

A reflectionless filter for load-pull measurements: design, simulation, and experimental characterization

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Abstract—Load-pull measurements are one of the most widely used test setups to support the research and development of various RF components and devices. Signal reflections, if occurred at any stage of the test system, negatively impact the characterization of devices under test. A common source causing these unwanted reflections is RF filters, which are conventionally designed to reflect energy outside their passband. Using a reflectionless filter that can suppress out-of-band reflections helps increase the accuracy of such a test setup. In this project, a high-pass reflectionless filter was designed, simulated, fabricated, and experimentally characterized, with an intended usage for testing applications covering a wide range of modern devices operating in RF/microwave spectrum up to 6 GHz. The developed filter suppresses out-of-band reflections below 2.3GHz and provides high transmission coefficients within the 2.3-6.0 GHz passband.

Index Terms—reflectionless filters

I. INTRODUCTION

Preserving signal selectivity and range are the main objectives of broadband communications designers. Filters attenuate unwanted signals and are ubiquitous in nearly all designs of electronics engineers. Conventional filters are designed to exhibit matched impedance in their pass-band to ensure that desired signals are passed. However, they are also designed to have poor impedance matching in their stop-band which causes reflection of the signal back through the signal chain [1]. Reflections result in signal degradation as they are trapped between the ports of a source and filter. These out-of-band reflections lead to undesired behaviors such as harmonics, interference, and noise [2].

Existing solutions to address a conventional filter's reflection include inserting attenuators and isolators between the filter and other reflective components (mixers, multipliers, circulators, amplifiers, etc.). These fixes create padding that dampens the standing waves from the reflections [3]. The effects of the reflections and resulting standing waves include gain compression, oscillations, reduced dynamic range, an increase in the number of invalid mixing products, unwanted resonances, more environmental sensitivity, biasing issues, etc. [4]. With the isolators and attenuators added, there is usually a need for an increase in gain, which increases cost, size, and the possibility of failure in the setup.

The field of electronic filter topology has been developing filter networks to absorb reflected signals since the early twentieth century [5][2]. Classical absorptive filters include

terminated diplexers, directional filters, and constant-resistance networks [2]. However, drawbacks to certain classical absorptive filters include 1) inability to achieve desired pass-band, transition-band, and stop-band characteristics such as those of Butterworth, Chebyshev type I and II, elliptic filters, 2) inability to cascade sections of filters together to alter the band shapes, 3) limited to lower orders, 4) restricted to narrow bandwidths, and 5) only absorptive at one port, 6) increased complexity of filter realizability [2]. A reflectionless filter would solve these problems without these trade-offs.

Reflectionless filters offer reflection coefficients (i.e., a parameter describing how much of a wave is reflected by an impedance discontinuity in the transmission line) of ideally zero at all ports of a device in both stop-bands and passbands [6] [2]. Matthew A. Morgan invented the reflectionless filter out of necessity when designing a filter for applications in radio astronomy receivers and has found the issue relevant in general for many broadband applications [5][7][8]. The filter's novelty lies in its topology. It provides matched impedance in a symmetric two-port system, allowing it to absorb all reflections and minimize standing waves in the signal chain [3]. Morgan realizes the symmetric network by even/odd mode analysis [3] [2]. This prototype aims to extend Morgan's concepts to design a high-pass reflectionless filter with characteristics unavailable on the market (i.e., Mini-Circuits) suitable for a load-pull test setup. The project overall aims to help meet customer expectations for a robust product by improving the accuracy of testing. Increasing the accuracy of testing has impacts on model extraction, model validation, final product testing, and reliability analysis for DUTs such as power amplifiers used in wireless communications transceivers.

II. PROBLEM DEFINITION

We are designing a reflectionless high-pass filter to be specifically set up in a load-pull test. Load-pull tests are crucial to characterizing devices that operate in the RF spectrum and under large-signal conditions. Certain specifications, such as device impedance, must be accurately characterized to maximize the signal power consumed and delivered by a device under test (DUT). Load-pull testing characterizes the circuit while varying the impedance presented to the DUT's input and output to obtain the optimal operation point of the device. As shown in Figure 1, a typical load-pull test setup consists of 1) a preamplifier to increase the source signal to a reasonable level, 2) a bias tee to adequately bias the RF device, 3) a source

impedance tuner, and 4) a low-loss coupler that sends a parallel of the signal to a network analyzer and passes it to a DUT [9]. In these setups, imprecision in measurement can occur due to leakage from passive components. Though designed to be ideal, passive components like inductors and capacitors exhibit some form of resonance due to manufacturing imperfections like insulation imperfection or dielectric losses. These parasitic effects are highlighted, especially when used amongst other reactive components.

