VHF Radio Beacon For CubeSAT

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Design Document for ECE 445, Senior Design, Spring 2013

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26 February 2013

Project No. 10

Contents

1 Introduction

1.1 Statement of Purpose

This project entails designing a backup communication system for a CubeSAT style satellite. The beacon, consisting of an FM transmitter circuit, will allow a terrestrial antenna to locate the satellite as it orbits around the earth. In addition to enabling location of the satellite, the beacon will transmit status data encoded in AFSK tones.

In general, size, power, and environmental factors (vibrational tolerance and thermal management) will play a crucial role in this project. If designed correctly, our project has the potential to be flown into space and operate for an indefinite period of time. The chance of our project actually flying on a rocket and operating in orbit for an extended period of time is reason enough to warrant interest.

1.2 Features

- 250 mW total power consumption
- 100 mW transmit power
- PCB Dimensions less than 3.5 by 1
- Survive vibrations from a rocket launch
- Withstand space environment
- Design for future development
- AFSK tone conversion and transmission

1.3 Benefits

- Tunable from 144-148 MHz in 6.25 kHz steps before launch
- Ability to locate satellite in orbit via terrestrial antenna
- Provides backup communications and status
- PIC-based to support legacy hardware
- Small size
- Power management capability

2 Design

2.1 Block Diagram

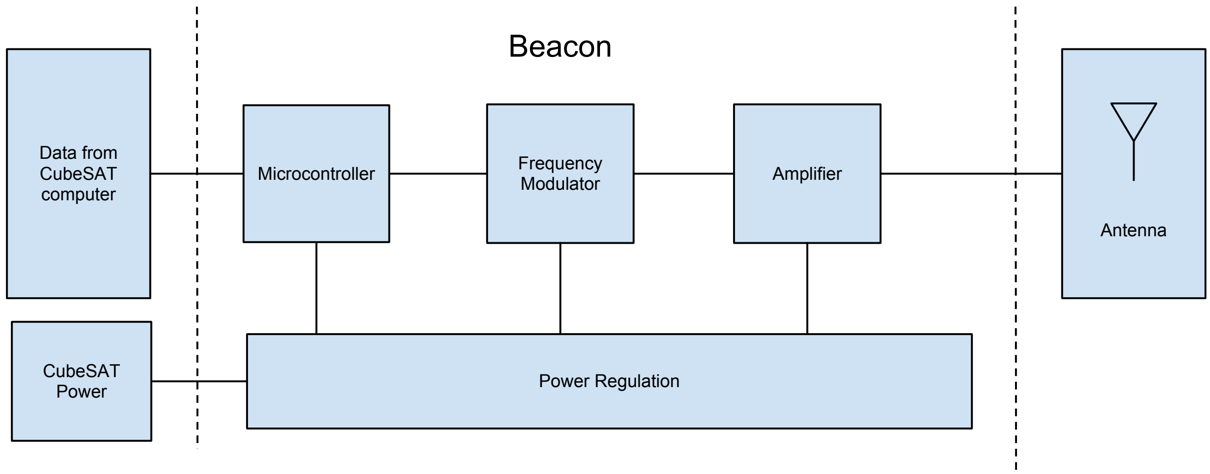

Figure 1: System block diagram

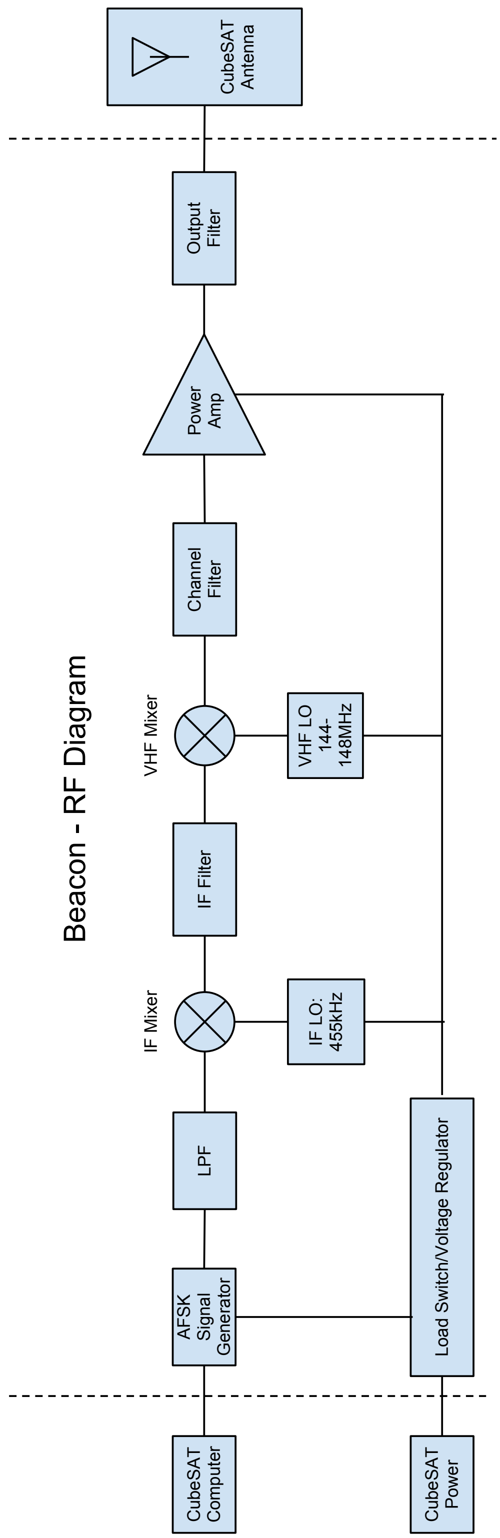

Figure 2: A more detailed block diagram of the transmitter.

2.2 Block Descriptions

2.2.1 Overview

- **Microcontroller**: Provides control for the system. This control includes turning devices on/off, AFSK tone generation, and communication with the CubeSAT main computer.

  1. AFSK Signal Generator: Interprets data from the CubeSAT onboard computer and converts data into AFSK tones. This conversion is achieved via a special DAC onboard the microcontroller.
  2. System Control: The microcontroller is the brain of the beacon. It will communicate with the CubeSAT main computer, control data transmission rates, and determine when devices can be powered on/off to conserve energy.

- **Frequency Modulator**: The data from the CubeSAT main computer is to be transmitted using FM as per the needs of the satellite. The Frequency Modulator unit will take the analog signal generated by the microcontroller and modulate the signal to 144-148MHz via frequency modulation. This unit will also incorporate a tuning ability so that a more specific frequency can be chosen from the operating range, preferably in 6.25 kHz increments.

  1. Low Pass Filter: This filter is used to smooth out the sine wave generated by the D/A pin on the microcontroller. Depending on the quality of the sine wave, a simple pi-filter scheme will be used. The most ideal case will be a simple capacitor.
  2. IF Mixer: A mixer is used to take the baseband AFSK signal from the low pass filter and modulate it up to a higher frequency. This modulation is necessary in order to filter out the image of the desired AFSK signal in later stages.
  3. IF Local Oscillator: This local oscillator generates the carrier frequency for use in the IF Mixer stage. It consists of a Colpitts tank oscillator circuit that is precisely tuned to 455kHz.
  4. IF Filter: The IF Filter module is needed to attenuate the image of the baseband AFSK signal. At XXX kHz, this filter will only allow one of the duplicate baseband signals to later stages.
  5. VHF Mixer: This mixer is used to modulate the IF signal to the 144-148MHz frequency range.
  6. VHF Local Oscillator: This local oscillator generates the FM carrier frequency for transmission in the 144-148MHz frequency band. It consists of a Colpitts tank circuit that is tunable to a region between 144-148MHz.
  7. Channel Filter: Because the VHF mixer stage again produces two signals, the IF and its image, a channel filter is necessary to allow only one of these signals to transmit.

- **Power Amplifier**:

  1. Amplifier: Boosts signal transmit power to a minimum of 100mW. This amplifier will consist of an RF amplifier IC that will be tuned to provide sufficient signal gain.
  2. Output Filter: Due to FCC regulations, spectral leakage outside of the designated band inside of the 144-148MHz region can lead to interference that disrupts communications with other satellites. A finely-tuned Pi-filter will ensure the output of the beacon is confined to its allowed bandwidth. From here, a coaxial, impedance-matched connection to the onboard antenna is made. This connection has been measured to have very low losses due to short cable lengths.

- **Power Management**:

  1. Load Switch: This circuitry will also include relays that can power stages on and off at the request of the microcontroller. One relay will be included for 3.3V power, and the other for 9V.
  2. Voltage Regulator: Changes and regulates all voltage levels to their required values. Since power and voltage coming from the CubeSAT power distribution system will be dependent on battery

charge levels, regulation circuitry is needed.

