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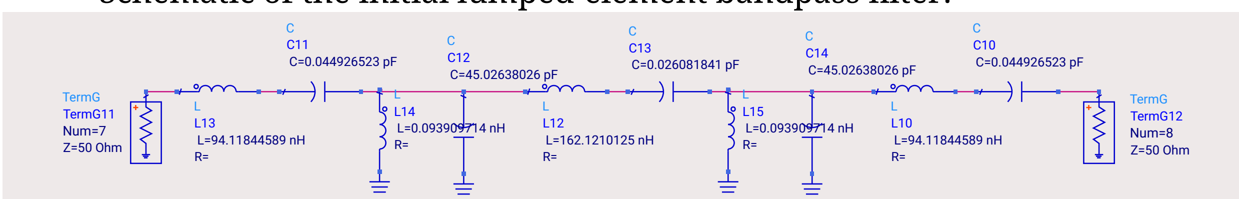
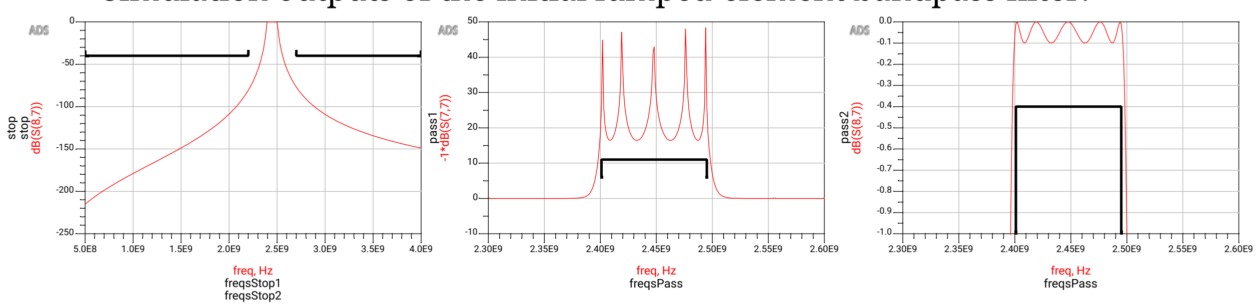
Passive RF
Chebyshev Filter Design

To design the Chebyshev filter, we first began transforming the prototype values of a Chebyshev lowpass filter with 0.1dB of ripple into capacitance and inductance values. To determine the minimum order required, we utilized the doubly terminated lumped element bandpass filter designer, and after designing, we chose the next highest odd-numbered filter order as our initial filter order (which was $N = 5$). We did this because we assumed that manufacturing tolerances and losses in the substrate would cause the smallest possible filter order to not meet design specifications. After deciding on a filter order and properly converting the prototype values into actual capacitances and inductances, we implemented and simulated our lumped element bandpass filter in Keysight's Advanced Design System (ADS).

Schematic of the initial lumped-element bandpass filter:

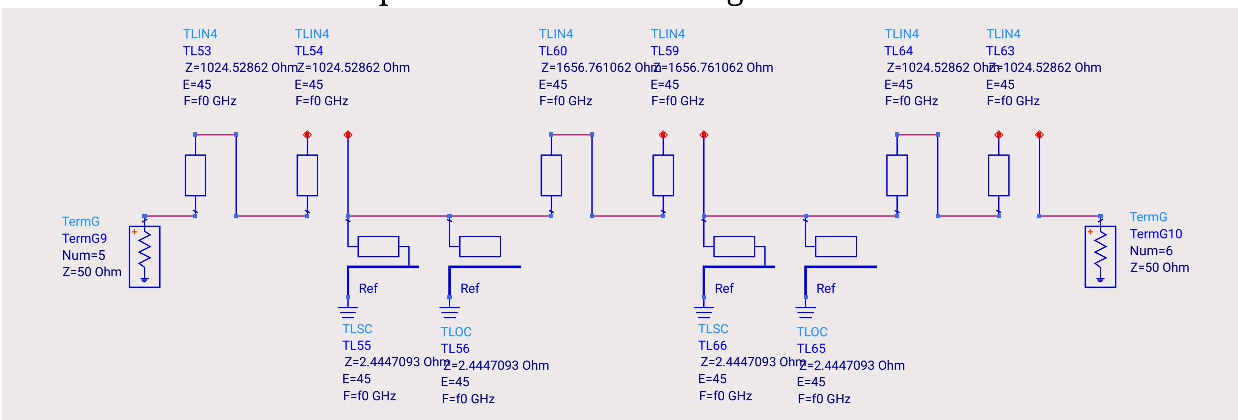


Simulation outputs of the initial lumped-element bandpass filter:

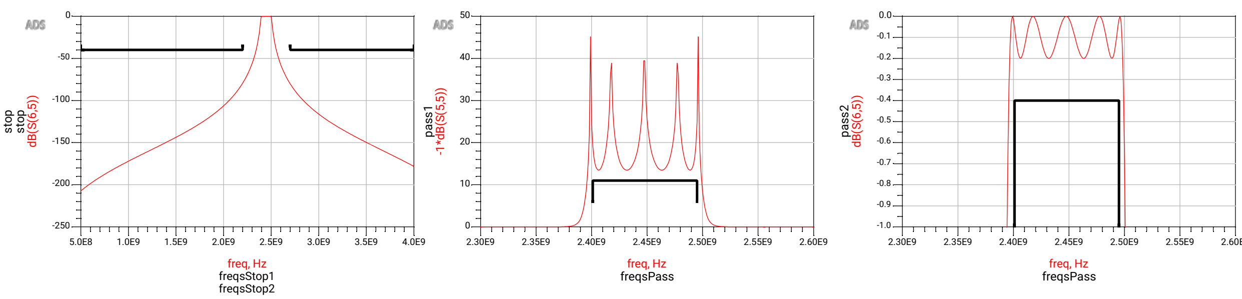


After verifying that our transformation from lowpass prototype values to actual bandpass inductances and capacitances was functioning, we began to attempt to convert our filter to something realizable with the technology available to us. We first started by converting our capacitances and inductances into series and shunt open and shorted stubs using Richard's transformation. This led to the following schematic and simulation output.

Schematic of bandpass filter after utilizing Richard’s Transformation:

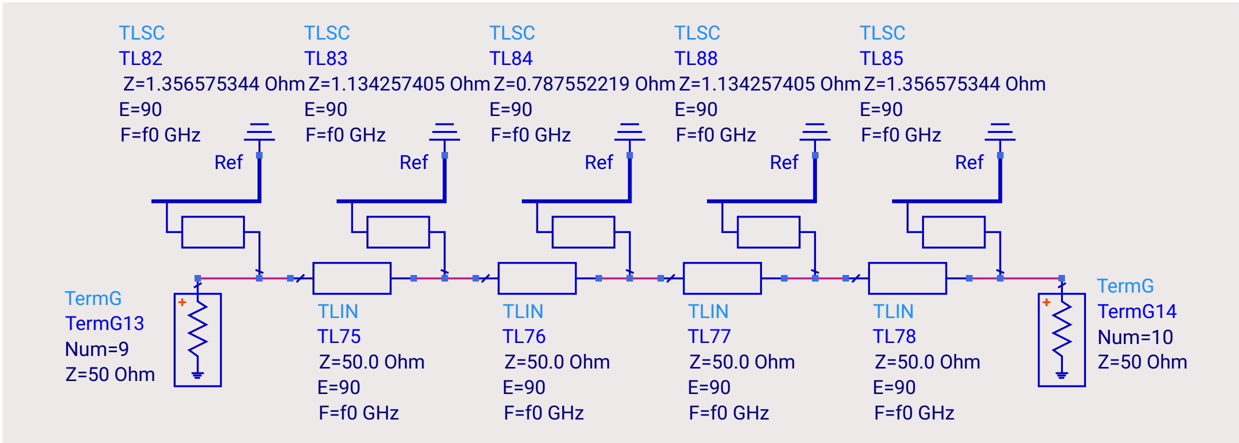


Simulation outputs of the bandpass filter after utilizing Richard’s Transformation:

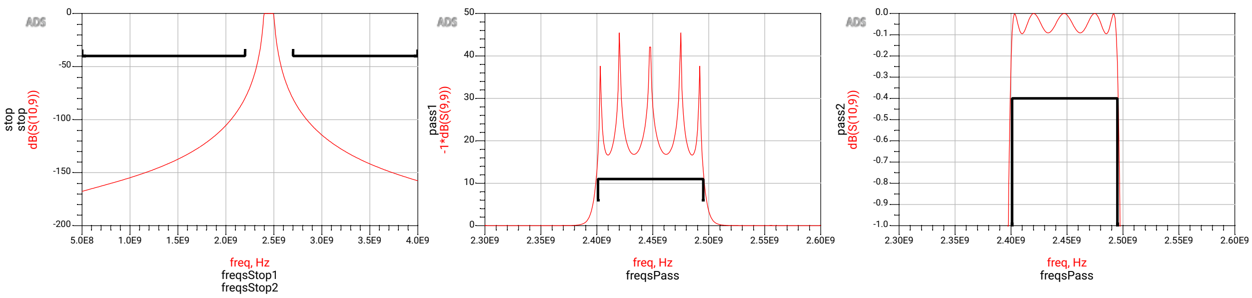


After getting proper outputs after utilizing Richard’s Transformation and ideal components, we attempted to utilize Kuroda’s Identities to convert the open and shorted series stubs into shorted and open shunt stubs, but at this time, our understanding of these identities was limited. This caused us to switch to a different approach of implementing the transmission line-based bandpass filter, so we moved on to attempting to use coupled resonators to implement the filter. Utilizing the formulas in the book allowed us to easily implement a coupled resonator bandpass filter design utilizing quarter-wave resonators.

Schematic of a bandpass filter utilizing a coupled resonator design:

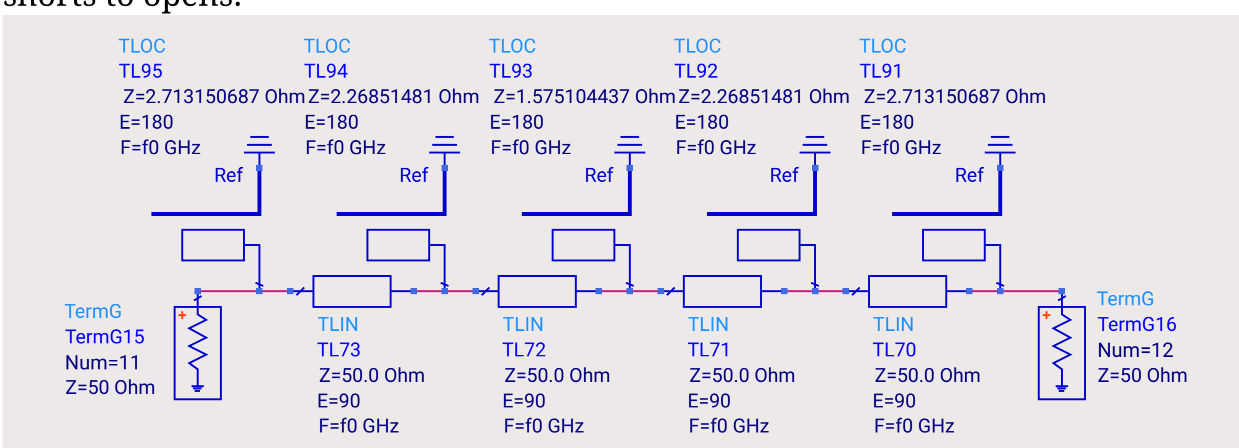


Simulation outputs of a bandpass filter utilizing a coupled resonator design:

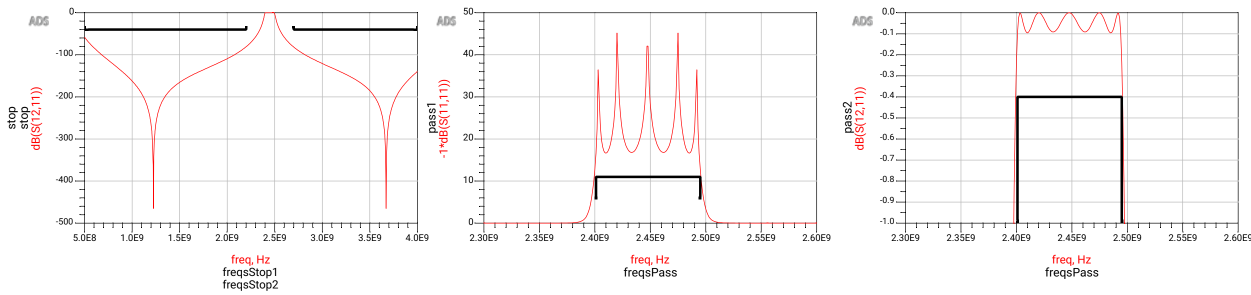


After getting proper outputs after converting the passband filter to a coupled resonator design, we replaced the coupled resonator's shorts with opens by modifying the electrical length of the stubs from $90°$ to $180°$.

Schematic of the coupled resonator bandpass filter after converting the shorts to opens:

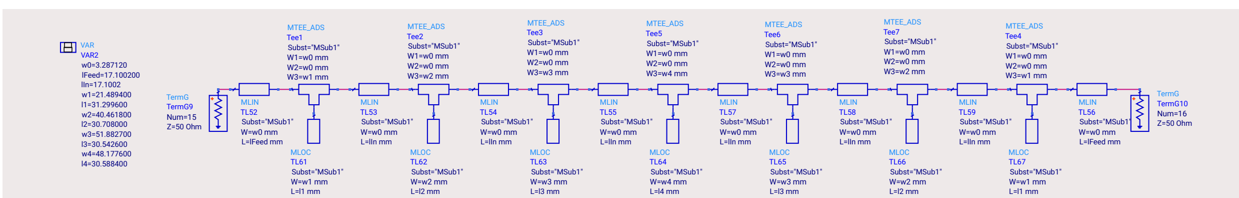


Simulation outputs of the coupled resonator bandpass filter after converting the shorts to opens:

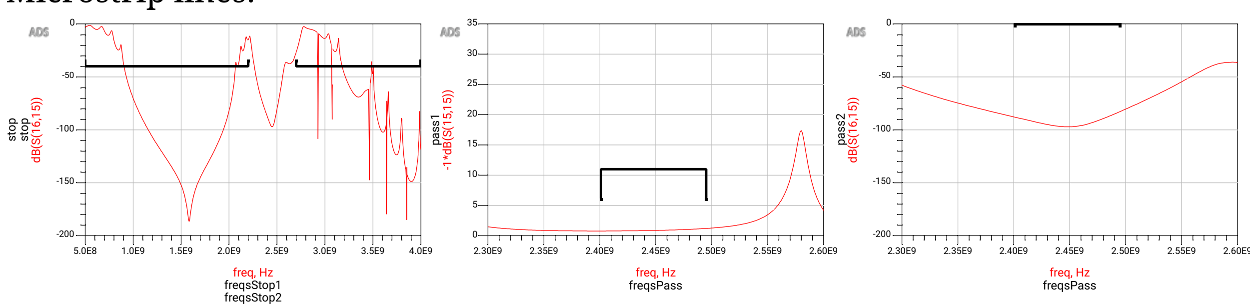


As this was the first design we achieved that had a response that met all design constraints and was realizable with our open stub only requirement, we attempted to convert the design from idealized components to microstrip line components, but we quickly ran into a problem. The impedances of the open stubs were so low that they were not physically realizable and had widths in the range of $5\,cm$ all the way up to $30\,cm$.