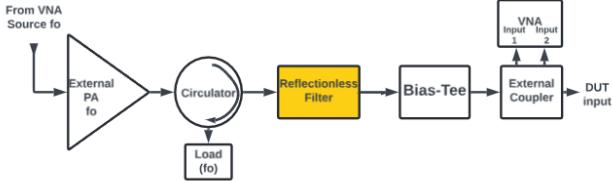


Figure 1: Block diagram of the front end of an active load-pull test set-up.

III. CONCEPT, REQUIREMENTS AND SPECIFICATIONS

The project idea arose from the student design competition hosted at the 2024 IEEE Microwave Theory and Technology Society's annual international conference. Research into reflectionless filters revealed that only one company provides these filters – Mini-Circuits. Mini-Circuits operates globally and supplies electronics to large companies such as Raytheon Technologies and BAE Systems. Appendix A shows the competitor (KXHF-K32+) to our reflectionless high-pass filter by Mini-Circuits. The KXHF-K32+ offers competitive performance, however it also violates some of the key specifications addressed below which we intend to improve upon. Our reflectionless high-pass filter offers a bandwidth within the 2.3 GHz to 6 GHz band. The bandwidth is significant in today's consumer electronics that encompass all devices that connect with Wi-Fi and Bluetooth.

A. Concept

When discussing and finalizing the engineering design, we settled on the following as an encompassing definition/scope of the concept:

- Design the filter using existing topologies
- Create a PCB prototype that functions within the technical specifications
- We can take a systems approach to the design process, enabling us to each create a filter and decide on which one works best
- Filter should be portable
- Filter should be able to be easily embedded in a generic load-pull test setup

B. Specifications

1. The passband should have a maximum insertion loss of 1.5 dB for the 2.3-6 GHz band
2. The stopband should have a minimum of 10 dB insertion loss below 1.7 GHz

3. The reflection parameters S11 and S22 should be lower than -13 dB between 1.7 GHz and 6 GHz
4. No active components (e.g., transistors and integrated circuits) are allowed to be used for this design
5. Any substrate materials and passive components (ceramic, multi-layered, etc.) can be used
6. The PCB prototype should not exceed 300 cm²
7. The board should have female-type connectors and should be suitable for 3.5 mm male connections
8. The operating temperature of the device should be from -55°C to 100°C

C. Realistic Constraints

Constraints were assessed from the team's knowledge of RF theory, fabrication parameters, assembly methods, component selection, simulation software, PCB design software, and budget considerations.

Collectively, the team has zero to introductory level of filter topology, transmission line theory, RF testing, RF simulation, PCB design, PCB fabrication, etc. A substantial period of research to grasp concepts was required.

Fabrication requirements by our chosen vendor (JLCPCB) required our board to be enlarged to 50x50 mm to ensure precision in the drilling of the ground via holes. The number of layers was limited to 1 to keep costs and complexity to minimum. With respect to our budget, we could only assemble one prototype due to PCB fabricators only allowing one design to be printed per order although we could get 5 copies of the design.

It was decided to use lumped elements instead of distributed elements to minimize complexity and produce a prototype within our schedule. The lumped elements must contain a self-resonant frequency much higher than our highest operating frequency of 6 GHz. Since we decided to perform the final assembly ourselves to reduce costs, we had to choose a component packaging size that was large enough that we could realistically pick and place by hand which became 0402 or 0.04 x 0.02 in.

The simulation and PCB design software were chosen to be Keysight Advanced Design System Altium Designer as the team wanted experience with software widely used in the industry. Simulations were performed with ideal circuits where the microstrips had were lossless and in scenarios with lossy microstrips. The length of the microstrips were kept to a minimum of 1 mm to reduce adding impedance and losses.

Table 1 shows a summary of the cost comparison between the two most well-known PCB fabricators. JLCPCB represents the actual final project account.

