Keysight RF Microwave Lab Courseware

RF Microwave Circuit Design, Simulation and Measurement Courseware, 5G NR n3

Lab 2: Filters (Solution)

Answer Sheet

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Edition

Edition 3, May 2023

Printed in:

Printed in Malaysia

Published by:

Keysight Technologies
Bayan Lepas Free Industrial Zone, 11900
Penang, Malaysia

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Table of Contents

Objective

In this lab, you will learn about RF and microwave filters including:

1. Ideal filter response versus real world
2. Common filter technologies used in industry (close-up and In-production assembly)
3. Filter companies and types of filters offered
4. Filter specifications

After this introductory information about filters, you will use a design specification as you design, synthesize, simulate, build and verify performance:

5. The Engineering Challenge – Decision Tree
6. Steps to design a custom filter (168.5 MHz lumped element filter)
    a. Determine specifications from system requirement
    b. Synthesize (Genesys Synthesis)
    c. Simulate (ADS/Momentum and EMpro)
    d. Prototype / Tune (X-MWblock on Prototype Station)
    e. Measure (FieldFox)
    f. Compare synthesis, simulation, and measurements to specification

Pre-Lab Setup Instructions

1. Prepare the required items as listed in “**Equipment Required**” and “**Accessories Required**” below.
2. Ensure the required software has been downloaded according to the “Software Required” list and install them on your Windows PC.
3. If you are using this lab as a print out, please copy the following files that are used in this lab to your computer:
   - **Lab2GENESYSworkspace.wsg**
   - **Lab2workspace_wrk.7zads**
4. The compressed **.7zads** folder should be de-compressed using **File > Unarchive…** from the ADS Main window to the root of the C:\ drive on your computer:
   - **Lab2workspace_wrk.7zads**

Equipment Required

1. A PC running Windows with internet access
2. Keysight FieldFox with Network Analyzer (NA) with options 210 and 211, 18 GHz or higher frequency. A bench NA with similar specifications may be substituted.

Accessories Required

1. X-Microwave Prototyping Plate, Screws, 1/16-inch Allen Wrench
2. Two X-MWprobe SMA connectors
3. X-MWblock filters
   a. LTCC Band Pass Filter, BFCN-1860+, XM-A6Y2-0204D, PCB #0029
   b. BAW Filter Centered at 1842.5GHz, TQQ0303, XM-B1F3-0404D, PCB #0473
   c. SAW Filter Centered at 168.5 MHz, 856512, XM-A3V3-0404D, PCB #0412
   d. Lumped Low Pass 168.5 MHz + 45MHz, XM-B1F4-1204D, PCB #0976

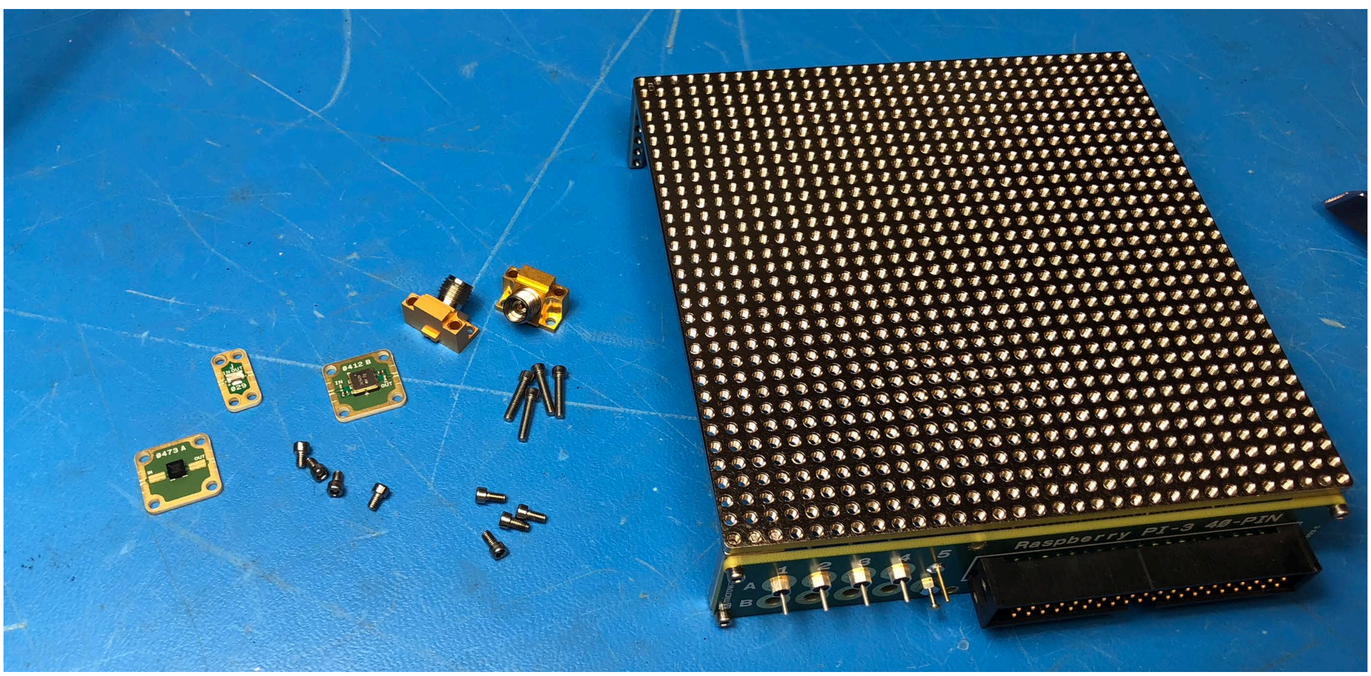


Figure 1. Accessories Required

Recommended Tools

1. 1/16-inch US Allen wrench
2. Fine tweezers
3. Straight pick
4. Sticky “jewel picker” stick

Software Required

1. Keysight PathWave GENESYS
2. Keysight PathWave ADS with Momentum
3. Keysight PathWave EMPro
4. Keysight FieldFox Data Link
5. Keysight PathWave BenchVue (optional)

Pre-study reading and viewing

1. Introduction to Genesys:
   https://www.keysight.com/en/pc-1297125/genesys-rf-and-microwave-design-software?nid=-34275.0.00&cc=US&lc=eng
2. Filter Synthesis (Genesys Synthesis):
   https://youtu.be/6sWroyFNIS8
3. Linear Simulation in Genesys:
   https://www.youtube.com/watch?v=DqNlMTSPQjA
4. Optimizing Filter Performance Using Integrated 3D EM Simulation:
   https://youtu.be/Z3dhIf1ruvc
5. X-MWSYSTEM Getting Started Documentation:
   https://www.xmicrowave.com/x-mwsystem/documentation/

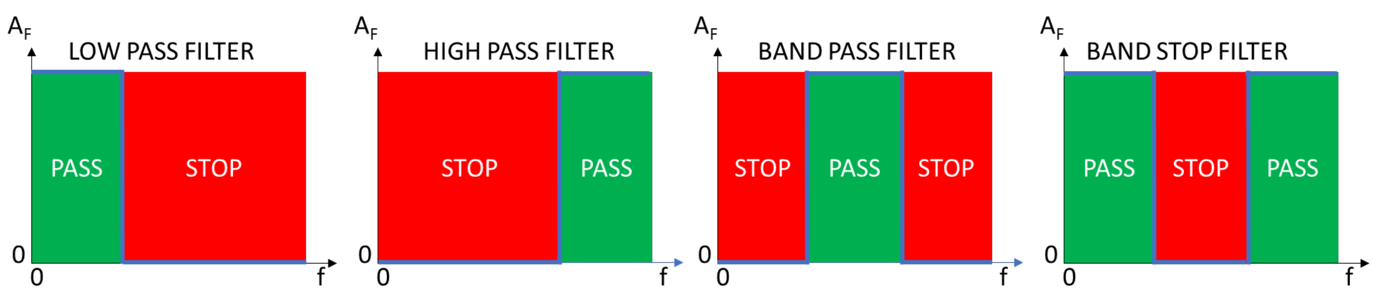
1 Background

RF and microwave filters are one of the most common building blocks of signal processing systems. They pass desired signals in a range of frequencies known as a passband, and they reject unwanted signals outside of the passband.

The four most common filter types are as follows.

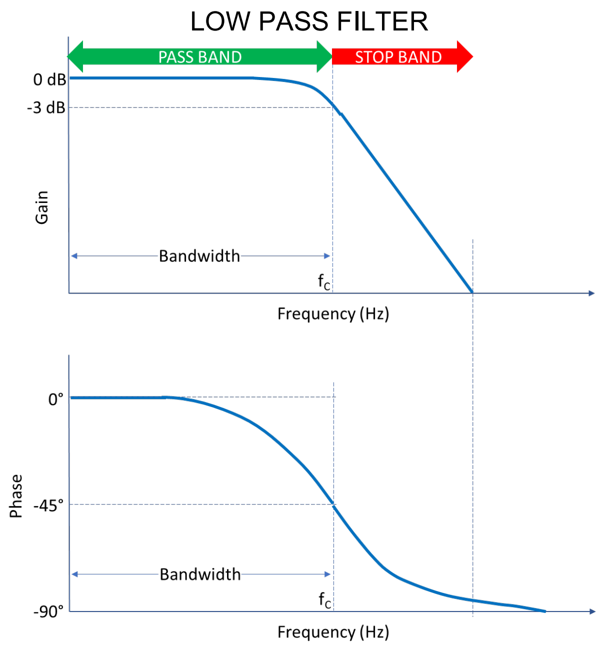
Filter Type	Description
Low Pass Filter	Passes low frequencies and rejects high frequencies. It is most often described using its 3-dB corner or cutoff frequency. The insertion loss increases dramatically above the cutoff frequency.
High Pass Filter	Passes high frequencies and rejects low frequencies. It is most often described using its 3-dB corner or cutoff frequency. The insertion loss increases dramatically below the cutoff frequency.
Band Pass Filter	Passes frequencies within a defined band and rejects lower and higher frequencies. It is most often described using a center frequency and 3 dB bandwidth of the pass band. The insertion loss (rejection) increases dramatically above and below the 3-dB bandwidth.
Band Stop Filter (Notch Filter)	Blocking a single frequency or band of frequencies, often used to reject one or more interfering tones. It is most often described using a center frequency and 3-dB bandwidth of the reject band. The insertion loss (rejection) decreases dramatically above and below the 3-dB bandwidth.

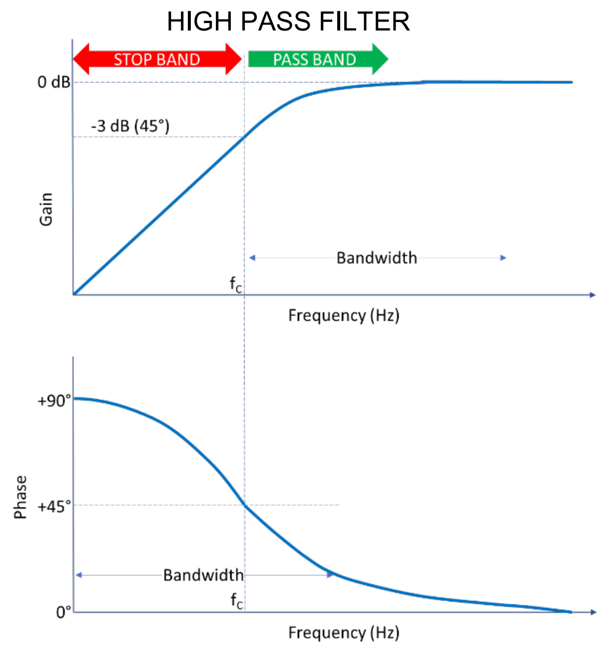
Here are ideal response plots of each filter type:

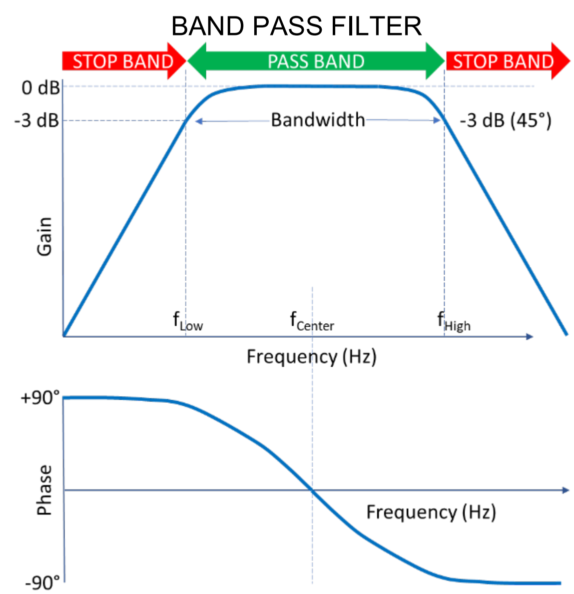


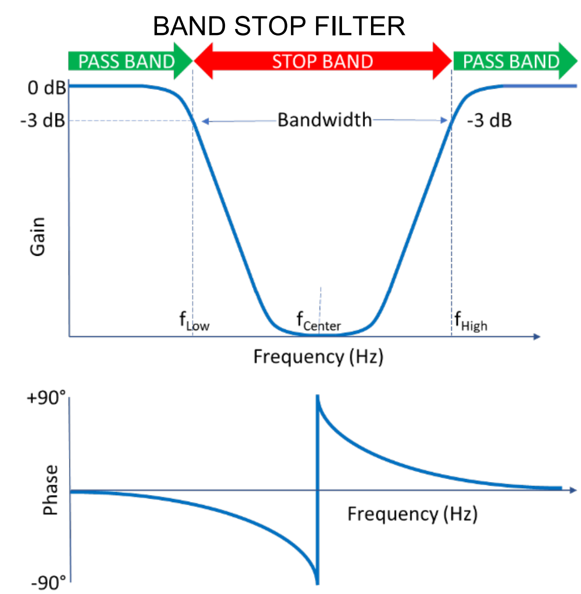
More realistic and detailed response plots of simple first-order mathematical implementations are shown next.

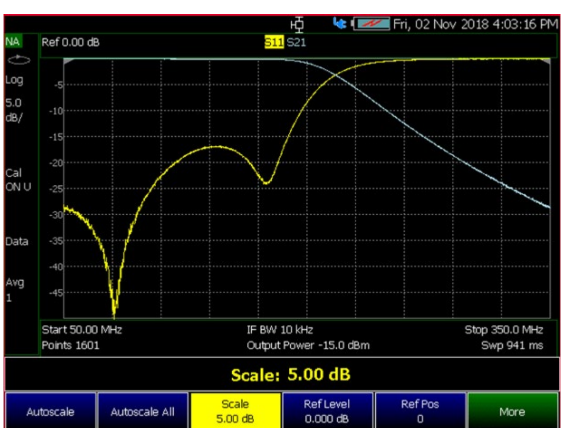
Of course, there is no such thing as an ideal filter that obeys its mathematical design exactly and pass and stop band responses vary. The real-world responses of low pass and band pass filters obtained from network analyzer screenshots are shown after the mathematical designs. These two screenshots show Gain (in blue) and Input Return Loss (in yellow). You will learn more about Return Loss and these measurements in this lab.

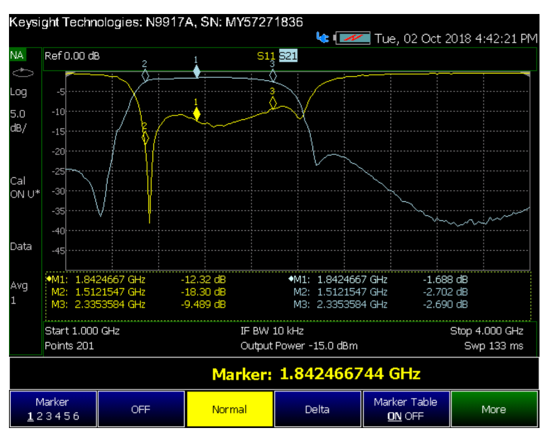

LOW PASS FILTER
PASS BAND
STOP BAND
0 dB
-3 dB
Gain
Bandwidth
fc
Frequency (Hz)
0°
-45°
-90°
Phase
Bandwidth
fc
Frequency (Hz)


HIGH PASS FILTER
STOP BAND
PASS BAND
0 dB
-3 dB (45°)
Gain
Bandwidth
fc
Frequency (Hz)
+90°
+45°
0°
Phase
Bandwidth
fc
Frequency (Hz)


BAND PASS FILTER
STOP BAND
PASS BAND
STOP BAND
0 dB
-3 dB
Bandwidth
-3 dB (45°)
Gain
fLow
fCenter
fHigh
Frequency (Hz)
+90°
Phase
Frequency (Hz)
-90°


BAND STOP FILTER
PASS BAND
STOP BAND
PASS BAND
0 dB
-3 dB
Bandwidth
-3 dB
Gain
fLow
fCenter
fHigh
Frequency (Hz)
+90°
Phase
Frequency (Hz)
-90°

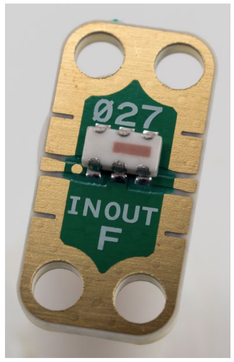
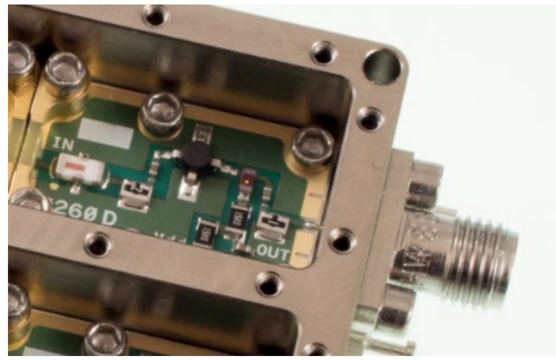
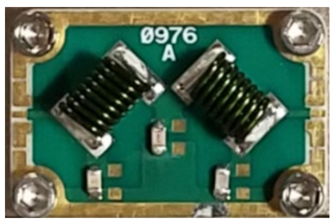
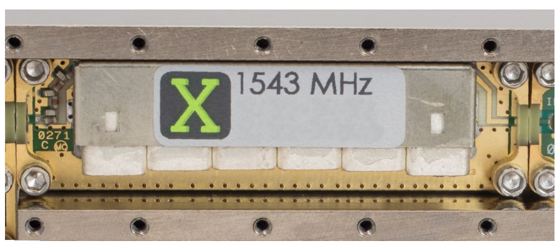
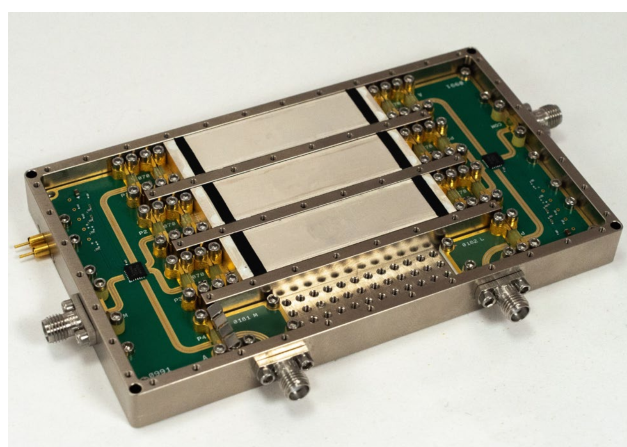

Fri, 02 Nov 2018 4:03:16 PM
Ref 0.00 dB
S11 S21
Start 50.00 MHz
Points 1601
IF BW 10 kHz
Output Power -15.0 dBm
Stop 350.0 MHz
Swp 941 ms
Scale: 5.00 dB
Autoscale
Autoscale All
Scale 5.00 dB
Ref Level 0.000 dB
Ref Pos 0
More


Keysight Technologies: N9917A, SN: MY57271836
Tue, 02 Oct 2018 4:42:21 PM
Ref 0.00 dB
S11 S21
Start 1.000 GHz
Points 201
IF BW 10 kHz
Output Power -15.0 dBm
Stop 4.000 GHz
Swp 133 ms
Marker: 1.842466744 GHz
Marker
OFF
Normal
Delta
Marker Table
More

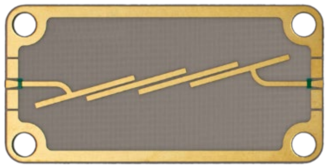
2 Filter Specifications

Specification (Unit)	Description
Passband (Hz)	The range of frequencies that pass through the filter with minimal attenuation or reflection.
Stopband (Hz)	The range of frequencies that are blocked by the filter typically with increased attenuation and reflection.
Insertion Loss (dB)	Amount of loss in the passband of the filter. This is often specified as rejection relative to the passband insertion loss.
High Side Rejection (dB)	Magnitude of attenuation in the stop band at frequencies on the high side of the passband.
Low Side Rejection(dB)	Magnitude of attenuation in the stop band at frequencies on the low side of the passband.
Passband Ripple (dB)	Peak-to-peak variation within the passband.
Shape Factor	A measure of the filter's selectivity. It is the ratio of a filter's 60-dB attenuation bandwidth to its 6-dB attenuation bandwidth.
Group Delay	The time it takes for signals to propagate through the filter, which may vary based on frequency.
Reoccurring Passband	Higher frequencies where a low pass or band pass filter fail to attenuate signals. This often occurs at a harmonic of the desired passband.

3 Common Filter Technologies (Physical Types and Attributes)

Technology	Close-Up Example	In-Production Assembly
Low Temperature Co-Fired Ceramic (LTCC) – 40 MHz to 12 GHz – Very small size – Minimal rejection – $2 to $6		
Lumped Element – 10 MHz to 12 GHz – Small size – High rejection – $50 to $500		
Ceramic – 100 MHz to 6 GHz – Moderate size – Moderate rejection – $50 to $400		
Cavity – 2 to 40 GHz – Large size – Very high rejection – $300 to $1000		

Planar

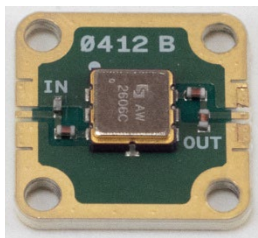


- 2 to 50 GHz
- Very small size
- High rejection
- $50 to $300

Tubular

- 10 MHz to 10 GHz
- Large size
- Very high rejection
- $300 to $600

SAW / BAW (Surface Acoustic Wave / Bulk Acoustic Wave)



- 100 MHz to 3 GHz
- Very small size
- Very high rejection
- $10 to $200

Suspended Substrate

- 2 to 50 GHz
- Medium size
- Very high rejection
- $200 to $800

Waveguide

- 2 to 100 GHz
- Large size
- Very high rejection
- $200 to $2000

Tunable

- 100 MHz to >10 GHz
- Very large size
- Very high rejection
- $1000 to $5000

4 Filter Companies

Exercise: Complete the table by researching the filter types in the vacant rows.

Instructor Answers embedded in table.

Company Info: **Name** **Website**	**LTCC**	**Lumped Element**	**Ceramic**	**Cavity**	**Planar**	**Tubular**	**SAW / BAW**	**Suspended Substrate**	**Waveguide**	**Tunable**
K&L Microwave klmicrowave.com	X	X	X	X	X	X	X	X	X	X
Lorch Microwave http://www.lorch.com/		X	X	X		X			X	X
Lark Engineering http://larkengineering.com			X	X				X		
Reactel https://reactel.com		X	X	X					X	
Mini-Circuits https://www.minicircuits.com	X	X	X	X	X	X				
Q Microwave http://qmicrowave.com		X	X							
DLI http://www.knowlescapacitors.com/Company.aspx#dielectric				X	X					
Marki Microwave https://www.markimicrowave.com/					X					
Qorvo https://www.qorvo.com/products/filters-duplexers/rf-filters							X			

5 The Engineer's Challenge

The engineering objective for most RF and microwave system designs is to design a system that meets all the specifications with reasonable margin and is manufacturable at the lowest cost within the allocated time. This requires swift development of clever solutions. You will soon discover that in microwave engineering every problem has many possible solutions. As you learn the tricks of the trade, master the tools, and gain experience you will get better and faster at achieving that clever design. You are probably asking yourself, "How do I start the design process?".

5.1 Single Mixer Converter Design Example

Objective: Design bandpass filters for the 5G band n3 downlink (1842.5 MHz center) to a first intermediate frequency (IF, 168.5 MHz center) using the receiver topology shown in Figure 2.

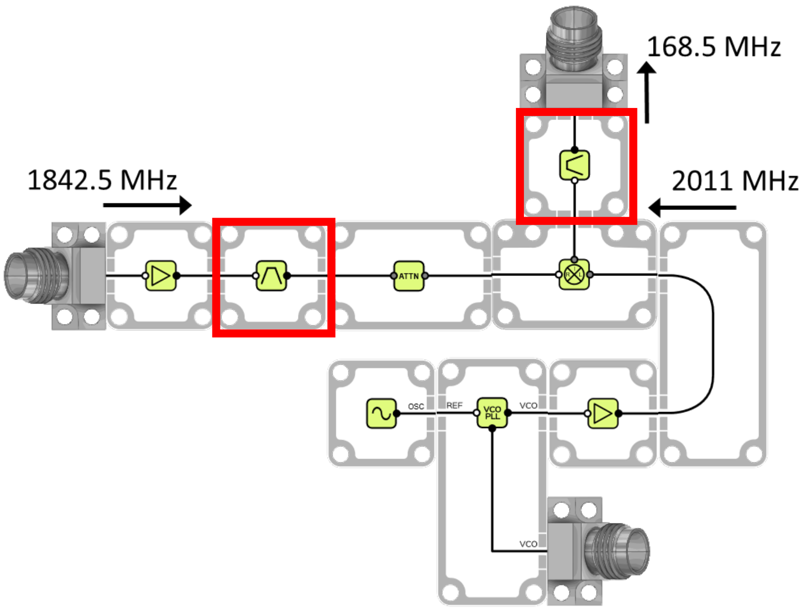


Figure 2. Single Mixer Converter Symbolic Block Diagram

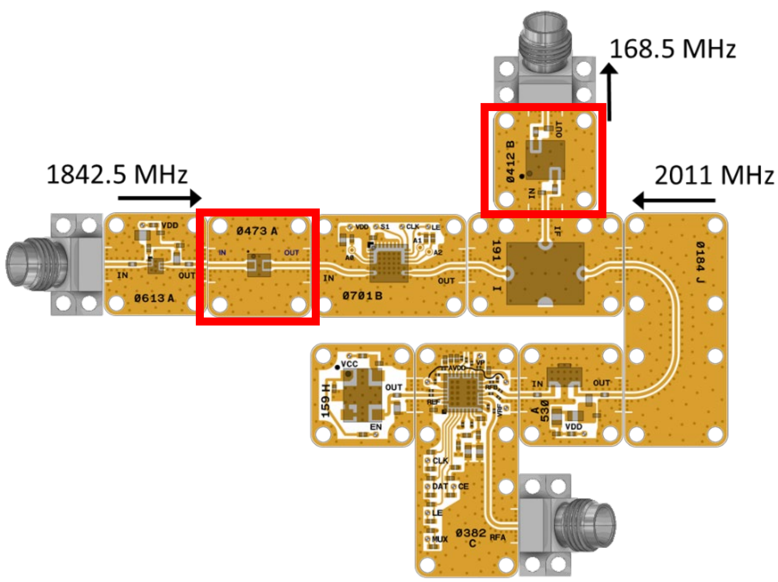


Figure 3. Single Mixer Converter Layout View

5.2 RF and IF Filter Design Specifications

Your design will be based on 5G specifications from this table.