2.2.2 Microcontroller

PIC16 Microcontroller

Inputs: Data, clock, and chip-select inputs will be used to receive a fixed length packet of 80 bytes using SPI protocol. A power good signal will be input from an onboard voltage regulator. To enable programming, an In Circuit Serial Programming (ICSP) connector will be connected to the controller.

Outputs: A binary signal to the load switch of the voltage regulator and a sine wave representing a bit in the packet will be outputs. The SPI connection also allows for communication back to the CubeSAT computer.

Description: The microcontroller will be a PIC16LF508. This is microcontroller was chosen due to its very low power operation and onboard DAC capability that can generate the analog signals we need. It will be programmed primarily in C in Microchips MPLAB X IDE. Parts that need to be very fast may be written in assembly. Specifically, it may possible to get a cleaner sine wave if the DACs voltage level is switched in assembly rather than C. The microcontroller will act as an SSI slave device and receive data from the satellites main CPU. After it has read an entire packet from the CPU, it will generate a AFSK signal of the packet at 600 baud, using the frequencies 1.2 and 1.8 kHz. After finishing transmitting the data, it will send an acknowledgement back to the CPU. Figure 3 shows the microcontroller's general program flow. The microcontroller will also control the power to the transmitter. When there is no data to transmit, the microcontroller will send a signal to the voltage regulator to shut off the power to the other components. A schematic of the microcontroller is shown in fig. 11 (page 13).

AFSK Signal Generator

Description: Signals of 1.5kHz and 2.3kHz will be generated. These tones will respectively serve as binary 0 and 1. Generation of these signals is provided by a DAC integrated into the PIC16. In order to minimize system resources, assembly code is used to quickly and efficiently generate these signals. A sample waveform is shown in fig. 4.

2.2.3 Frequency Modulator

Low Pass Filter

Input: The baseband, sinusoidal signal generated by the PIC16 DAC will enter the FM module through the low pass filter.

Output: A smoothed-out and more spectrally clean version of the signal generated by the PIC16 will be output to the next stage of the FM module.

Description: The low pass filter is necessary because of the inherent inaccuracy of Digital-to-Analog conversion. Due to the relatively low resolution of the onboard DAC, the granulated sine-wave approximation generated by the PIC16 will produce noise and higher-order signal harmonics that could potentially ruin the desired signal beyond recognition. To account for this behavior, a Pi-filter topology will be used for this stage of the FM modulator, as shown in figure 5 (page 22). A Pi-filter yields the flexibility to swap out components and fine-tune the transfer characteristics should the simulated filter behave incorrectly.

IF Mixer

Input: A smoothed-out baseband sinusoid from the Low Pass Filter will enter as an input signal. The IF carrier signal generated by an onboard oscillator will be input to the mixer as the second input.

Output: A single output consisting of two FM signals, each at the 455 kHz carrer frequency ± the respective baseband frequencies.
Description: A mixer is a necessity in any FM radio circuit. The mixer modulates the baseband signal to a higher, intermediate frequency (IF). This intermediate modulation allows for greater distinction and filtering of the baseband signal and its image. IF generation and mixing is necessary because constructing a filter with sufficiently narrow bandwidth unwanted baseband image. The effect of having two stages of mixing is shown in figure 6.
The mixer chosen to perform this task is the NXP Semiconductor SA602. The SA602 as shown in figure 7 was chosen for a few reasons, one of which is the convenient integration of parts. Since size is a critical requirement for the beacon, a two-for-one mixer-oscillator was viewed as a great deal both in terms of simplicity and device footprint. Additionally, this IC will be used again in the later VHF mixer stage, further decreasing the complexity of the design. It will be used here to interpret signals in the kHz range, while in the next mixer stage MHz signals will be used.

IF Local Oscillator
Input: The local oscillator is directly integrated into the SA602, so all that is required is an external resonator circuit.
Outputs: The local oscillator generates a signal that is directly fed into the IF Mixer stage.
Description: The local oscillator chosen to use for IF is a simple colpitts oscillator.. A 455kHz signal is generated with the primary goal of filtering the signal image present at this stage of the FM transmitter. Using the tank circuit of figure **??**, it is known that the resonant frequency is given by equation 7. Choosing inductance $L = 1$ mH, it can be seen that the lumped series capacitance values are:

$$C = \frac{C_1 C_2}{C_1 + C_2} \tag{1}$$

$$f_0 = \frac{1}{2\sqrt{LC}} \tag{2}$$

$$C = \frac{1}{(2\pi f_0)^2 L} \tag{3}$$

$$C = \frac{1}{(2\pi 455 \text{ kHz})^2 \times 1 \text{ mH}} \tag{4}$$

$$C = 122 \text{ pF} \tag{5}$$

The capacitors that make up the equivalent capacitance above will be adjustable in order to account for capacitor manufacturer tolerance. The 455 kHz oscillating frequency needs to be as precise as possible, so the resonating capacitors will consist of an adjustable pair of 100-200pF capacitors.

IF Filter
Input: A single FM signal consisting of two baseband signals mirrored around the IF oscillator frequency.
Outputs: The same FM signal, but with one of the baseband components attenuated.
Description: The critical piece of all IF components is the IF filter. Without it, the baseband signal and its image would be too close together to filter out at the VHF mixer stage. Thus, the IF filter is carefully chosen to attenuate the image of the baseband signal.
In order to save PCB-real estate, a monolithic solution is normally preferred to the predominating Pi Filters of the beacons design. Fortunately, a much smaller topology has thankfully been integrated into a single-chip solution by Murata as the CFWLB455KGFA-B0 Ceramic Filter. It is a passive component, so the only

power that is absorbed by the device will be due to signal insertion losses. This component is essentially a very low bandwidth ceramic filter that is used to eliminate the signal image. The Murata filter has an incredibly steep 3-dB rolloff as seen in figure 8 and was chosen above other filters due to this characteristic. In fact, the bandwith is so small that the IF carrier frequency may have to be tuned to slightly less than 455kHz to ensure that the desired signal is not attenuated!

VHF Mixer

Inputs: A filtered version of the IF signal consisting of a sinusoid at around 455 kHz from the IF Filter will enter as an input signal. The VHF carrier signal generated by an onboard oscillator will be the second input to the mixer.

Outputs: A single output consisting of two FM signals, each at the 144-148MHz carrer frequency ± the respective baseband frequencies.

Description: Similar to the IF Mixer, the VHF Mixer stage is used to further modulate the baseband signal to a higher frequency. The SA602 mixer-oscillator as depicted in figure 7 will be used as the basis for this stage. The VHF local oscillator is a closely related module as it generates the carrier frequency for use in frequency modulation.

VHF Local Oscillator

Outputs: The local oscillator is directly integrated into the SA602, so all that is required is a resonator output. **Description:** The local oscillator chosen to use for VHF is again a tank circuit as shown in figure 9 (page 26), the main driver of which is located inside of the SA602. This time, however, the frequency is much higher at 144-148MHz, and as per the needs of the CubeSAT team needs to be tuneable on-the-fly immediately before launch.

Performing a capacitance calculation similar to the IF local oscillator tank circuit and choosing $L = 1uH$, and $f_0 = 144$ to 148 MHz range:

$$C = \frac{C_1 C_2}{C_1 + C_2} \tag{6}$$

$$f_0 = \frac{1}{2\sqrt{LC}} \tag{7}$$

$$C = \frac{1}{(2\pi f_0)^2 L} \tag{8}$$

$$C = \frac{1}{(2\pi \times 144 \text{ MHz})^2 1 \text{ uH}} \tag{9}$$

$$C = 1.22 \text{ pF @ 144 MHz} \tag{10}$$

$$C = 1.16 \text{ pF @ 148 MHz} \tag{11}$$

Thus, the capacitors will need to provide a capacitance in the range of 1.16-1.22 pF. To accomplish this adjustability, two 1.5-3pF variable capacitors will be used in the tank circuit..

Channel Filter

Input A single FM signal consisting of two baseband signals mirrored around the VHF oscillator frequency.

Outputs: The same FM signal, but with one of the baseband components attenuated.

Description: Due to stringent frequency bandwidth allocation requirements, the beacon cannot afford to transmit any signals outside of the allocated region of the spectrum. This filter removes the signal image generated by the previous FM mixer stage. This filter is required to operate in a relatively strict regime, as

the image has to be vastly attenuated while allowing the signal to be transmitted. With an IF of 455kHz, the signal and its image will be located about 1MHz apart in frequency space. Thus, a relatively narrow 1 MHz bandwidth is estimated to sufficiently attenuate the image.
To achieve this filtering, a Butterworth filter was designed as shown in figure 13 (page 15). This filter topology yields great flatness at the center of the band as well as pronounced corner frequencies. Due to the ability of the beacon to transmit on various frequencies in the 144-148 MHz range, this filter has the necessity of tunability. Although the footprint of the design is increased when compared to a single filter, this design will allow for easy customizability to a specific frequency band.

