CUBESAT GROUND STATION RADIO FREQUENCY CHAIN - ELECTRICAL SYSTEM

by

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ECE4416 Electrical/Computer Engineering Design Project

Final Design Analysis and Test Report

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1. Final Analysis of Design Concept

The group has revised the preliminary design of the Ground Station RF chain to reflect changes in the design of the components and the placement of these components throughout the chain. The final iteration of the RF chain design is a result of refining the system level design criteria. Refer to Figure 1 for a diagram of the revised RF chain.

Software Defined Radio (SDR)

The SDR is a software based radio communication device that allows for versatile and efficient design of the RF chain. The SDR will be programmed to emit a signal within the Western CubeSat team's licenced frequency band, which is within the amateur radio band.

Transmitting Arm Bandpass Filter

This bandpass filter is required to filter the transmitted signal immediately following the SDR. The Ground Station is not allowed to transmit signals outside of the purchased frequency license. Therefore, this bandpass filter will be designed to eliminate spectral leakage outside of this frequency band that would interfere with other users in the amateur radio band. The design requirements for this bandpass filter will include a centre frequency of 436.5MHz and a bandwidth of 24kHz as expected in the frequency license. This filter will be designed as a digital filter implemented in the SDR.

Transmitting Arm Notch Filter

The signal emitted from the SDR may contain unwanted harmonic frequencies [2] due to having a high transmission power, and from the SDR's internal clock bit rate. If the bandpass filter following the SDR does not eliminate all of the harmonic frequencies, a notch filter will be implemented after the bandpass filter to eliminate the remaining harmonics. Like the bandpass, the notch filter will also be digital and programmed directly into the SDR.

Transmitting Arm Power Amplifier

The power amplifier following the notch filter will need to amplify the transmitted signal to reach a power of approximately 1W. This level of power is needed for the transmitted signal to reach the CubeSat in space. Noise insertion of this amplifier will be calculated after testing, and the amplifier must be impedance matched in order to ensure maximum power transfer [3]. To reach the 1W power requirement, the RF chain design may require a chain of multiple power amplifiers. This concept will be further explained in the Prototype Fabrication section of this report.

Junction Circulator

The junction circulator will connect the transmitting and receiving arms of the RF chain, ensuring the transmitted and received signals are kept separate, preventing signal leakage between the arms that could potentially damage circuit components.

Central Arm Bandpass Filter

Higher up on the central RF chain following the junction circulator will be another bandpass filter. This bandpass filter is required when receiving a signal, to protect the junction circulator which has an input range of 10 MHz and 0dB attenuation. Therefore the design requirements of this bandpass filter include a 10 MHz bandwidth from 431MHz - 441MHz. Initial testing of analog bandpass filters using inductors and capacitors resulted in poor performance, unrealistic component values and undesired bandwidth. The final design iteration must consider the use of transmission lines to implement this bandpass filter.

Surge Protector

A surge protector will be placed after the bandpass filter towards the top of the RF chain. The surge protector will ensure any power surges from lightning strikes do not damage any components in the Ground Station chain.

Polarity Switch

The polarity switch will be placed between the surge protector and the antenna in the RF chain. It will serve the purpose of directing transmission signals emitted by the antenna in a specific direction of propagation, and it makes the signal beam more directive [4].

Antenna

The antenna will have a Yagi Uda configuration and will be situated at the top of the RF chain. The antenna will perform two main functions. During signal transmission, the antenna will take in the electrical energy it receives from the transmitting arm of the Ground Station, convert it into electromagnetic (EM) energy, then radiate this energy outwards into space as EM waves. When receiving a signal, the antenna will accept EM energy from its surrounding environment, convert it into electrical energy, and feed it down into the receiving arm of the Ground Station.

Receiving Arm Low Noise Power Amplifier

The first component following the junction circulator in the receiving arm of the Ground Station will be a low noise power amplifier. This component will be needed to amplify the weak and attenuated signal received from the CubeSat. Amplifying the power of the received signal is needed to recover the information imbedded in the signal for further processing [3]. It is important that this power amplifier is

‘Low Noise’ in order to avoid adding additional noise to the received signal. Again, this amplifier will need to be impedance matched to ensure maximum power transfer.