Table 1. 5G Specifications

Band	Duplex mode	f (MHz)	Common name	Subset of band	Uplink [A 1] (MHz)	Downlink [A 2] (MHz)	Duplex spacing (MHz)	Channel bandwidths [2] (MHz)
n1	FDD	2100	IMT		1920 – 1980	2110 – 2170	190	5, 10, 15, 20
n2	FDD	1900	PCS (Blocks A–F)	n25	1850 – 1910	1930 – 1990	80	5, 10, 15, 20
n3	FDD	1800	DCS		1710 – 1785	1805 – 1880	95	5, 10, 15, 20, 25, 30

Source: 3GPP TS 38.101-1 Release 15 (2017-12)

Table 2. 5G Receiver Requirement

Parameter	Filter Requirement
RF Bandpass Specification	
Center Frequency (CF)	1842.5 MHz
Insertion Loss at CF	< 2 dB
Passband Flatness Re CF +/- 30 MHz	< 1 dB
Rejection < 1785 and > 1920 MHz	> 40 dB
IF Filter Specification	
Center Frequency (CF)	168.5 MHz
Insertion Loss at CF	< 10 dB
Passband Flatness Re CF +/- 12.5 MHz, sufficient to cover Ch BW to 25 MHz	< 1 dB
Rejection > 337 MHz (2 x 168.5 MHz)	> 30 dB

Note that the IF Filter is consistent with either a bandpass or lowpass design.

6 Filter Design

Objective: Evaluate off-the-shelf Filters for the Receiver design and design a Lumped Element Filter.

Filter Design Decision Tree

First, you will take the red path for two purchased filters, and then you will take the blue path for a fully designed filter, allowing you to compare synthesized, simulated and measured results to the design specification.

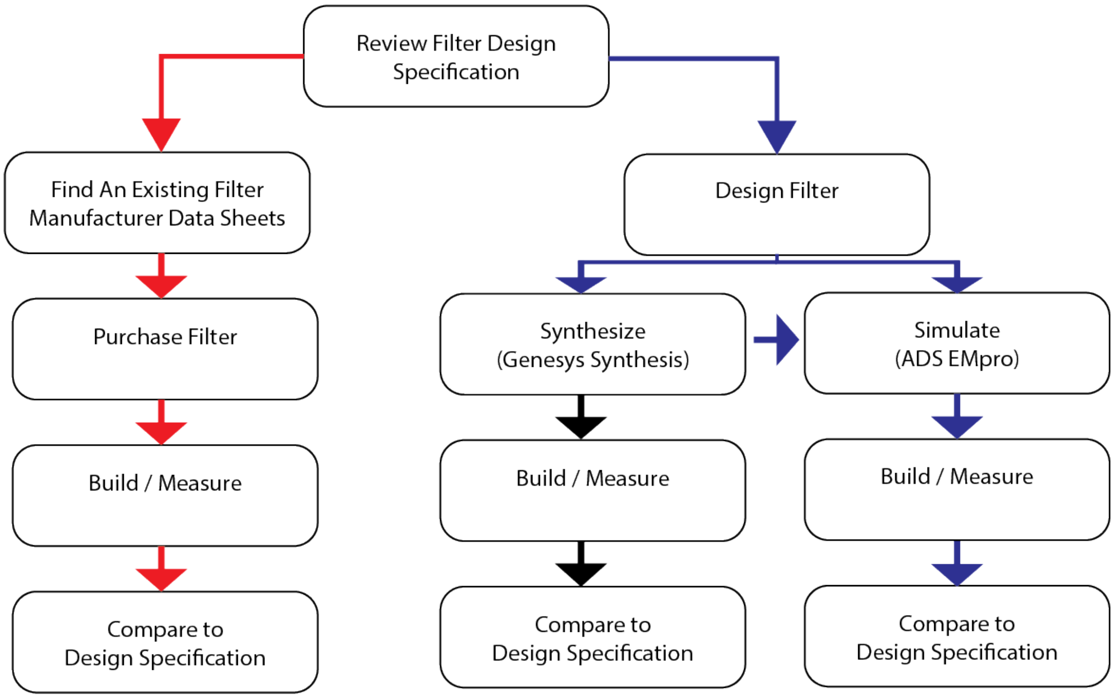


Figure 4. Filter Design Decision Tree

You will continue to refer to this diagram throughout the lab. The final solution must meet the design specification in all desired operating conditions. Therefore, it is important that your measured results match the synthesis and simulation results.

6.1 Evaluate Off-the-Shelf RF and IF Filter Choices

6.1.1 Evaluate an LTCC Filter for the RF Filter

In this lab exercise, you will learn how to analyze an off-the-shelf filter, selected by manufacturer data sheet. This is the red path on the left side of the decision tree. The RF bandpass filter specification requires 1842.5-GHz center frequency (5G Band n3 Downlink) with a need to reject out-of-band signals and to achieve a desired spectral purity.

First, you will evaluate an LTCC filter and then compare it against alternatives.

Start by downloading the data sheet for the **Mini-Circuits BFCN-1860+**

– Website: https://www.minicircuits.com/WebStore/dashboard.html?model=BFCN-1860%2B

– Datasheet: https://www.minicircuits.com/pdfs/BFCN-1860+.pdf

Review the data sheet specifications against the requirements. Does the filter satisfy the requirements?

Procedure to Measure the Filter Performance

1. Turn on the FieldFox and open Network Analyzer (NA) mode.
2. Connect the cables and configure the network analyzer for a S11 measurement.
3. Calibrate (Full 2-Port Mechanical Cal) [Appendix A] for the Full Span of the FieldFox with 1601-point resolution. If recently calibrated, you may instead recall the calibrated FieldFox state **WIDE** created in Appendix A in the Transmission Line lab. A 201-point resolution will be sufficient.

NOTE Your start and stop frequency may vary depending on the NA used. The N9917A FieldFox will use 30 kHz to 18 GHz.

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4. Ensure that the filter is attached to the prototyping plate: **XM-A6Y2-0204D, PCB #0029**.
5. Attach two X-MWprobes (See instructions from Lab 1) and connect the cables.

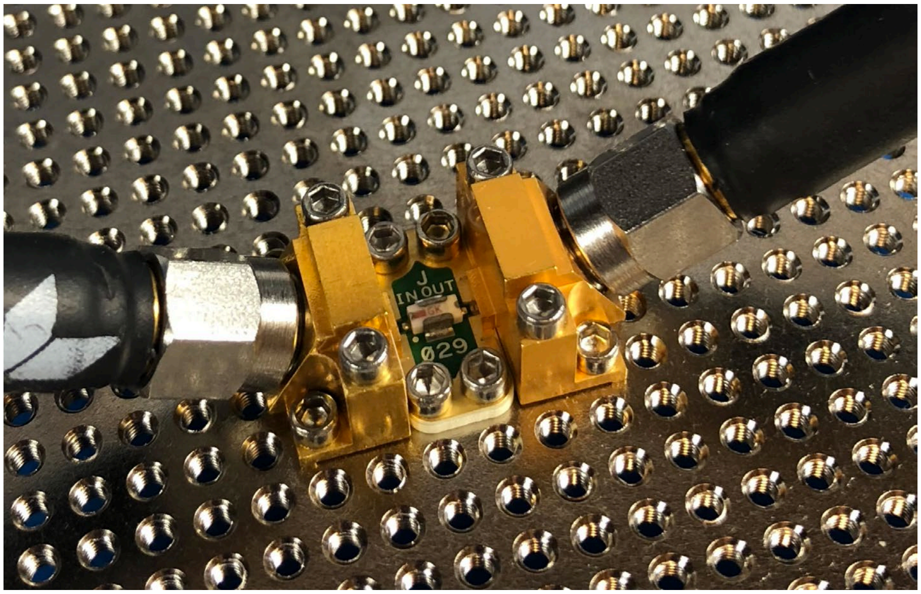


Figure 5. Mini-Circuits LTCC Filter with X-MWprobe Installed

6. You may find it useful to use Keysight BenchVue to record measurements. For more information, see the Appendix in the first lab.
7. Record numeric results on the table below.

8. Press **Frequency > Start** and set to **1 GHz** and **Stop** to **4 GHz** to zoom into the pass band and take the key measurements. You should either re-cal or recall the calibrated FieldFox state **1842.5** created in Appendix A in the Transmission Line lab.
9. Zoom in further in **Freq** and **Scale** if needed such that the passband fills at least 2 full grid units on the screen. Use the Markers to make the insertion loss measurements shown in the image below.
   a. Select **Marker > Select Marker 1 > Normal**.
   b. Use the dial to move it to the location on the plot.
   c. Note: It may be helpful to view the markers in a table.
   d. Repeat for all your key measurements as shown in Results.
10. Record results on the table below. Insertion Loss is obtained from S21.

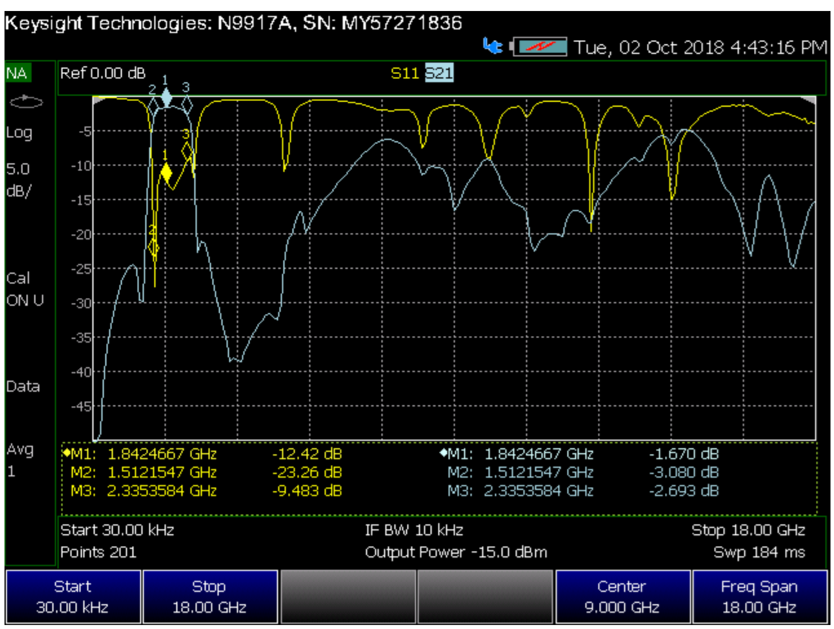
Measurement Results

Instructor Answer:

Table 3. LTCC Filter Results

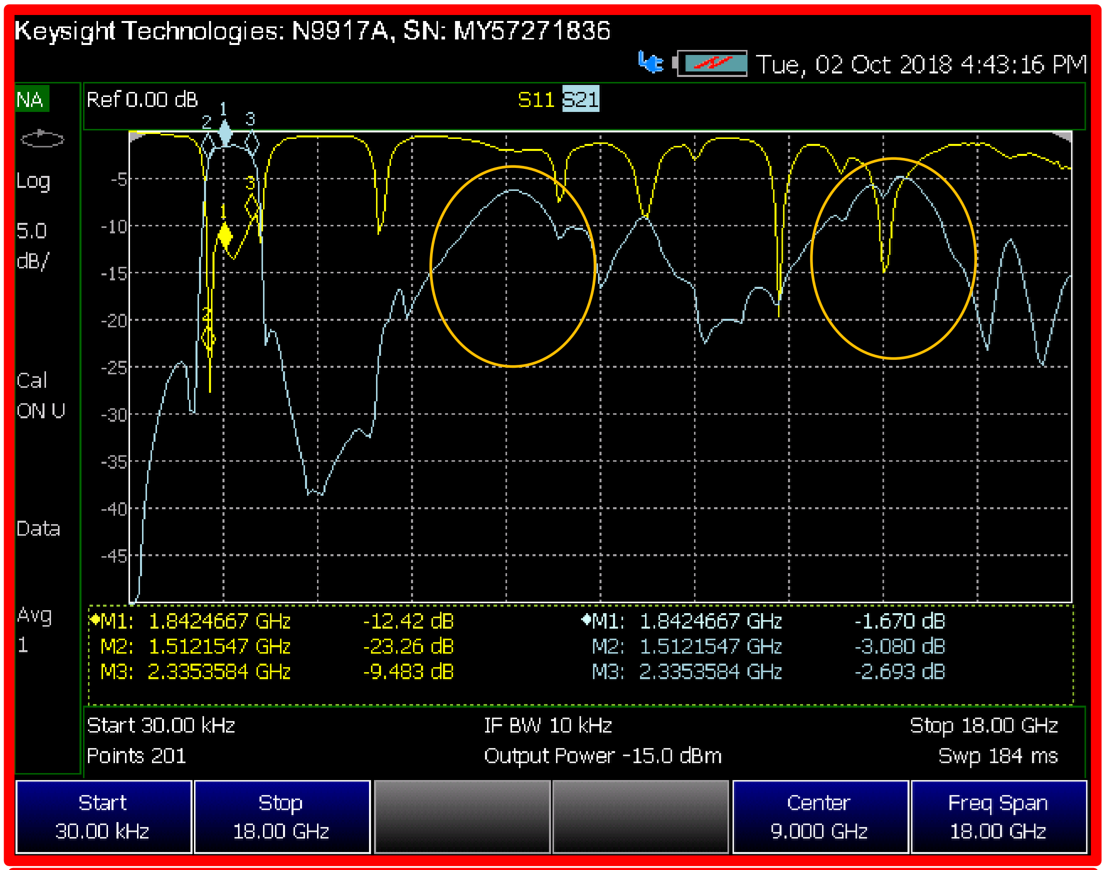
Band Pass Filter	Center Frequency CF	Insertion Loss at CF	Add Loss at 1812.5 MHz re CF	Add Loss at 1872.5 MHz re CF	Rejection at 1785 MHz	Rejection at 1920 MHz
Requirement	1842.5 MHz	< 2 dB	< 1 dB	< 1 dB	> 40 dB	> 40 dB
XM-A6Y2-0204D		1.688 dB	1 dB	1 dB	Same as Ins Loss	Same as Ins Loss

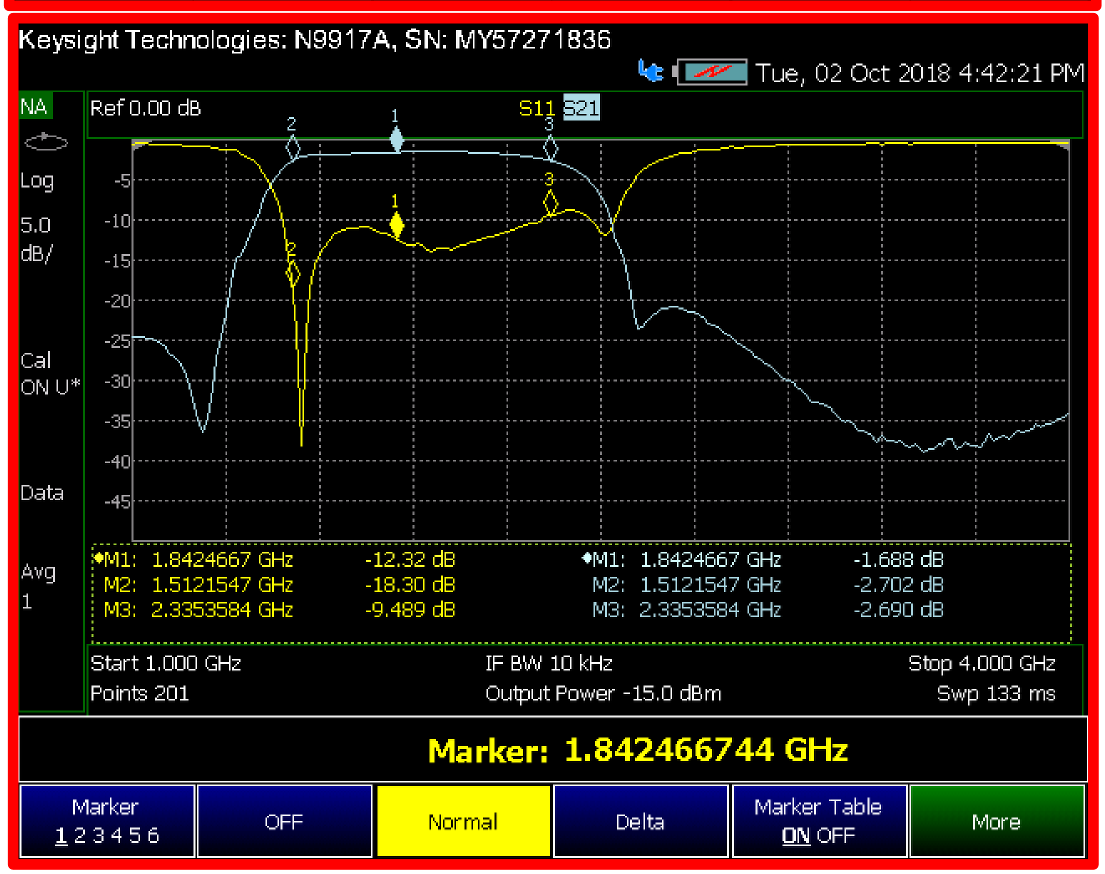
1. In what frequencies do you see a recurring passband? Hint: Less than 10 dB rejection.



Instructor Answer:
~7.2 GHz. (CF x 4)
~14.4 GHz (CF x 8)

Tan circles show recurring passbands


Keysight Technologies: N9917A, SN: MY57271836
Tue, 02 Oct 2018 4:43:16 PM
NA
Ref 0.00 dB
S11 S21
Log
5.0
dB/
Cal
ON U
Data
Avg
1
M1: 1.8424667 GHz -12.42 dB
M2: 1.5121547 GHz -23.26 dB
M3: 2.3353584 GHz -9.483 dB
M1: 1.8424667 GHz -1.670 dB
M2: 1.5121547 GHz -3.080 dB
M3: 2.3353584 GHz -2.693 dB
Start 30.00 kHz
Points 201
IF BW 10 kHz
Output Power -15.0 dBm
Stop 18.00 GHz
Swp 184 ms
Start 30.00 kHz
Stop 18.00 GHz
Center 9.000 GHz
Freq Span 18.00 GHz


Keysight Technologies: N9917A, SN: MY57271836
Tue, 02 Oct 2018 4:42:21 PM
NA
Ref 0.00 dB
S11 S21
Log
5.0
dB/
Cal
ON U*
Data
Avg
1
M1: 1.8424667 GHz -12.32 dB
M2: 1.5121547 GHz -18.30 dB
M3: 2.3353584 GHz -9.489 dB
M1: 1.8424667 GHz -1.688 dB
M2: 1.5121547 GHz -2.702 dB
M3: 2.3353584 GHz -2.690 dB
Start 1.000 GHz
Points 201
IF BW 10 kHz
Output Power -15.0 dBm
Stop 4.000 GHz
Swp 133 ms
Marker: 1.842466744 GHz
Marker 1 2 3 4 5 6
OFF
Normal
Delta
Marker Table ON OFF
More

2. Would you select this this filter to provide 40 dB rejection below 1785 and above 1920 MHz?

   Instructor Answer:

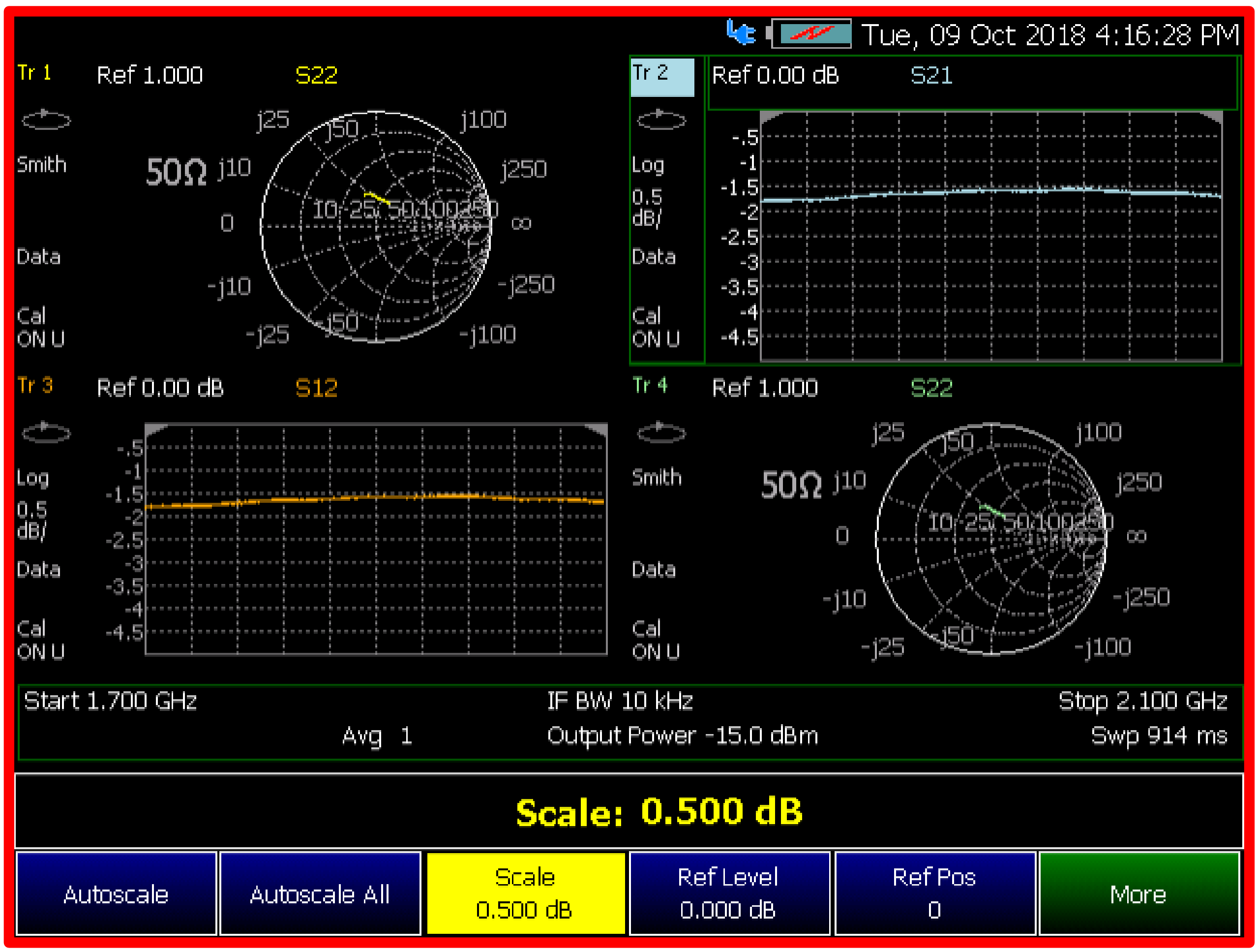
   No. Since the passband extends to the required frequencies of rejection and the filter never actually achieves 40 dB rejection except below very low frequencies.

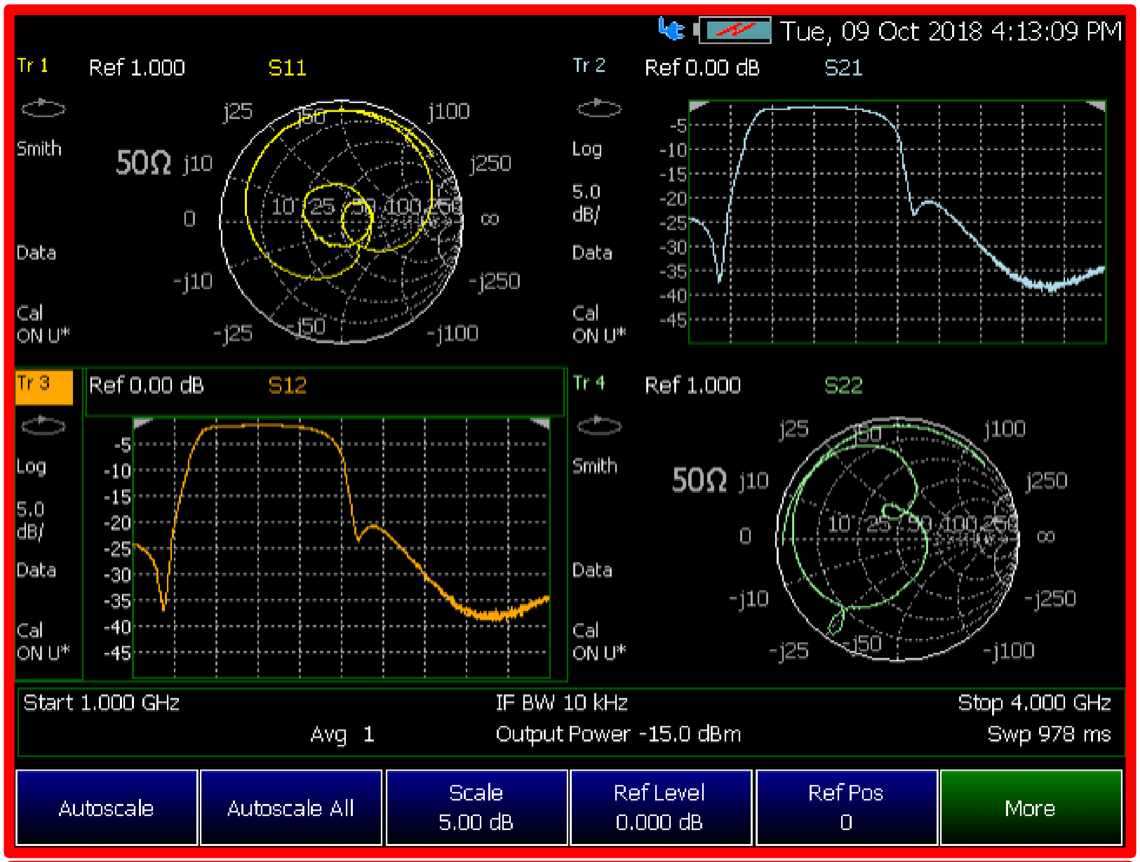
3. Discuss S11 and S22 and display their Smith charts. To configure a Smith chart, got to **Measure**, select the **Snn** and change the **Format** to **Smith**.