Schematic of the first attempt at bandpass filter design utilizing Microstrip lines:



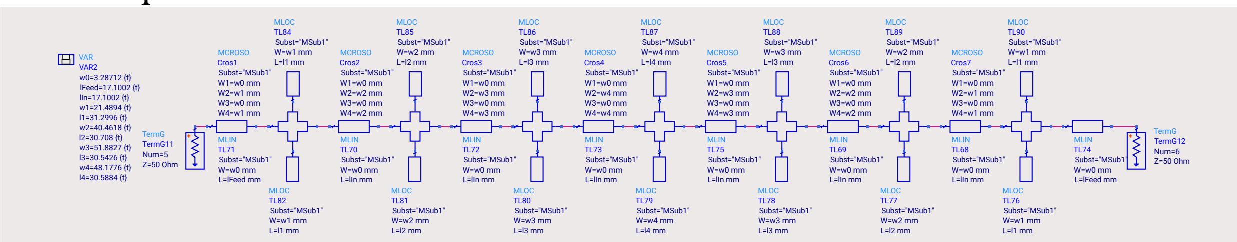
Simulated outputs of the first attempt at bandpass filter design utilizing Microstrip lines:



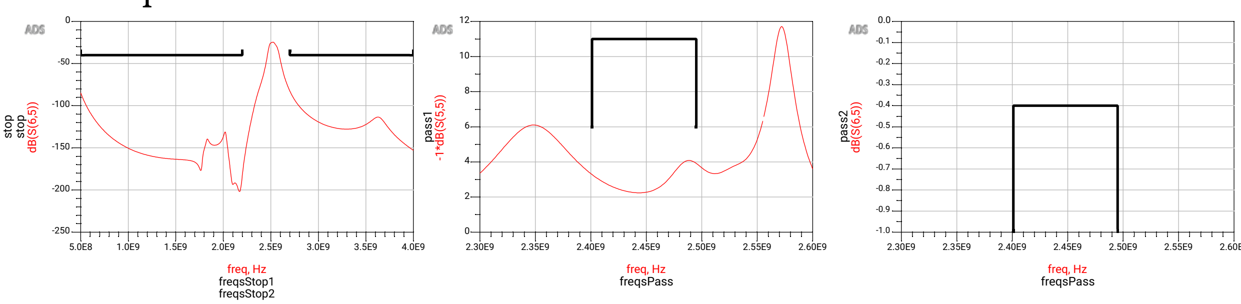
The reason the filter order of the schematic shown above is 7th order is because at the time we were under the incorrect assumption that increasing the filter order would always lead to a better filter response besides resistive losses, and thus we interchangeably went between 5th and 7th order filters throughout most of our design process (some of our 7th order designs can be seen in Appendix A).

Even utilizing the optimizer, we could not get a 5th or 7th order filter of this design to work on microstrip lines due to the impossibility of the geometry, so we attempted to utilize other types of stubs. The first modification we attempted to use instead of a single-sided stub was to use a cross and have a stub on both sides of the primary transmission line.

Schematic of the second attempt at bandpass filter design utilizing Microstrip lines:

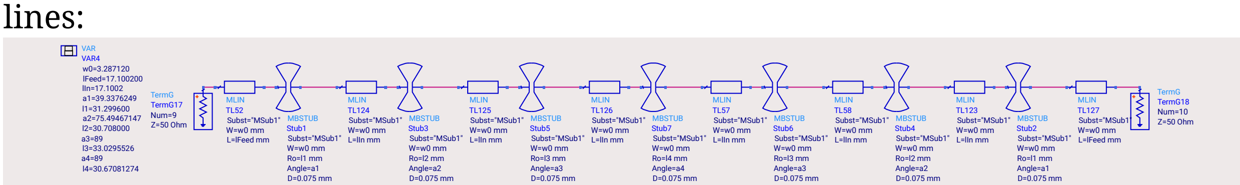


Simulated outputs of the second attempt at bandpass filter design utilizing Microstrip lines:

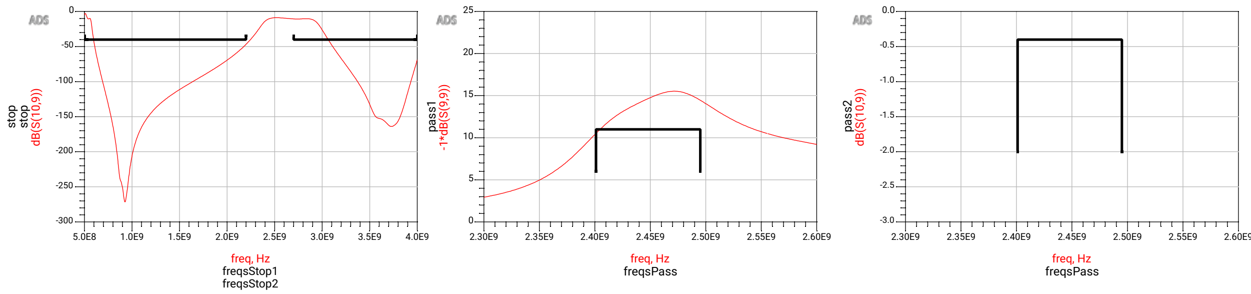


Even after optimizing, this design as well was not feasible. At this point, we went to office hours and received guidance on methods we could utilize to make the current design work. Professor Morris recommended we attempt to utilize butterfly stubs.

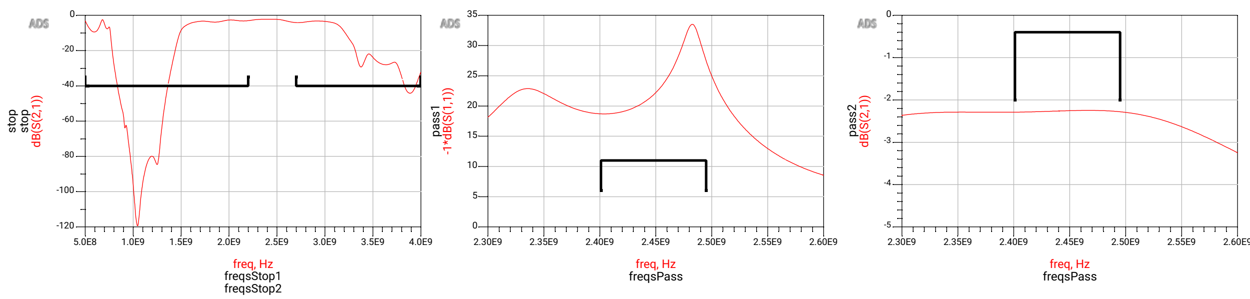
Schematic of the third attempt at bandpass filter design utilizing Microstrip lines:



Simulated outputs of the third attempt at bandpass filter design utilizing Microstrip lines:

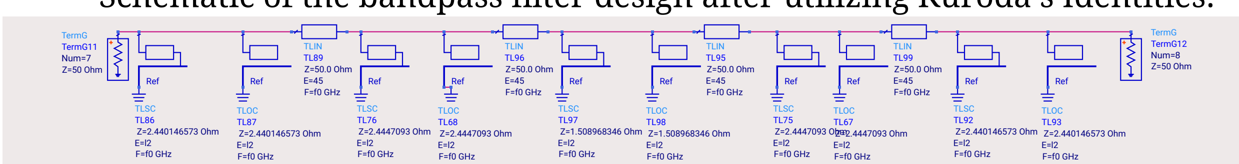


Simulated outputs of the third attempt at bandpass filter design utilizing Microstrip lines after optimizing:

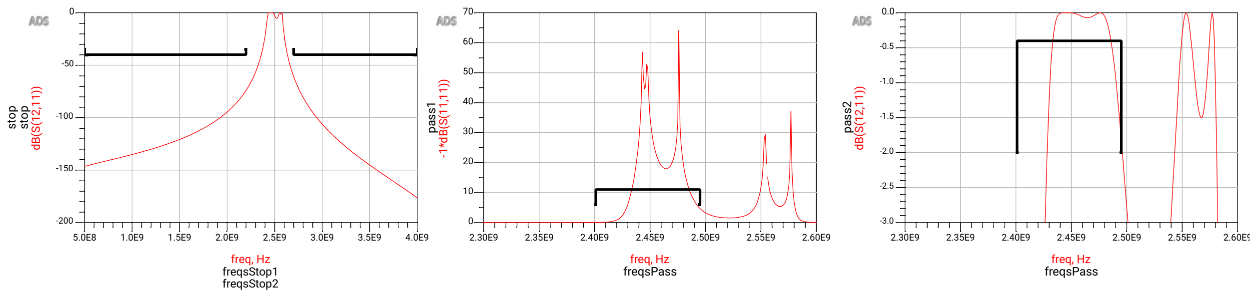


At this point, we realized that utilizing the coupled resonator approach may be more difficult than necessary, so we looked through the textbook and slides to find another approach. By now, our understanding of filter design had increased enough that we decided to attempt to use Kuroda's Identities again. This time, we were somewhat successful in utilizing the identities.