2.2.4 Amplifier

Power Amplifier
Input: The input will be the baseband signal modulated at 144-148 MHz.
Outputs: An amplified version of the input signal up to or past 100mW (20dBm) of transmit power.
Description: The power amplifier stage is crucial for allowing the beacon to close the link with a terrestrial receiver. It has been shown through calculation and measurement by the CubeSAT team that 100 mW of transmit power is sufficient for this task [2].
The amplifier circuit also needs to function inside of the 144-148 MHz range and not introduce any deleterious harmonics into the signal.
The Texas Instruments THS9001 is an RF-Amp built for this purpose. It can provide more than 20dBm of gain with sufficient input signal strength, and is impedance matched at 50 Ω at both the input and output ends. Monolithic packages are again prefereable for the beacon due to stringent size and power concerns. Should the output power be determined to be too low for proper transmission at 100 mW, space in the circuit will be left to cascade an identical amplifier.

Output Filter
Inputs: The amplified 100mW signal.
Outputs: A signal that will finally be passed to the transmitting antenna via an onboard coaxial connection.
Description: The output filter provides a general cleanup of all parasitic IF, oscillator, and coupled frequencies that are still included in the signal. Spectral leakage is unwanted at this point, as it would cause harmful interference to other users of the 144-148 MHz frequency band. As with most other filters in the beacon, a Pi-topology will be used for this filter. The output impedance of the circuit will be 50 Ω to ensure an optimal match with the antenna. This matching will be accomplished by placing an L-pad depicted in figure 10 immediately before the coaxial connection. Because the output impedance of the RF amplifier will be 50 Ω, the input impedance of this stage needs to be 50 Ω as well.

2.2.5 Power Management

Voltage Regulator
Inputs: Battery power from the CubeSAT, as well as an ON/OFF control signal from the PIC16 Microcontroller.
Outputs: Power from the CubeSAT battery is passed out of this module and onto the proper PCB power plane.
Description: As its name implies, the voltage regulator provides a stable power source from which all 5V components will operate. While the CubeSAT solar batteries will supply a relatively safe and stable output voltage from 6-8V (est.), stricter regulation is critical to ensure the proper and repeatable operation of all filters and precisely tuned mixers. Thus, a regulated output of 5V has been chosen around which all devices

(excluding the PIC16 and relevant 3.3V logic) is based. The TI TPS77350 is a simple, standard, fixed voltage regulator that can fill this role, and can provide extra current should an emergency need arise.
In addition to simple regulation, a load switch is integrated into the TPS77350. A load switch is a convenient way to control power by simply turning the supply current on and off to all connected devices. By turning off power at the source as opposed to controlling every device on the beacon individually, power control is as simple as setting a timer on the PIC16.
Thus, the main reason this IC was chosen was yet again a two for one deal. Instead of using a separate load switch component, integration will save power and PCB area. The TPS77350 can fulfill both of these roles due to its low OFF current (< 1 uA @ 25 °C), low ON resistance ($< 1\ \Omega$), and high current supply capability (250 mA). The regulator also features reverse current protection so that the beacon can in no way harm the satellite itself.

2.3 Schematics

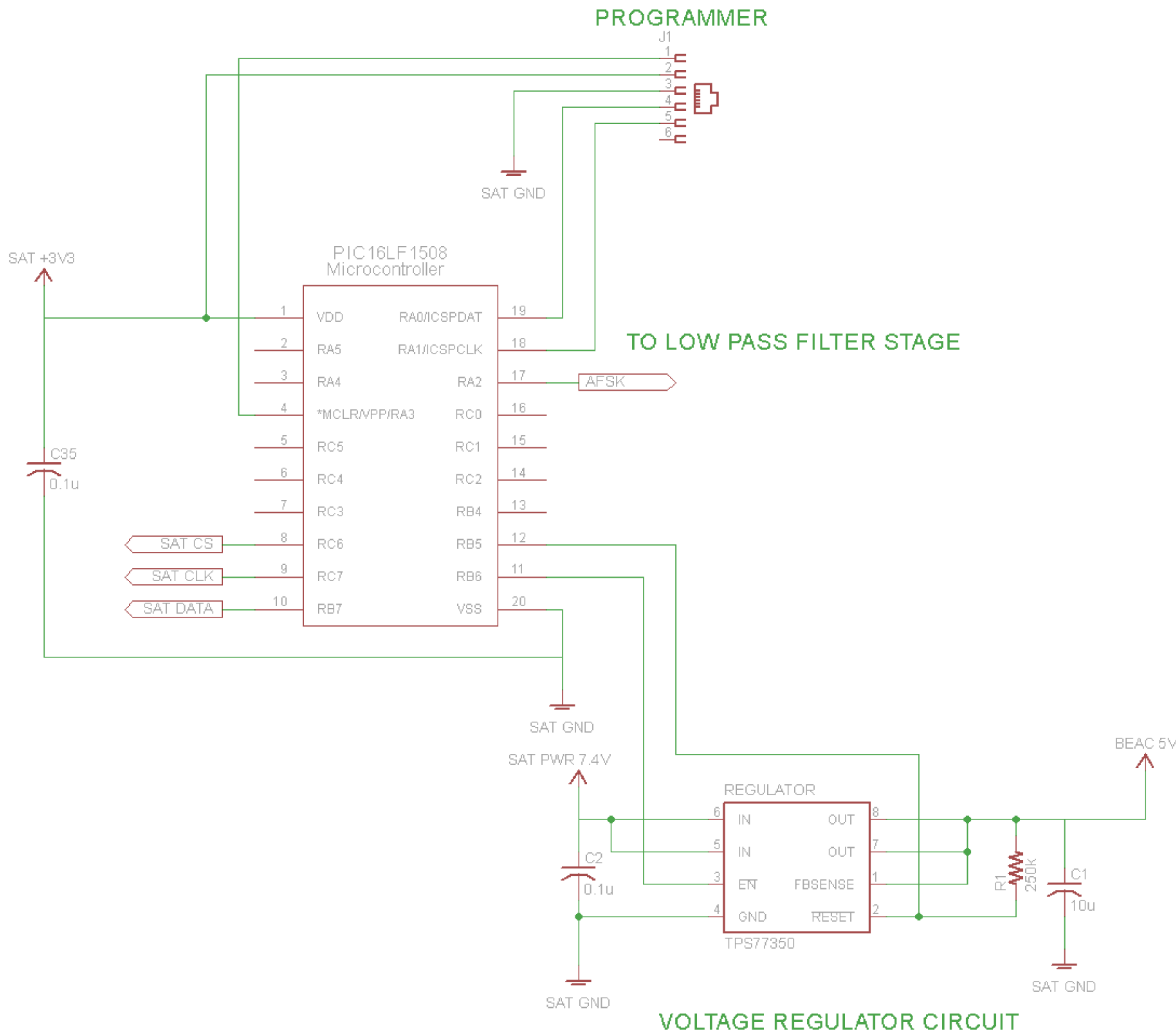

Figure 11: Schematic of the microcontroller and power control sections of the transmitter.