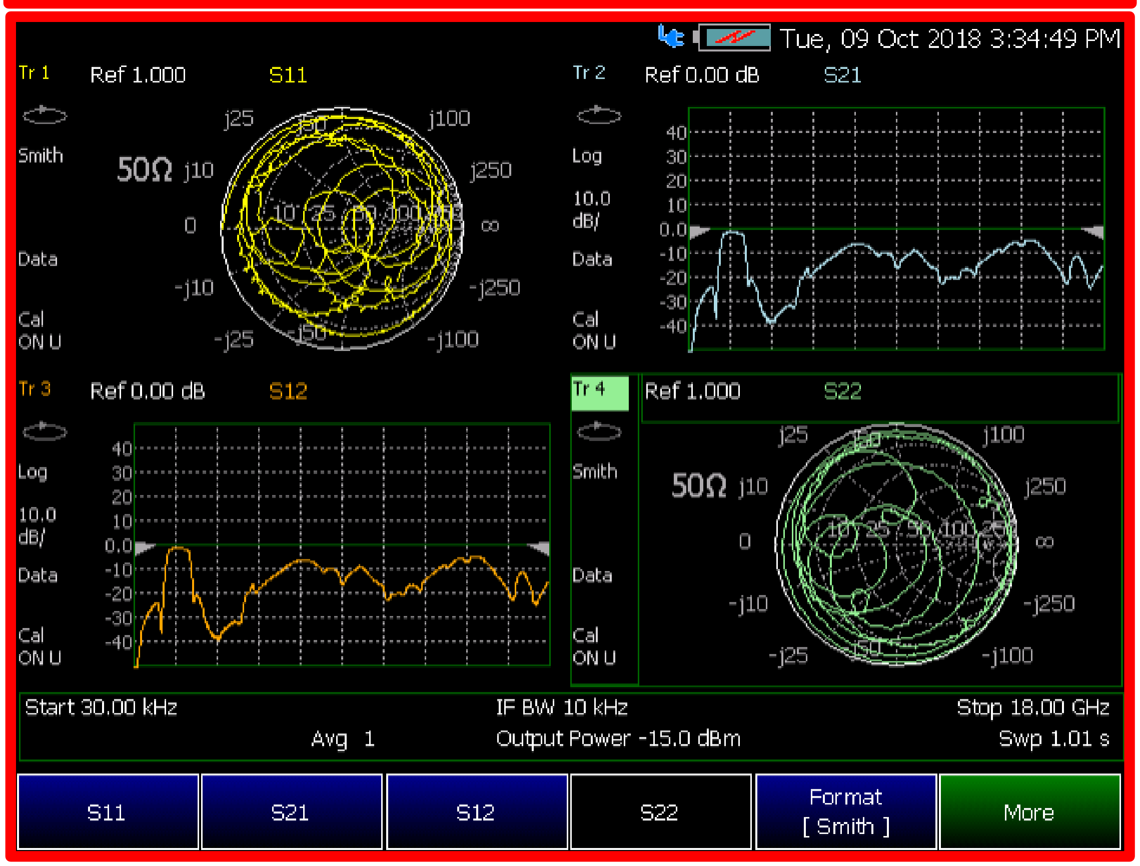
   Instructor Answer:

   The previous Log Mag chart shows low reflection (high return loss) in the pass band indicating that power is being transmitted, but high reflection (low return loss) in the stop band indicating that power is being reflected rather than transmitted. Very similar S11 and S22 indicate a bilateral device.

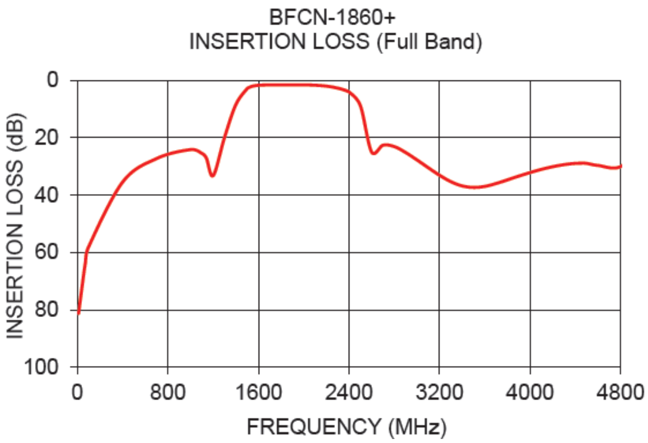
   The Smith chart is graduated in Impedance instead of Return Loss. Scrolling the frequency marker along the Smith charts shows that the exact 50-ohm match is outside the passband, not necessarily a problem since the magnitude of impedance near the passband may still be close enough to 50-ohms to provide sufficient match.

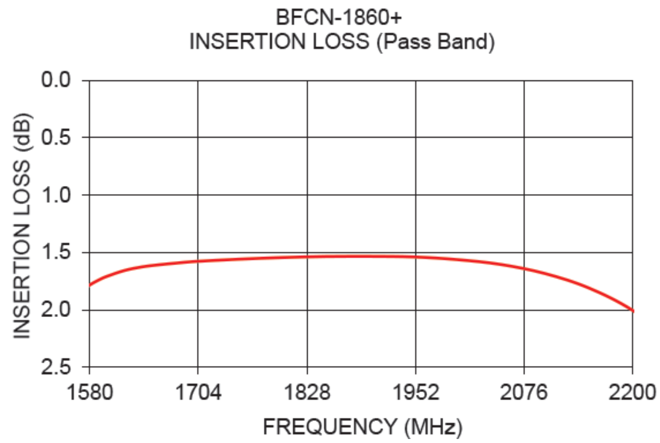



Tue, 09 Oct 2018 4:13:09 PM
Tr 1 Ref 1.000 S11
Smith
Data
Cal ON U*
Tr 2 Ref 0.00 dB S21
Log
5.0 dB/
Tr 3 Ref 0.00 dB S12
Tr 4 Ref 1.000 S22
Start 1.000 GHz
IF BW 10 kHz
Stop 4.000 GHz
Avg 1
Output Power -15.0 dBm
Swp 978 ms
Autoscale
Autoscale All
Scale 5.00 dB
Ref Level 0.000 dB
Ref Pos 0
More


Tue, 09 Oct 2018 3:34:49 PM
Tr 1 Ref 1.000 S11
Smith
Data
Cal ON U
Tr 2 Ref 0.00 dB S21
Log
10.0 dB/
Tr 3 Ref 0.00 dB S12
Tr 4 Ref 1.000 S22
Start 30.00 kHz
IF BW 10 kHz
Stop 18.00 GHz
Avg 1
Output Power -15.0 dBm
Swp 1.01 s
S11
S21
S12
S22
Format [Smith]
More

4. How does this part compare to its data sheet? (Review the data sheet for the **BFCN-1860+**)

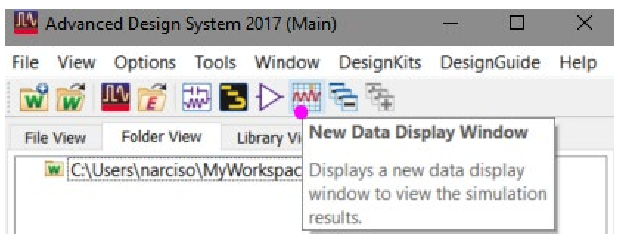




Instructor Answer:

While the values are similar, there is slightly greater insertion loss and seems to have a wider bandwidth. Also, the actual response is not symmetric as is shown in the data sheet page 2 figure showing typical frequency response.

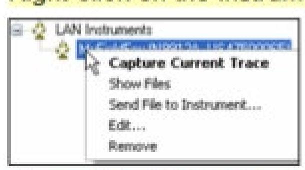
5. In a new ADS workspace, add a **New Data Display Window**.



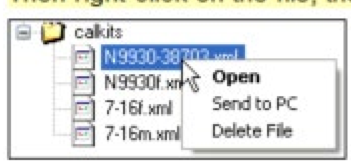
6. **Save** the measurement as an **S2P** file to the FieldFox **Internal Device** or **USB Device**, transfer to your computer using **Keysight FieldFox Data Lin**k (**Send to PC**) or a **USB** memory stick, then using the **Data File Tool…**, **Read data file into dataset** the S2P file from the FieldFox NA. In the screen capture below, the name of the dataset **LTCC_WIDE**. A sample LTCC.s2p is provided below.

Using **Keysight FieldFox Data Lin**k: **Save**, then **Show**, then **Send to PC**.

Right-click on the instrument, then **Show Files**.

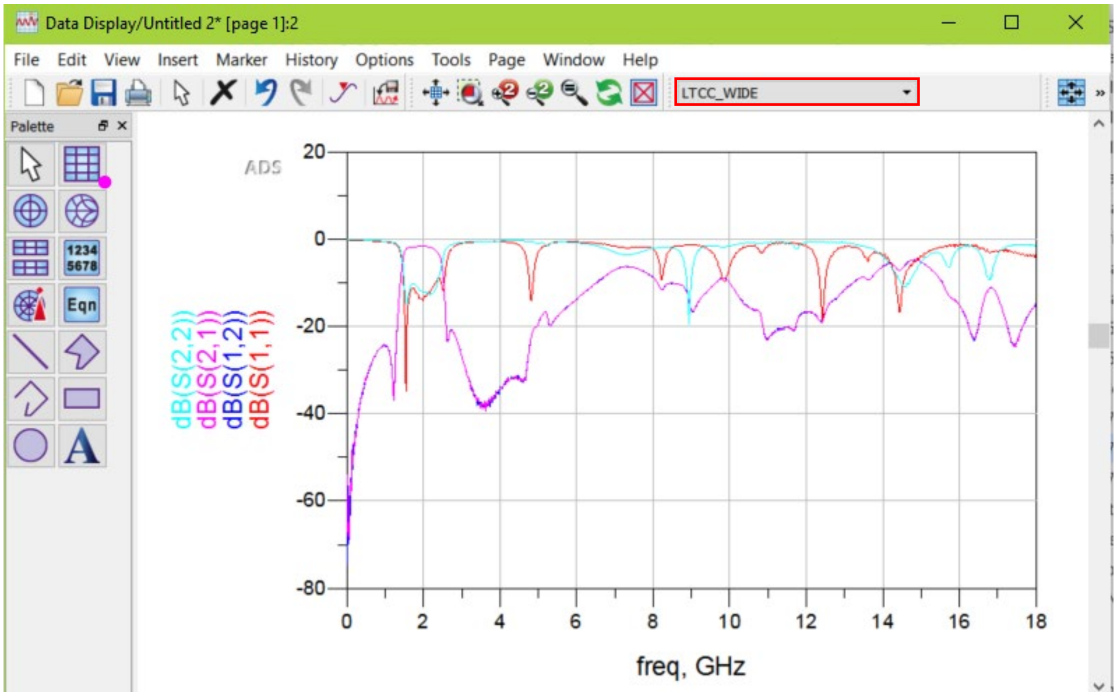


Then right-click on the file, then **Send to PC**.

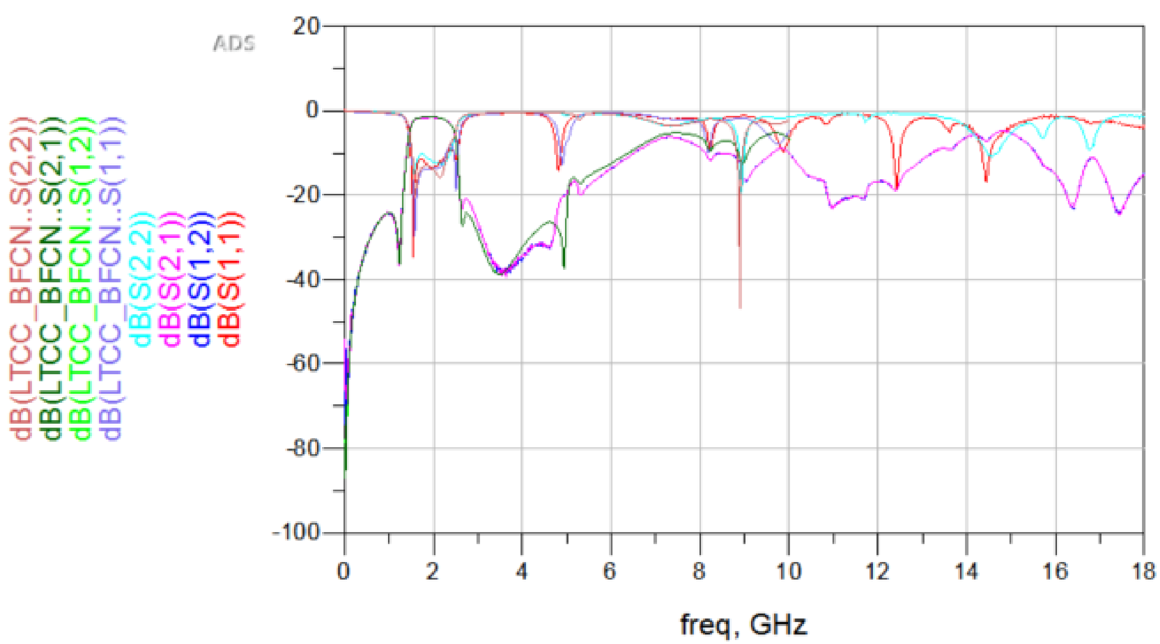


Note about SnP or "Touchstone" Files: These files contain small-signal S-parameters described by frequency-dependent linear network parameters for 1- to 10-port components.

7. Plot the measured data by clicking the Rectangular Plot icon and selecting S11, S12, S21, and S22 from the **LTCC_WIDE** dataset. You may want to review the method in the previous lab.



8. **Read data file into dataset** the S2P file from the manufacturer's website. In the screen capture below, the name of the dataset is **LTCC_BFCN**. If you prefer, the manufacturer's file: **BFCN-1860+_TB-824+Unit1_with_Port_Ext.s2p** is provided below.



9. Repeat with **Frequency > Start** and set to **1 GHz** and **Stop** to **4 GHz** using the calibrated FieldFox state **1842.5.**

6.1.2 Evaluate a BAW Filter for the RF Filter

Evaluate the BAW filter against the required RF Filter specification. Fill out the table below measured performance. Compare the results of the BAW filter to the LTCC.

Start by downloading the data sheets for the **Qorvo TQQ0303** BAW Filter:

- Website: https://www.qorvo.com/products/p/TQQ0303
- Data sheet: https://www.qorvo.com/products/d/da005775

Procedure to Measure the Filter Performance

1. Disconnect the SMA cables from the probe.
2. Press **Frequency > Start** and set to **30 KHz** and **Stop** to **18 GHz (Full Span)** and take the key measurements. You should either re-cal or recall the calibrated FieldFox state **WIDE** created in Appendix A in the Transmission Line lab.
3. Carefully remove each X-MWprobe and the RF BPF from the prototyping plate. If the filter is presently part of the 5G Receiver system, remove only X-MW anchors on top of it (leave the anchors in place and tight on the X-MWblocks on either side of the filter so that the Ground-Signal-Ground (GSG) jumpers are retained) and slowly slide it out, underneath and being careful not to damage the GSG jumpers.

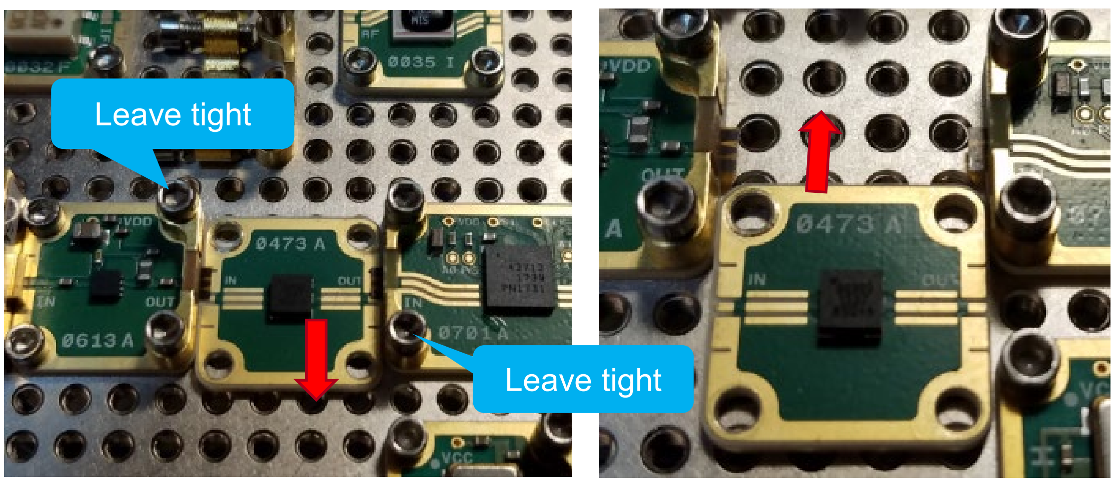
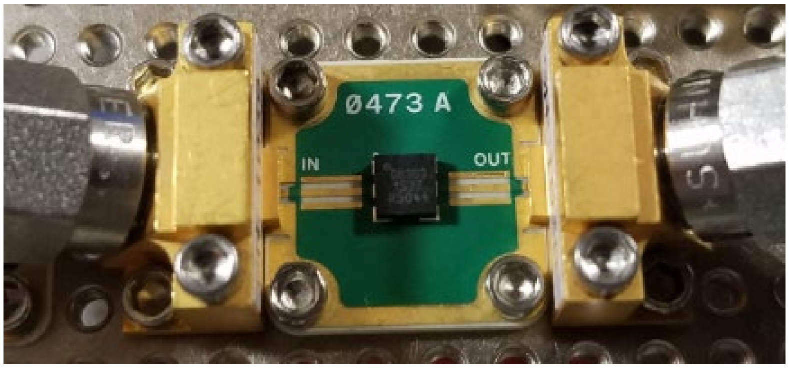


Figure 6. Removing the RF BPF X-MWblock

When you return and re-install the X-MWblock carefully slide it under the two GSG jumpers.

WARNING While this procedure to remove a passive X-MWblock from between two others may be used on a passive device, it should not be attempted on an active device that has either a bias or control block below it as the pogo pin may be damaged. Those X-MWblocks can be removed by first removing the anchors from adjacent block and then lifting the board straight up off the X-MWplate.

4. Ensure the BAW filter is attached to the prototyping plate and secured with 4 screws: **XM-B1F3-0404D, PCB #0473**. Re-attach the probes and connect the cables.



5. Measure using the same procedure as above.
6. Press **Frequency > Start** and set to **1 GHz** and **Stop** to **3 GHz** to zoom into the pass band and take the key measurements. You should re-cal or recall the calibrated FieldFox state **1842.5** created in Appendix A in the Transmission Line lab.
7. Record results on the table below and download and compare the measure versus the manufacturer's S-Parameters as in the previous task.

Measurement Results

Instructor Answer is embedded in the table below.

Table 4. BAW Filter Results

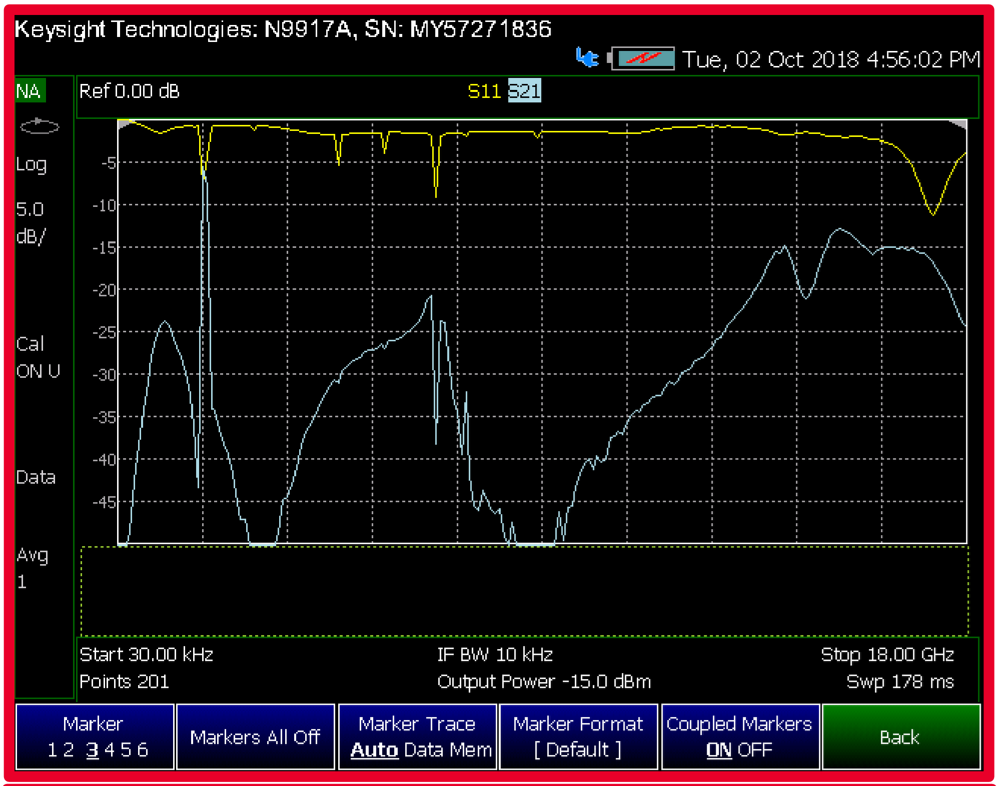
Band Pass Filter	Center Frequency CF	Insertion Loss at CF	Add Loss at 1812.5 MHz re CF	Add Loss at 1872.5 MHz re CF	Rejection at 1785 MHz	Rejection at 1920 MHz
Requirement	1842.5 MHz	< 2 dB	< 1 dB	< 1 dB	> 40 dB	> 40 dB
XM-B1F3-0204D		1.255 dB	< .9 dB	< .4 dB	> 40 dB but…	> 40 dB but…

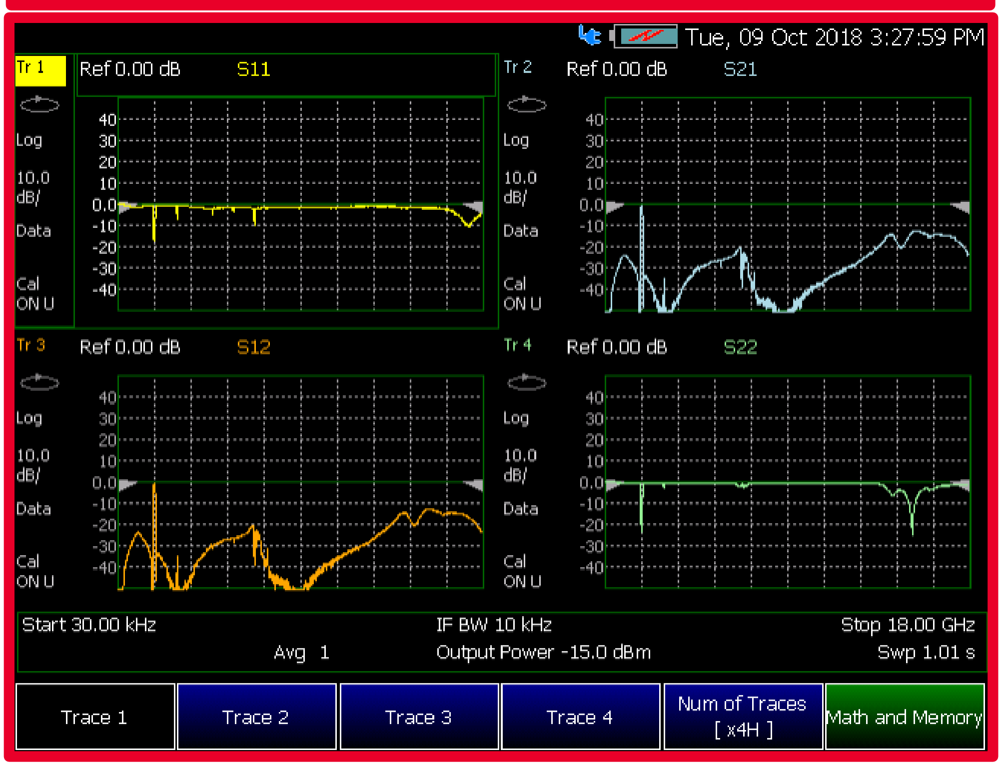
… rejection degrades substantially below 1700 and above 1920

1. What frequencies do you see a recurring passband?

   Instructor Answer:

   There are no recurring passbands.

