is through a form of superposition known as even/odd analysis. In this form of analysis, the even and odd lines of symmetry of the circuit are found to split the circuit in two. The even line of symmetry is the line where the circuits and sources are identical. The odd line of symmetry is the line where the circuits are identical and the sources are opposite. The points where the even line intersects the circuit are replaced with open circuits and the points where the odd line intersects the circuit are replaced with short circuits. The circuits are then analyzed and the results from the even and odd circuits are added. From this analysis, we can derive the S parameters of the couplers. Analyzing the phase shift between ports is more easily done through a visual analysis. The phase shifts occur due to interference between the signal taking multiple paths to a certain point in the coupler. Furthermore, every fourth of a wavelength that the signal travels, the phase is shifted 90 degrees. Since all of the legs of both couplers are in increments of a fourth of a wavelength, we can easily see how the phase shifts and isolation occur in the couplers above.

Initial Results & Corrections:

After my boards were fabricated, I added SMA connectors to each port location and measured the S parameters on a 3 GHz network analyzer. My results were far from ideal:

Ideal Values

Branchline	(dB)
S21	-3
S31	-3
S41	-40

2 to 3 Phase Shift 90

Actual Values

Branchline	2.4 GHz
S21	-11
S31	-10
S41	-11

2 to 3 Phase Shift 143

Ratrace	(dB)
S21	-3
S31	-40
S41	-3

2 to 4 Phase Shift 180

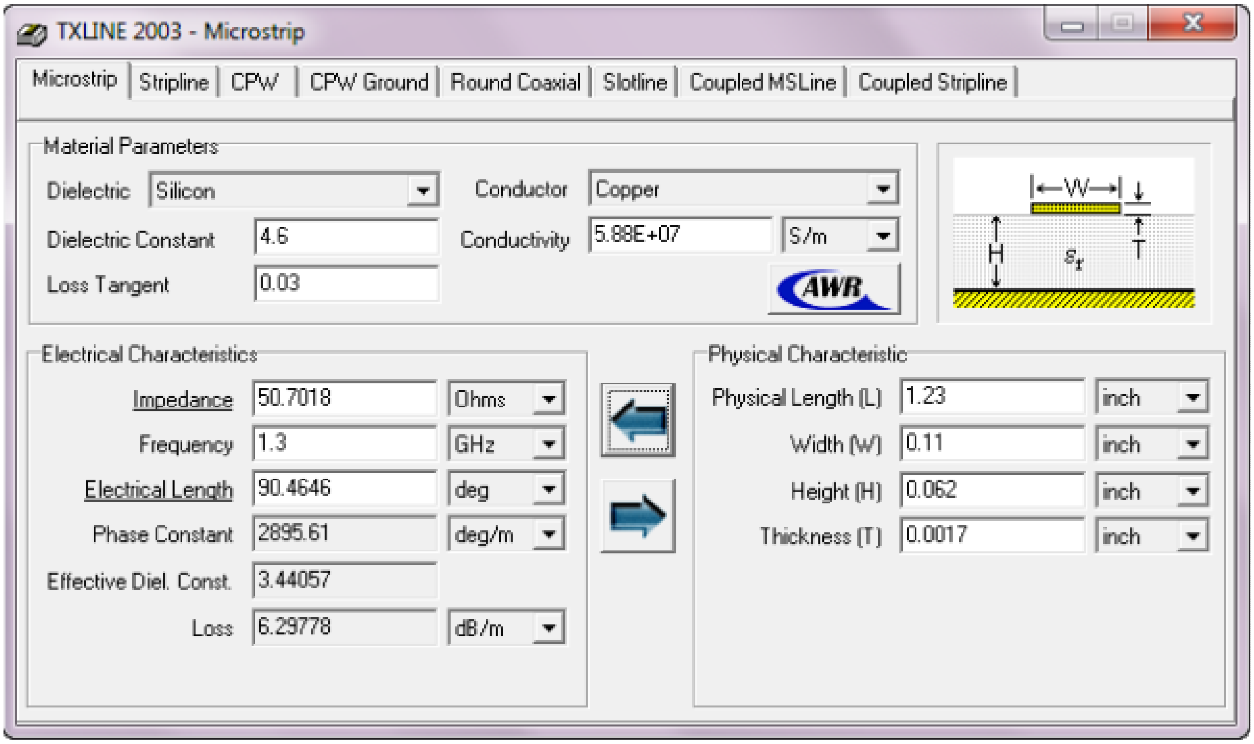
Ratrace	2.4 GHz
S21	-8
S31	-7
S41	-11

2 to 4 Phase Shift 71

It is apparent that the actual results are far from the ideal values. After some thought and a conversation with Dr. Kwok, I realized I had made a two notable mistakes. First, when measuring the S parameters of the couplers, I did not terminate the other two ports with fifty ohm loads. Leaving the ports open instead of correctly terminating them causes reflections. Furthermore, I realized that I failed to take the dielectric constant into account when calculating my wavelength. After some research, I learned that microstrip transmission lines had an effective dielectric constant, based on the dielectric constant of the substrate, the height of the substrate, and the width of the copper microstrip transmission line. Using the effective dielectric constant equation from earlier and the fixed length of my traces, I calculated my ε_{eff} to be around 3.44.