Receiving Arm Bandpass Filter

The final bandpass filter will be placed between the low noise power amplifier and the SDR on the receiving arm of the Ground Station. The purpose of this bandpass filter is to limit the bandwidth of the received signal even further, to a centre frequency of 436.5 MHz and 24 kHz bandwidth. This bandwidth limitation is needed in order to eliminate any other unwanted signals and improve signal to noise ratio of the received signal. Like in the transmitting arm, this bandpass filter will be designed as a digital filter, programmed into the SDR’s receiving side.

2. Prototype Fabrication

The Capstone working prototype will include components beginning with the SDR and terminating after the central arm bandpass filter. Refer to Figures 2 and 3 to review the block diagram of prototype’s transmitting and receiving components. Although the surge protector, polarity switch and antenna will not be included in the Capstone working prototype, these components will be implemented in future testing going forward with the Cubesat project. The transmitting and receiving sides of the prototype will be connected together using coaxial cable and the appropriate connectors.

*Refer to Table 1 in the Appendix for costs details.

Bandpass Filters

The two bandpass filters on the transmitting and receiving arms of the Ground Station will both be programmed into the SDR as a digital filters, therefore adding no costs to the project. The prototype of the central arm bandpass filter will depend on further design iterations and testing using transmission lines or analog components (i.e. currently an unknown number of capacitors, resistors, and inductors.).*

Notch Filter

The notch filter on the receiving arm of the Ground Station will be designed after signal transmission testing on the SDR. After testing to observe the signal that the SDR outputs, the team will then be able to determine what harmonic frequencies will need to be removed from the signal using the notch filter. This filter will be a digital filter programmed into the SDR.*

Power Amplifiers

Both power amplifiers on the transmitting and receiving arms of the Ground Station will be purchased. On the transmitting arm, to reach the power output requirement of 1W, a cascaded configuration of multiple power amplifiers will need to be implemented. Whereas on the receiving arm, only a single low noise power amplifier will be needed. This low noise amplifier will amplify the power of the weak incoming signal received from the CubeSat, to a level needed for optimal digital signal processing. Before purchasing any of these amplifiers, testing and analysis will need to be done on each component of the Ground Station chain in order to determine the noise temperature of the system. The noise temperature will indicate how much power is lost throughout the system, which will form the design requirements needed for each of the power amplifiers.

Junction Circulator

The junction circulator chosen for the Ground Station design is a coaxial circulator manufactured by UIY, that has model number UIYCC3538A431T441SF. The circulator is rated for up to 100W within a frequency band of 431-441MHz.*

Surge Protector

The surge protector that will be included in the RF chain is manufactured by PolyPhasor. It is a bulkhead coaxial RF surge protector with model number GT-NFF-AL. This model has a surge current of 20kA, max power of 90W and is effective in frequencies up to 6GHz.*

Polarity Switch

The selected polarity switch is the PS-70CM from M2 Antenna Systems, Inc. This specific model is a polarity kit designed to work with the chosen antenna, ensuring low insertion noise into the component itself. Since the switches were designed for NASA, they have a very broad range, from 100-500 MHz and handles power transmission of up to 150W.*

Antenna

The antenna will be a Yagi Uda configuration manufactured by M2 Antenna Systems, Inc. The antenna has model number 436CP16 compatible with the polarity switch kit, and has optimum gain between 432-440MHz.*

SDR

The SDR the team will be using in the Ground Station design has already been purchased by Western's CubeSat Team, therefore adding no cost to this project. This SDR covers a frequency range of 70MHz-6GHz and requires a DC input voltage of 6V. It has 2 transmitting and 2 receiving channels, and it is compatible with Linux, Windows and Mac operating systems. The team will program the SDR using MATLAB to transmit and filter the outgoing and incoming signals.

3. Validation and Testing Strategy

Western's CubeSat team has not yet obtained the license to transmit signals in the frequency band of 431MHz - 441MHz. Therefore, the testing will be performed in the Wi-Fi band ~900MHz.