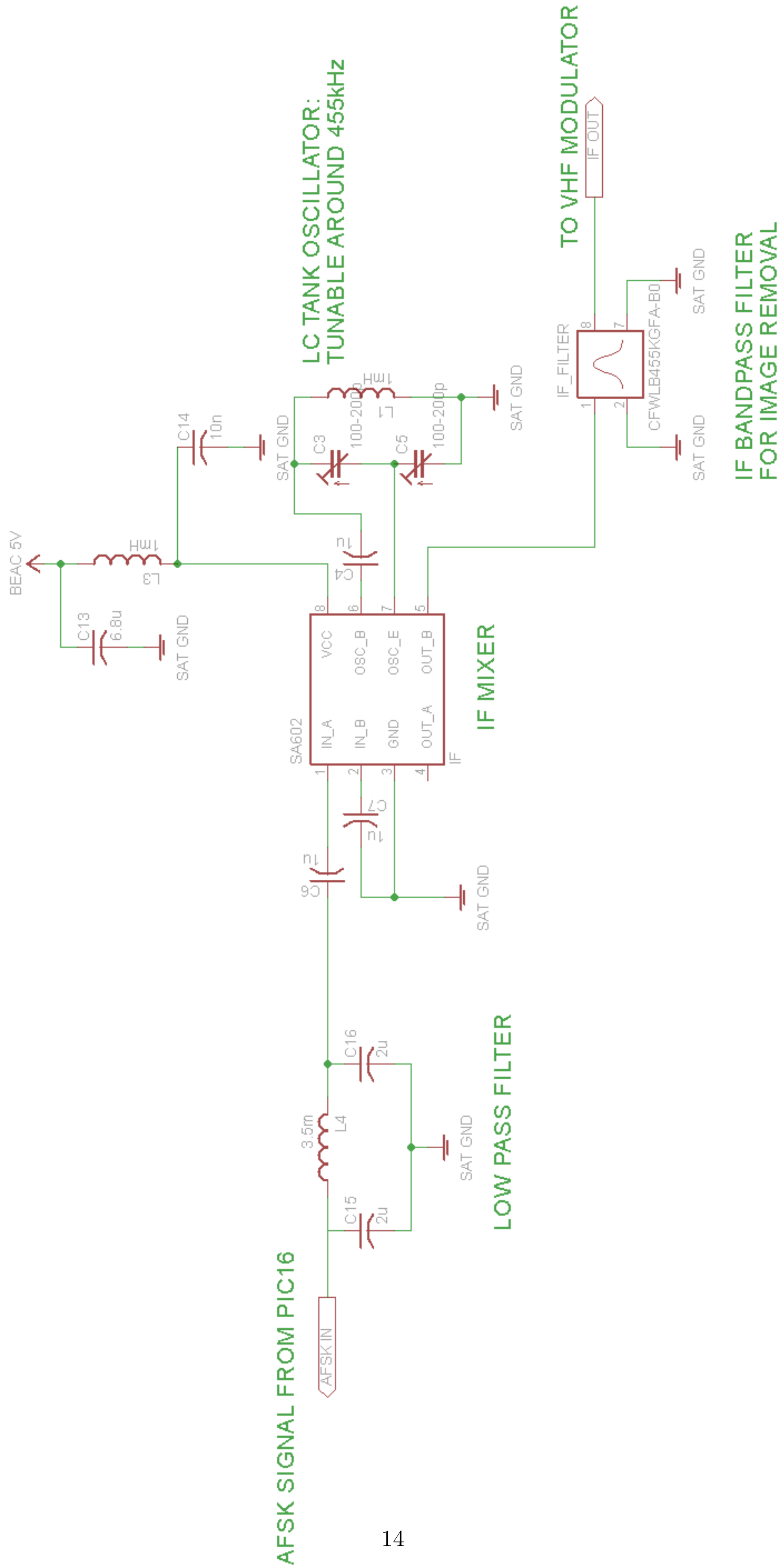

Figure 12: Schematic for IF (455 kHz) mixer.

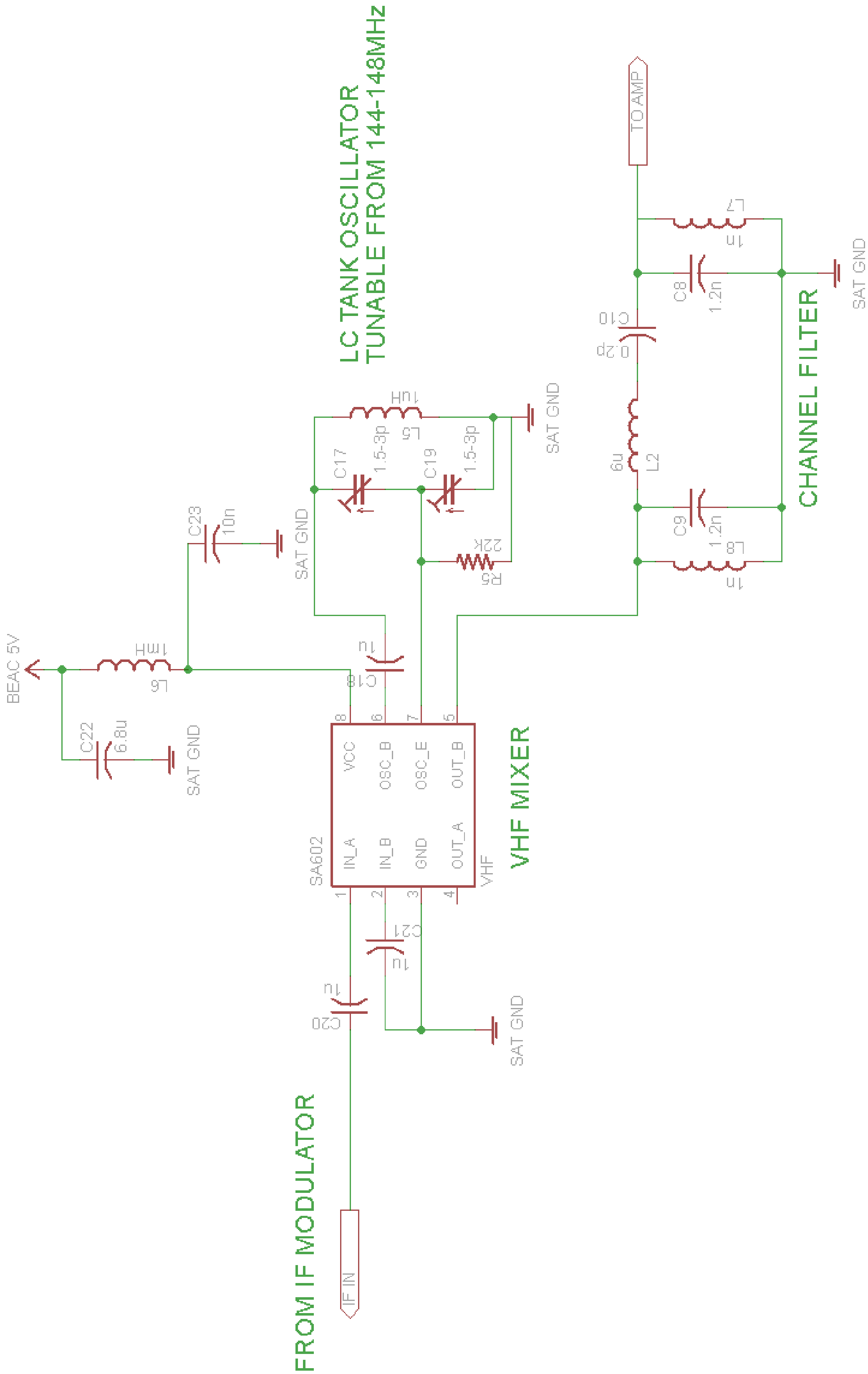

Figure 13: Schematic for VHF mixer. Modulates the IF signal to the transmission frequency.

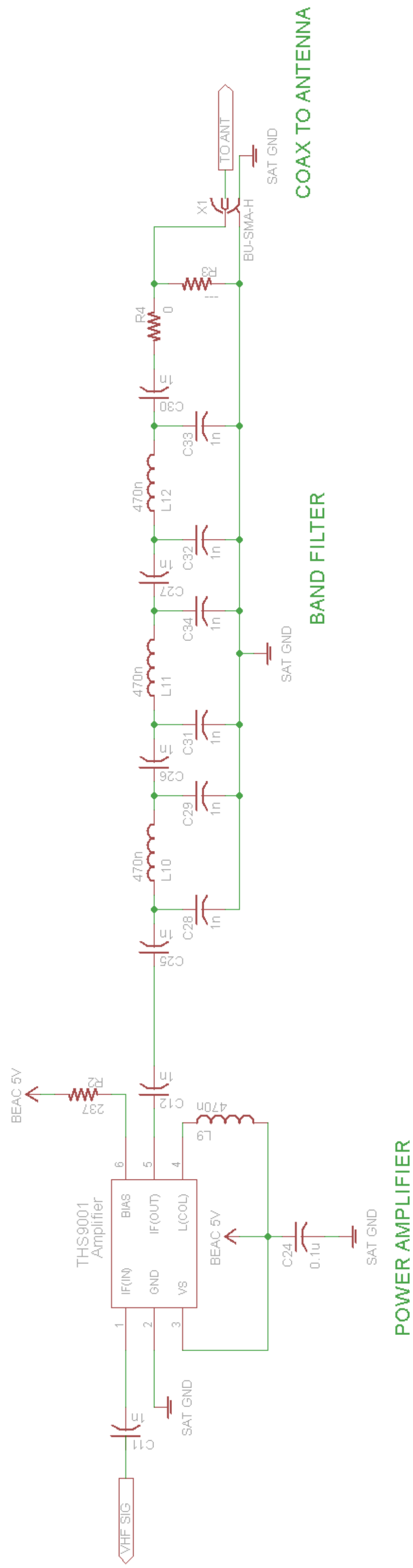

Figure 14: Amplifier and filter to drive antenna.