Items	PCB Fabricators	
	JLCPCB	PCBWay
Components (inductors, capacitors, resistors, connectors)	\$34	\$34
PCB fab (board, stencil, solder paste, shipping)	\$140	\$354
Total	\$174	\$388
Final budget	-\$24	-\$238

Table 1: Project Cost

IV. Ethical, Professional, and Contemporary Issues

A. Ethical and Professional Issues

The RHPF was analyzed through an ethical and professional perspective in terms of consumer safety, environmental impact, materials sourcing, patent infringement, and product reliability. Hazards posed to life are relatively minimal. Combustion has low probability as the product does not have a power source. Chemically, the product is safe to handle and uses lead-free materials. The materials sourced are reportedly conflict-free [10]. A patent does exist for deriving a reflectionless filter. However, the method is widely available in academic literature and may be used for research purposes [11]. Mini-Circuits possesses a license for manufacturing and distribution.

B. Contemporary Issues

The International Institute of Electrical and Electronics Engineers created the IEEE 802.11 standard which adopted the 2.4 GHz transmission band and its network standards which governs nearly all devices connected by Wi-Fi or Bluetooth. IEEE 802.11 has had several evolutions vastly improving network performance with the inclusion of the 5 GHz and 6 GHz bands [12]. Investments by electronics manufacturers will be required to meet the market demand for devices compatible with the newer standards. Therefore, investments in characterizing the performance of devices should be of interest. A reflectionless filter is one example of a small investment that gives a manufacturer a means to improve accuracy in a device test setup. Furthermore, the applications of a reflectionless filter may be applied not just load-pull test setup but to any RF transceiver system.

V. STANDARDS

Engineering standards relevant to the filter's PCB design, ruggedness, and electromagnet compatibility with its environment were considered. These standards serve to fulfill the needs of load-pull test operators. The filter is expected to perform in laboratory environments with ambient temperatures and relative humidity. Our prototype will not have a case to protect it from electromagnetic interference however in a comparable Mini-Circuits filter that includes a case it is rated to withstand 2000V using testing standard ANSI/ESD STM 5.1-2001 Human body model (HBM).

In terms of PCB performance and safety, the Institute of Printed Circuits (IPC) standard, IPC-2221, was referred to for managing conductor spacing, creepage, and insulation requirements. Our components and conductors are distanced apart by at least 1 mm, which exceeds IPC-2221 standards.

IPC-TM-650 2.5 and 5.5 were referred to ensure that characteristics of dielectric substrates were validated as noted in their respective data sheets.

The ruggedness of passive components employed in our filter have been tested under military standard MIL-STD-202 for thermal shock, vibrational stability, and mechanical stress.

VI. FILTER DESIGN

A. Topology

We designed our filter using one of Matthew A. Morgan's patented reflectionless filter topologies. Morgan describes this topology and how he derived it in his patent US 8,392,495 B2 and in his book *Reflectionless Filters* [2][11]. Figure 2 shows a third order low-pass reflectionless filter. Making this a high-pass reflectionless filter is a matter of swapping the inductors and capacitors [2].

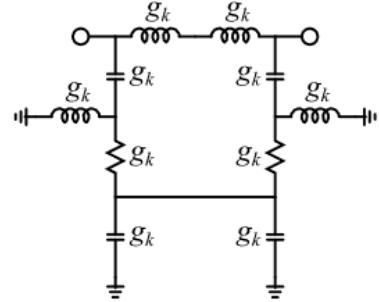


Figure 2: Third Order Low-pass Reflectionless Filter Topology [2]

In his book Morgan provides Equation 1 and Equation 2 which are used to scale reactive component values to the desired cutoff frequency for reflectionless high-pass filters. In these equations Z_0 is characteristic impedance, Y_0 is characteristic admittance, ω is the cutoff frequency, and g_k is a scaling factor. Morgan derives the values of constant g_k that may be used to scale the filter response to different frequencies of interest, including the 3 dB corner frequency and 1 dB corner frequency. Given specification 1 in section II B, we opted to use the scaling factor relating to the 1 dB corner frequency while calculating values for our reactive components. For 1 dB corner frequency calculations $g_k = 0.5592$.

$$L = \frac{Z_0}{g_k \omega}$$

Equation 1 [2]

$$C = \frac{Y_0}{g_k \omega}$$

Equation 2 [2]

Using Equation 1 and Equation 2 inductance and capacitance values were calculated for a high-pass filter with a 1 dB cutoff frequency of 2.3 GHz. The resulting component values are $L = 6.0 \text{ nH}$ and $C = 2.47 \text{ pF}$.

