Project 3 - Rat-Race Coupler Design

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Background

The goal of this project was to create a rat-race coupler with the following specifications listed below.

- Center frequency: 5 GHz
- 3 dB FBW: 15%
- Insertion Loss: <3 dB
- Coupling Factor: 6 dB

The substrate specified was Rogers 5880 HH with a top/bottom copper cladding of 17 micrometers, dielectric constant of 2.2, and a dielectric thickness of 0.062 inches. The coupler was to be inserted in the same 1.25 inch by 1.5 inch test fixture (measured with a 50-ohm system) from the two previous projects.

Design Process

The design for this rat-race coupler was as follows. It began with following Example 7.9 from the book that showed a rat-race coupler with an equal power split between the coupled and through ports. The strips going to the ports had an impedance of 50 ohms, while the ring had a characteristic impedance of 70.7 ohms ($\sqrt{2}Z_o$). As always, the corresponding lengths and widths to a certain microstrip were determined by using the LineCalc tool and entering the desired specifications and line properities. As for the curve structure, the procedure was to determine the circumference of the ring by using a standard MLIN element and then utilizing the fact that the total electrical length of the curve was 540 degrees (equivalent to the 6 quarter-wavelength components in the ring). Using the LineCalc tool, the length of the corresponding line was calculated. Then, by using the fact that $Circumference = 2\pi r$ is equivalent to this length, the "Radius" value of each MCURVE element was determined. In our case of a 415 mil radius, the circumference and hence the corresponding length of one microstrip line is $2\pi r = 2610\,mil$. The "Angle" value of each curve depended on which two ports the curve separated. For a rat-race coupler, each curve is 60 degrees except for the one between the isolated and through ports (4 and 2, respectively) that is 180 degrees. The lengths of the strips going out to the ports did not really matter; the main design procedure here was to tune the impedance of the ring itself to get the desired specifications. The schematic for this design is seen in Figure 1.

After the equal-split coupler was designed, the next step was to decrease the coupling factor from around 3 dB to around 6 dB. The impedance of the ring structure was decreased in order to cause less power to go to the coupled port and more to go to isolated and input ports. The main structure that had to be altered here was the semi-circle with length of three-quarters of a wavelength, between Port 2 and Port 4. As seen in the board layout in Figure 2 later, this line was quite thin and thus had a higher impedance that helped reach the coupling requirement between Port 3 and Port 1. The impedance of the other parts of the coupler was also decreased by tuning the widths, but not by that much because it had a negative effect on our insertion loss and made it dip below 3 dB. There is definitely a more systematic way of designing this, but the method we used gave good results and was quite intuitive from the beginning so we decided to stick with it.

After getting the schematic ready, the main challenge for this project was the board layout. Fitting the coupler in the desired board size and pin layout was quite the challenge, therefore, some copper extensions needed to be added using the Polygon tool, especially for ports 1 and 4. This was simply done by adding the necessary shapes, using approximately the same widths of the output ports that they are extending (for a smaller mismatch), to connect the rat-race coupler's outputs to the pins of the board. Also for the purposes of getting the design to fit, the impedance of the ring itself had to be adjusted slightly too (exactly what we were trying to avoid, unfortunately). After finally fitting the design into the board, the insertion loss specification was met, but not by that good of margin: we had an insertion loss of 2.951 in our simulations at the center frequency. It met the specification in the simulation, but we did not expect it to meet it for the actual measurement due to loss in the microstrip and slight discrepancies in calibration. As for the coupling factor, it was about 5.780 at 5GHz in the simulation. However, although we easily meet the 5 GHz center frequency and 15% FBW requirements from the through port (S21) plot, our coupling (S31) plot showed a slight deviation of where the center frequency appeared to be and shifted it to around 5.3 GHz. There, the coupling factor was slightly off at 6.29 dB. Nevertheless, our simulation results were extremely close to, if not exactly met, the given specifications. The simulation and measurement results are seen in the next section.