Schematic of the bandpass filter design after utilizing Kuroda's Identities:

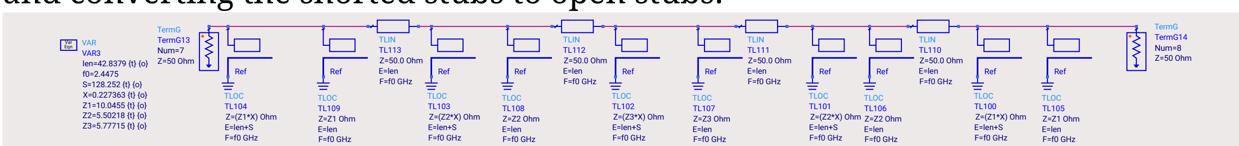


Simulated output of the bandpass filter design after utilizing Kuroda's Identities:

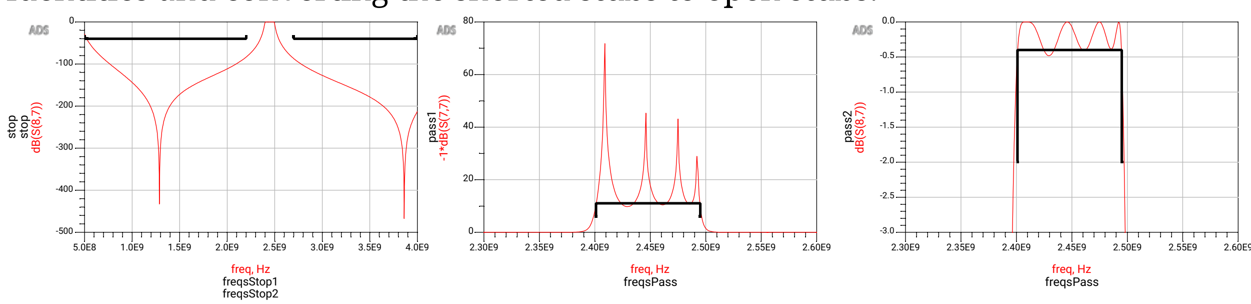


After getting acceptable outputs after utilizing Kuroda's Identities, we converted the shorted stubs to open stubs. We did not optimize the response of the bandpass filter with open and shorted stubs because we knew we were going to do that with the design that only had open stubs, and thus might be realizable with our manufacturing constraints.

Schematic of the bandpass filter design after utilizing Kuroda's Identities and converting the shorted stubs to open stubs:

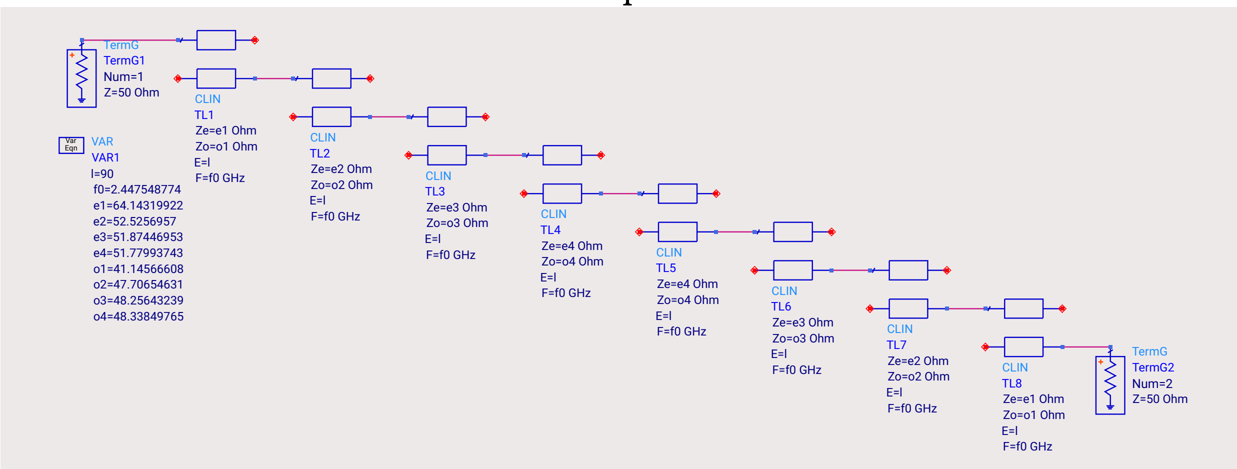


Simulated output of the bandpass filter design after utilizing Kuroda's Identities and converting the shorted stubs to open stubs:

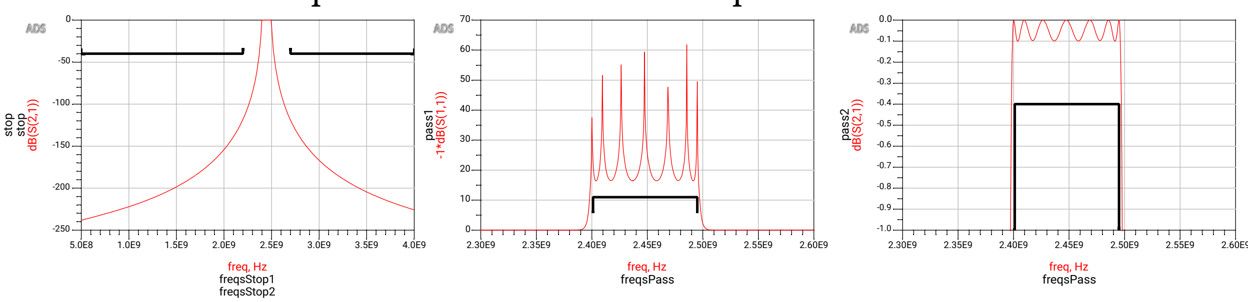


After optimizing the open stub only, post Kuroda identity conversion, ideal bandpass filter, we realized that the same issues we had with the coupled resonator bandpass filter apply to this design. At this point, we had tried most of the designs explained in the textbook that we would be able to machine, so we attempted to use the filter designing tools in ADS. After attempting every SmartComponent in the Passive Circuit DG – Microstrip Circuits Palette in ADS, we realized that a coupled line filter seemed to be the most realizable. This was because the coupled line filter SmartComponent was the SmartComponent that had the best S_{21} response of the SmartComponents that were able to design bandpass filters, and additionally, it did not error when attempting to design a filter (like the Microstrip Stub Bandpass Filter SmartComponent). Due to this decision, we decided to read the coupled line filter section in the textbook and began to experiment with coupled line filters. We quickly were able to design an ideal coupled line filter.

Schematic of an ideal 7th order coupled line filter:

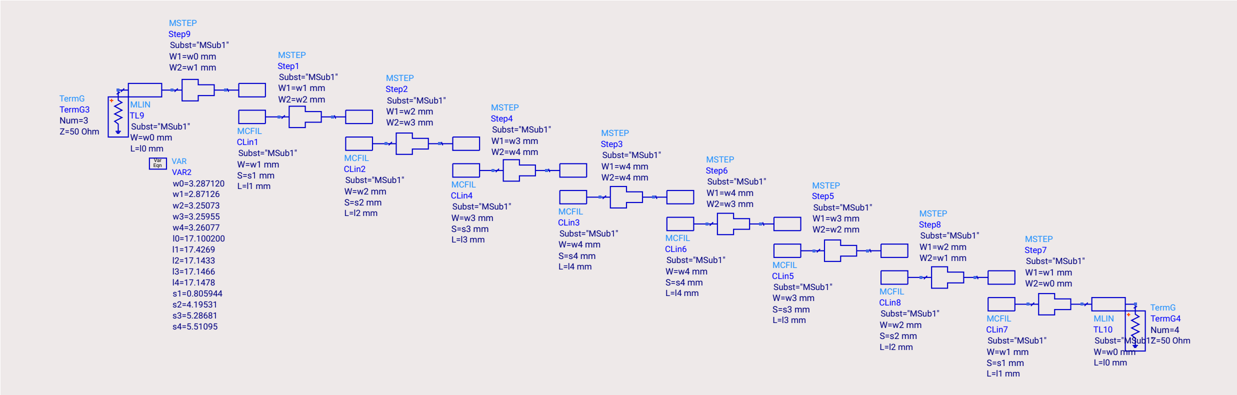


Simulated output of an ideal 7th order coupled line filter:

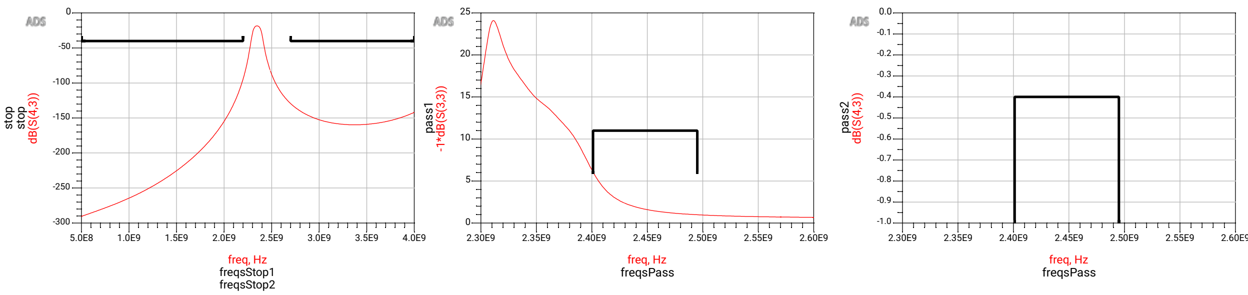


After realizing the feasibility of this design, we moved to designing the coupled line filter out of microstrip couplers. We quickly realized that this filter design was much more feasible than our previous ones, as the width, length, and spacing given by Linecalc were within reason.

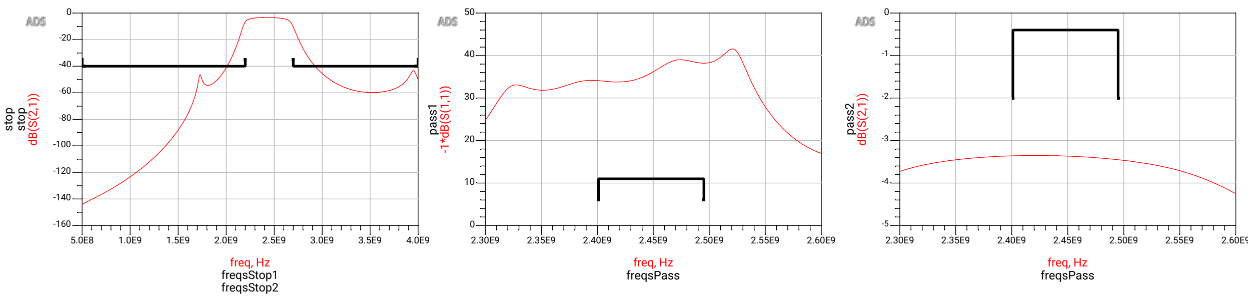
Schematic of a 7th order bandpass coupled line filter:



Simulated output of a 7th order bandpass coupled line filter:

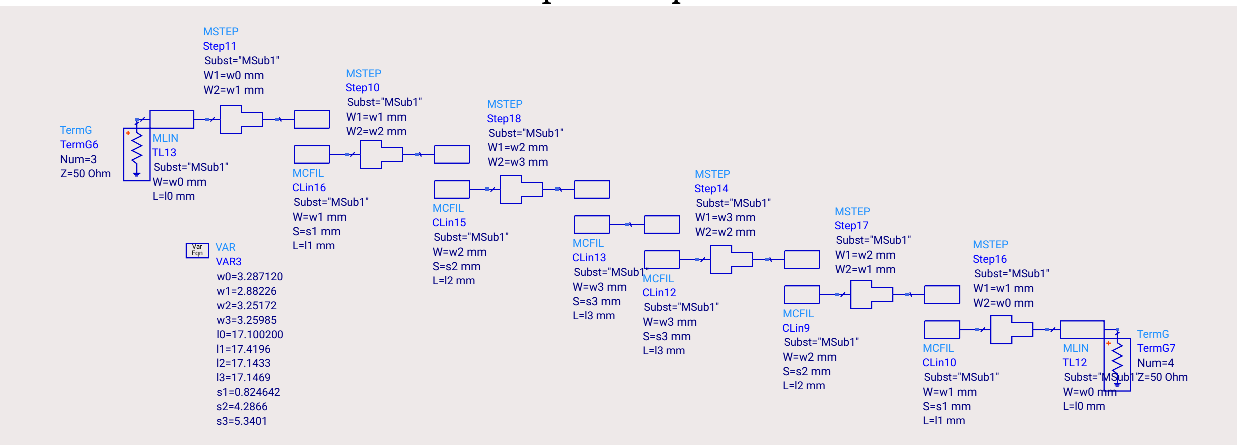


Simulated output of a 7th order bandpass coupled line filter after optimizing:

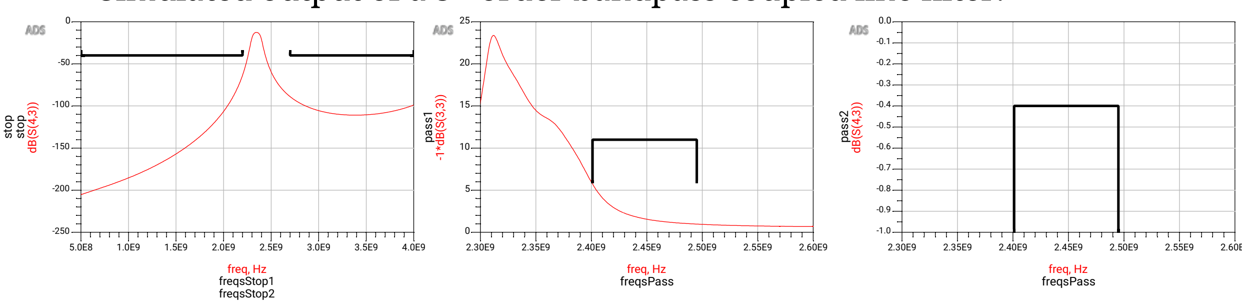


It was around this time that we were beginning to realize that higher order filter does not necessarily always mean a better response, so we also tried a 5th order coupled line filter.

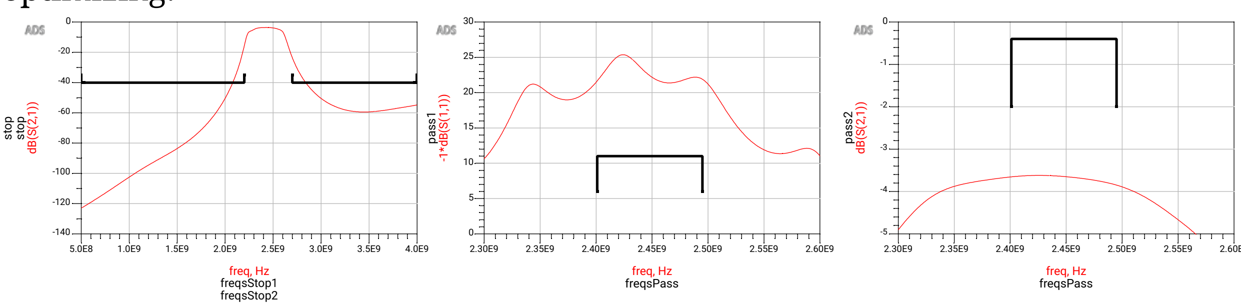
Schematic of a 5th order bandpass coupled line filter:



Simulated output of a 5th order bandpass coupled line filter:



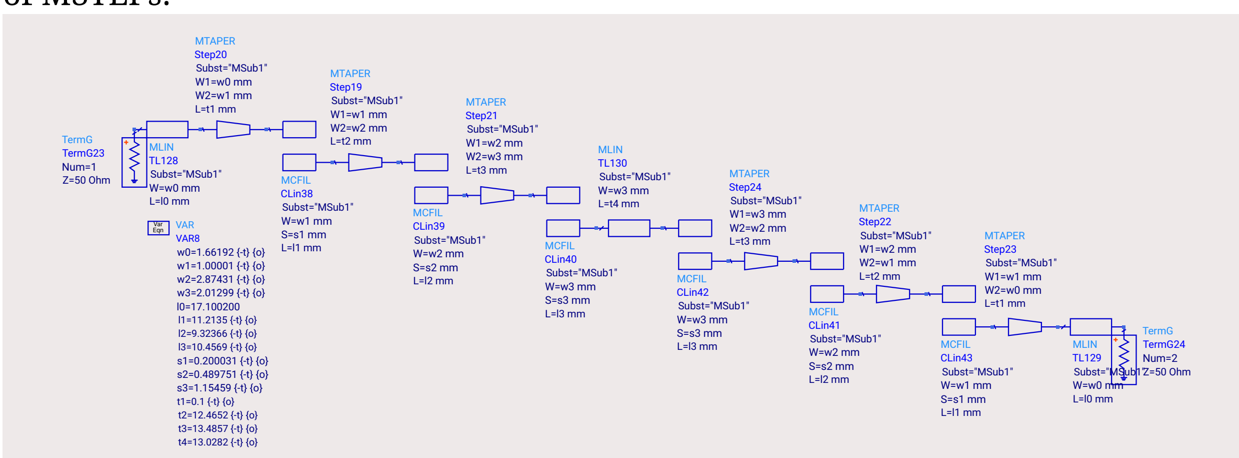
Simulated output of a 5th order bandpass coupled line filter after optimizing:



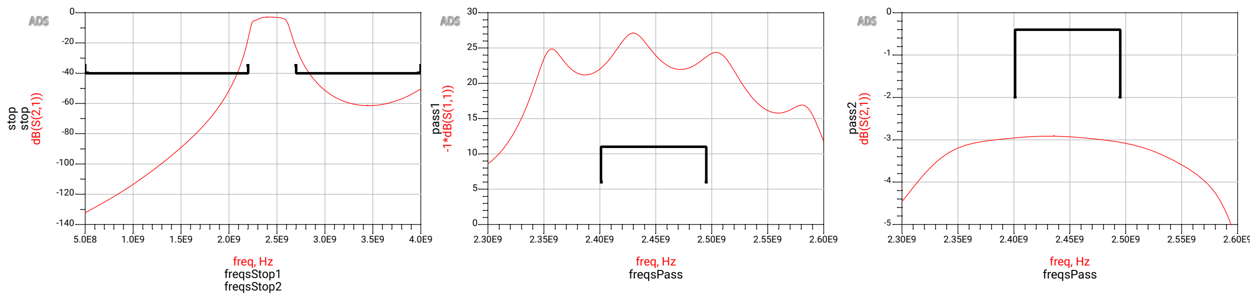
After this entire process, we realized that perfectly achieving all the design constraints is very difficult, if not impossible, with the given substrate and the restriction of not being able to use shorts. So, we decided that if we could get a response that looks like a bandpass filter with a pass band in the requisite range, and it was manufacturable, we would accept that design. After deciding to move forward with the 5th order coupled line filter, we decided to generate the layout to verify feasibility. When doing this, we realized there was a problem in our design, namely, due to the widths of the couplers, both edges of one coupler were connected to the next. We decided to use tapers instead of an abrupt step to solve this problem.

Problem with the first final design's layout:

Schematic of 5th order bandpass coupled line filter with MTAPERs instead of MSTEPs:

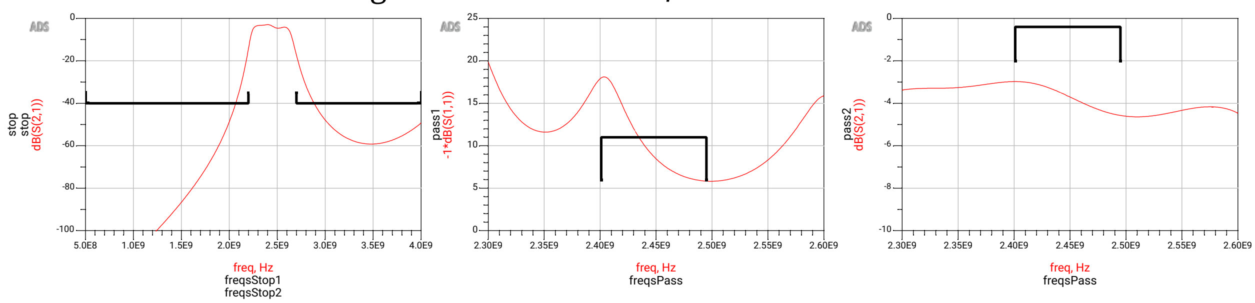


Simulated output of 5th order bandpass coupled line filter with MTAPERs instead of MSTEPs:

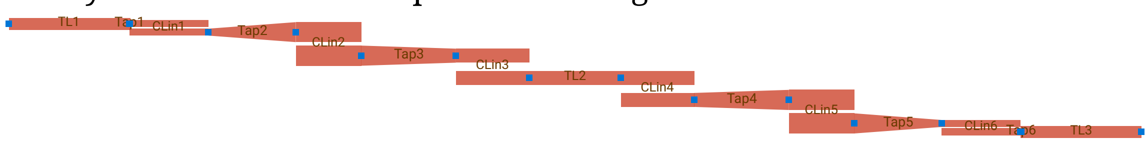


We then decided to round all of our values to the closest $0.1\,mm$ to better simulate manufacturing tolerances. This step shows how the narrow bandwidth required for this component is very susceptible to μm changes in the design.

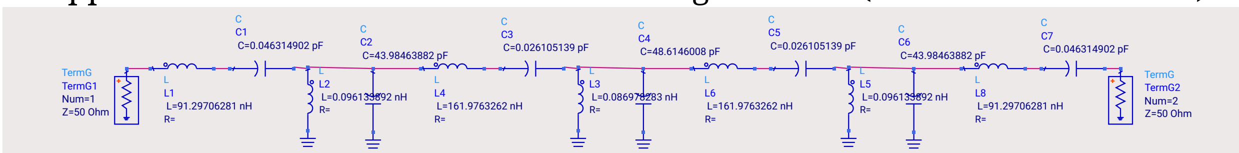
Simulated output of the 5th order bandpass coupled line filter with MTAPERS after rounding to the nearest $100\,\mu m$:

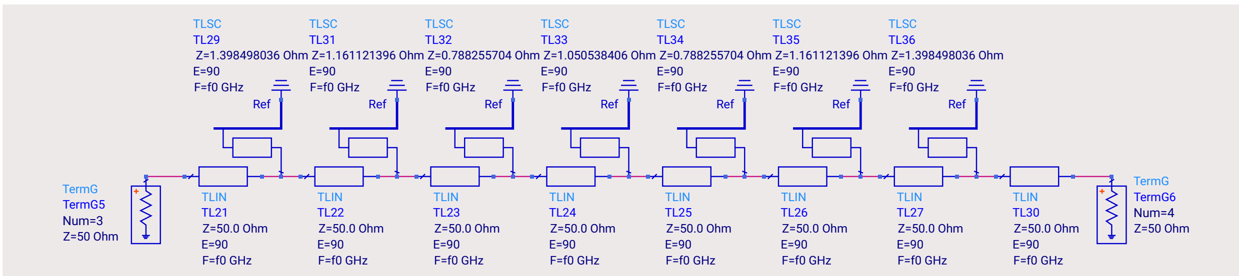


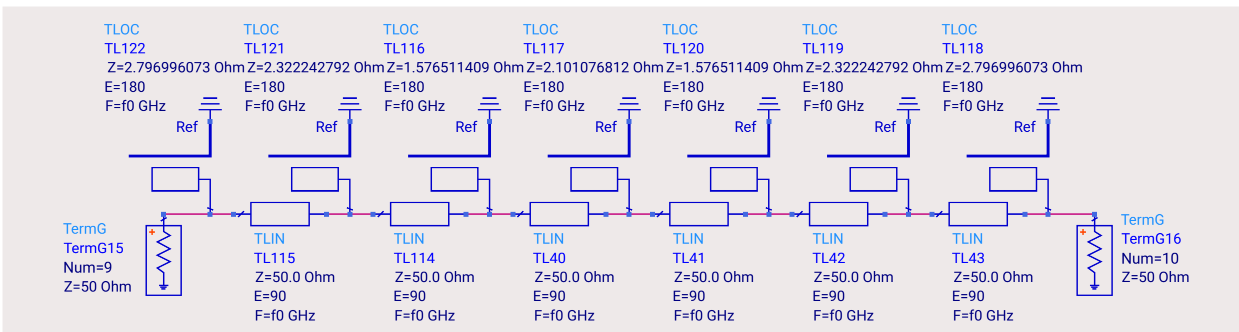
Layout of the final bandpass filter design:

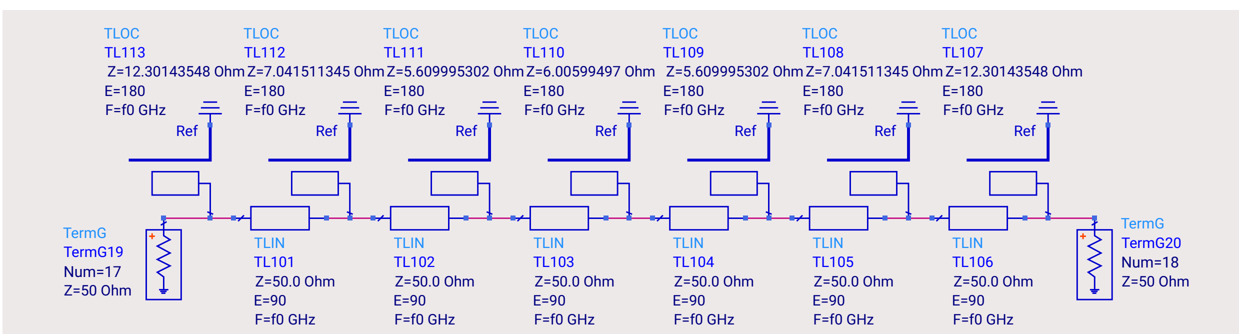


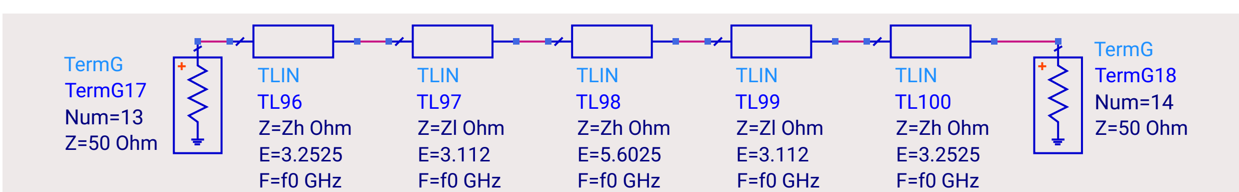
Appendix A: Schematics of Additional Designs Tested (that were not deleted)

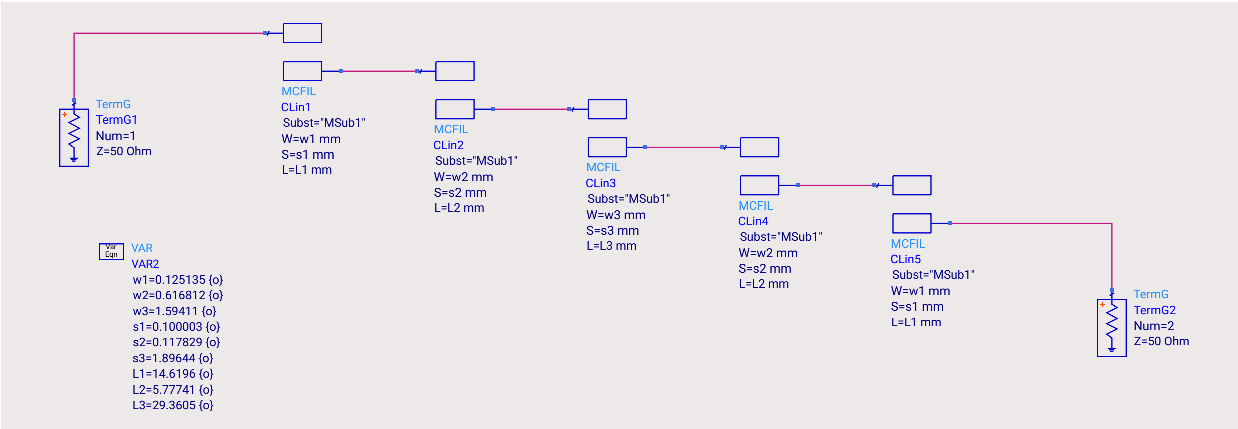




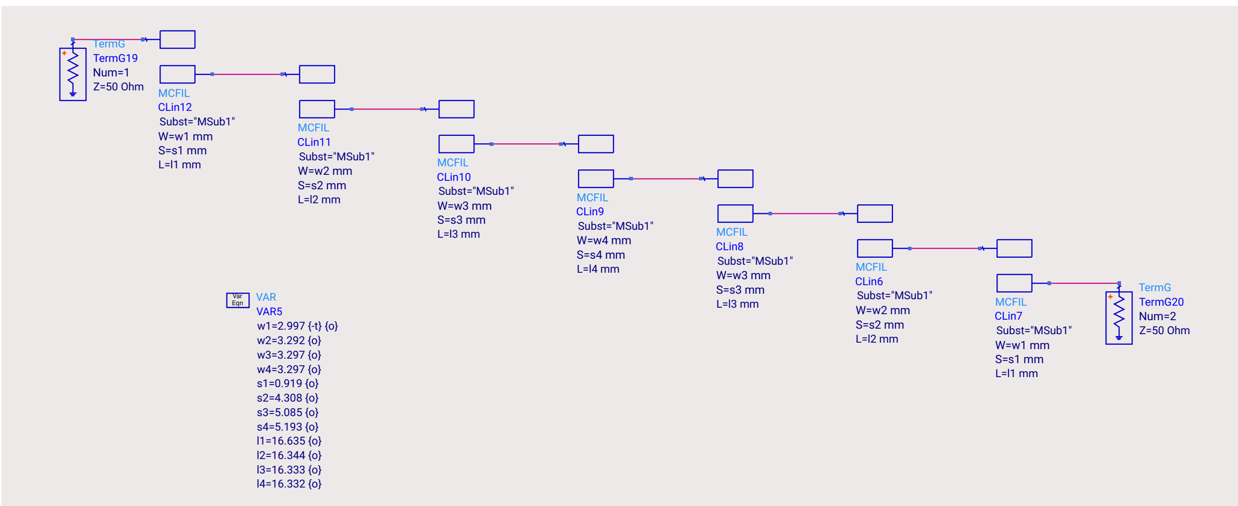








TermG
TermG1
Num=1
Z=50 Ohm
MCFIL
CLin1
Subst="MSub1"
W=w1 mm
S=s1 mm
L=L1 mm
MCFIL
CLin2
Subst="MSub1"
W=w2 mm
S=s2 mm
L=L2 mm
MCFIL
CLin3
Subst="MSub1"
W=w3 mm
S=s3 mm
L=L3 mm
MCFIL
CLin4
Subst="MSub1"
W=w2 mm
S=s2 mm
L=L2 mm
MCFIL
CLin5
Subst="MSub1"
W=w1 mm
S=s1 mm
L=L1 mm
TermG
TermG2
Num=2
Z=50 Ohm
Var
Eqn
VAR
VAR2
w1=0.125135 {o}
w2=0.616812 {o}
w3=1.59411 {o}
s1=0.100003 {o}
s2=0.117829 {o}
s3=1.89644 {o}
L1=14.6196 {o}
L2=5.77741 {o}
L3=29.3605 {o}