Figure 3 is an S21 and S11 plot of an Advanced Design System (ADS) simulation of a third order high-pass reflectionless filter using the inductor and capacitor values calculated above. The horizontal lines in the figure represent the -1.5 dB , -10 dB , and -13 dB specifications. The plot shows that a third order filter alone does not have a steep enough roll-off to meet the design specifications in section III B.

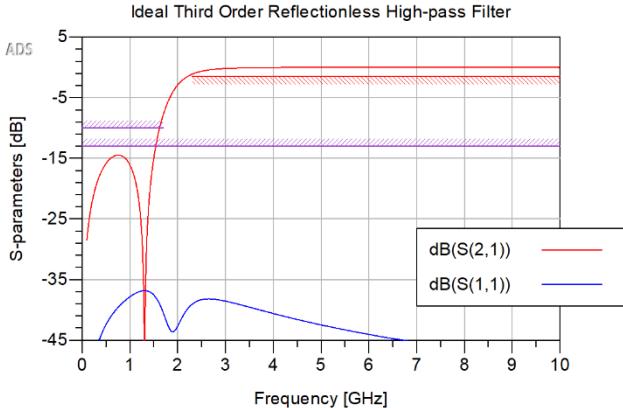


Figure 3: ADS Simulation of Ideal Third Order Reflectionless High-pass Filter

In Reflectionless Filters Morgan describes multiple methods to increase filter roll off. The two simplest methods are cascade filters and increase filter order. Increasing filter order dramatically improves roll-off but reduces insertion loss in the stop band. A combination of higher order filters and lower order filters can provide a balanced roll-off and stop band performance [2]. To meet the design specifications for this project our team settled on a cascade of a fifth order, a third order, and another fifth order filter. Figure 4 is the circuit schematic for this filter cascade. The ideal frequency response of this filter cascade is shown in Figure 5.

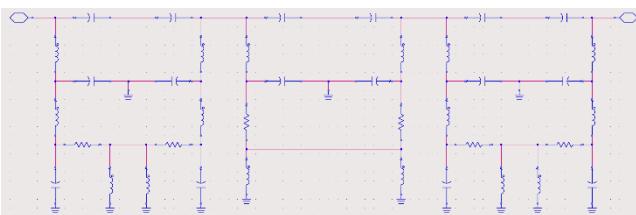


Figure 4: Schematic of a Fifth Order, Third Order, Fifth Order Reflectionless High-pass Filter Cascade

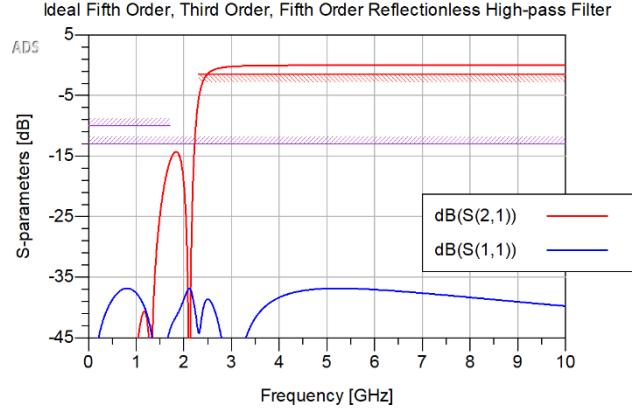


Figure 5: ADS Simulation of an Ideal Fifth Order, Third Order, Fifth Order Reflectionless High-pass Filter Cascade

B. Substrate Material

The substrate materials our team considered were FR4, Rogers RO4003C and Rogers RO4350B. FR4 was considered because it is inexpensive. The Rogers materials were considered due to their low loss tangents over a broad bandwidth. Both Rogers RO4003C and Rogers RO4350B performed very well in our ADS schematic simulation. RO4003C was ruled out due to the inability to find a supplier of the material that would fit our budget. Our FR4 simulation did not meet our minimum design specifications, therefore Rogers RO4350B was selected for the substrate material.