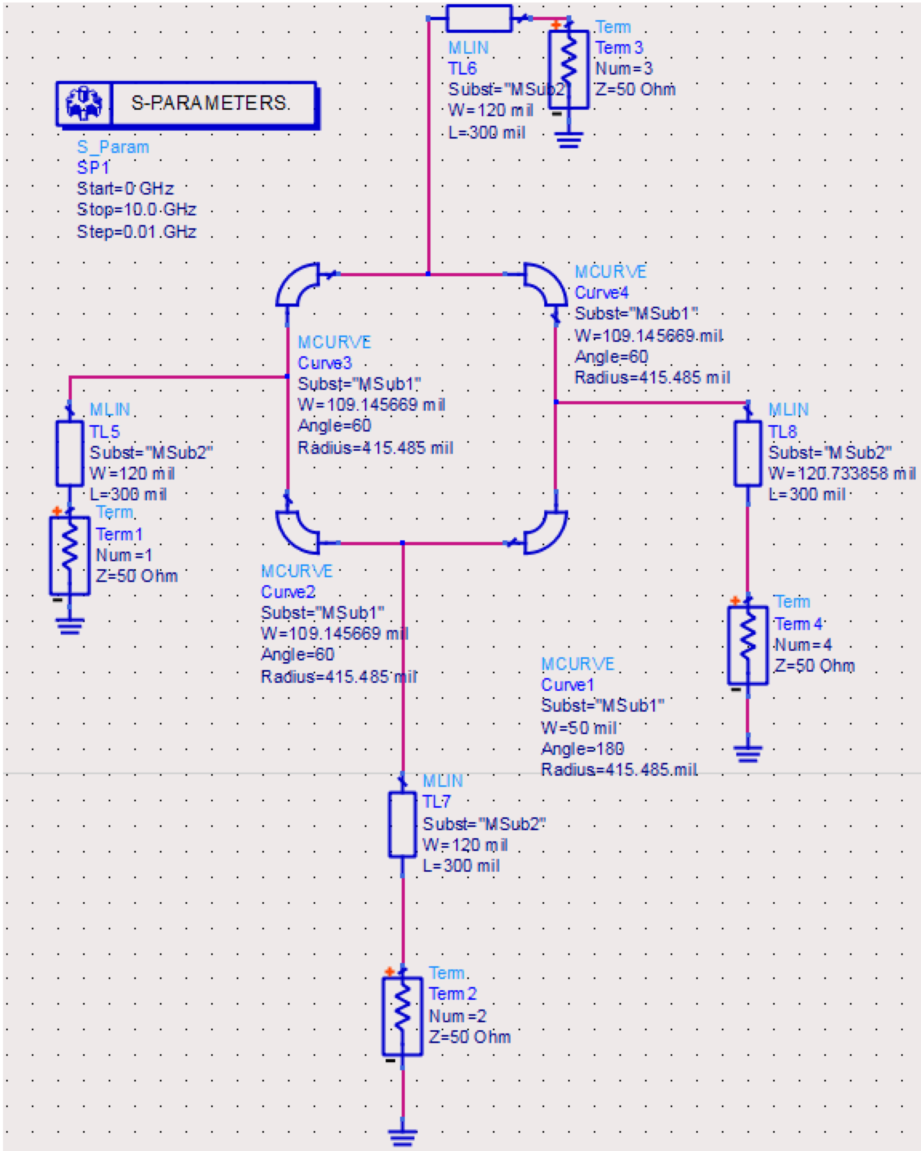

Figure 1: Rat-Race Coupler Schematic

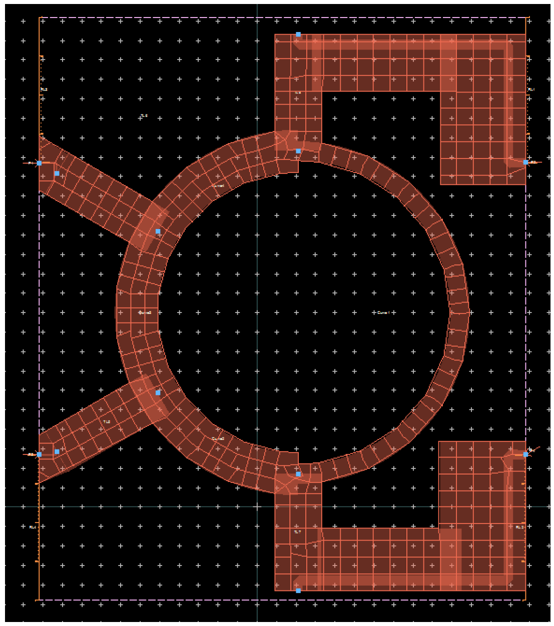

Figure 2: Board Layout

Results

S21 Results - Port 2 (Through)