TermG
TermG19
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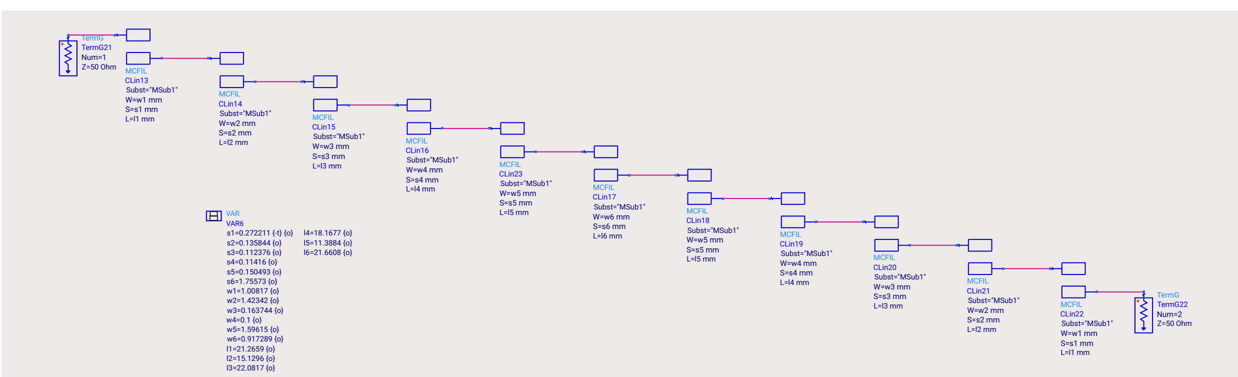
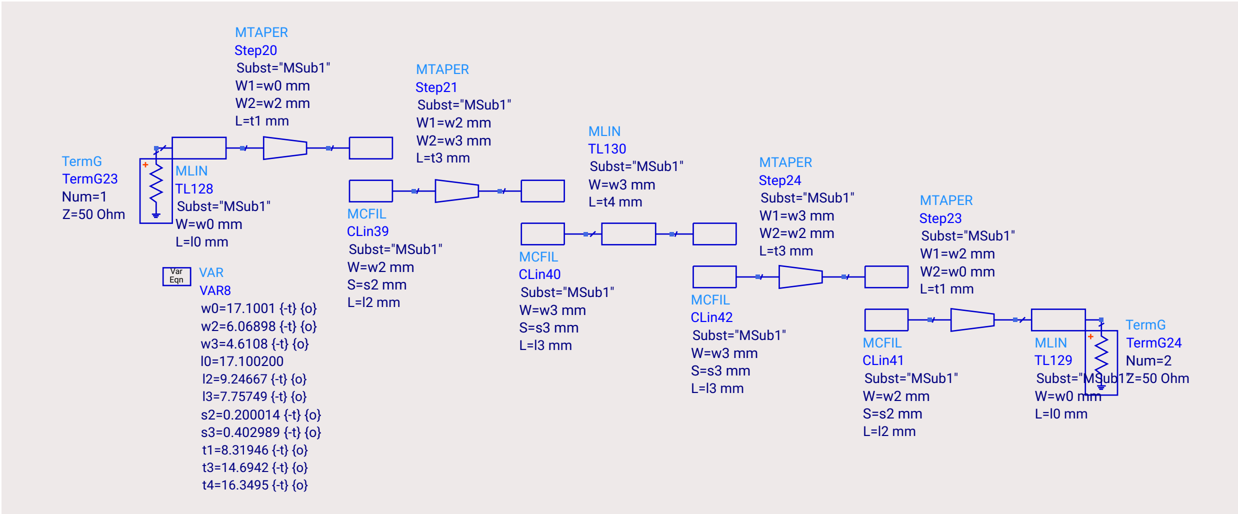
Z=50 Ohm
MCFIL
CLin12
Subst="MSub1"
W=w1 mm
S=s1 mm
L=l1 mm
MCFIL
CLin11
Subst="MSub1"
W=w2 mm
S=s2 mm
L=l2 mm
MCFIL
CLin10
Subst="MSub1"
W=w3 mm
S=s3 mm
L=l3 mm
MCFIL
CLin9
Subst="MSub1"
W=w4 mm
S=s4 mm
L=l4 mm
MCFIL
CLin8
Subst="MSub1"
W=w3 mm
S=s3 mm
L=l3 mm
MCFIL
CLin6
Subst="MSub1"
W=w2 mm
S=s2 mm
L=l2 mm
MCFIL
CLin7
Subst="MSub1"
W=w1 mm
S=s1 mm
L=l1 mm
TermG
TermG20
Num=2
Z=50 Ohm
Var
Eqn
VAR
VAR5
w1=2.997 {-t} {o}
w2=3.292 {o}
w3=3.297 {o}
w4=3.297 {o}
s1=0.919 {o}
s2=4.308 {o}
s3=5.085 {o}
s4=5.193 {o}
l1=16.635 {o}
l2=16.344 {o}
l3=16.333 {o}
l4=16.332 {o}



TermG
TermG21
Num=1
Z=50 Ohm
MCFIL
CLin13
Subst="MSub1"
W=w1 mm
S=s1 mm
L=l1 mm
MCFIL
CLin14
Subst="MSub1"
W=w2 mm
S=s2 mm
L=l2 mm
MCFIL
CLin15
Subst="MSub1"
W=w3 mm
S=s3 mm
L=l3 mm
MCFIL
CLin16
Subst="MSub1"
W=w4 mm
S=s4 mm
L=l4 mm
MCFIL
CLin23
Subst="MSub1"
W=w5 mm
S=s5 mm
L=l5 mm
MCFIL
CLin17
Subst="MSub1"
W=w6 mm
S=s6 mm
L=l6 mm
MCFIL
CLin18
Subst="MSub1"
W=w5 mm
S=s5 mm
L=l5 mm
MCFIL
CLin19
Subst="MSub1"
W=w4 mm
S=s4 mm
L=l4 mm
MCFIL
CLin20
Subst="MSub1"
W=w3 mm
S=s3 mm
L=l3 mm
MCFIL
CLin21
Subst="MSub1"
W=w2 mm
S=s2 mm
L=l2 mm
MCFIL
CLin22
Subst="MSub1"
W=w1 mm
S=s1 mm
L=l1 mm
TermG
TermG22
Num=2
Z=50 Ohm
VAR
VAR6
s1=0.272211 {-t} {o}
s2=0.135844 {o}
s3=0.112376 {o}
s4=0.11416 {o}
s5=0.150493 {o}
s6=1.75573 {o}
w1=1.00817 {o}
w2=1.42342 {o}
w3=0.163744 {o}
w4=0.1 {o}
w5=1.59615 {o}
w6=0.917289 {o}
l1=21.2659 {o}
l2=15.1296 {o}
l3=22.0817 {o}
l4=18.1677 {o}
l5=11.3884 {o}
l6=21.6608 {o}


MTAPER
Step20
Subst="MSub1"
W1=w0 mm
W2=w2 mm
L=t1 mm
MTAPER
Step21
Subst="MSub1"
W1=w2 mm
W2=w3 mm
L=t3 mm
MLIN
TL130
Subst="MSub1"
W=w3 mm
L=t4 mm
MTAPER
Step24
Subst="MSub1"
W1=w3 mm
W2=w2 mm
L=t3 mm
MTAPER
Step23
Subst="MSub1"
W1=w2 mm
W2=w0 mm
L=t1 mm
TermG
TermG23
Num=1
Z=50 Ohm
MLIN
TL128
Subst="MSub1"
W=w0 mm
L=l0 mm
MCFIL
CLin39
Subst="MSub1"
W=w2 mm
S=s2 mm
L=l2 mm
MCFIL
CLin40
Subst="MSub1"
W=w3 mm
S=s3 mm
L=l3 mm
MCFIL
CLin42
Subst="MSub1"
W=w3 mm
S=s3 mm
L=l3 mm
MCFIL
CLin41
Subst="MSub1"
W=w2 mm
S=s2 mm
L=l2 mm
MLIN
TL129
Subst="MSub1"
W=w0 mm
L=l0 mm
TermG
TermG24
Num=2
Z=50 Ohm
Var Eqn
VAR
VAR8
w0=17.1001 {-t} {o}
w2=6.06898 {-t} {o}
w3=4.6108 {-t} {o}
l0=17.100200
l2=9.24667 {-t} {o}
l3=7.75749 {-t} {o}
s2=0.200014 {-t} {o}
s3=0.402989 {-t} {o}
t1=8.31946 {-t} {o}
t3=14.6942 {-t} {o}
t4=16.3495 {-t} {o}