C. Component Selection

Our team chose to use Murata LQW and LQG series inductors and GJM series capacitors in our filter. These components have high Q factors, for surface mount devices. The Q factor, or quality factor “is a measure of the loss of a resonant circuit—lower loss implies a higher Q” [13]. These components also have ADS library support from Murata. Murata’s ADS models helped our team make a more accurate simulation before building a prototype of our circuit.

D. Tuning the Filter Using ADS

A key property of a reflectionless filter is that it must be impedance matched to the network the filter is embedded in. Our filter is designed to have an impedance of 50 ohms, as that is a common impedance used in RF systems. We used the ADS Line Calc tool to calculate the microstrip width that would give our transmission lines a 50 ohm impedance while using a Rogers RO4350B substrate.

With the substrate material and components selected we made a schematic simulation in ADS that takes into account the loss of the transmission lines and the loss of the components used. Initially the lossy circuit did not meet our design specifications. The ADS optimization and tuning tools allowed us to rapidly try different value components from the Murata library to adjust the frequency response of the design.

While tuning the circuit, we realized that as long as the cascade is symmetrical, each filter in the cascade does not have

to be symmetrical for the design to retain its reflectionless property. For our design this means that the fifth order filters on the ends of our cascade may be mirror images of each other. This increases the number of reflectionless options, allowing our team to better tune the circuit to the design specifications. Figure 5 shows the S parameters of the ADS schematic simulation after tuning the filter to meet the design specifications of this project.

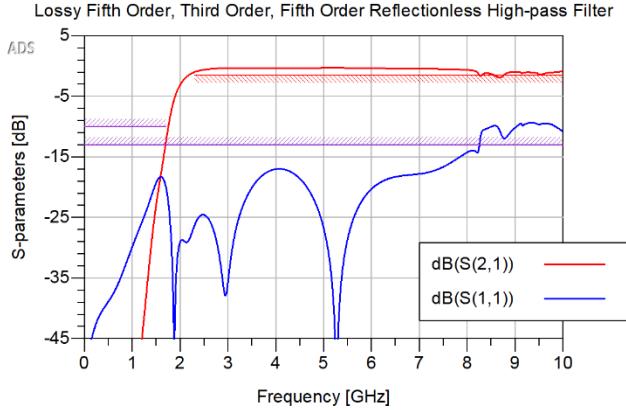
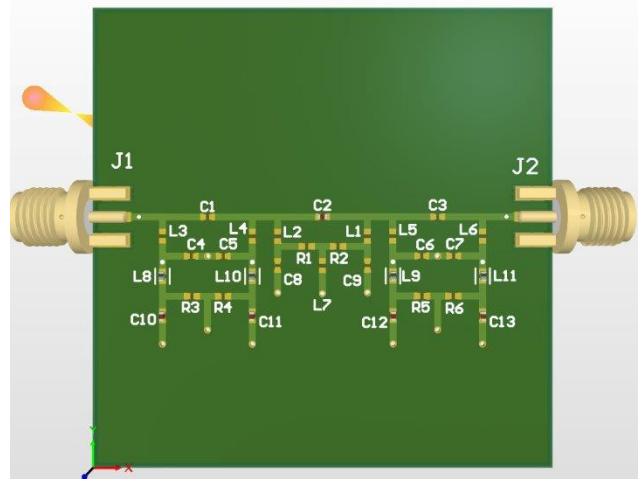


Figure 5: ADS Simulation of the Lossy Fifth Order, Third Order, Fifth Order Reflectionless High-pass Filter Cascade



The layout was then exported from Altium Designer back to ADS for an electromagnetic simulation. The electromagnetic simulation of the filter layout. Figure 7 shows the electromagnetic simulation results and the schematic simulation results plotted together for comparison. The electromagnetic simulation shows the cutoff frequency shifted down slightly and larger reflections in the passband.