Central Arm Band Pass Filter	Verification
Successfully passes required signal (~900MHz +/- 10MHz)	• Conduct frequency response analysis by varying signal generator or microcap simulation frequency between (~900MHz +/- 10MHz) and verify passband attenuation is roughly 0 dB
Receiving Arm Bandpass Filter	**Verification**
Successfully passes required signal (24 kHz bandwidth centered at ~900MHz)	• Conduct frequency response analysis using MATLAB of the designed digital filter. Verify passband attenuation is roughly 0 dB
Notch Filter	**Verification**
Determine Notch Filter Frequency Requirements from SDR output signal	• Program SDR to output signal at ~900MHz and 24kHz bandwidth • Record internal clock bite rate of SDR • Use Spectrum Analyzer to determine the frequency of harmonic outputs
Design digital notch filter to eliminate harmonic outputs if present	• Conduct frequency response analysis using MATLAB of the designed digital filter. Verify notch filter eliminates frequency harmonics determined in above step
SDR (Programmed in MATLAB)	**Verification**
Transmission Channel – Notch and Bandpass filter implementation	• Implement digital transmission arm bandpass filter in SDR output • Implement digital notch filter in SDR output and connect to Spectrum Analyzer • Transmit a test signal in the Wi-Fi band at ~900MHz • Verify all harmonic outputs are eliminated • Verify transmitted signal is within 24kHz bandwidth • Record SNR
Receiving Channel – Bandpass filter implementation	• Send a test signal from signal generator into receiving arm in the Wi-Fi band at ~900MHz • Implement receiving arm digital bandpass filter in SDR • Verify input signal is within 24 kHz bandwidth • Record SNR

ANSYS

The team will use an engineering design and simulation software called ANSYS to model the radiation pattern of the Ground Station antenna. It will be essential to find the radiation pattern of the emitted signal in order to calculate the half power beamwidth, directivity gain and radiation angles θ and ϕ of the antenna. These variables are needed to calculate the noise temperature of the antenna, and to determine how much of the transmitted signal power will reach the CubeSat in space.

4. Preliminary Validation and Results Analysis

Central Arm Bandpass Filter

First Design Iteration - LC Bandpass Filter

The LC bandpass filter design shown in Figure 4 was designed using the lowpass to bandpass transformation for a Butterworth prototype. Although the frequency response in Figure 5 shows a bandpass of 10 MHz centred around 436 MHz as required, the component values are unrealistic and there is a 4 dB loss across the pass band. The lowpass to bandpass transformation often gives impractical component values [1]. As a result, this method of designing bandpass filters is not suitable. After consultation with Professor Primak, it was recommended that a LC Coupled Resonator Filter be considered.

Second Design Iteration - LC Coupled Resonator Filter

In coupled resonator filters, the centre frequency of the filter is determined by the frequency of the resonator, and the bandwidth is determined by the coupling between the resonators [1]. Figure 6 shows a capacitive coupled bandpass filter using 2 resonators. The frequency response in Figure 7 shows a non-0dB passband region. However, the component values are more realistic than the LC Bandpass Filter.

5. Conclusion

Going forward in the project, a list of finalizing tasks will be completed. To remain within the team's legal bandwidth, a recalibration of the prototype testing plan will be developed. Transmission lines will be used for the central bandpass filter instead of using analog components. Noise temperature equations for each block in the RF chain will be formulated along with the amplifier design specifications. Using the developed equations, the Ground Station will undergo various testing cycles. The design and testing process for the project is an ongoing task in which the team has dedicated their time to develop ideal techniques in order for the end product to be successful.