Final Simulation:

Luckily, I took the effective dielectric constant into account for my trace width calculations, so my fabricated boards would still be useable. Before conducting a more thorough simulation of the couplers, I utilized the TX Line tool from AWR to confirm the design specifications.



Material Parameters

Dielectric: Silicon

Dielectric Constant: 4.6

Loss Tangent: 0.03

Conductor: Copper

Conductivity: 5.88E+07 S/m

Electrical Characteristics

Impedance: 50.7018 Ohms

Frequency: 1.3 GHz

Electrical Length: 90.4646 deg

Phase Constant: 2895.61 deg/m

Effective Diel. Const.: 3.44057

Loss: 6.29778 dB/m

Physical Characteristic

Physical Length (L): 1.23 inch

Width (W): 0.11 inch

Height (H): 0.062 inch

Thickness (T): 0.0017 inch

Figure 7: TX Line tool from AWR

After confirming the specifications, I ran a second, more detailed, round of simulations with AWR Microwave Office. These simulations are in the appendix as well.

Results:

Ideal Values

Branchline	(dB)
S21	-3
S31	-3
S41	-40

2 to 3 Phase Shift

Actual Values

Branchline	1.39 GHz
S21	-7.8
S31	-6.2
S41	-32

2 to 3 Phase Shift 92.0

90

Ratrace	(dB)
S21	-3
S31	-40
S41	-3

2 to 3 Phase Shift 180

Ratrace	1.31GHz	1.35GHz
S21	-7	-6.8
S31	-37.2	-40.3
S41	-6.9	-6.6

2 to 4 Phase Shift 178.7, 180.0

After correcting the calculated specifications and correctly terminating the unused ports, the measurements were much closer to the ideal values. The isolation powers and phase shifts are accurate enough for the couplers to be identified as such by their S parameters alone.

Sources of Error:

The measured data deviates from the ideal values in a few notable locations. First, the power outputs on the transmitted and coupled port are between 3.2 and 4.8 dB lower than expected. Also, the working frequency of the branch line coupler is 90 MHz higher than designed.

Possible causes for the power loss could be the low and unstandardized quality of the boards fabricated by an inexpensive company, such as Express PCB. With a stated dielectric constant range of 4.3 to 4.9, I chose 4.6, the center value, arbitrarily. Furthermore, I was unable to calibrate the system to take the loss of the cables and connectors into account. The cables used were old, lengthy N-type connector cables, connected to N-type to SMA connector adapters to low quality SMA cables, which were connected to the SMA connectors at each port. Each junction adds opportunity for loss through imperfect connection and impedance matching. I did not complete a full calibration with the cables and connectors I used in my measurements. According the Agilent Technologies' RF and Microwave Measurement Fundamentals, SMA connectors are notorious for breaking down and changing impedances after the first use. Furthermore, most connectors have a specific torque specification as a guarantor of measurement repeatability. Unfortunately, I did not have the exact torque specification for the connectors I used nor did I have a torque wrench. I tightened the SMA connectors to handtight, which is a quantitatively poor For the rat-race coupler, Express PCB translated my circular traces into a combination of line segments to create imperfect circular traces. This could cause reflections, but the angles between line segments are small and there are far too many bends to model in an AWR simulation.

My first thought for a source of error for the 90 MHz frequency mismatch from measured to ideal for the branch line coupler was the trace lengths. I reexamined the boards and noticed that my placement of the connectors on the branch line coupler had effectively shortened the length of the branches. On the contrary, my placement of the connectors on the rat-race was done in a way that did not change the lengths. The position of the connectors gave the branch line coupler branches an effective length of 1.15 inches. Recalculating the working frequency at this length gave 1.39 GHz.

Final Remarks

My failure to correctly design and fabricate a 2.4 GHz coupler turned out to be a net positive. The process of understanding my mistakes and working backwards from physical results to theory strengthened my knowledge about how the different parameters affect the transmission through microstrip. I wrote my paper chronologically instead of a more traditional format to highlight the problems I faced and what I learned by resolving them. I am also still researching other topics related to the technology of microstrip transmission and playing with a few free RF and EM simulation tools. I found the TX Line and tuning tools on AWR Microwave Office very helpful for grasping a better understanding of how changing different parameters affected the system as a whole. In addition to the education, my project is also a success because the 1.3 GHz hybrid coupler and 1.4 GHz quadrature coupler are both functional.

References:

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