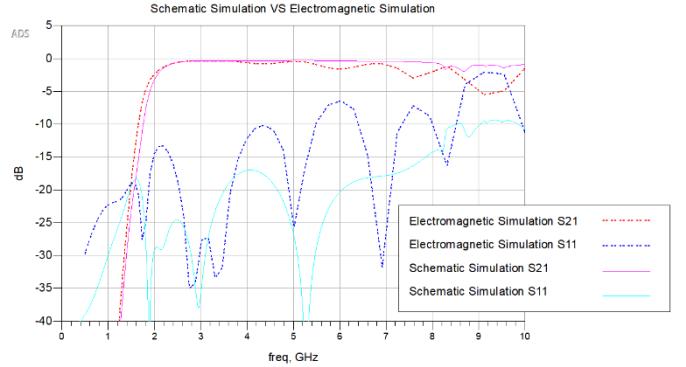


Figure 7: Schematic Simulation vs Electromagnetic Simulation

VIII. FILTER FABRICATION

The filter PCB was fabricated by JLCPCB, a PCB manufacturer in China. JLCPCB was selected because it was the only manufacturer that would fabricate a PCB with a Rogers substrate within our budget. The cost of JLCPCB mounting the SMD components exceeded the budget for this project, so the team opted to assemble the PCB using the reflow oven in the senior design lab at the University of North Texas. The team was aware that this DIY method may affect the filter's performance, but it was necessary to stay within budget.

IX. FILTER IMPLEMENTATION AND RESULTS

A. Prototype Testing

The prototypes were tested using a Rohde and Schwarz ZVB 20 vector network analyzer. The filter's s-parameters were collected at 3000 frequency points between 100 MHz to 10 GHz. Figure 8 is an image of the test setup. Figure 9 shows S21

and S11 collected from each prototype. Figure 10 shows the Prototype 1 measurements plotted with the most similar commercially available product, the Mini-Circuits KXHF-K23+. Our design has a steeper roll off than the competitor, but the competitor has a wider bandwidth and a lower peak reflection power.