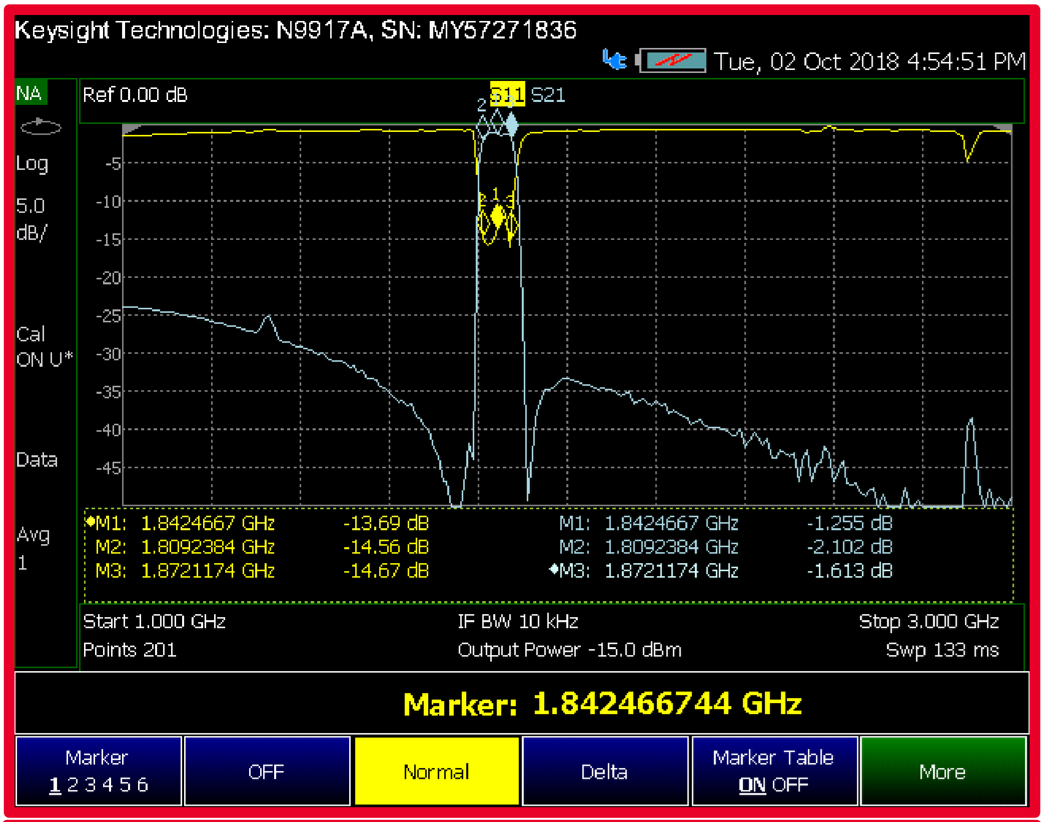


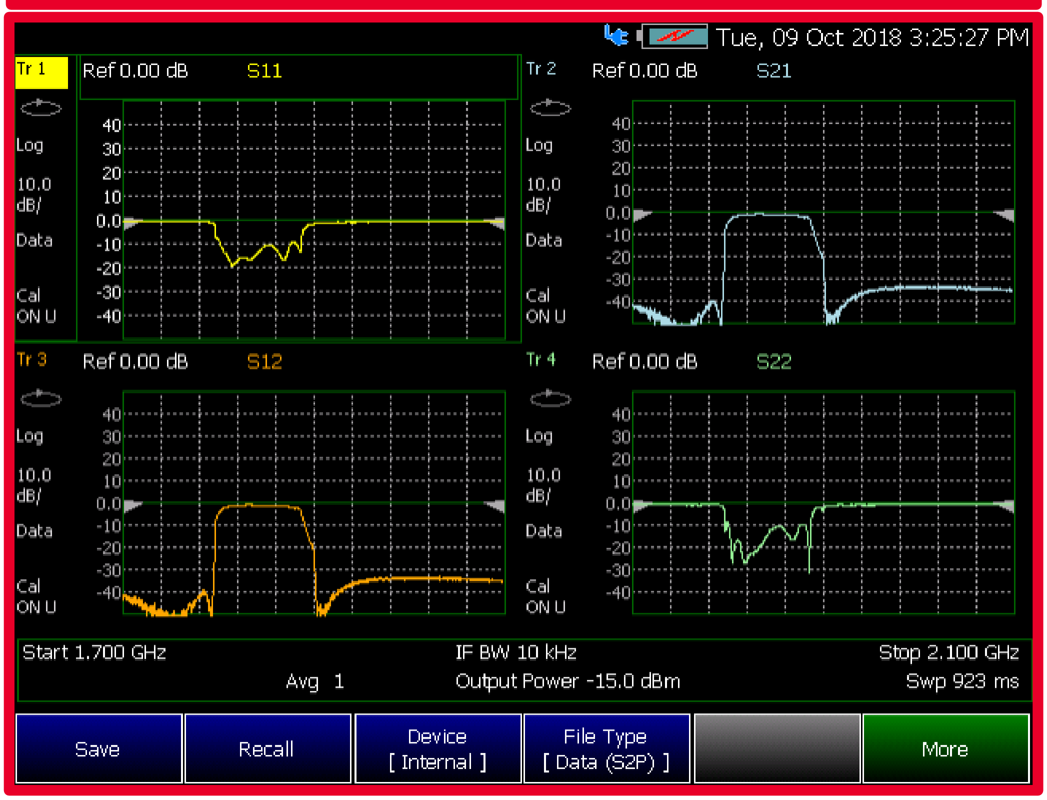


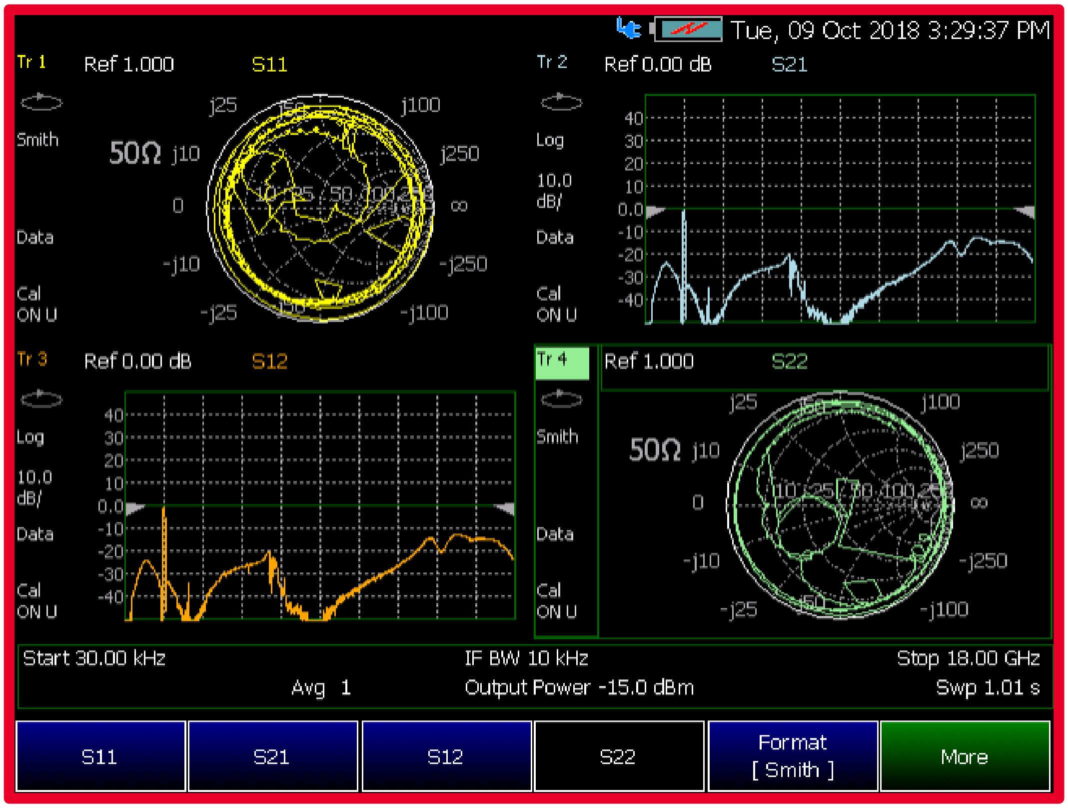
2. Would you select this this filter to provide 40 dB rejection below 1785 and above 1920 MHz?

Instructor Answer:

Maybe, provided the rest of the system can accommodate the “lobes” of degraded rejection below 1700 and from 1925 to 2400.


Keysight Technologies: N9917A, SN: MY57271836
Tue, 02 Oct 2018 4:54:51 PM
NA
Ref 0.00 dB
S11 S21
Log
5.0
dB/
Cal
ON U*
Data
Avg
1
M1: 1.8424667 GHz -13.69 dB
M2: 1.8092384 GHz -14.56 dB
M3: 1.8721174 GHz -14.67 dB
M1: 1.8424667 GHz -1.255 dB
M2: 1.8092384 GHz -2.102 dB
M3: 1.8721174 GHz -1.613 dB
Start 1.000 GHz
IF BW 10 kHz
Stop 3.000 GHz
Points 201
Output Power -15.0 dBm
Swp 133 ms
Marker: 1.842466744 GHz
Marker
1 2 3 4 5 6
OFF
Normal
Delta
Marker Table
ON OFF
More


Tue, 09 Oct 2018 3:25:27 PM
Tr 1
Ref 0.00 dB
S11
Tr 2
Ref 0.00 dB
S21
Tr 3
Ref 0.00 dB
S12
Tr 4
Ref 0.00 dB
S22
Log
10.0
dB/
Data
Cal
ON U
Start 1.700 GHz
IF BW 10 kHz
Stop 2.100 GHz
Avg 1
Output Power -15.0 dBm
Swp 923 ms
Save
Recall
Device
[Internal]
File Type
[Data (S2P)]
More

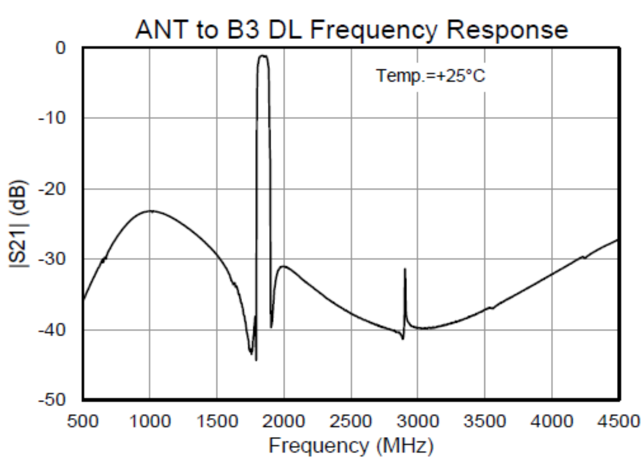


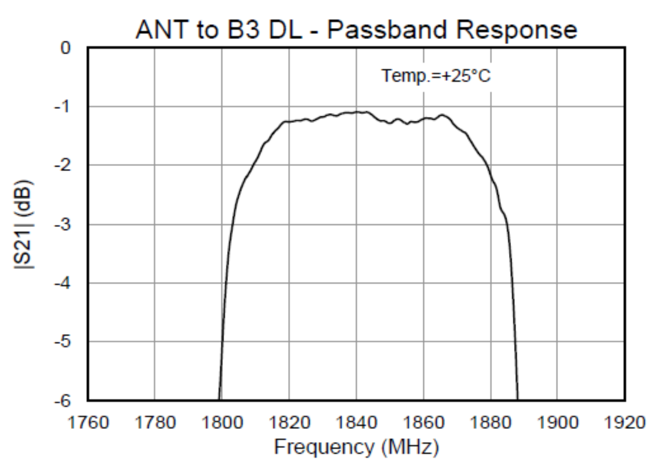
3. Discuss S11 and S22 and the Smith chart.

   Instructor Answer:

   Very similar S11 and S22. There is low reflection (high return loss) in the pass band indicating that power is being transmitted, but high reflection (low return loss) in the stop band indicating that power is being reflected rather than transmitted.

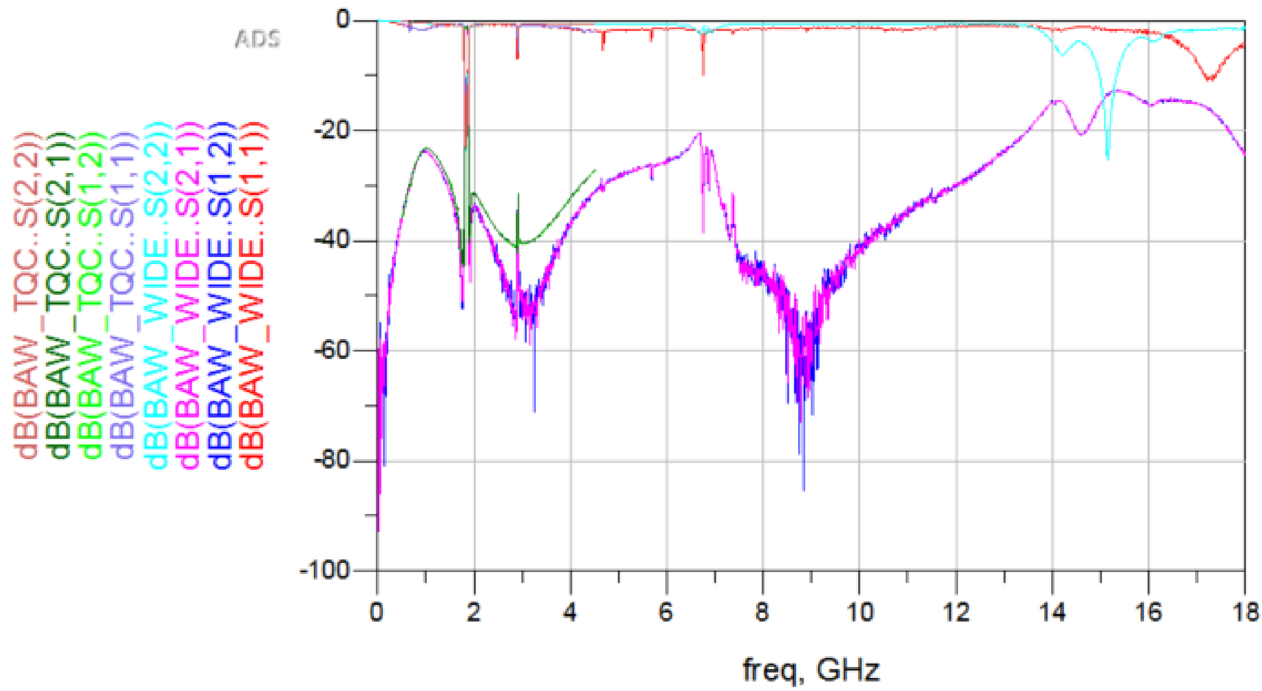
4. How does this part compare to its data sheet? (Review the data sheet for the TQQ0303.)





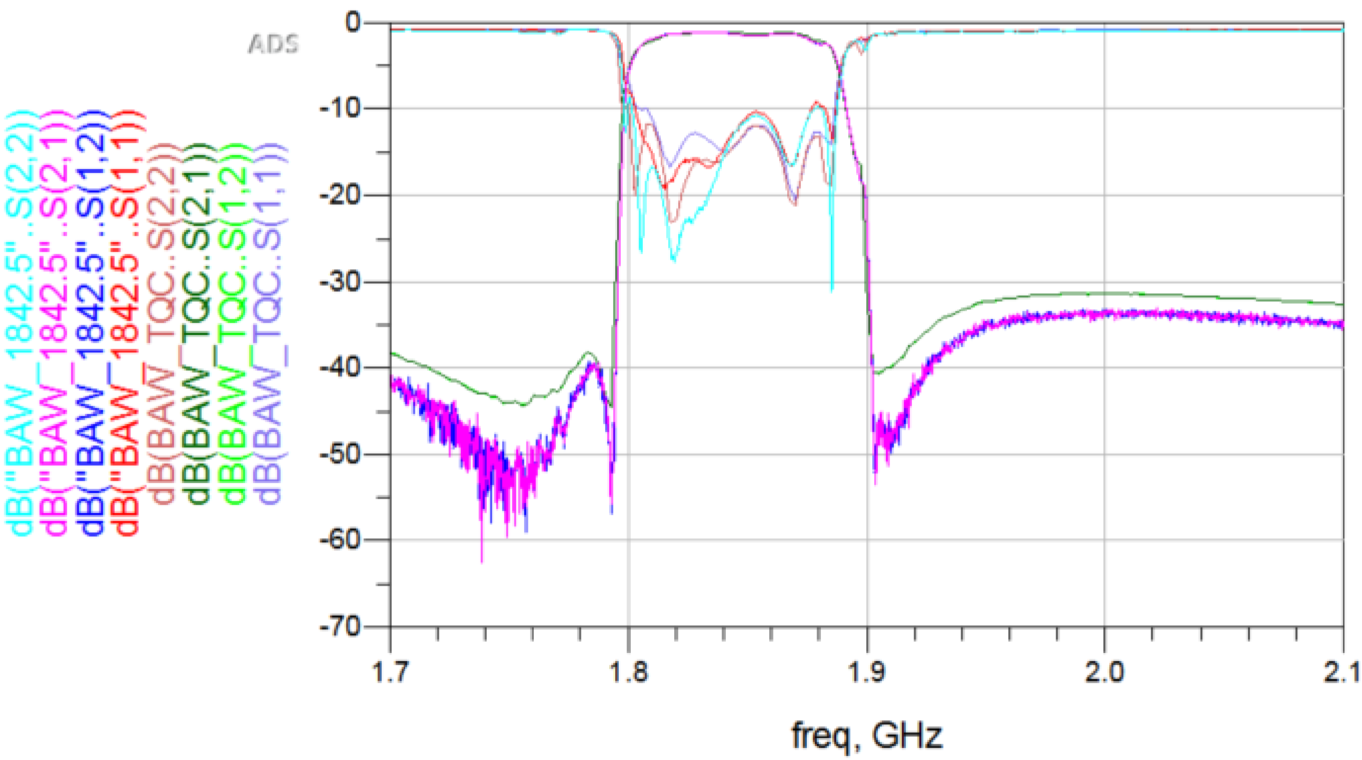
   Instructor Answer:

   Using the same procedures as the previous filter to overlay measured and manufacturer performance, it can be seen they are nearly identical except for out-of-band rejection. The 5 to 10 dB difference there is not likely material to the receiver design.



TQQ0303_003.s2 BAW_1842.5.s2 BAW.s2p

Note how the different frequency record lengths display differently.



6.1.3 Evaluate a SAW Device for the IF Filter

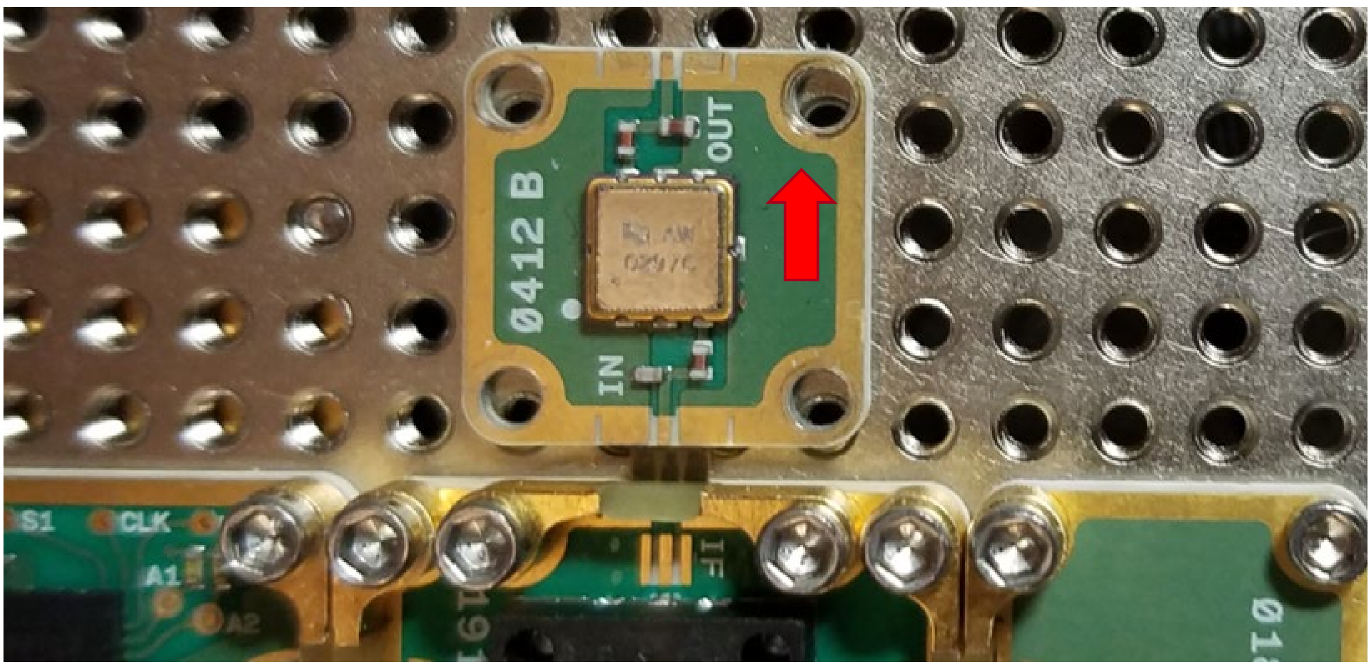
Evaluate the SAW filter against the required Intermediate Frequency (IF) filter specification. Fill out the table below as you take the measurements.

Start by downloading the Data sheet for the **Qorvo 856512**

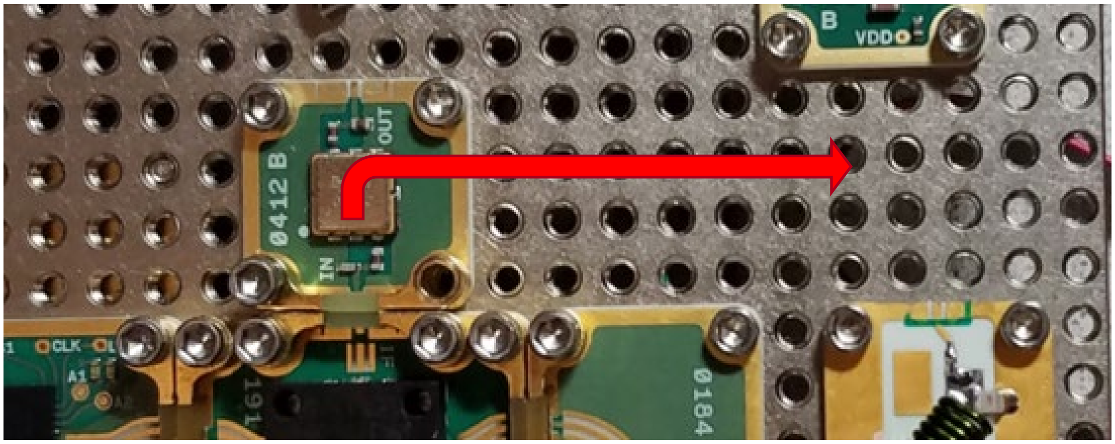
- Website: https://www.qorvo.com/products/p/856512
- Data sheet: https://www.qorvo.com/products/d/da002930

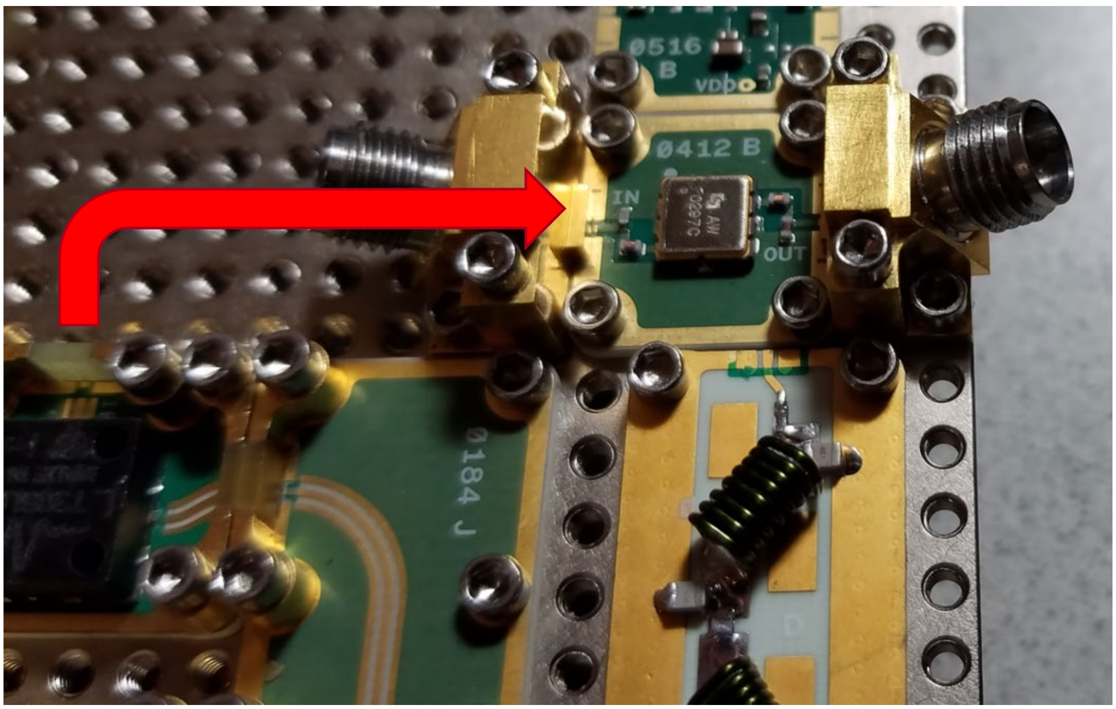
Procedure to Measure the Filter Performance

1. Disconnect the SMA cables from the probe.
2. Press **Frequency > Start** and set to **30 KHz** and **Stop** to **18 GHz (Full Span)** and take the key measurements. You should re-cal or recall the calibrated FieldFox state **WIDE** created in Appendix A in the Transmission Line lab.
3. Carefully remove each X-MWprobe and return the BAW filter to its original position on the prototyping plate.
4. Since the SAW filter **XM-A3V3-0404D, PCB #0412** is presently part of the 5G Receiver system, remove only X-MWanchor on top of it (leave the anchor in place on the X-MWblock adjacent to the SAW filter so that the GSG jumper is retained) and slowly slide it out, underneath and being careful not to damage the GSG jumper.