2.4 Calculations and Simulations

2.4.1 Link Budget

It is necessary that our beacon's signal be able to reach the antenna at our ground station. The beacon will transmit at 140 MHz. Using the free space model, we can calculate the maximum path loss:

$$\begin{aligned}\text{Maximum Path Loss} &= 32.4\text{ dB} + 20\log(d_{\text{km}})\text{ dB} + 20\log(f_{\text{MHz}})\text{ dB} \\ &= 32.4\text{ dB} + 20\log(8000)\text{ dB} + 20\log(140)\text{ dB} \quad [2] \\ &= 144.86\text{ dB}\end{aligned}$$

Our transmission power will be 100 mW, which in dBm is 20 $(30 + 10\log(0.1))$ [2]. The feeder loss for our transmitter will be quite low, since the radio is close to the antenna on the cubeSAT. We will assume this loss is about 0.2 dB and that the antenna's gain is about 2 dBI (which is reasonable for a whip antenna on a cubeSAT), so our effective isotropic radiated power should be about 21.6 dBm [2].

$$\begin{aligned}\text{EIRP} &= \text{Transmission Power} - \text{Feeder Loss} + \text{Antenna Gain} \\ &= 20\text{ dB} - 0.2\text{ dB} + 2\text{ dB} \qquad [2] \\ &= 21.8\text{ dB}\end{aligned}$$

To calculate the quality of our received signal we also need to know the polarization mismatch, the ionospheric propagation mismatch, the antenna's gain, the antenna's feeder loss, and the noise floor. We will let these be 3 dB, 1 dB, 12.34 dBI, 5.5 dB, and −130 dBm, respectively.

$$\begin{aligned}\text{Max Range Received Signal} &= \text{EIRP} - \text{Max Path Loss} - \text{Mismatch Loss} - \text{Propagation Loss} \\ &\quad + \text{Antenna Gain} - \text{Feeder Loss} \qquad [2] \\ &= 21.8\text{ dB} - 144.86\text{ dB} - 3\text{ dB} - 1\text{ dB} + 12.34\text{ dB} - 5.5\text{ dB} \\ &= -120.22\text{ dB}\end{aligned}$$

$$\begin{aligned}\text{Quality Assessment} &= \text{Max Range Received Signal} - \text{Noise Floor} \\ &= -120.22\text{ dB} - (-130\text{ dB}) \\ &= 9.78\text{ dB}\end{aligned}$$

So, at the ground station, we should expect a SNR of about 9.78 dB.

2.4.2 Simulations

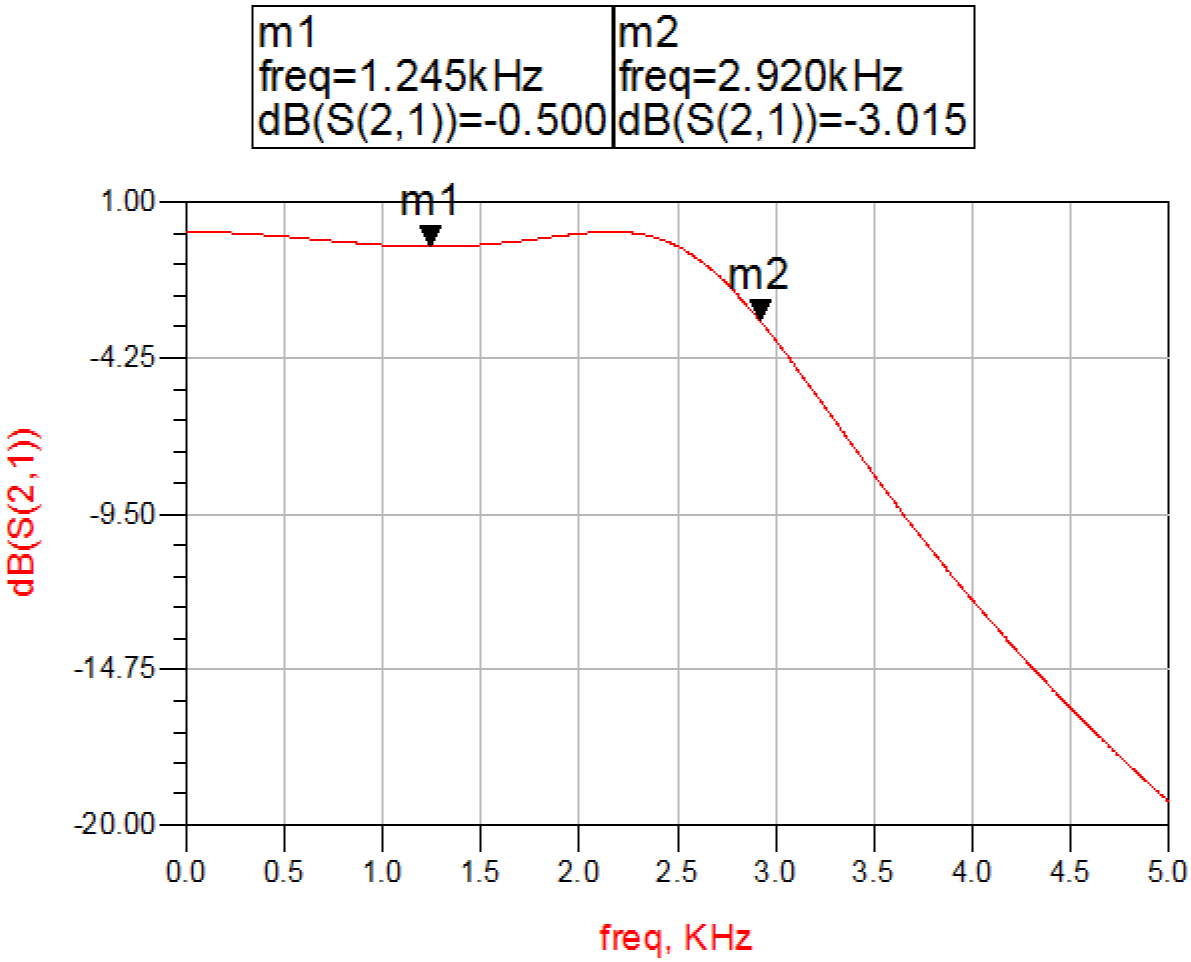

Figure 15: The frequency response of the lowpass filter (figure 5 on page 22).