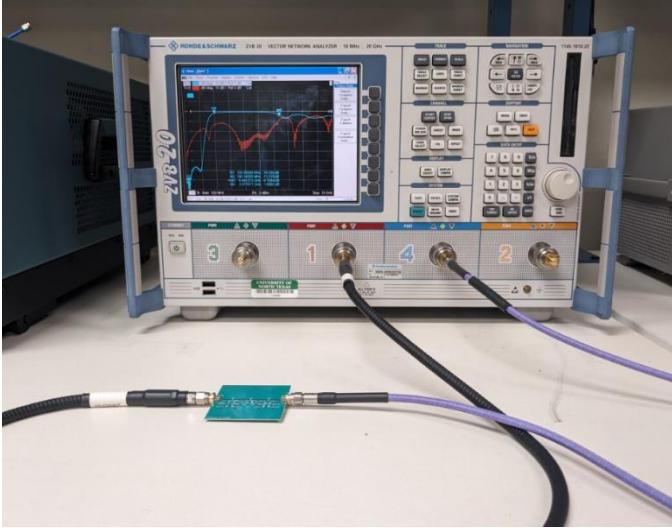


Figure 8: Prototype Test Setup

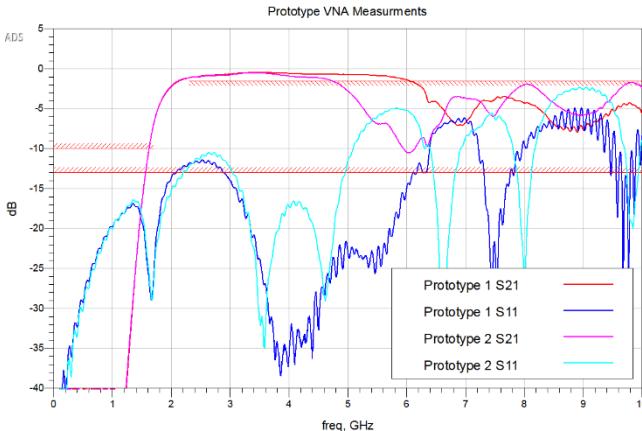


Figure 9: Prototype 1 vs Prototype 2 Test Results

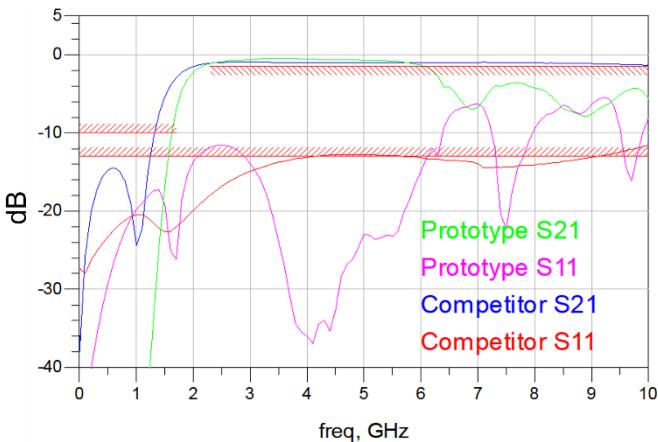


Figure 10: Prototype 1 vs Mini-Circuits Product

There is a significant difference in the measurements of the prototypes. This is likely due to the assembly method used. The components were mounted by our team rather than by the PCB manufacturer to keep the project within budget.

The measurements show that the prototype is a high-pass filter with suppressed reflection across the filter's operating range. The measurements also reveal that the prototype misses on some of the design specifications outlined in section III B. Specifically, neither prototype meets stopband insertion loss requirement or the -13dB S11/S22 requirement.

B. Comparing Measurements to Simulation

Figure 11 shows the measurements taken from Prototype 1 plotted with the electromagnetic simulation. The simulation does not perfectly predict the measurement results, but it did acutely show the cutoff frequency shifting down and increased reflections in the passband relative to the schematic simulation.

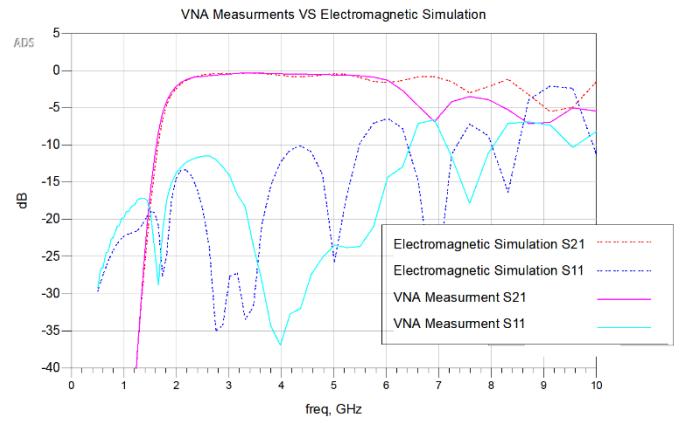


Figure 11: Prototype 1 VNA Measurements vs Electromagnetic Simulation

C. Issues to Correct

Although not all the design specifications were met, the results are promising. The prototype is a high-pass filter with a steep roll-off and suppressed reflections in the stopband. The design may be adjusted to scale the cutoff frequency up 100 MHz to meet the required insertion less specifications. The cause of the S11/S22 spike at 2.5 GHz will have to be identified and suppressed in the next version of this filter.

X. FUTURE IMPLEMENTATIONS

The next iterations of the RHPF would need to address the out-of-spec S11 and S22. Three variables to address include the PCB material, components, and microstrips. The lower Q-factors and self-resonant frequencies of lumped-element inductors are known to incur parasitic effects and can be resolved by transforming them into distributed-elements while the capacitors may remain as lumped-elements. The process of transformation to a distributed-element prototype is well known and can be adapted to reflectionless filters [2][13]. Richard's transformations show us the relationship between lumped

reactances and transmission-line stubs while Kuroda identities create transmission-line substitutions that make the reflectionless filter realizable [2][13]. Given we have target frequency parameters, the physical parameters must be made constructable and would have to start with the selection of a substrate thickness, dielectric constant ϵ_r , and strip width to limit unwanted impedance [2][14]. The constructability would also be guided by the limits of the fabricator. The significantly lower cost of materials and fabrication would be a significant advantage for the distributed-element prototype [15].

XI. TIMELINE

Reference Appendix B.

XII. TEAM WORK DISTRIBUTION

Research	All
Designs	All
Simulations	Robert, Olasubomi
CAD work	Eli
PCB assembly	Robert, Eli
Testing	All

XIII. CONCLUSION

The project identifies an industry need for increased accuracy in the load-pull measurements of DUTs to meet the stringent expectations of customers. The opportunity to increase accuracy was identified in absorbing the signal reflections caused by elements in the load-pull setup that negatively impact the characterization of DUTs. A novel high-pass filter that absorbs these reflections was designed for implementation into the setup. The simulated filter garnered promising results however the prototype did not perform to our specifications. A promising path to improvement lies in transforming our design into distributed elements that provide performance and economic advantages.