5. Rotate 90 degrees and place the SAW filter to the right of its original position so that two X-MWprobes can be attached on either side.





6. Attach two X-MWprobes and measure using the same procedure as before.

NOTE When you return and re-install the X-MWblock carefully slide it under the GSG jumper.

---

7. Press **Frequency > Start** and set to **50 MHz** and **Stop** to **350 MHz** to zoom into the pass band and take the key measurements. You should re-cal or recall the calibrated FieldFox state **168.5** created in Appendix A in the Transmission Line lab.
8. Record results in the table below and download and compare the measure versus the manufacturer's S-Parameters as in the previous task.

Measurement Results

Instructor Answer is embedded in the table below.

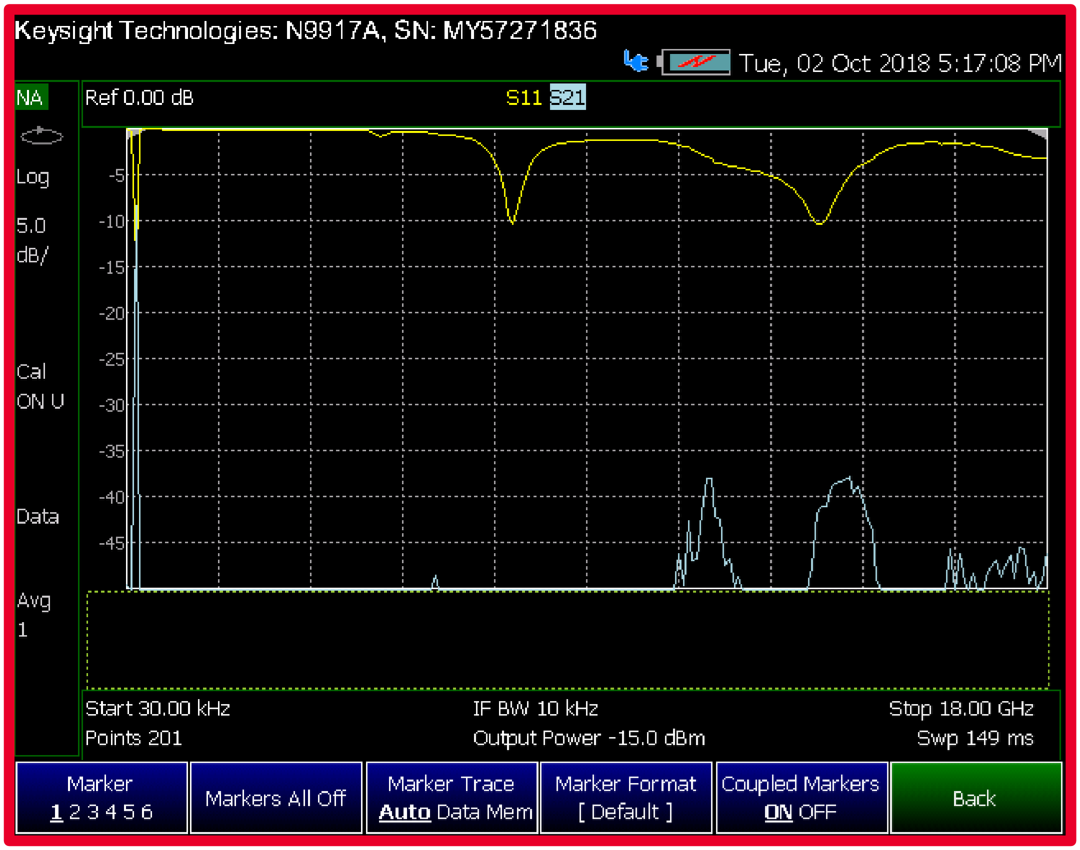
Table 5. SAW Filter Results

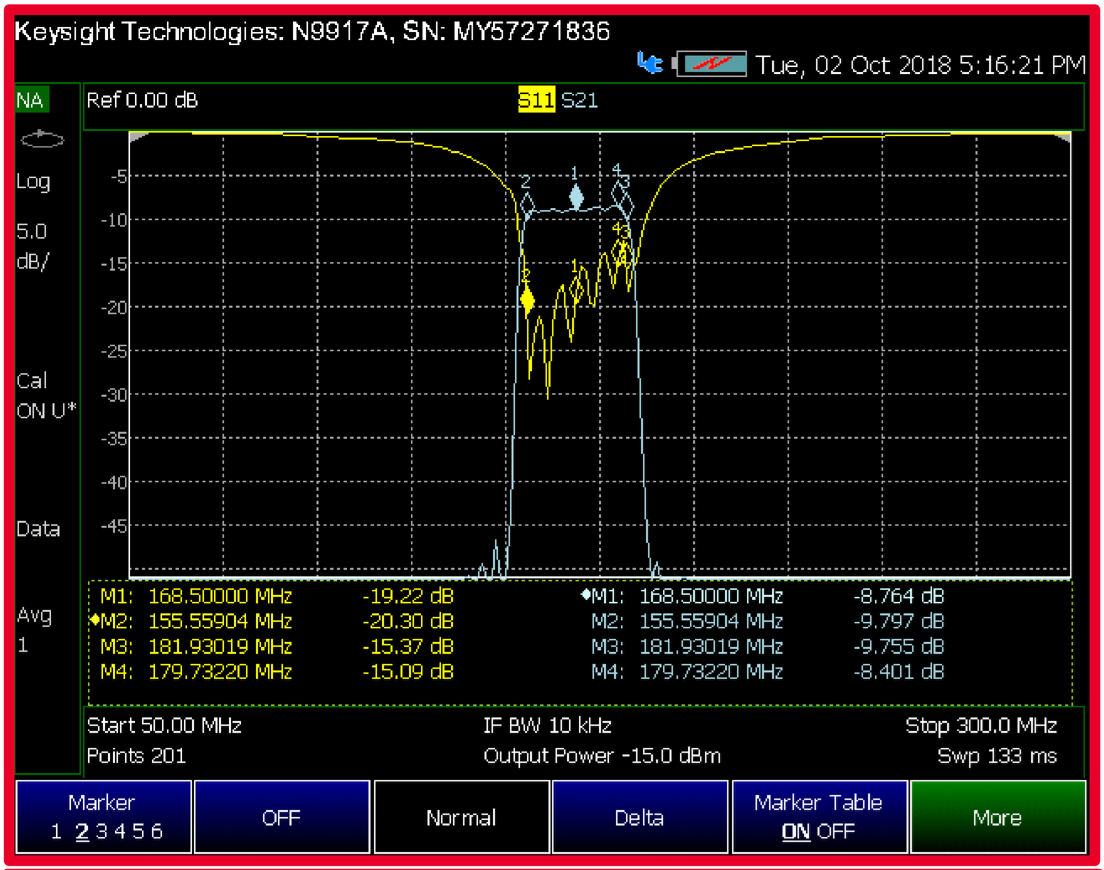
Band Pass Filter	Center Frequency CF	Insertion Loss at CF	Loss at 156 MHz re CF	Loss at 181 MHz re CF	Rejection at 337 MHz
Requirement	168.5 MHz	< 10 dB	< 1 dB	< 1 dB	> 30 dB
XM-A3V3-0404D		8.75 dB	1 dB	1 dB	> 50 dB

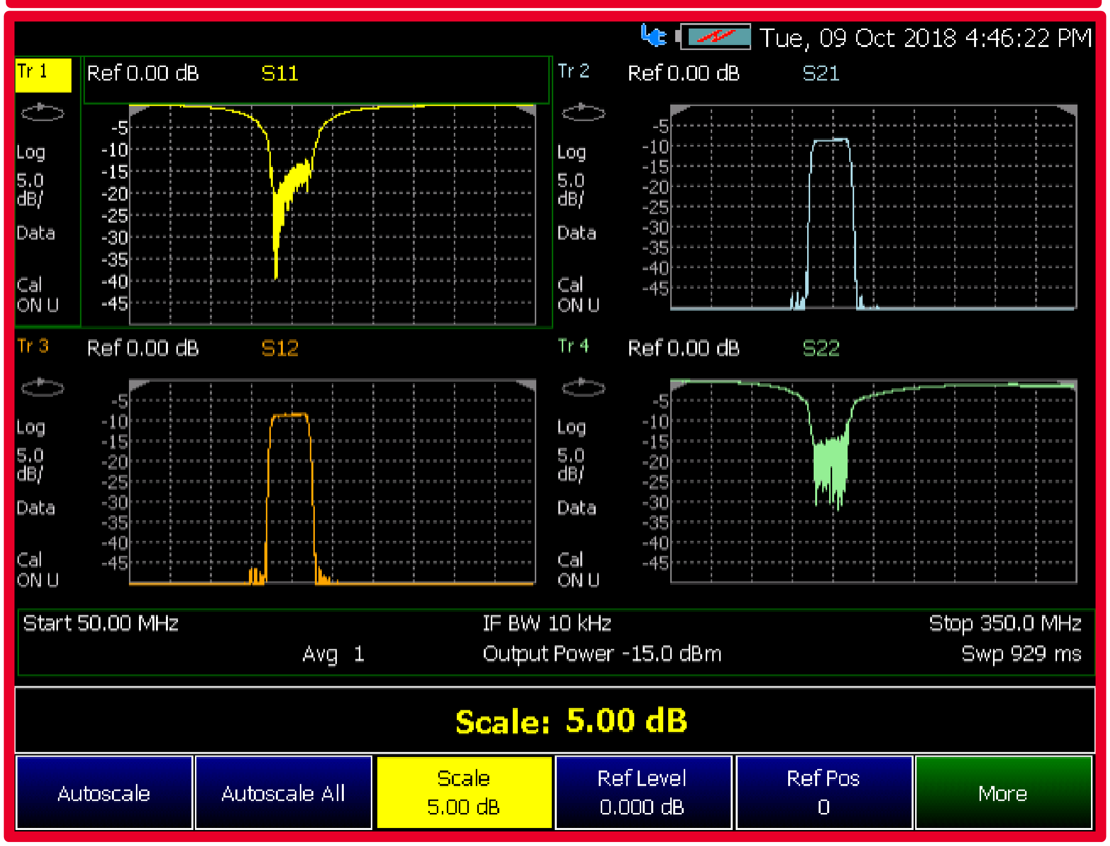
1. Would you choose this filter to provide 30 dB rejection above 337 MHz (2 x 168.5)?

   Instructor Answer:

   Yes.




Keysight Technologies: N9917A, SN: MY57271836
Tue, 02 Oct 2018 5:16:21 PM
NA
Ref 0.00 dB
S11 S21
Log
5.0
dB/
Cal
ON U*
Data
Avg
1
M1: 168.50000 MHz -19.22 dB
M2: 155.55904 MHz -20.30 dB
M3: 181.93019 MHz -15.37 dB
M4: 179.73220 MHz -15.09 dB
M1: 168.50000 MHz -8.764 dB
M2: 155.55904 MHz -9.797 dB
M3: 181.93019 MHz -9.755 dB
M4: 179.73220 MHz -8.401 dB
Start 50.00 MHz
Points 201
IF BW 10 kHz
Output Power -15.0 dBm
Stop 300.0 MHz
Swp 133 ms
Marker 1 2 3 4 5 6
OFF
Normal
Delta
Marker Table ON OFF
More

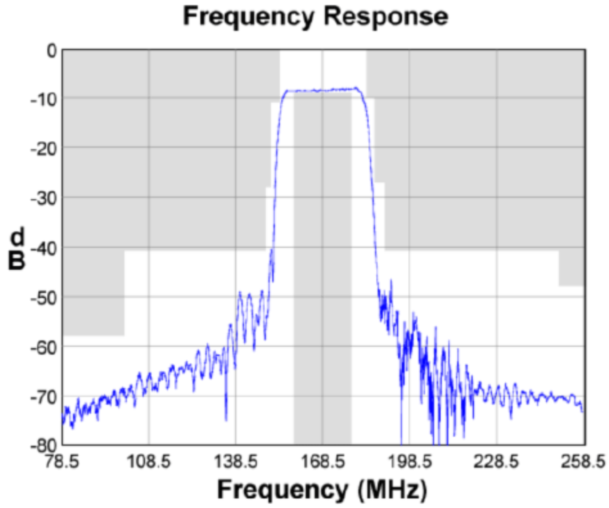

Tue, 09 Oct 2018 4:46:22 PM
Tr 1
Ref 0.00 dB
S11
Tr 2
Ref 0.00 dB
S21
Tr 3
Ref 0.00 dB
S12
Tr 4
Ref 0.00 dB
S22
Start 50.00 MHz
Avg 1
IF BW 10 kHz
Output Power -15.0 dBm
Stop 350.0 MHz
Swp 929 ms
Scale: 5.00 dB
Autoscale
Autoscale All
Scale 5.00 dB
Ref Level 0.000 dB
Ref Pos 0
More

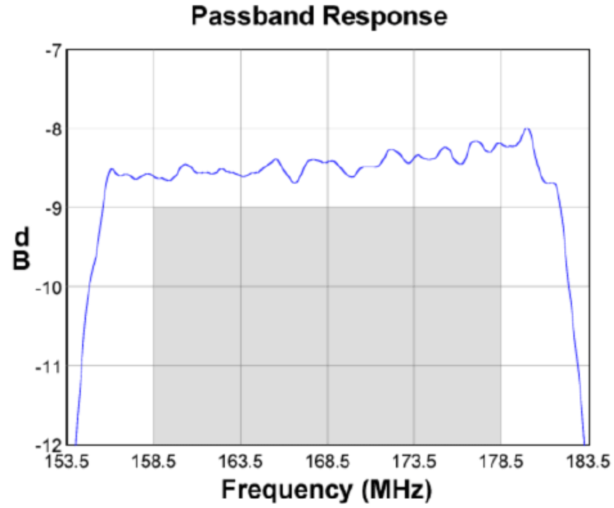
2. How might this part's insertion loss affect the design of the single mixer converter?

   Instructor Answer:

   The insertion loss may be too high, > 8 dB.

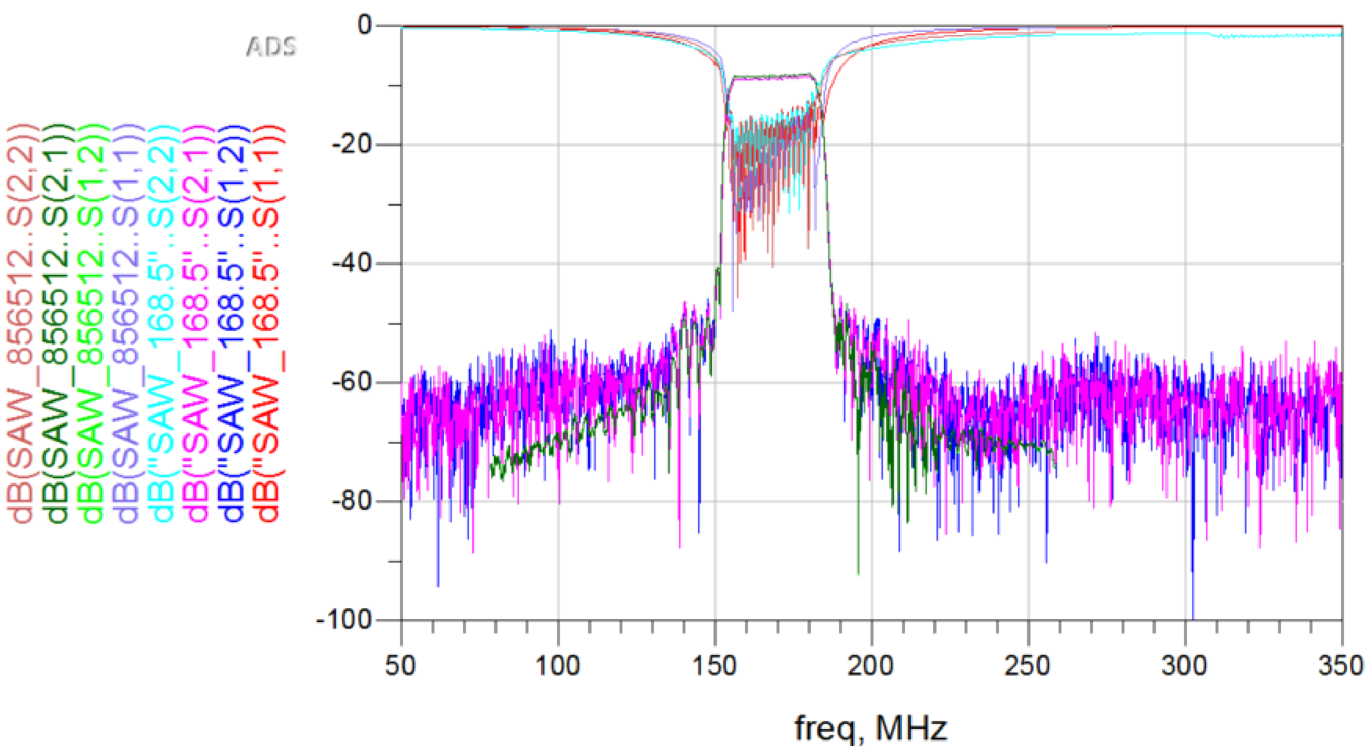
3. How does this part compare to its data sheet? (Review the data sheet for the Qorvo 856512.) Compare passband and stop band performance.





SAW_168.5.s2p

856512NM.S2P



   Instructor Answer:

   Measured performance is very similar to datasheet and the manufacturer's data.

6.2 Design a Lumped Element Low Pass Filter for the IF Filter

Now taking the right blue path in the decision tree, you will design a 190 MHz LPF to meet the IF Filter specification. This is because the existing SAW Filter's high insertion loss might affect the design of the single mixer converter. You will synthesize a Lumped Element Filter and then compare the simulated results to actual measurements. Then you will have a chance to tune the filter for improved performance.

The Filter X-MW PCB used for this exercise will be #0976. Note that in this case two capacitors are sometimes used to allow fine tuning of the capacitance per pad.

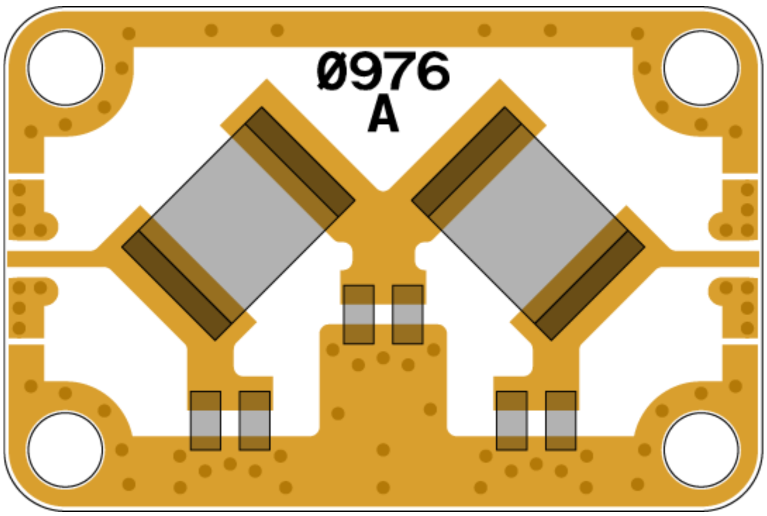


Figure 7. Lumped Element X-MWblock, PCB 0976

For the purposes of this lab, you will use the filter without the housing.

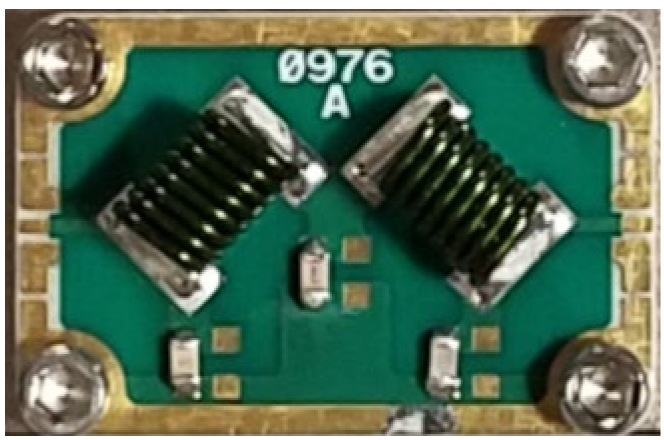
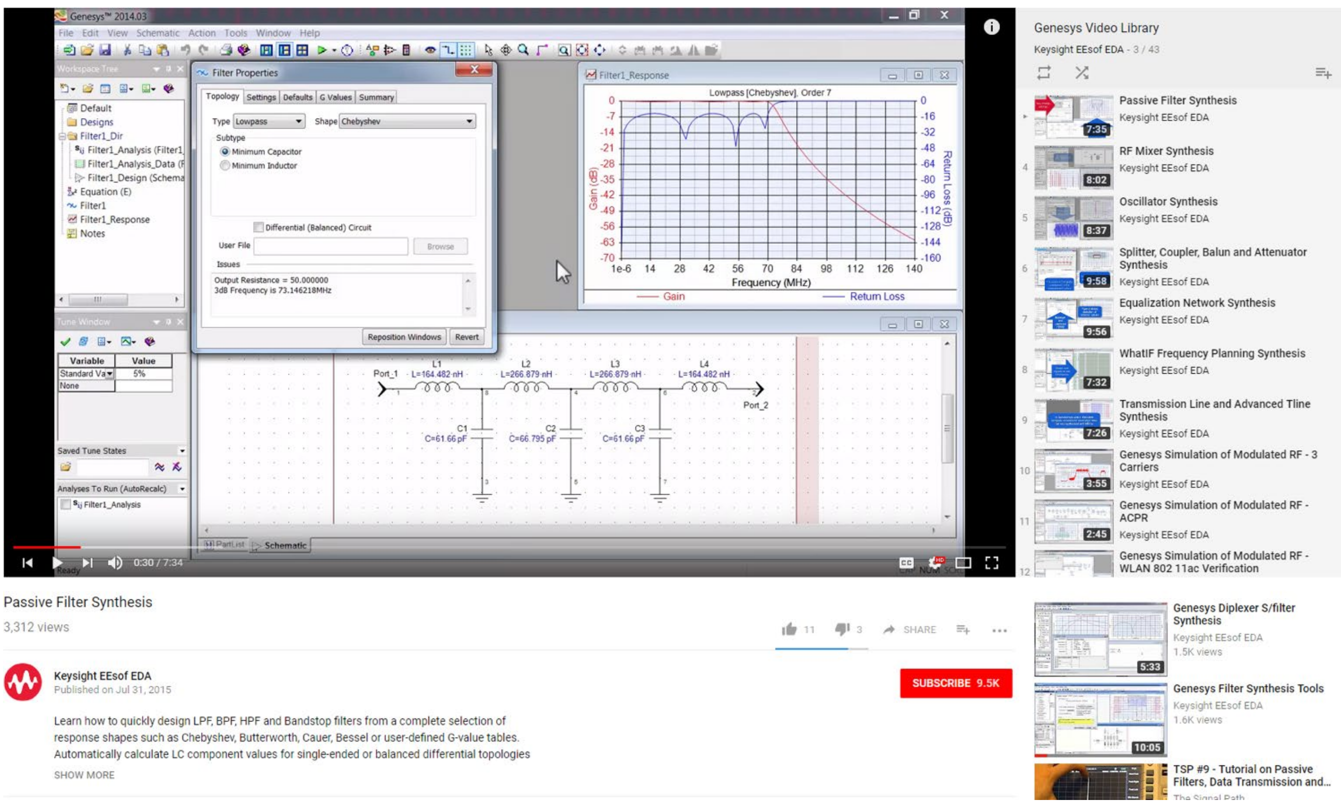


Figure 8. Lumped Element Filter

In this lab, you will utilize Keysight Genesys to synthesize a filter and ADS to simulate its behavior. Keysight Genesys employs different types of simulation including Linear, RF System (Spectrasys), and Harmonic Balance. In this lab, you will use with Linear, which is the fastest and simplest simulation for basic circuits and systems. You will simulate Gain and Return Loss. Review these three videos:

1. Introduction to Genesys: https://www.keysight.com/en/pc-1297125/genesys-rf-and-microwave-design-software?nid=-34275.0.00&cc=US&lc=eng
2. Filter Synthesis (Genesys Synthesis): https://youtu.be/6sWroyFNlS8
3. Linear Simulation in Genesys: https://www.youtube.com/watch?v=DqNlMTSPQjA

In subsequent labs, you will use RF System simulation to incorporate Multi-source signal sources and non-linear characteristics such as Intermodulation Products (IP3), Gain Compression and Saturation, and Harmonic Balance to predict harmonics, mixing products, and phase noise.