<u>**Appendix**</u>

Figure 1. Revised RF Chain Block Diagram

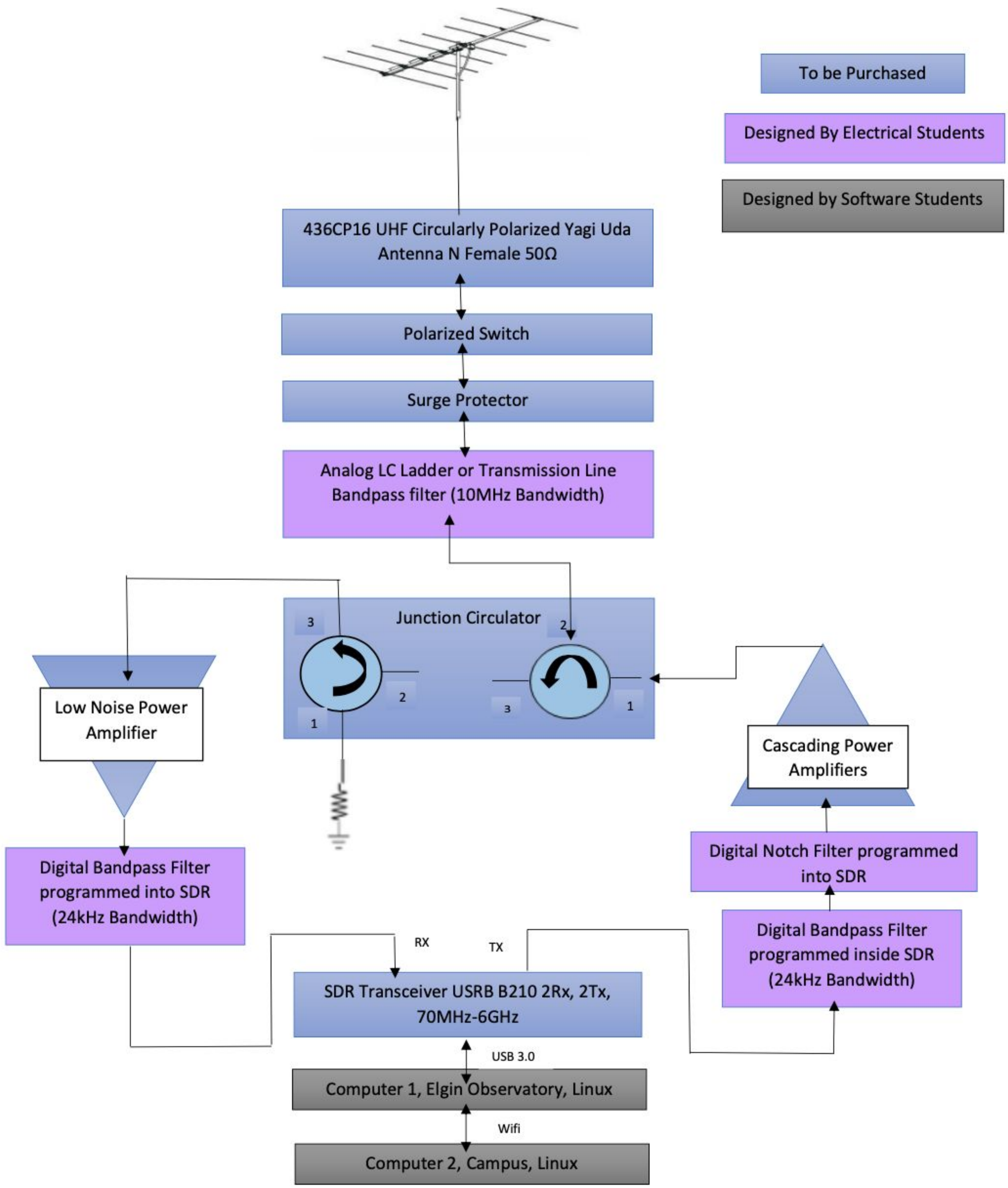


Figure 2: Transmitting Prototype

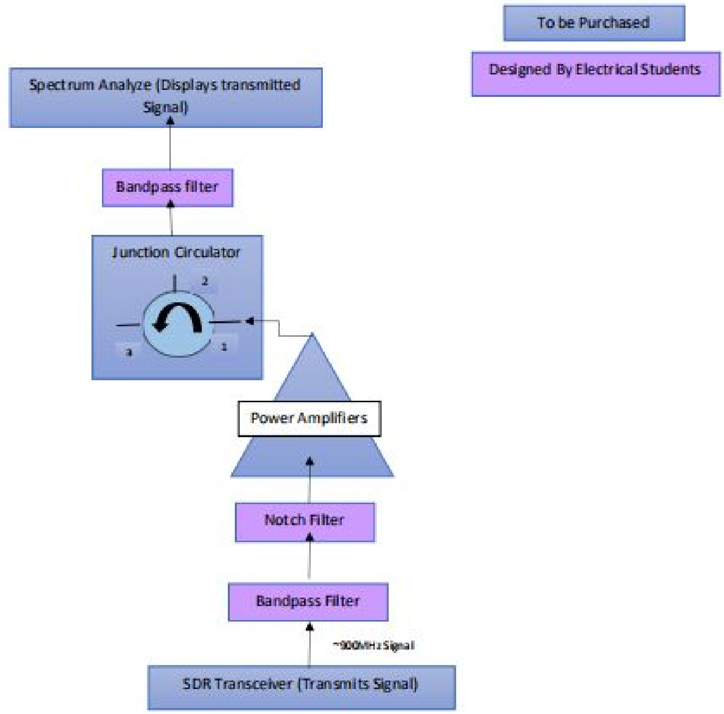


Figure 3: Receiving Prototype

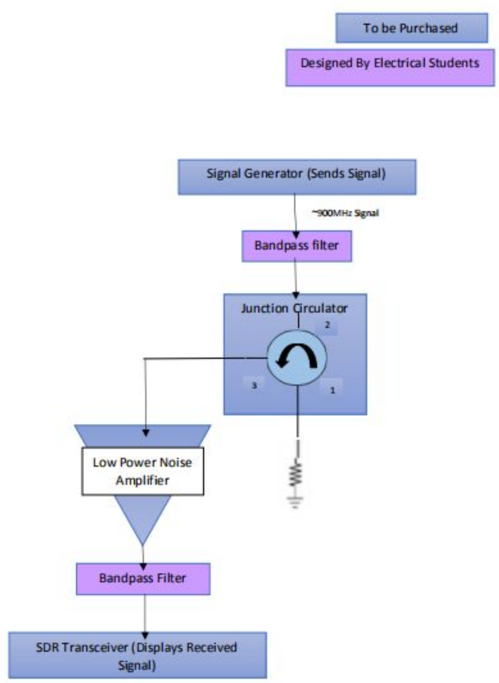


Table 1. Component and Price List

Component	Cost	Provided by Western CubeSat? (Y/N)
Bandpass filters	Model dependant	**N**
Notch filters	No additional cost	**N**