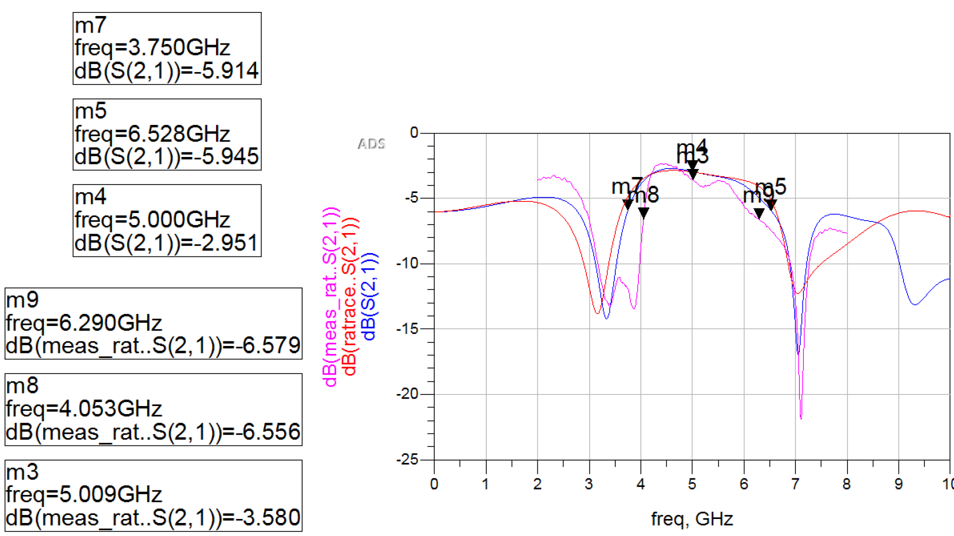

Figure 3: S21 Results - Through Port

The results for the through port are seen in Figure 3 above. The blue trace is the simulated board result, the red trace is the schematic result (shown for reference), and the pink trace is the measurement result. All three results were placed on top of each other (on the same plot) for this report to show how nicely the measured results fit the simulated ones (for a design that needed so many adjustments in the board layout). As seen from the markers on the simulated results plot, the 3dB BW was determined the M7 marker since it was closer to the center frequency. Thus, the 3 dB BW was calculated to be $2 \times (5 - 3.750) = 2.500\,GHz$, which is more than 15% FBW. As for the measurement result, dictated by the M8 marker, the 3 dB BW

$2 \times (5 - 4.053) = 1.894\,GHz$, which was also more than 15% FBW. Thus, the center frequency and FBW specifications were met. The insertion loss for the simulation was 2.951 dB at the center frequency. As for the actual measurements, the insertion loss was 3.580, which is does not quite meet the <3 dB requirement. This was, as discussed previously, expected, since the simulation insertion loss was cutting it close anyway and it did not well represent the effects of the different microstrip widths/impedances as in a real environment. Nevertheless, our insertion loss was still relatively low and quite reasonable.

S31 Results - Port 3 (Coupled)