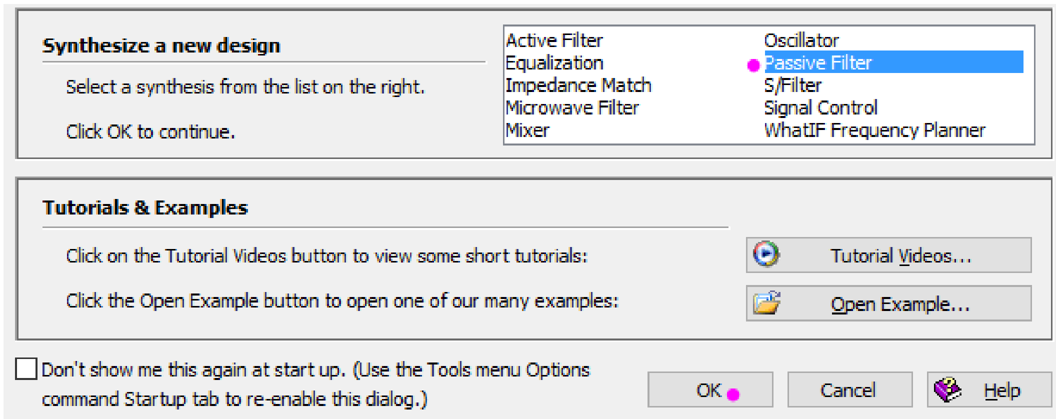
6.2.1 Synthesize the Lumped Element Filter

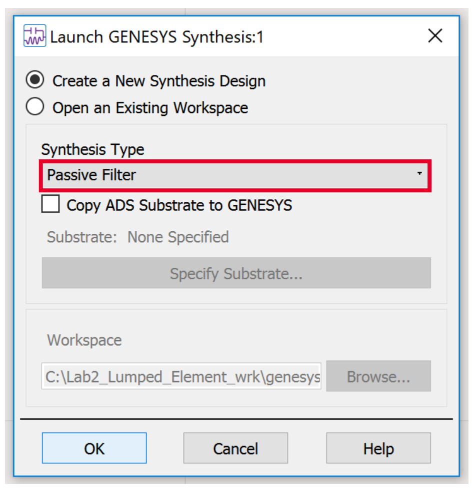
1. Open Genesys software and create a new Schematic in your workspace.

    a. Select **File > New** or click the **Start Page** icon: 

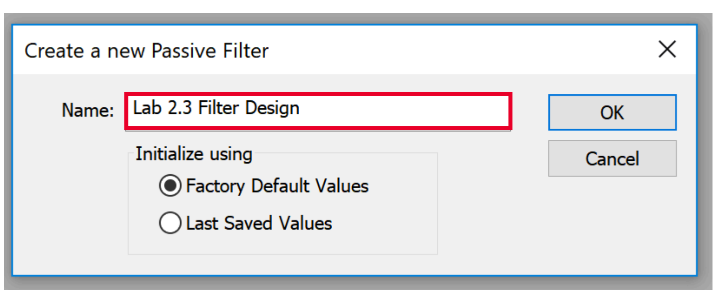
    b. Name it **Genesys Lumped Synthesis**.

2. In the new window, select **Tools > GENESYS Synthesis** or go to **Synthesize a new design** and select **Passive Filter** and select **OK.**

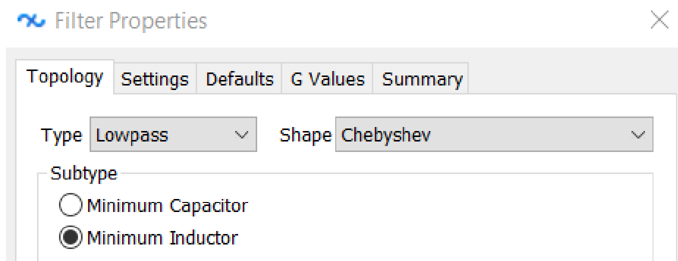




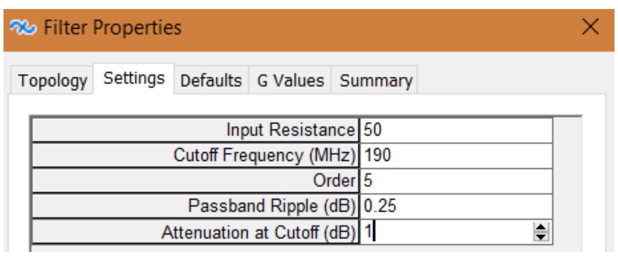
3. Name your filter **Lab 2.3 Filter Design** and click **OK**.

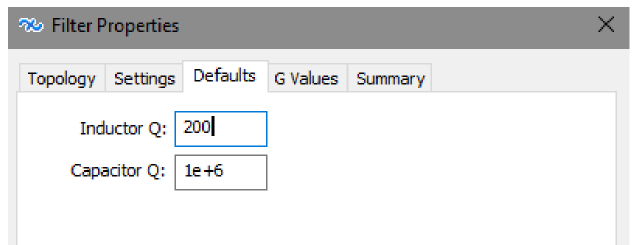


4. Select the following settings:
    a. **Topology**: **Minimum Inductor**

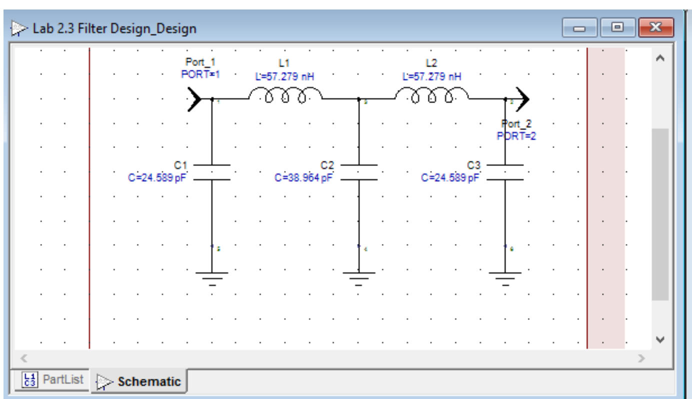


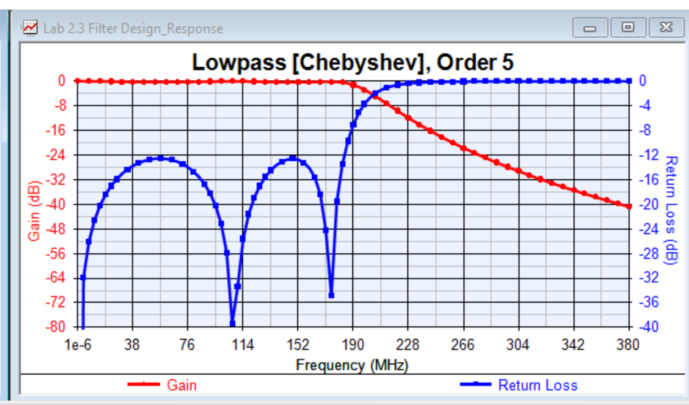
    b. **Settings**: **190 MHz** at **-1 dB**, and **order = 5**, Inductor **Q = 200** (on **Defaults** tab)





The filter result from the initial synthesis looks like this.





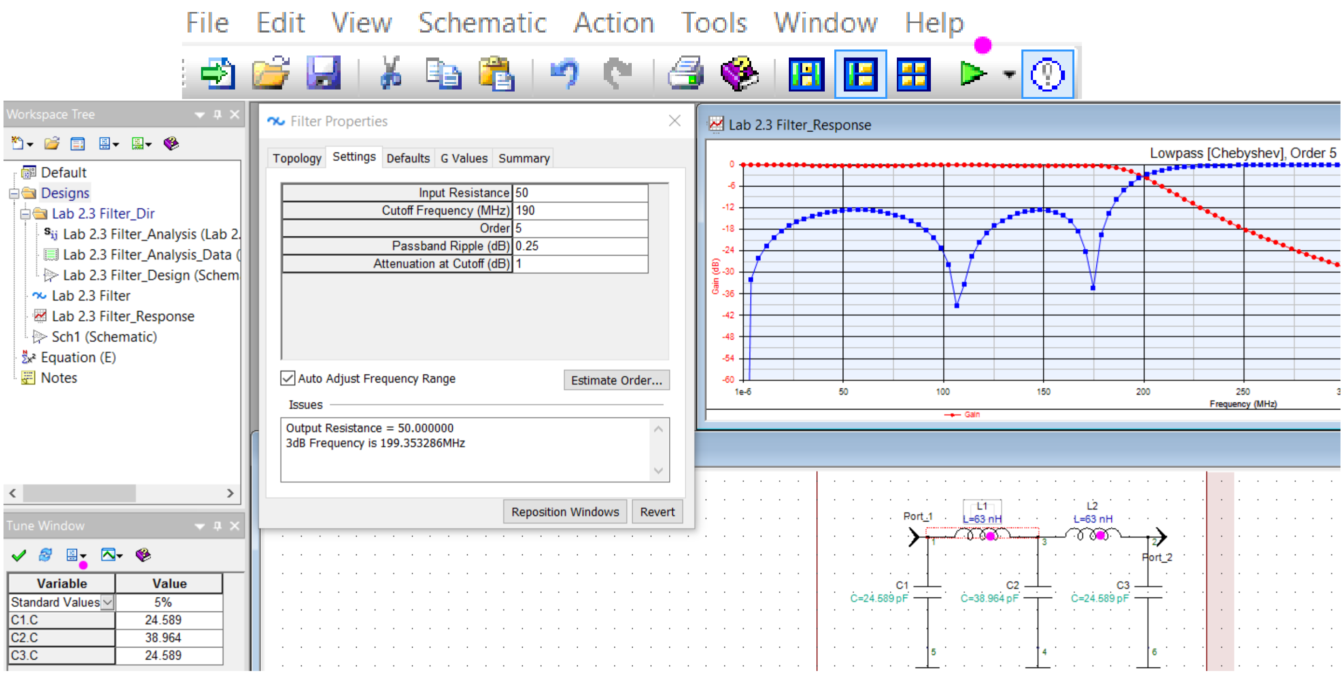
4. Record Component Values in the table below.

Instructor Answer:

C1	L1	C2	L2	C3
24.589pF	57.279nH	38.964pF	57.279nH	24.589pF

5. You now choose a high-Q air-core inductor, near 57.279nH. A 68nH 1515SQ-68NH from Coilcraft is near enough. You will want the filter to be tuned with the inductor coil turns spread just a little bit. This will allow a little tunability for later. Let's assume a spreading that reduces the inductance to 63nH and recalculate the capacitors in Genesys.

   a. Double-click on each inductor to edit Properties, change its value to 63nH and **Run Analyses**.



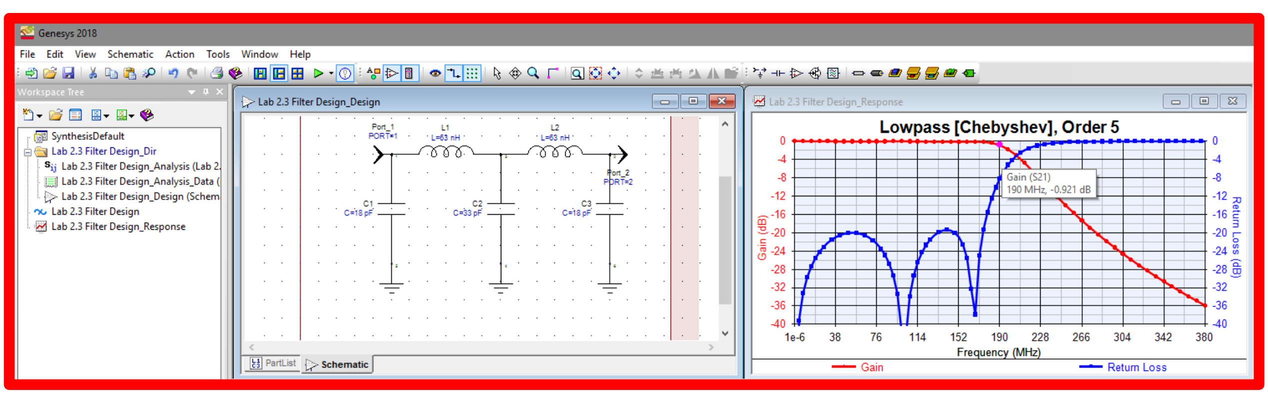
   b. Then highlight the component(s), in this case the three capacitors in the schematic and click on the Variable Options icon in the Tune Window and select C1, C2, and C3 to be tuned using Standard Values.

6. Before tuning you will notice the filter cutoff frequency drops substantially due to the change to **63 nH**. Can you select new values, hitting the green **Run Analyses** icon at the top to return to a similar cutoff? Can you continue to tune to improve return loss in the passband? What values did you select?

   Record your component values and filter response.

   Instructor Answer:

C1	L1	C2	L2	C3
18pF	63nH	33pF	63nH	18pF



7. Normally, you would now move the design to ADS for layout and simulation using the following steps, but **to save time, Keysight has created this for you and you may skip steps a, b, … below.**
    a. First, save the workspace (Anywhere on your computer is fine. This is necessary before exporting.)
    b. File > Export Schematics to ADS.
    c. Open the ADS Workspace and open the schematic from Folder View.
    d. You can double-click a component to see its imported values.
    e. Save All.
    f. Open the schematic, verify that it looks as expected, and click **Layout** > **Generate/Update Layout…** to begin a PCB layout in ADS.

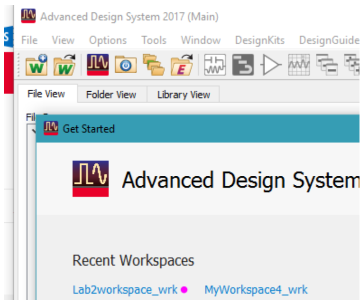
    Instructor Answer:

    When finished you may check your work by opening the pre-prepared solution by opening the file **Lab2GENESYSworkspace.wsg** in folder **M1_L2.**

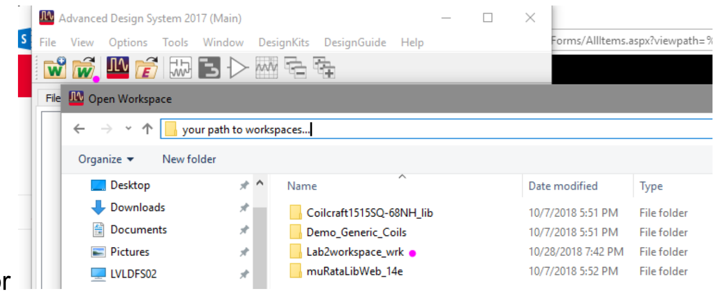
6.2.2 Run Pre-prepared Inductor Simulations

The ADS layout and simulations have been completed for you. From the ADS Main menu **Unarchive…** the file **Lab2workspace_wrk.7zads** from the folder **M1_L2** to the root of the **C:** drive on your computer.

NOTE You may be able to simply open the workspace directly if it has already been unarchived on the computer.



or



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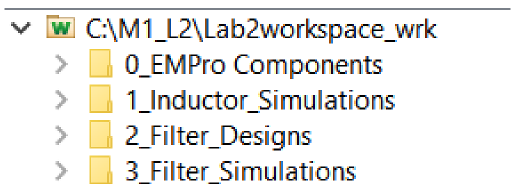
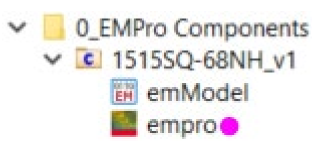
1. Open the ADS **Lab2workspace_wrk** in the ADS workspace. From the folder view you will see:



2. Note that the first folder **0_EMPro Components** contains three subfolders each containing an empro model of a Coilcraft CC1515SQ-68NH inductor. Double-click a model to view it.

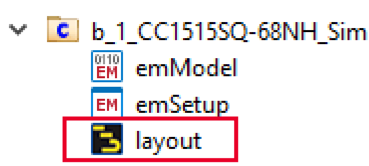
   CC1515SQ-68NH_v1 off-the-shelf
   CC1515SQ-68NH_v2 with the coils spread a bit
   CC1515SQ-68NH_v3 with the coils spread a little bit more



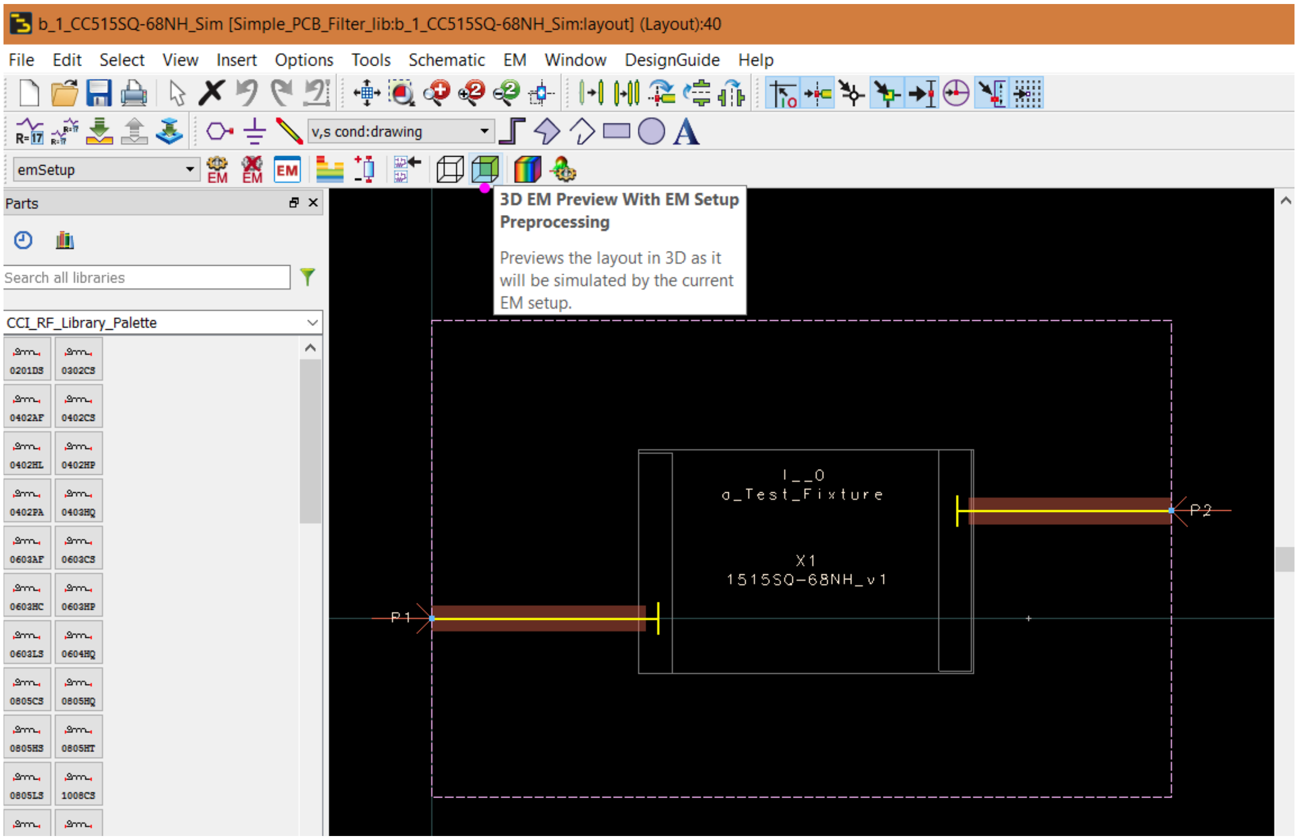
   It also contains a Parameterized Model **CC1515SQ_1-8T**. The Parameters may be varied. After reviewing these, it is recommended to close the files without saving.

3. From the second folder **1_Inductor_Simulations**, expand the cell and open the **layout** file for simulation of each of the three inductors:

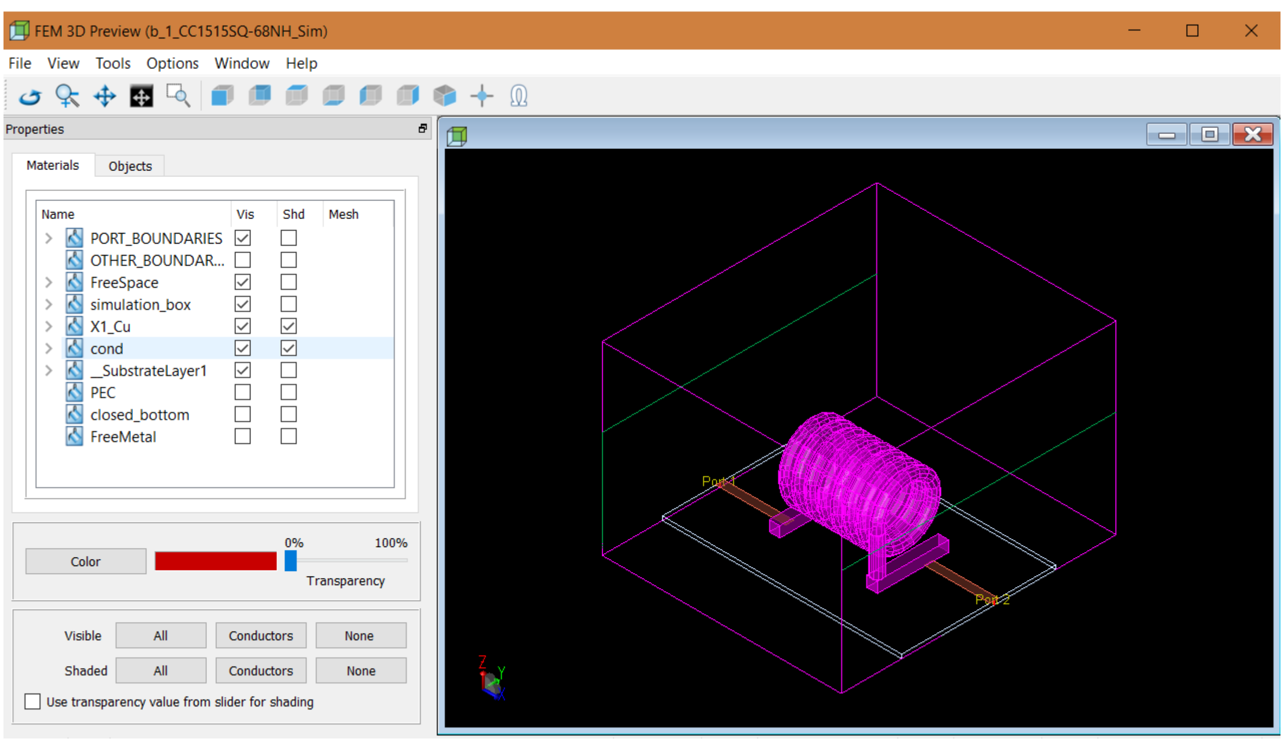
   b_1_CC1515SQ-68NH_Sim off-the-shelf
   b_2_CC1515SQ-68NH_Sim with the coils spread a bit
   b_3_CC1515SQ-68NH_Sim with the coils spread a little bit more



4. Click the 3D EM Preview (or the multi-colored button **Visualization**) to see the layout to test the inductor.



5. Observe the 3D model by rotating and zooming.



6. Open the Data Display window for the measurement of the inductor:

   1_Inductor_Simulations > b_1_CC1515SQ-68NH_Sim.dds

7. The dataset converts S(1,1) to Z(1,1) according to:

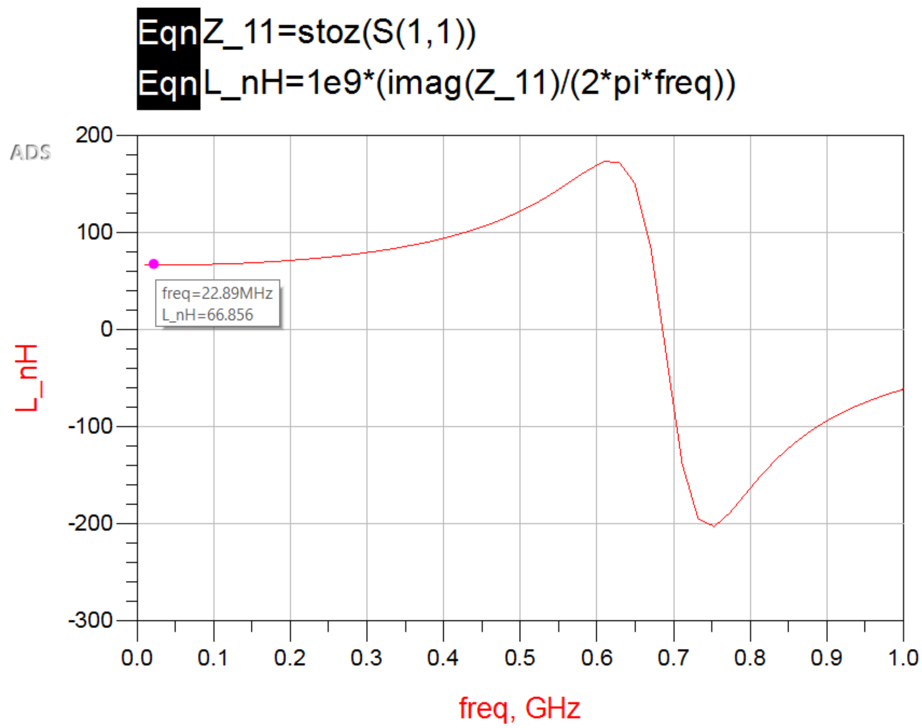
   Z11 = 50*(1+S11)/(1-S11)

   It has modeled the reactance of the physical inductor as a frequency-varying inductor.

   $X = 2\pi fL \rightarrow L = X/2\pi f$

   Thus, as the reactance varies with frequency due to parasitic capacitance between the turns of the coil, so does this model of inductance.

8. Hover with your cursor over a frequency as near as possible to the cutoff frequency.



9. Observe that the reactance becomes negative (capacitive) at 700 MHz. How will this phenomenon affect your filter?

   Instructor Answer:

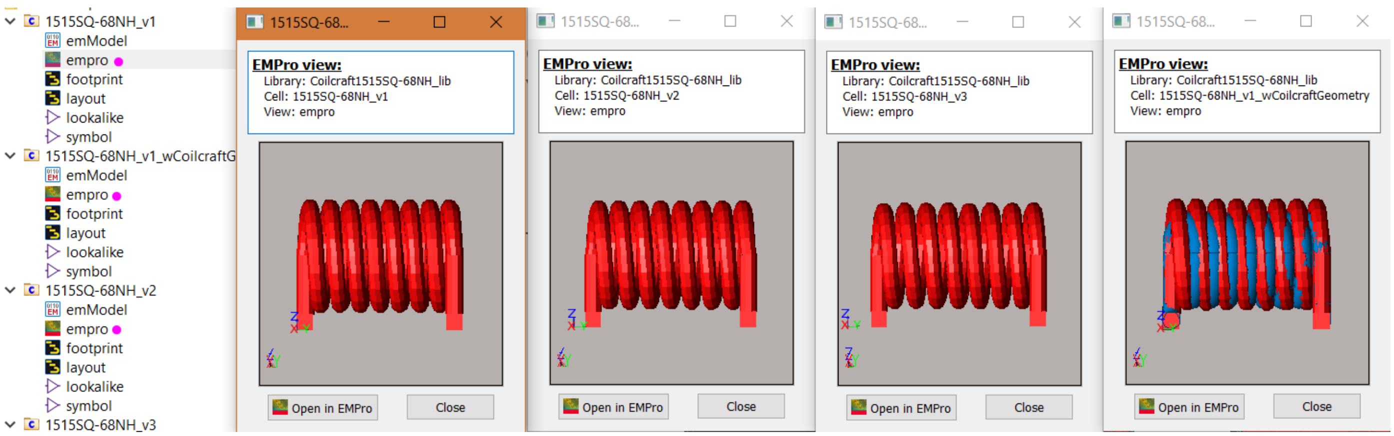
   Little impact because it is well beyond the cutoff frequency.