Power amplifiers	Model dependant	**N**
Junction Circulator	$45.00	**Y**
Surge Protector	$47.50	**Y**
Polarity Switch Kit	$245.99	**Y**
Antenna	$295.95	**Y**
Software Defined Radio	Model dependant	**Y**

Figure 4. First Iteration, Third-Order Butterworth Bandpass Filter

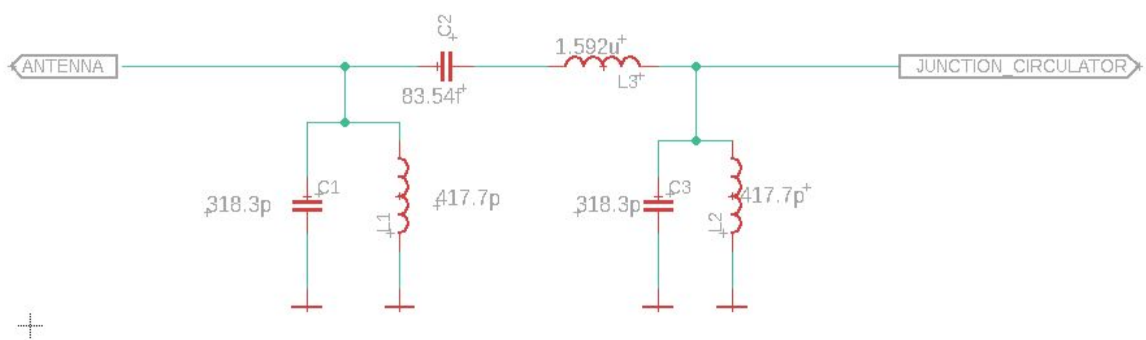


Figure 5. First Iteration, Third-Order Butterworth Bandpass Filter Frequency Response