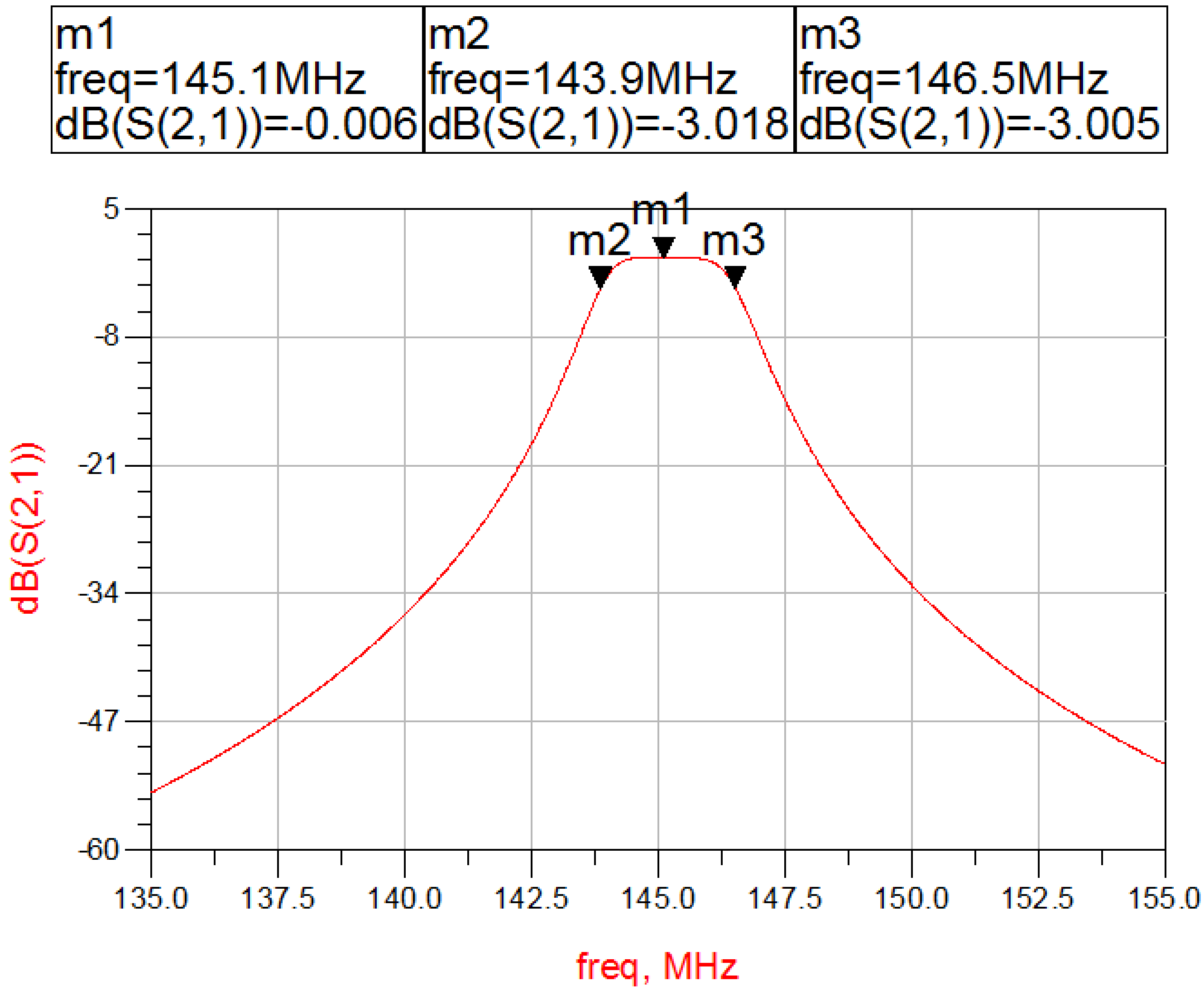

Figure 16: The frequency response of the channel filter (figure 13 on page 15).

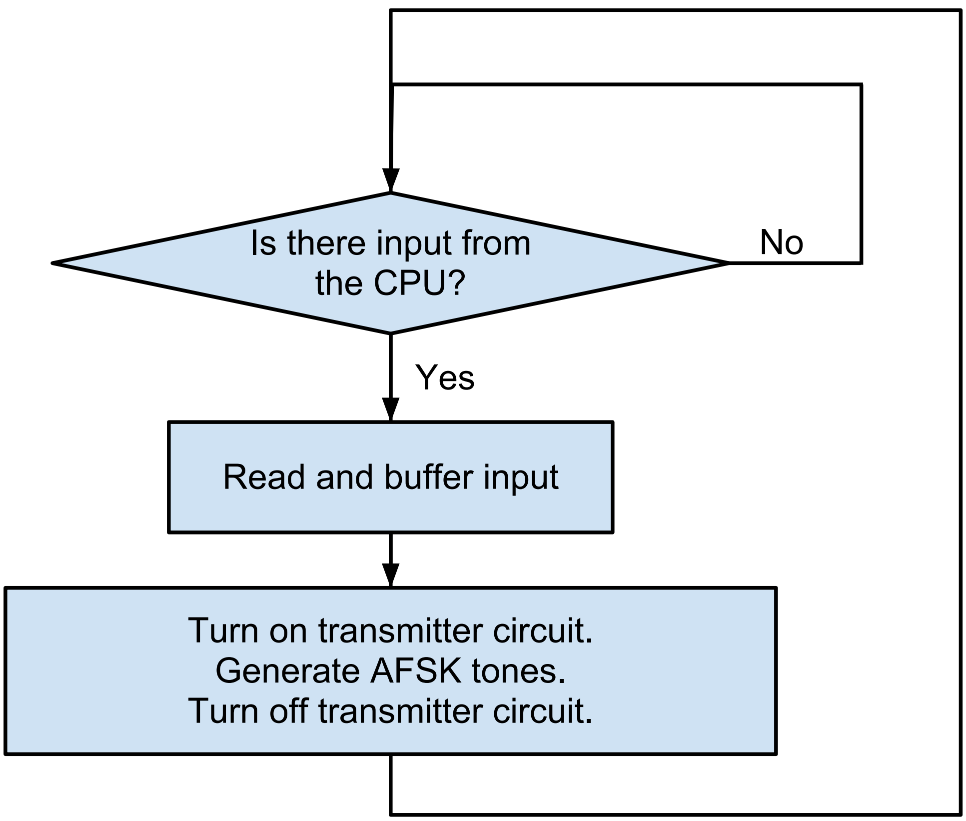

Figure 3: The operation of the PIC microcontroller

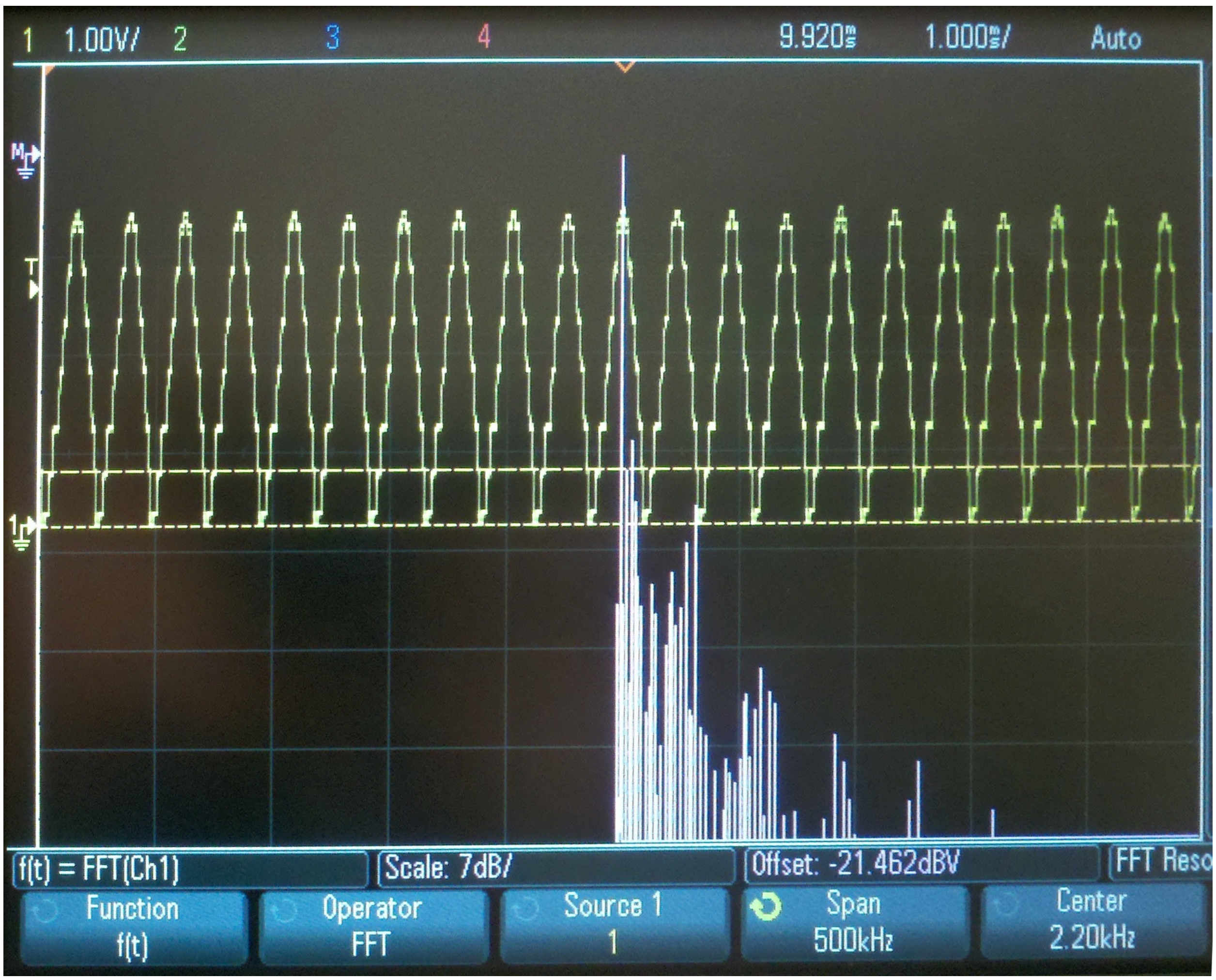

Figure 4: A sample 2.2kHz output sinusoid from the PIC16 DAC.