10. Open the **layouts** and **3D EM Preview** or **Visualization** and datasets for the remaining two versions of the inductor:

    b_2_CC1515SQ-68NH_Sim the same inductor with the turns manually spread slightly
    b_3_CC1515SQ-68NH_Sim the same inductor with the turns manually spread slightly more

You may find it convenient instead to go back to the first folder **0_EMPro Components** and double-click the physical inductor models to view their **EMPro** previews.

1515SQ-68NH_v1
1515SQ-68NH_v2
1515SQ-68NH_v3
1515SQ-68NH_wCoilCraft has v1 superimposed with the manufacturer's physical model, showing a slight coil twist but the same length):



11. Note differences. How does the L vary with the length of the inductor specifically spacing of the turns? Complete the table.

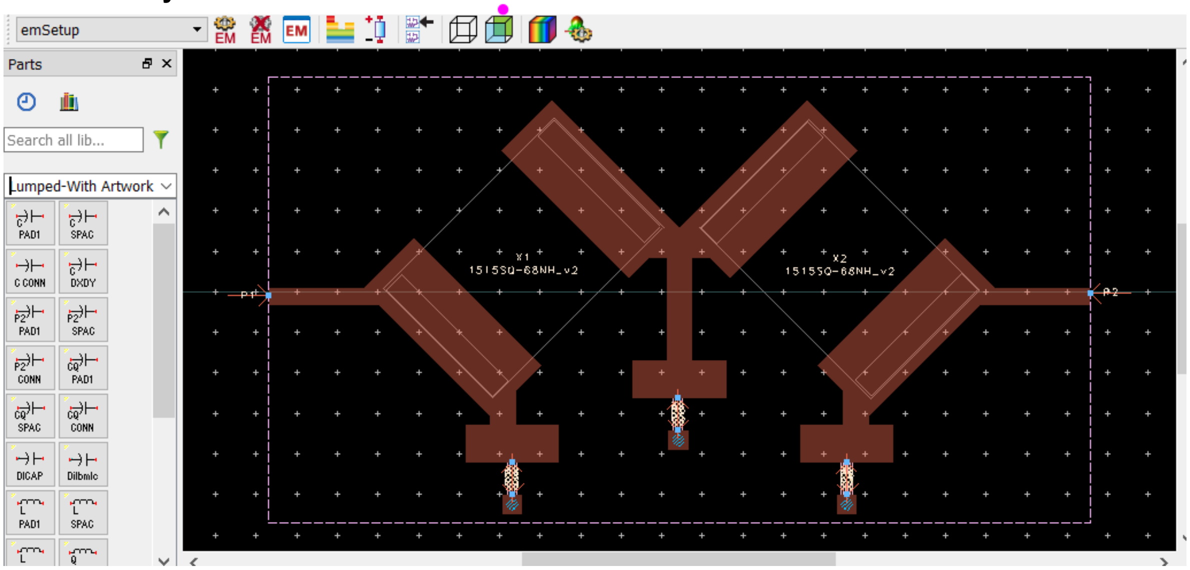
L_nH initial	L_nH spread	L_nH spread more
67	63	59

Instructor Answer:
Inductance decreases as the spacing between the turns increases.

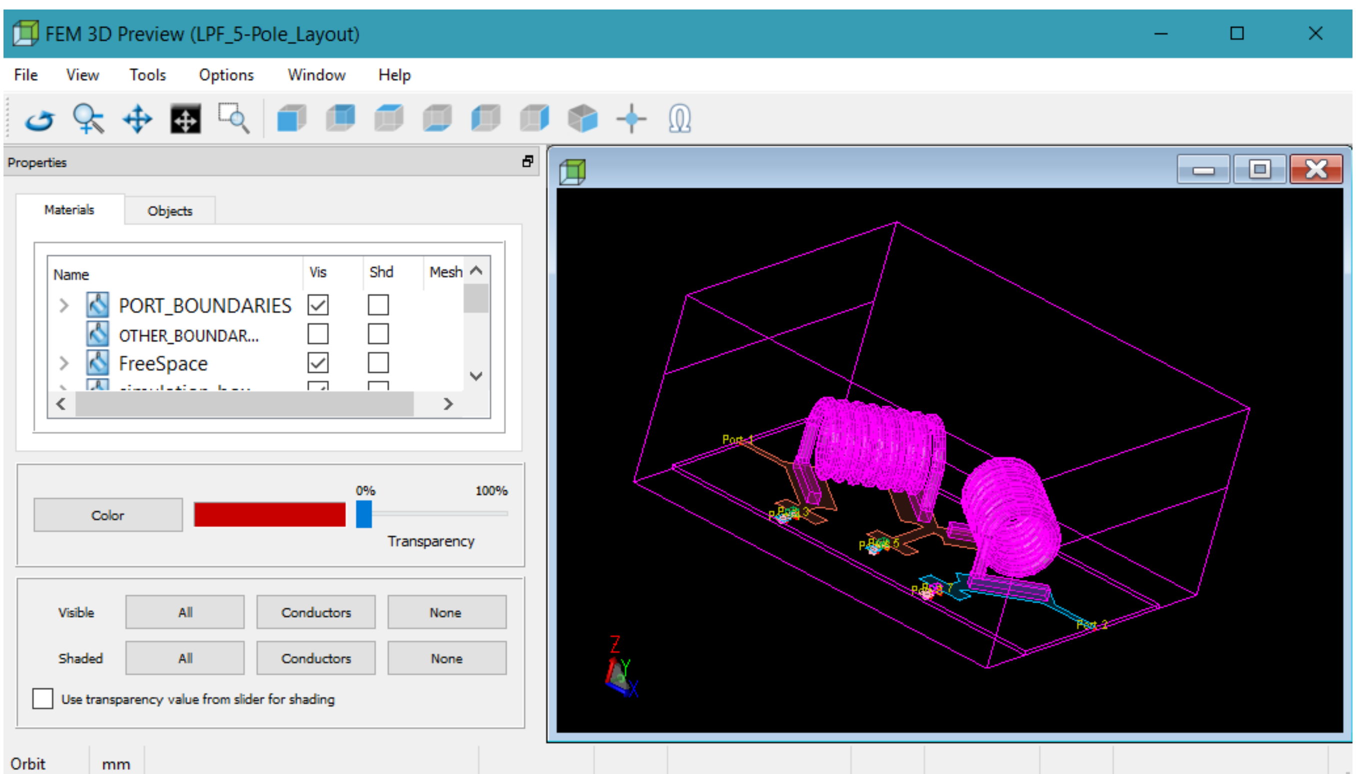
6.2.3 Run the Pre-prepared Low Pass Filter Simulation

1. Open the Low Pass Filter **layout** file under the cell: **2_Filter_Designs > LPF_5-Pole_Layout.** This filter has used the simulation with inductor turns spread just enough to decrease its inductance to 63 nH: **b_2_CC1515SQ-68NH_Sim**.

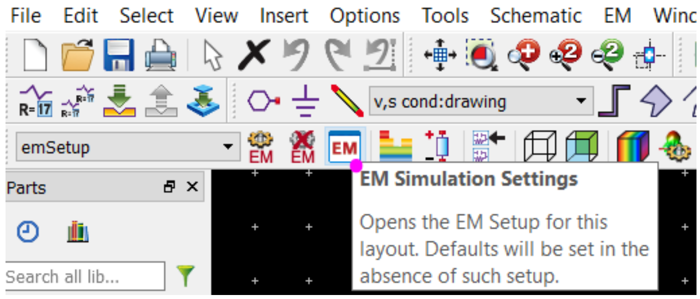
   Here is the **layout**.

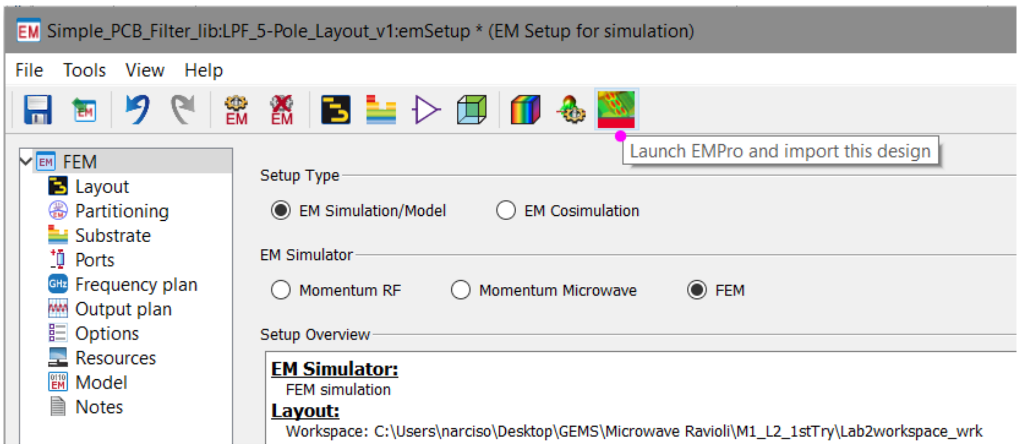


2. Click the 3D EM Preview icon noted above to see the filter simulated in 3D.

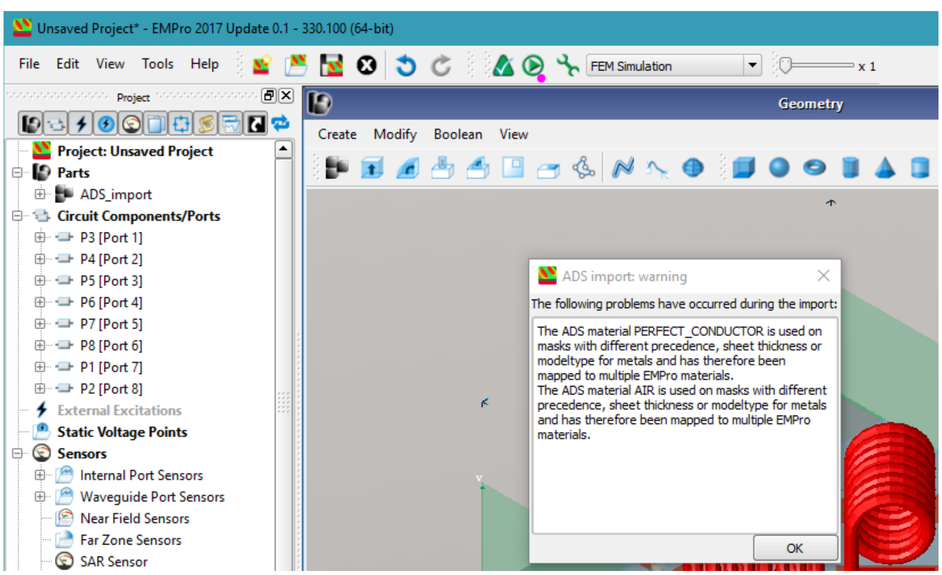


3. From the EM Simulation Settings, click **Launch EMPro and import this design**.





4. Grab a point with the mouse button and observe as you rotate the 3D image.
5. If you have time, run the EM simulation (this may require several minutes) by clicking the green button shown below and name the output something other than **LPF_5-Pole_Layout_v1**.



Examine the results (procedure in the previous lab). Why do they not show the designed LPF response?

Instructor Answer:

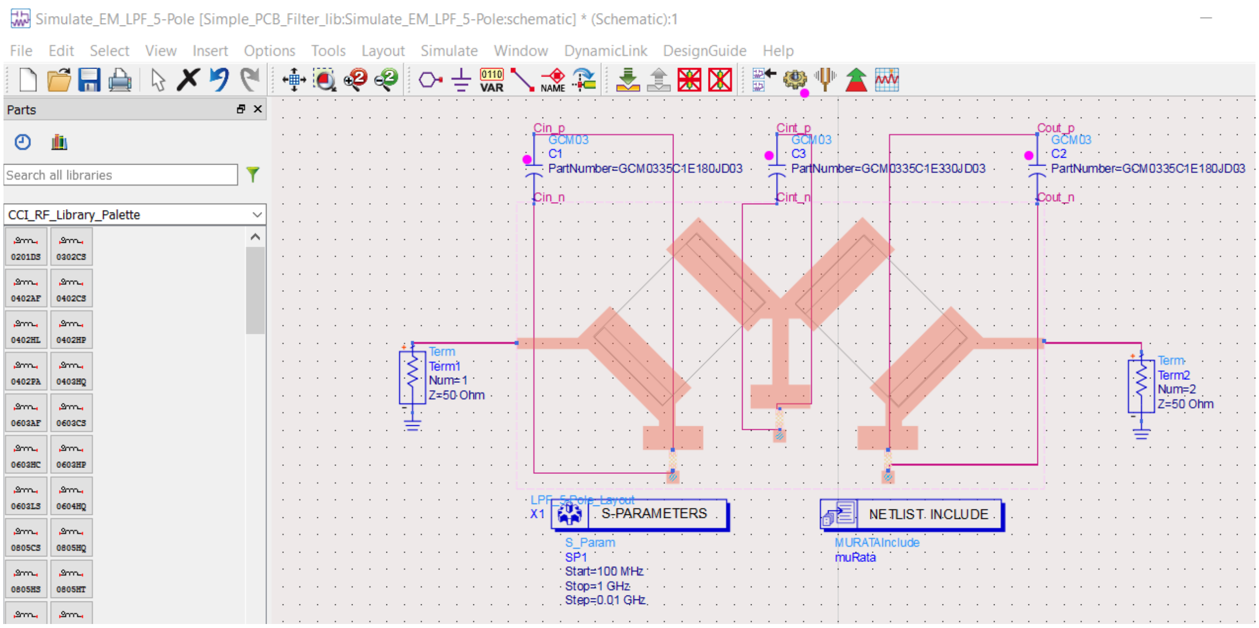
Only the inductors and lines were simulated, no capacitors.

6. Why is the filter laid out in this fashion?

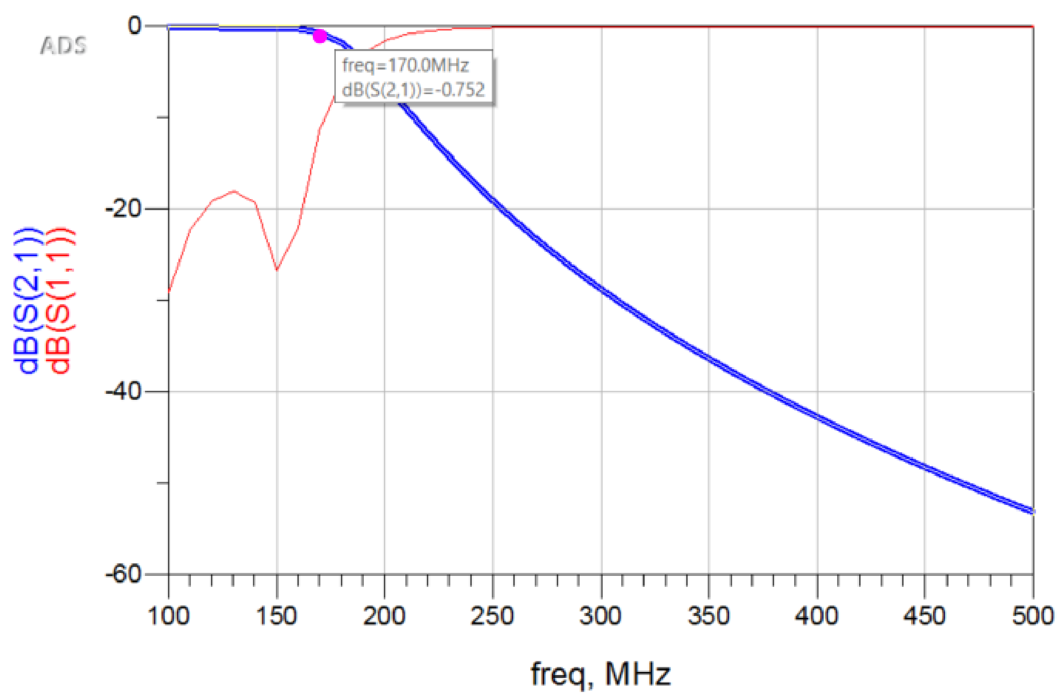
   Instructor Answer:

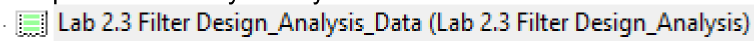
   Mutual inductance is minimized by placing the inductors at right angles to each other.

7. Open the Low Pass Filter **schematic** file under the cell: **Simulate_EM_LPF_5-Pole** which integrates the **emModel** and the S-parameter dataset from the cell **LPF_5-Pole_Layout**. The capacitors are real 18, 33 and 18 pF surface mount components:



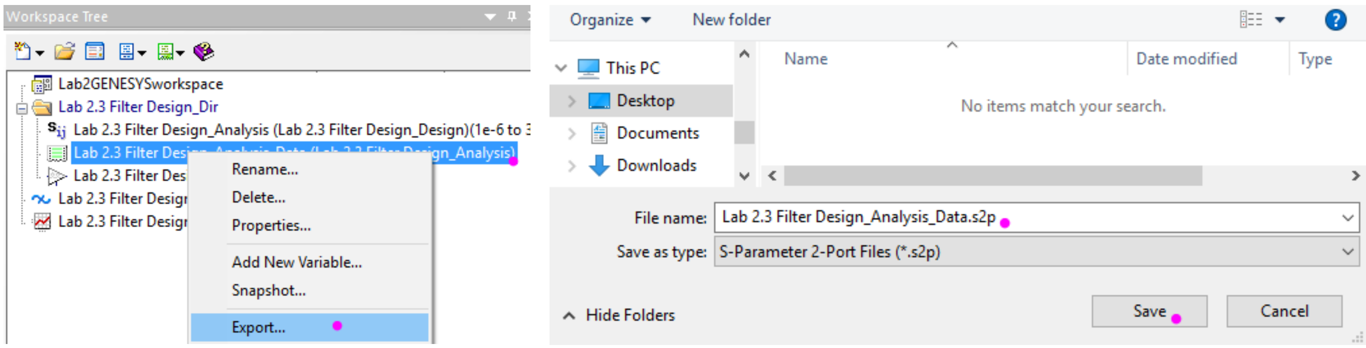
8. Click the Simulate icon shown above to generate the dataset (or just click the dataset).



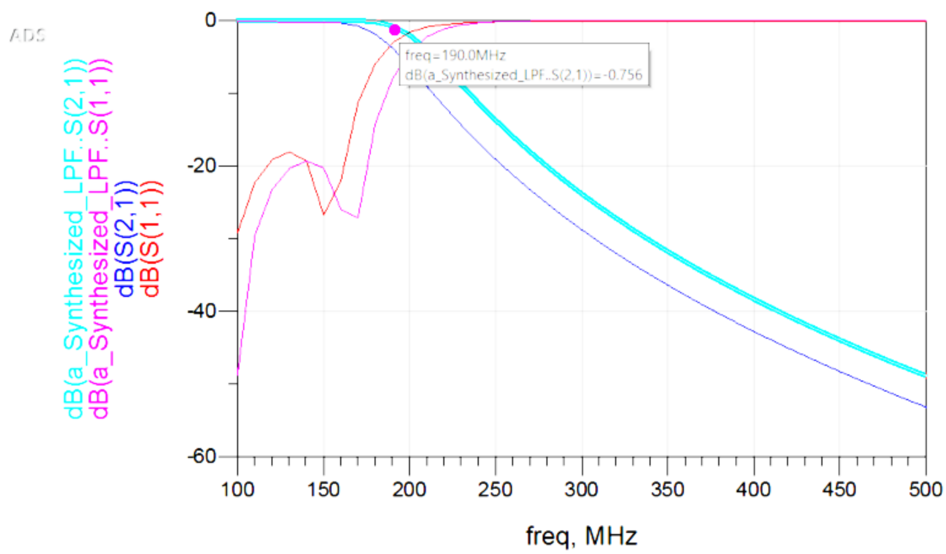
9. Reopen the Genesys analysis schematic in **Lab2GENESYSworkspace.wsg**, right-click on 

, and export the **.s2p** file as shown below.

An example data file from Genesys is provided.



10. Then add the S-Parameters of the Genesys-synthesized circuit for comparison.



11. What is the 1 dB cutoff frequency of the simulated filter? How does it compare with the ideal response you calculated using GENESYS? Why is the cutoff frequency lower?

Instructor Answer:

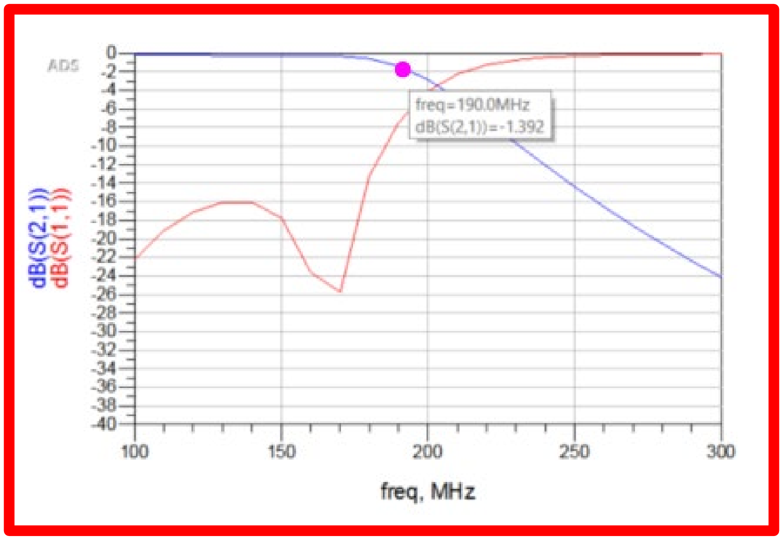
The 1 dB cutoff frequency of the EM-model with real capacitors is less than 190 MHz due to parasitic capacitance from the inductor pads on the PCB to ground plane. The capacitance from the turns of the coil to the ground plane may have some additional effect.

12. Try changing capacitors to return the cutoff frequency to the specified value. This is done by creating a new cell named **Simulate_EM_LPF_5-Pole_v1** using **Copy Cell.** What happened?

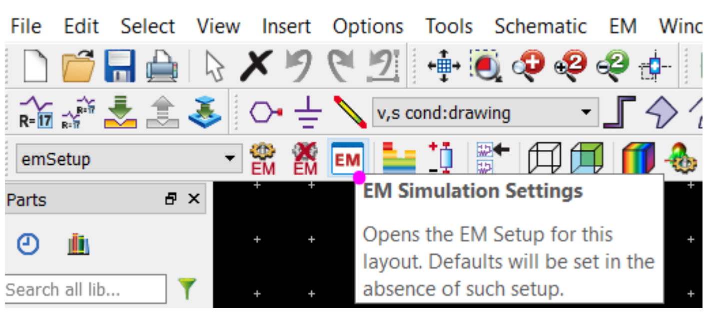
Instructor Answer:

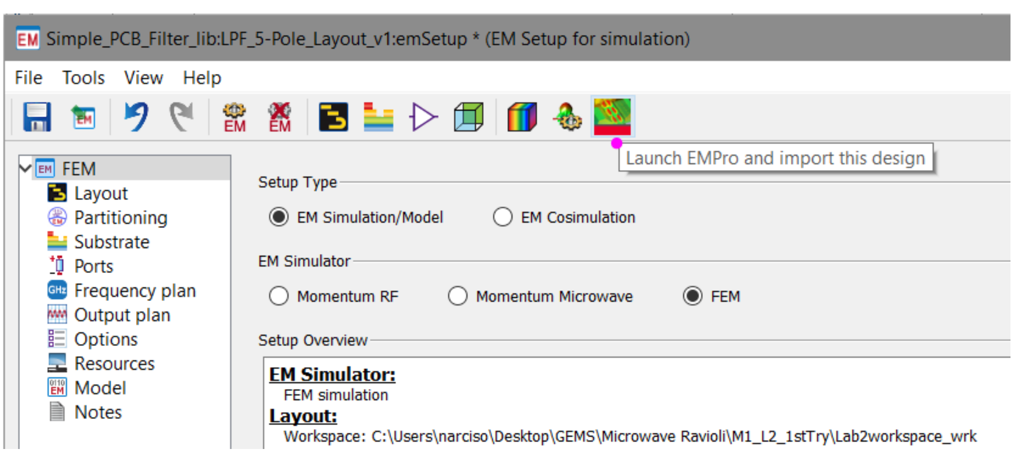
C1	C2	C3
15pF	27pF	15pF

The values above increased the LPF cutoff to approximately 185 MHz but were not exactly the right ones since component choices were limited. This is common in practice. When you test the actual X-MWblock, you will notice that two capacitors may have been placed in parallel to achieve an optimum value.



13. From the EM Simulation Settings, click **Launch EMPro and import this design**.





6.2.4 Open in EMPro to Understand Filter Response

Open EMPro to examine the design using a 3D electromagnetic simulation. It will include inductor parasitic capacitances, mutual inductance, trace coupling, and other 3D effects, but not the surface-mount capacitors.

Background Video of a similar design: (Time 2:52) Link*:* https://youtu.be/Z3dhIf1ruvc

7 Measure the Performance of the Built Low Pass Filter

Objective: Measure the performance of the Lumper Element LPF and compare to the simulated design.

For the purposes of this lab, the filter has been provided so you will start with a pre-built filter and your objective will be to measure (and later tune) it's performance. You will evaluate the SAW filter against the required Intermediate Frequency (IF) filter specification. Fill out the table below as you take the measurements.