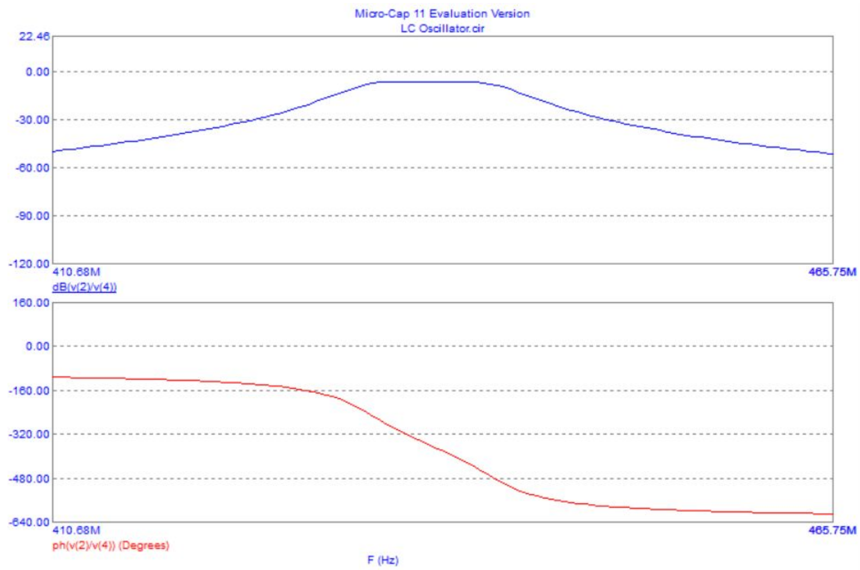


Figure 6. Second Iteration, LC Coupled Resonator Filter

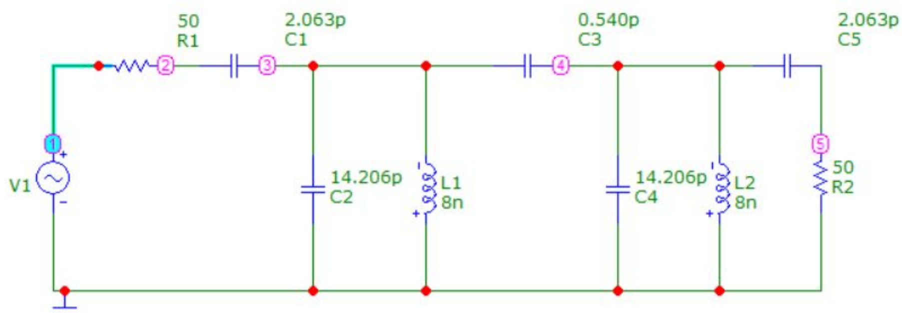
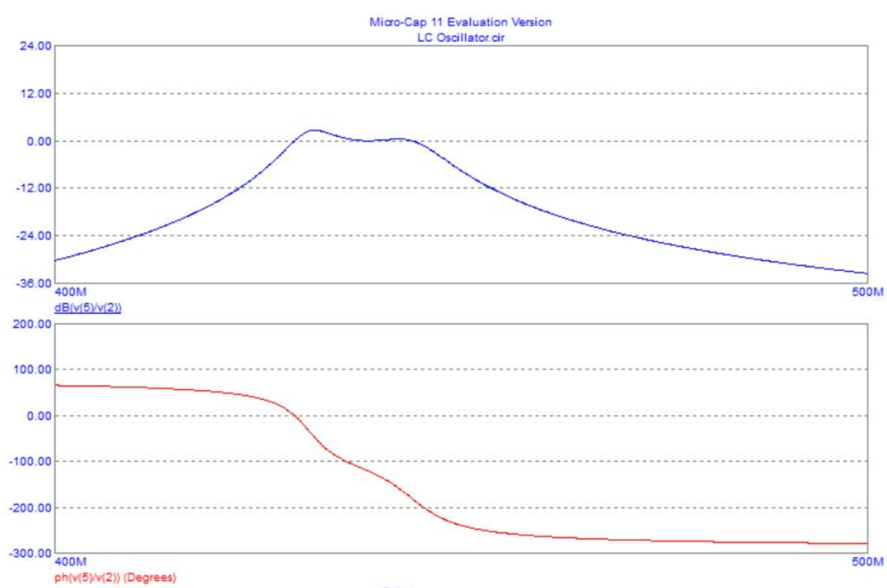


Figure 7. Second Iteration, LC Coupled Resonator Filter Frequency Response



References

[1] High, Q., Frequencies, C., & High, M. (2009). Chapter 7 RF Filters Introduction, 1–26.

[2] N. Mitchell, "Electrical Capstones Definitions," pp. 1–20, 2019.

[3] What is a Power Amplifier? Types, Classes, Applications. (2018, February 5). Retrieved from www.electronicshub.org

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[5] N. Mitchell *et al*, "UHF-LinkBudget-Western," pp. 1–12, 2019.