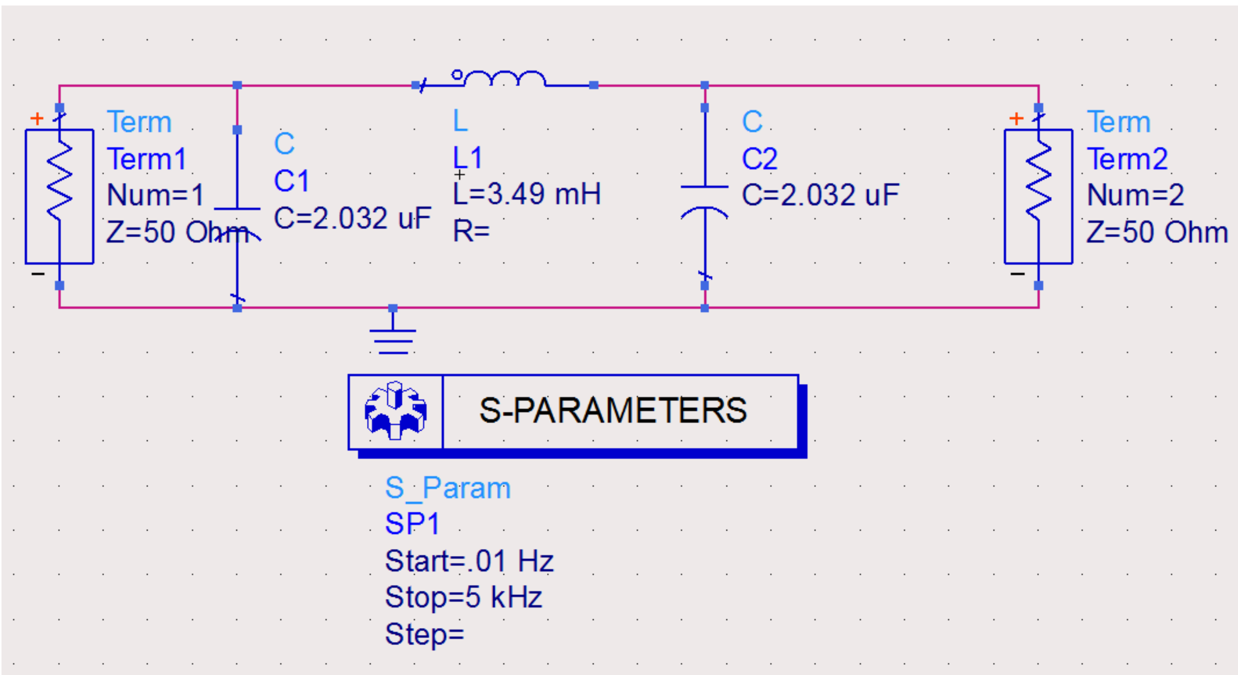

Figure 5: Standard Pi-filter schematic. [5]

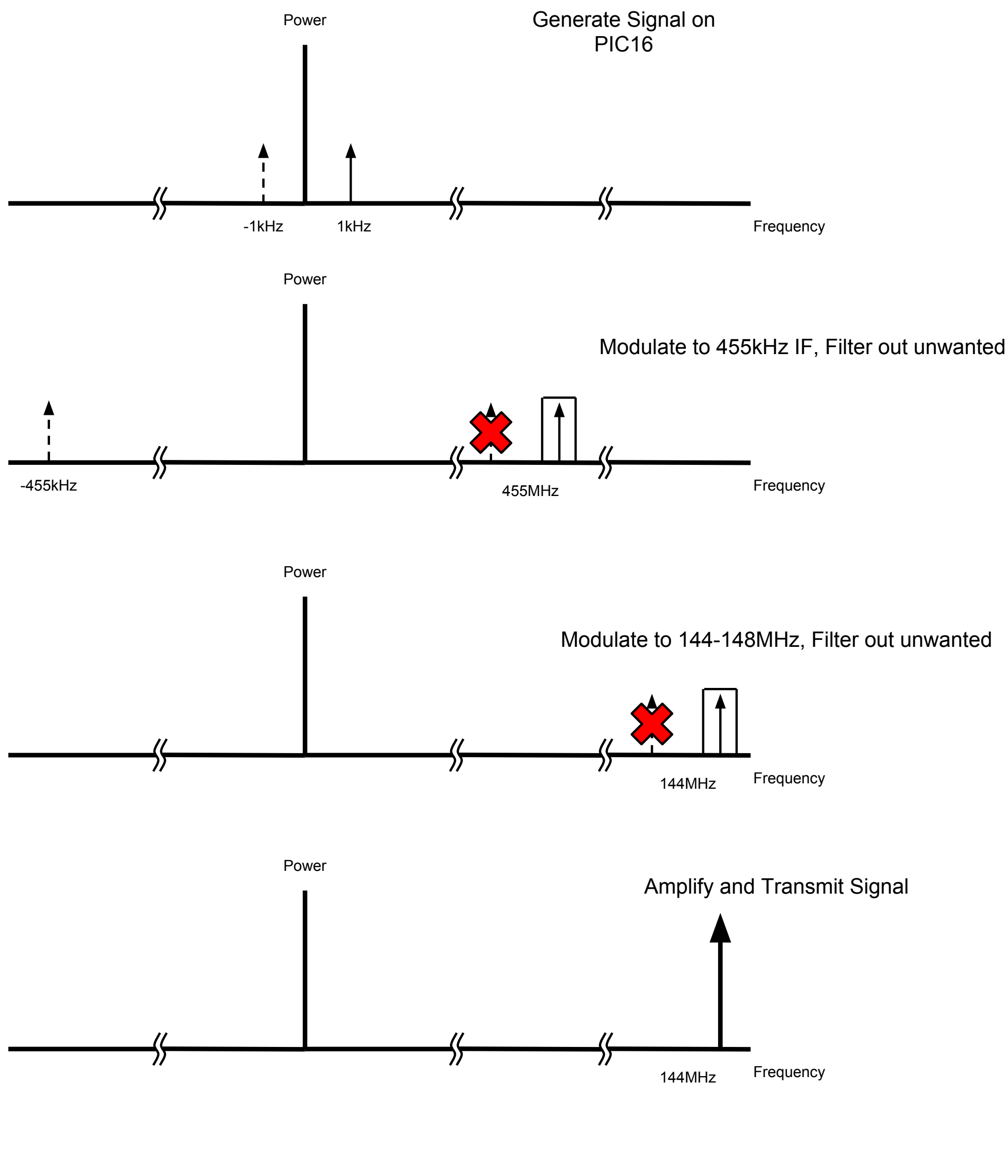

Figure 6: Multistage mixing.