7.1 Procedure to Measure the Filter Performance

1. Disconnect the SMA cables from the probe.
2. Press **Frequency > Start** and set to **30 kHz** and **Stop** to **18 GHz (Full Span)** and take the key measurements. You should re-cal or recall the calibrated FieldFox state **WIDE** created in Appendix A in the Transmission Line lab.
3. Ensure the X-MWblock for the Lumped Element Filter **XM-B1F4-1204D, PCB #0976** is attached to the plate and attach X-MWprobes to both sides. Measure S11 and S21.

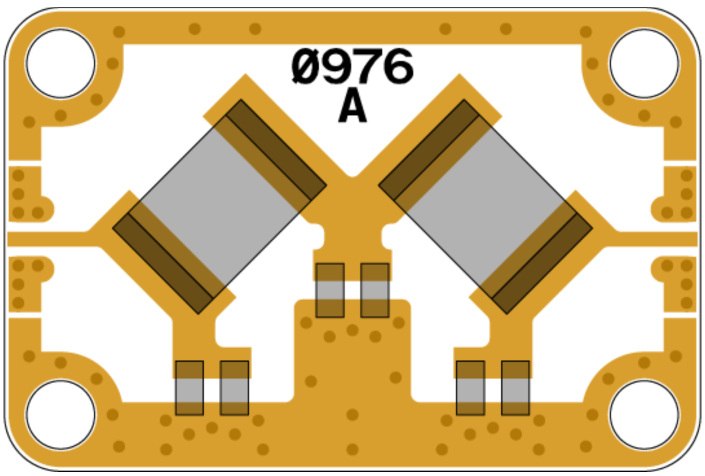


Figure 9. Lumped Element Filter Layout View

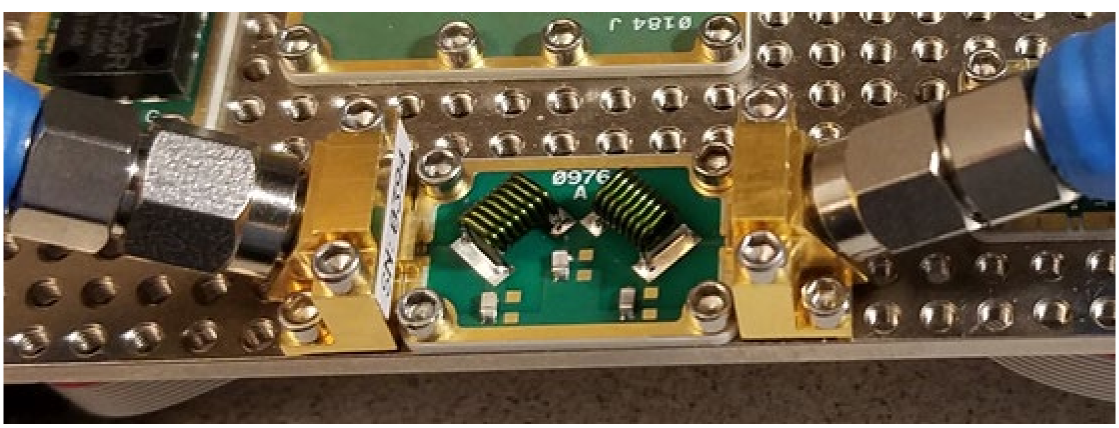


Figure 10. Lumped Element Filter with X-MWprobes

4. Press **Frequency > Start** and set to **50 MHz** and **Stop** to **350 MHz** to zoom into the pass band and remeasure. You should re-cal or recall the calibrated FieldFox state **168.5** created in Appendix A in the Transmission Line lab.
5. Record results on the table below and download and compare the measure versus the manufacturer's S-Parameters as in the previous task.

Measurement Results

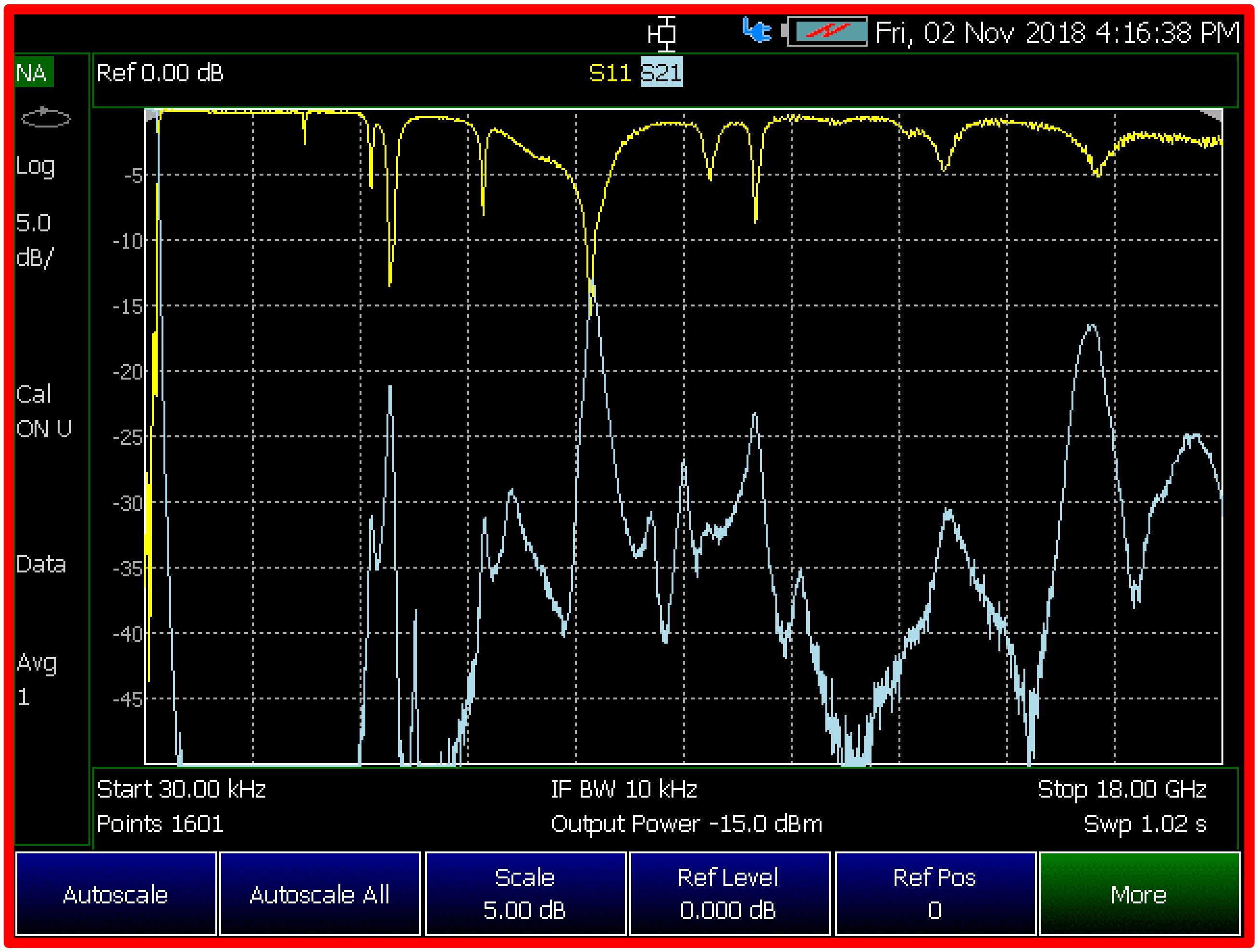
Instructor Answer:

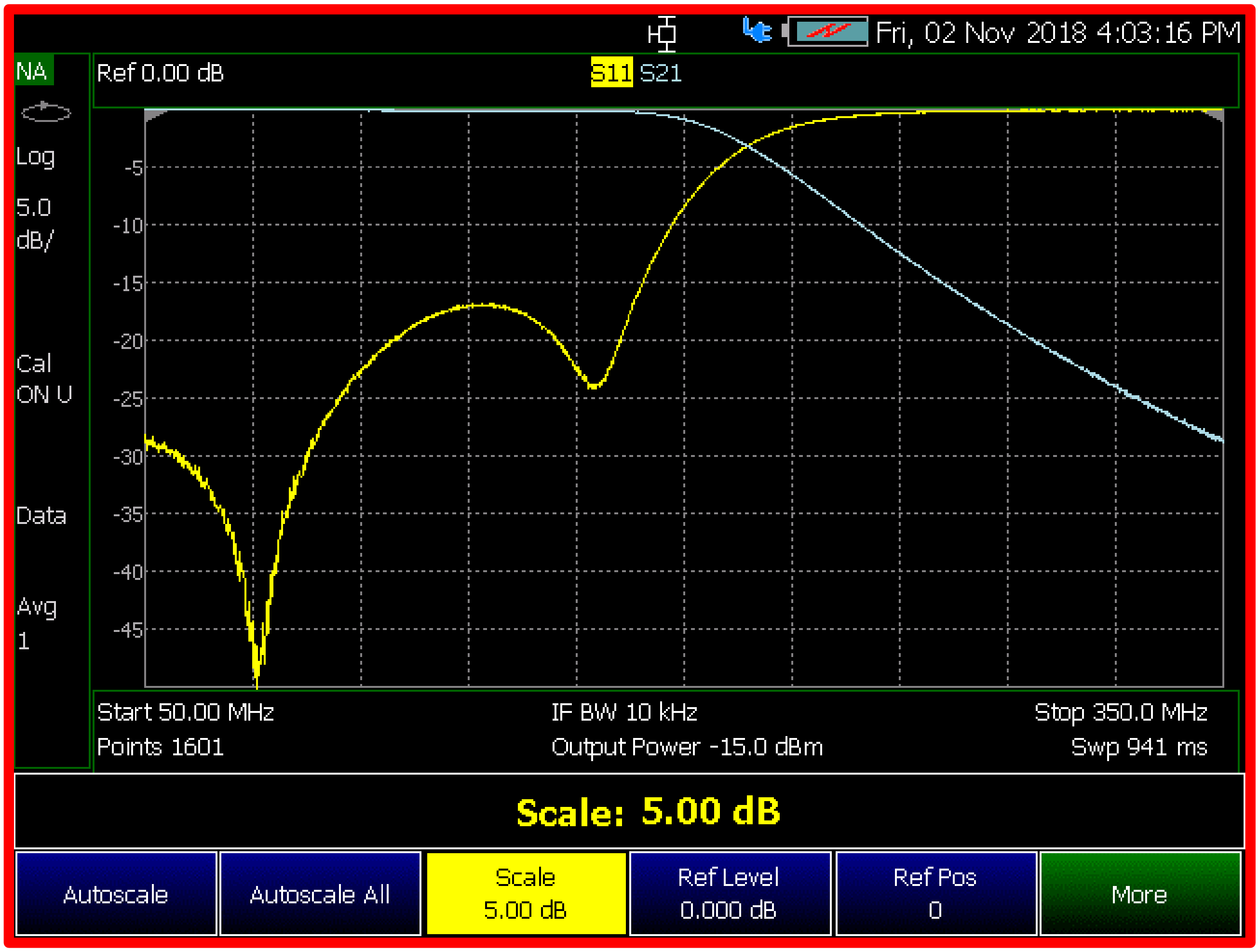
Band Pass Filter	Center Frequency CF	Insertion Loss at CF	Loss at 156 MHz re CF	Loss at 181 MHz re CF	Rejection at 337 MHz
Requirement	168.5 MHz	< 10 dB	< 1 dB	< 1 dB	> 30 dB
XM-A3V3-0404D	LPF, not BPF	< 1 dB	0.2 dB	0.2 dB	28 dB

1. Would you choose this filter to provide 30 dB rejection above 337 MHz (2 x 168.5)?

Instructor Answer:

Yes, but only up to 3.6 GHz and note that it did not quite achieve 30 dB rejection at 337 MHz.





2. How might this part's insertion loss affect the design of the single mixer converter?

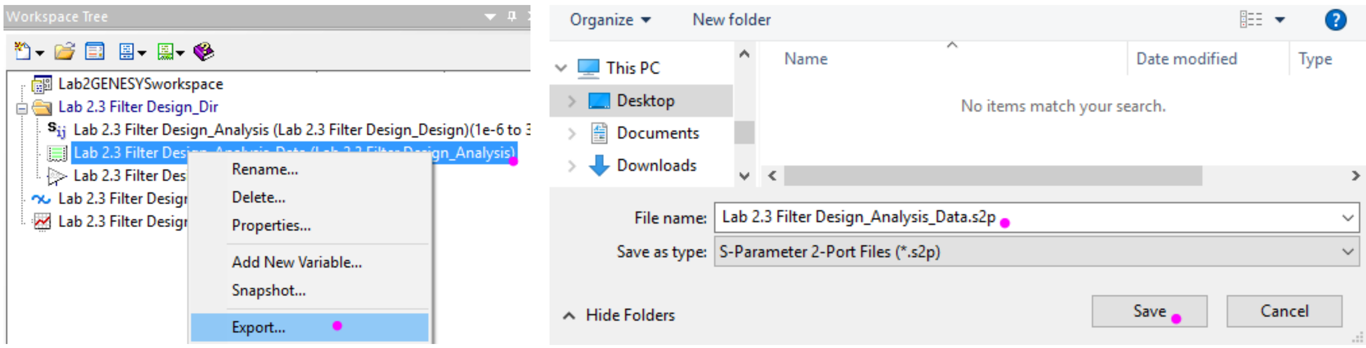
Instructor Answer:

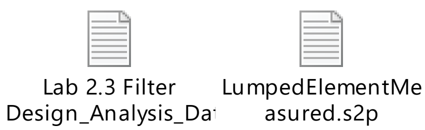
The insertion loss is very low and should not be a problem.

7.2 Plot Synthesized, Simulated and Measured Data on the Same Plot

1. Reopen the Genesys analysis schematic in **Lab2GENESYSworkspace.wsg**, right-click on Lab 2.3 Filter Design_Analysis_Data (Lab 2.3 Filter Design_Analysis), and export the **.s2p** file as shown below.

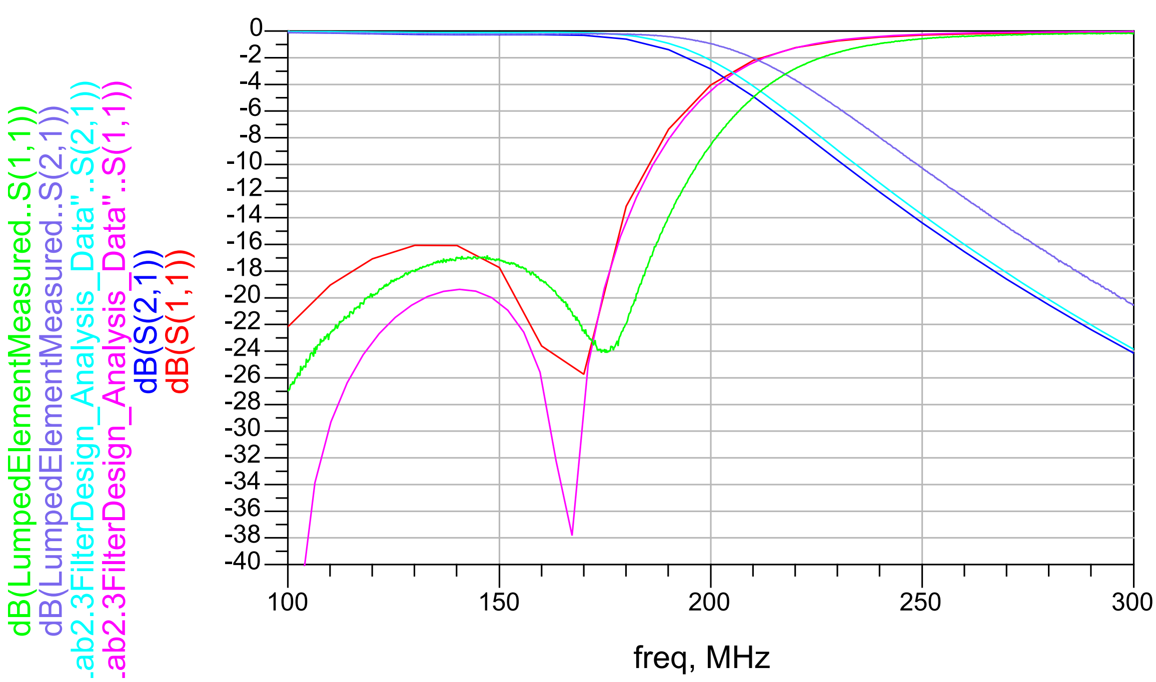
   Example data files from Genesys and from the FieldFox are provided.





2. Reopen the ADS workspace **Lab2workspace_wrk** and your **Simulate_EM_LPF_5-Pole_v1** data display, **convert with the Data File Tool…** and add the Genesys-simulated and measured **.s2p** files to the graph for comparison. A sample measured file is provided. Why does the measured filter have a higher cutoff than the ideal or simulated? Discuss your results.

   Hint: Use markers with .



Instructor Answer:

The added markers highlight the three traces:

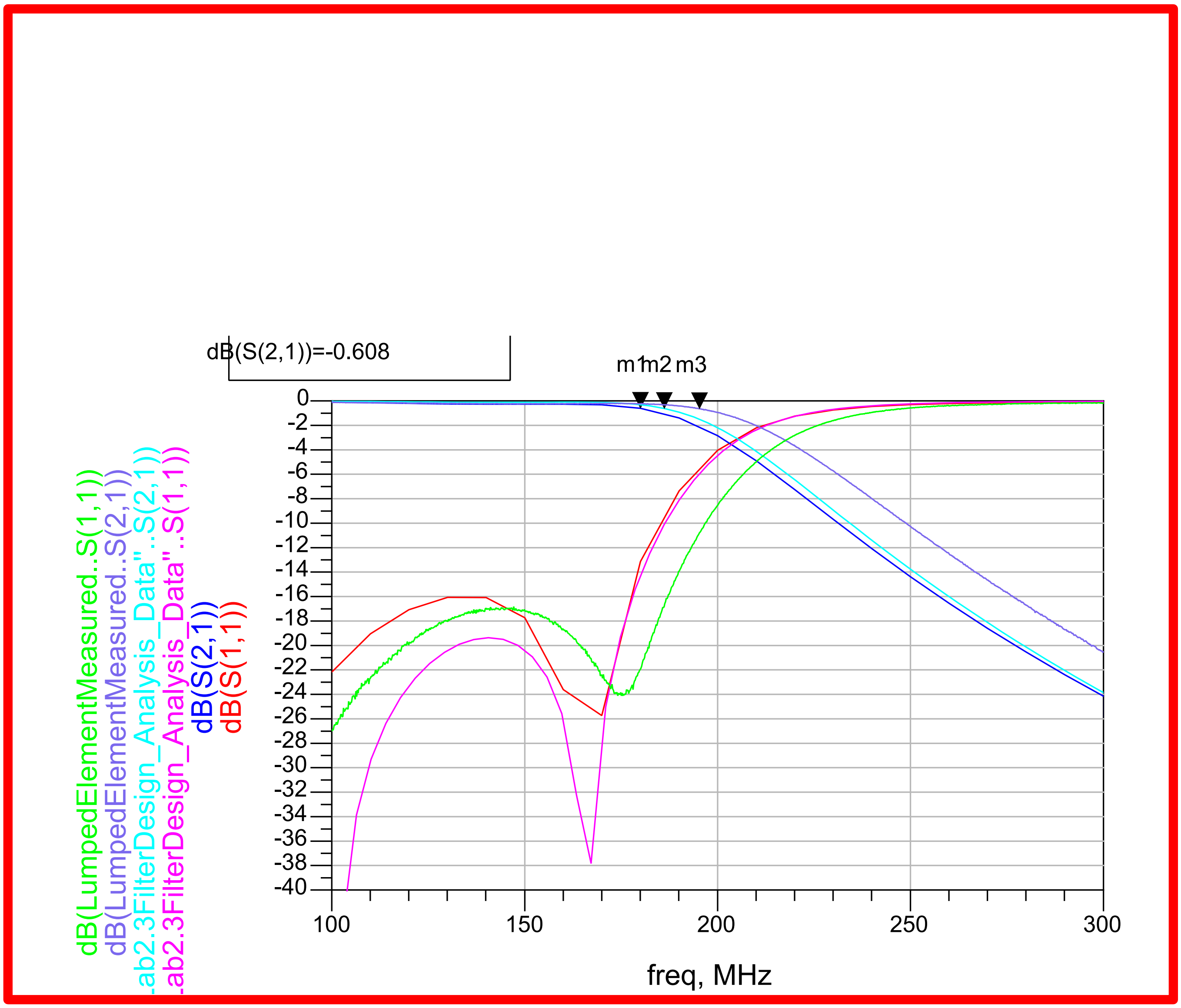
m1: ADS EM Simulation with 3D-simulated inductors and circuit traces

m2: Genesys Ideal Simulation with Lumper Element models only

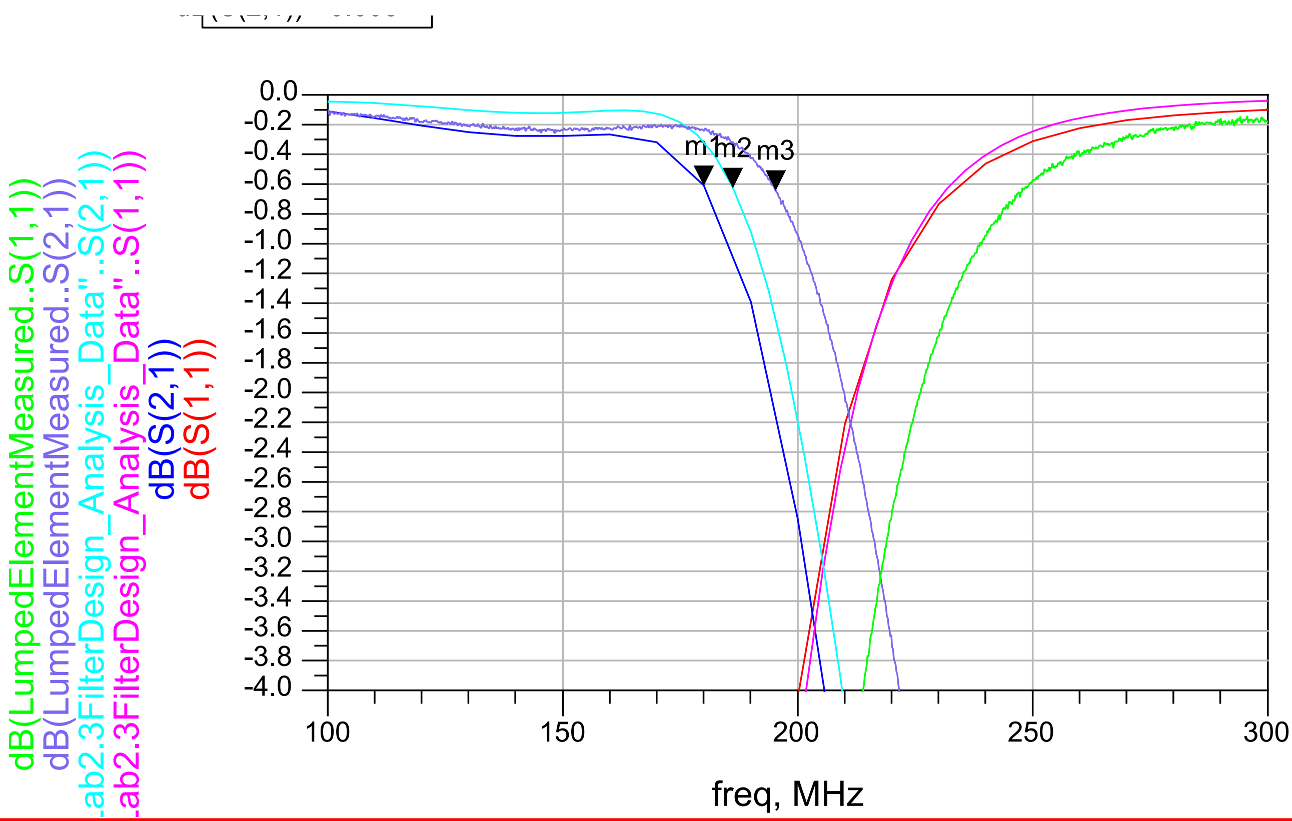
m3: Measured

The measured filter's cutoff may be higher that the ideal or simulated because the inductor coils may be spread too much (by the previous student?) producing a lower inductance and hence a higher cutoff according to the simple 2-pole equation for cutoff.

$$fc = \frac{1}{2\pi\sqrt{LC}}$$



Same plot with higher resolution.



7.3 Tune the LPF by Hand

1. Ensure that you are displaying both S21 and S11 as large as possible on the same display effects.
2. Use a non-metallic pick (such as a toothpick) to gently and very-slightly spread the coils of the two inductors in the filter while watching the FieldFox display.
3. Press the coils closer together using two picks.
4. Describe the changes of the filter response.

Instructor Answer:

The measured filter's cutoff increases when the inductor coils are spread to produce a lower inductance and hence a higher cutoff. The cutoff decreases when the two ends of the coil are pressed together.

7.4 Select the IF Filter

Although the lumped element filter has better insertion loss and may have sufficient rejection at 337 MHz, its size and cost may make it unsuitable for use in mass-produced mobile systems. You will choose the second-best filter, the SAW filter, for the 5G n3 Receiver.

Since this filter has significantly higher insertion loss, how will the radio design proceed?

Instructor Answer:

1. Make up for the extra loss in the subsequent IF and digital filters
2. The mixing products at mf_c-nf_{lo}, where m and n = 2, 3, …, the second, third, and so forth may fold back to near zero frequency after the IF filter. For this reason, the IF filter will have to reject DC which is a characteristic of the BAW but would have required a dc-blocking capacitor in front of or after the lumped element filer.
3. The IF filter characteristic limits the noise and can perform the anti-alias function for the sampling ADC after the IF filter.

Post-Lab Writeup

1. Provide screen captures of all measured data in a single document
2. Label each plot according to the lab step where it was captured.
3. If your results do not match your expectations, explain why.

Appendix A: FieldFox Calibration

Please see Appendix in the first Lab Sheet.

Appendix B: Saving Data on the FieldFox

Please see Appendix in the first Lab Sheet.

This information is subject to change without notice.

Edition 3, May 2023

Published in Malaysia
www.keysight.com