ACKNOWLEDGMENT

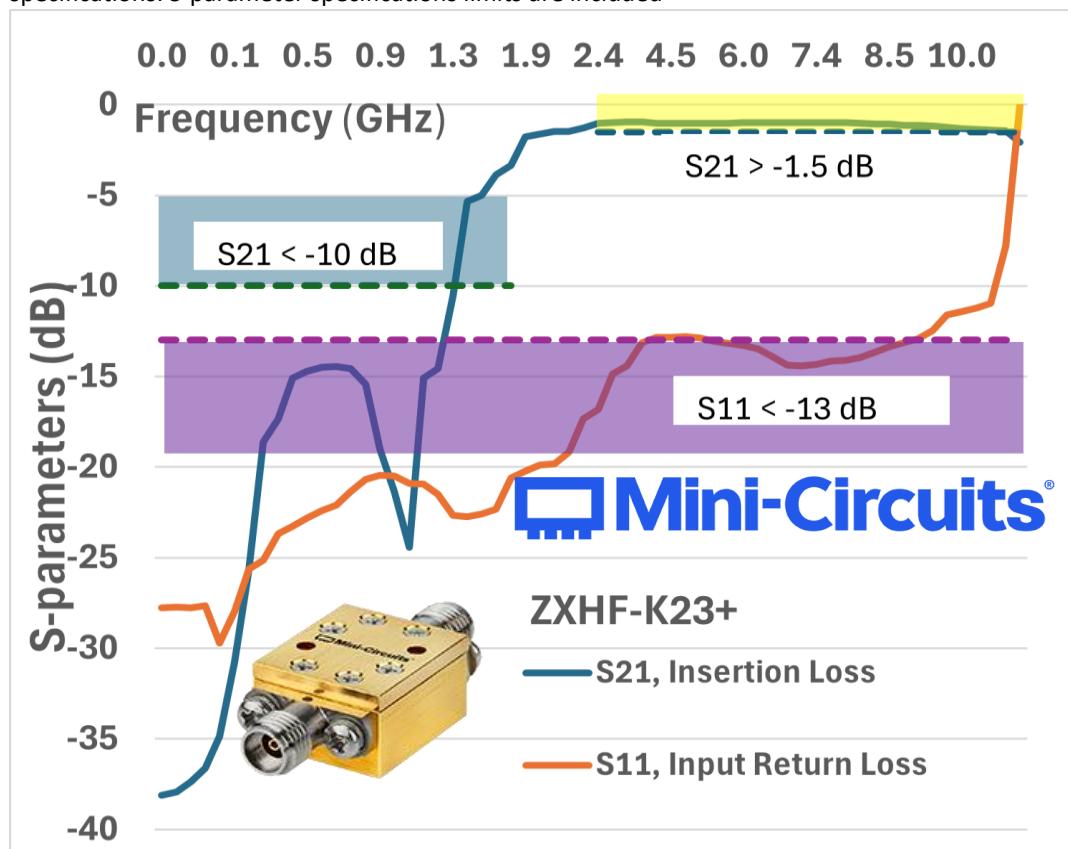
We would like to express our gratitude to 1) our advisor, Dr. Hung Luyen, for his guidance, professionalism, and use of his lab equipment, 2) Son Vu for his technical guidance, 3) Dr. Shengli Fu for his encouragement, and 4) the UNT Department of Electrical Engineering administrative staff for the behind-the-scenes work.

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APPENDIX

Appendix A: Competitor Reflectionless Filter vs. project specifications. S-parameter specifications limits are included



Appendix B: Project Timeline

Activities	2024			
	Jan-March	April-June	July-Sept	Oct-Nov
Research	a, b			
Proposal		c		
Simulation	d	d	e, f	
PCB Design			g	
PCB Fab			h	
PCB Testing				
Report, Poster, Presentation				

a. Project selected
b. Introductory research
c. Proposal final submission
d. Designs generated
e. Champion design selected
f. Materials finalized
g. PCB CAD model finalized
h. PCB fabrication ordered