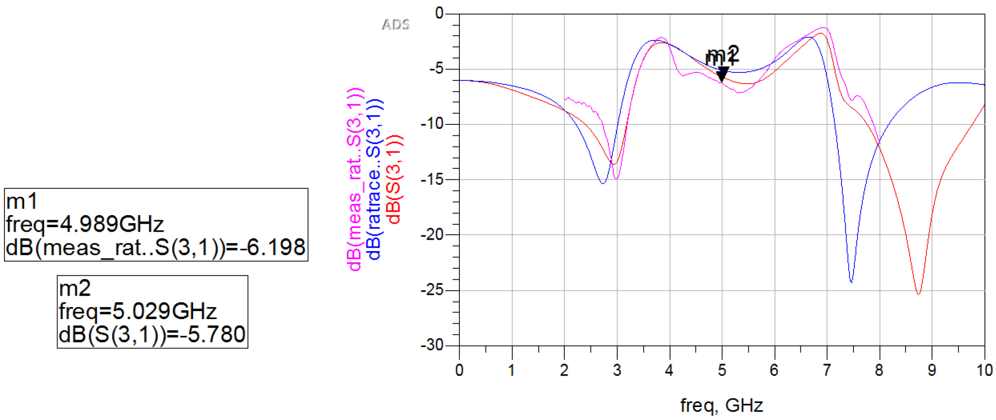

Figure 4: S31 Results - Coupled Port

The result shown in red is the board simulation result, the one in blue is that from the schematic, and the one in pink is the one from the measurement. At 5 GHz, the coupling factor from the simulation is seen to be 5.780 dB, while that from the simulation is 6.198 dB. Although the measurement result does not exactly meet the design requirement, it is still close. This discrepancy is, again, due to things like losses that appear in a real measurement unit. These errors could be introduced from the testing unit, or the fact that Momentum does not account for all the losses in the microstrip lines.

S41 Results - Port 4 (Isolated)

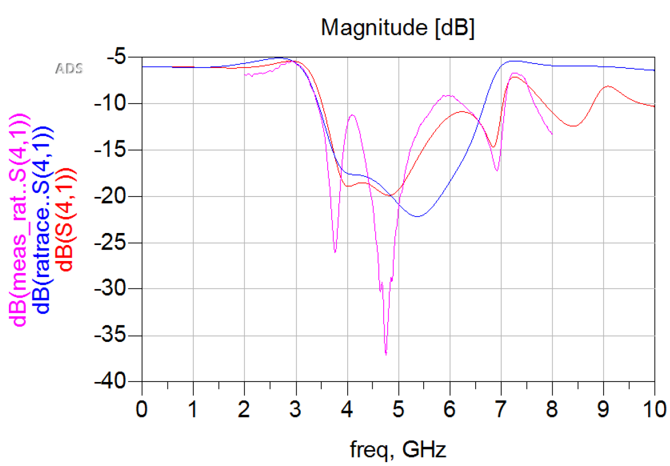

Figure 5: S41 Results - Isolated Port

For the S41 results, the plot in red is the board simulation, blue is the schematic simulation, and pink is the measurement. There were no strict requirements on the isolated port, however, it is expected to have a low value mainly because we usually do not want any power going there. The results from the simulation showed about 20 dB of isolation around the center frequency, however, the measurement seemed to range from 10 dB to 20 dB. This might explain the decreased power flow to the coupled and through ports.

S11 Results - Port 1 (Incident)

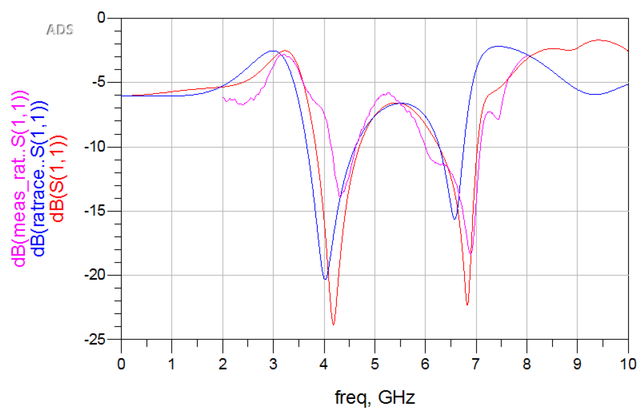

Figure 6: S11 Results - Input Port

For the S11 results, the plot in red is the board simulation, blue is the schematic simulation, and pink is the measurement. This measurement was also expected to have a very low value, since we do not usually want reflections at the input for a coupler and want all the power to go to the coupled and through ports. Although it was nice seeing a clean correlation between the measurements and simulations, a reflection at the input ranging from -5 dB to -15 dB was slightly high. This also explains why the coupling factor and insertion loss were a bit off, but the fact that our simulations had similar results too indicates that there were some adjustments in the actual design that should have been made accordingly.

Conclusion

Overall, this project was quite successful. Although the coupling and insertion loss specifications were not exactly met, they were very close and proved that our design method was successful for this project. The results from the simulations matched up nicely with the measurements, too. To better account for the losses of the actual microstrip in the measurements, we could have tried to adjust our design to aim for better respones at the input port and the isolation port. Nevertheless, the results were promising and could be improved with a bit of tuning for future design projects.