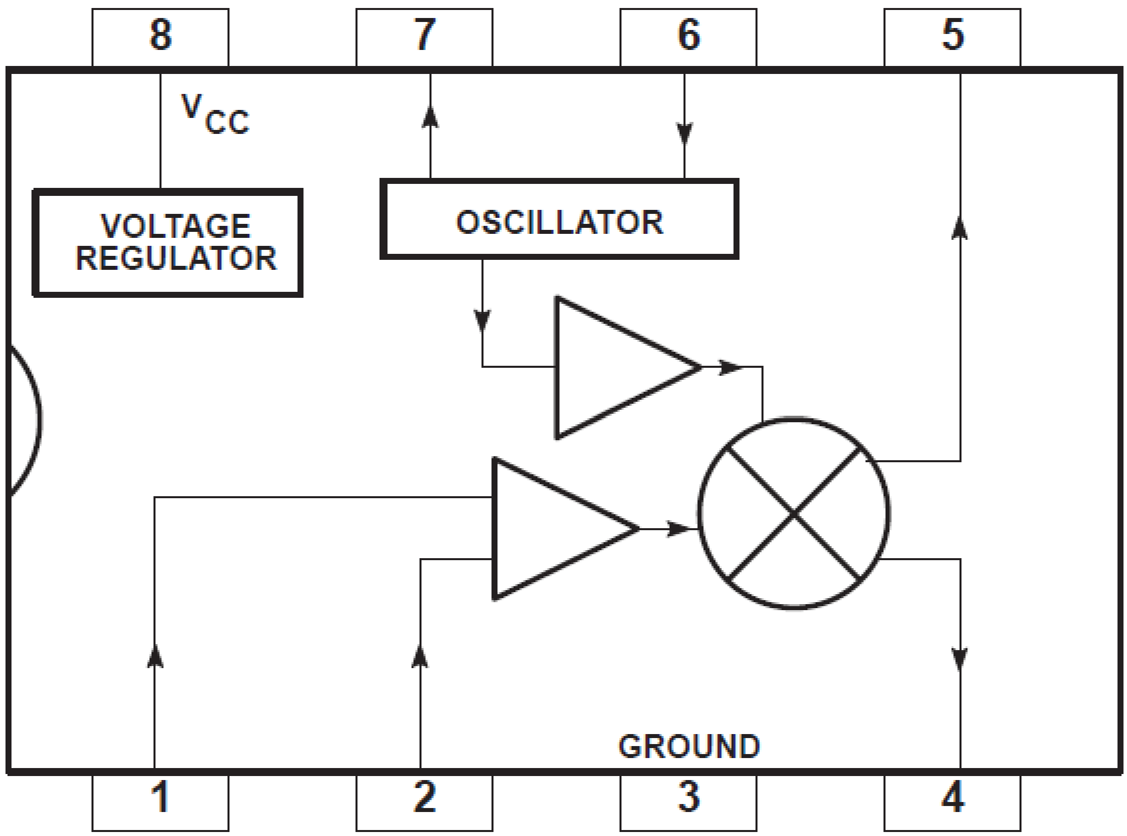

Figure 7: Schematic of SA602 mixer-oscillator chip

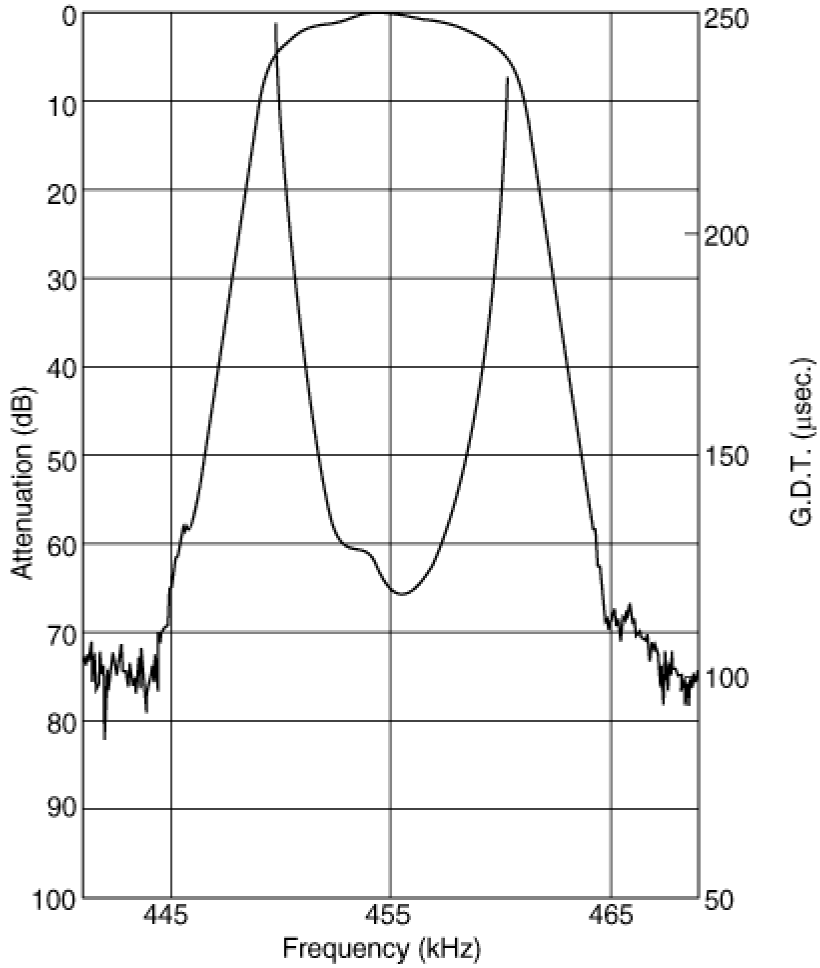

Figure 8: Frequency Response of Murata CFWLB455KGFA-B0 Ceramic Filter. [?]

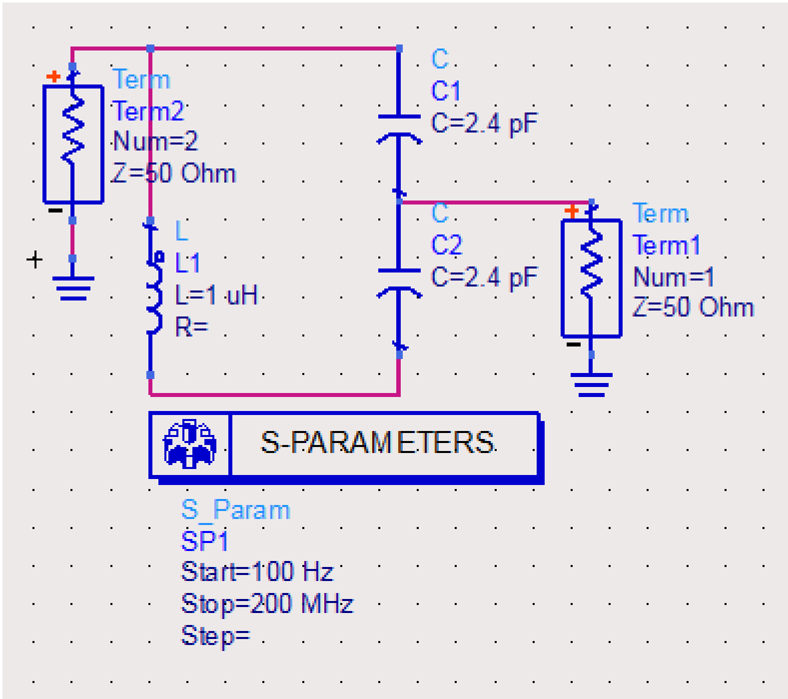

Figure 9: LC tank for VHF Local Oscillator

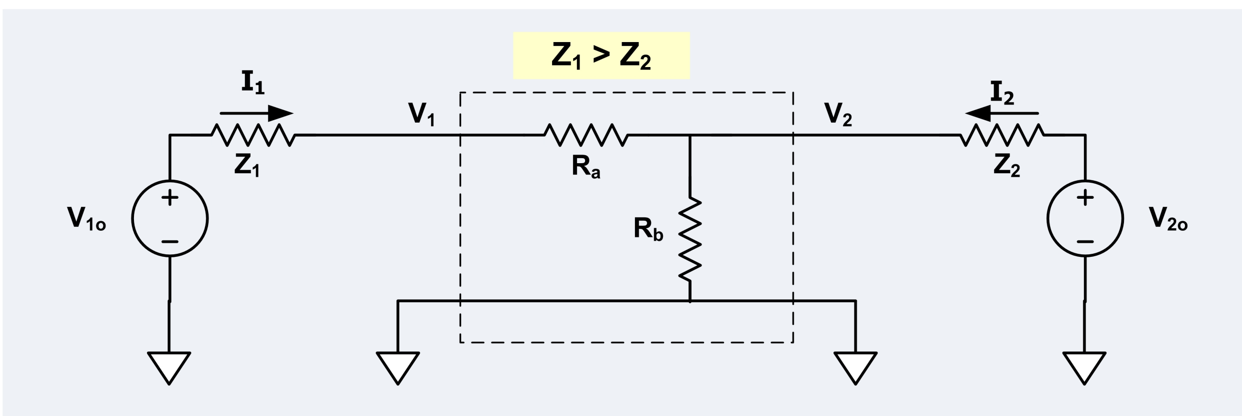

Figure 10: A standard L-Pad impedance matching section.

3 Requirements and Verification

Microcontroller	Verification
Microcontroller receives 3.2-3.6 Volts	Attach a multimeter between pins 1 (high) and 20 (low). Read the voltage, it should be between 3.2 and 3.6 Volts
The PIC is programmed with the latest version of the code 1. The ICD is connected to the computer 2. The ICD is connected to the circuit 3. Latest program is loaded onto the PIC	Open the latest version of the code in MPLAB X IDE. Then, press Program. 1. MPLAB does not ask you what device you want to use to program the PIC. 2. The device ID read by MPLAB is not 0x0. 3. MPLAB outputs successfully programmed
Communicates with cubeSAT 1. Receives data over the SPI data bus 2. Sends an Acknowledge byte back to the cubeSAT CPU after finishing sending its data	1. Attach the SPI data bus to a Bus Pirate. Attach the Bus Pirate to a computer. Open a serial communications program and connect to Bus Pirate. Send m to open the menu. Select 5, which is SPI. Then, send a string in quotes. Connect the ICD, and open MPLAB X IDE. Read the contents of the PICs memory, it should contain the string sent. 2. Connect to the SPI to a Bus Pirate as described above. Send a string of at least 80 bytes. Then send r to read the reply, it should be 0xAA
Generate AFSK signal 1. Generates a 1.5 ± 0.01 kHz signal for zero and a 2.3 ± 0.01 kHz signal for one for every bit in the 80 bytes in memory corresponding to the data packet	1. Load the test program that already has a packet in memory which is just 0xF2 eighty times. Connect pin 17 to an oscilloscope. The output should be 2.3 ± 0.01 kHz for 16 cycles, 1.5 ± 0.01 kHz for 4 cycles, 2.3 ± 0.01 kHz for 4 cycles, and 1.5 ± 0.01 kHz for 2 cycles, repeated many times.
Turns on voltage regulator only when needed 1. When not transmitting, the enable line to the voltage regulator is low. 2. It should turn on voltage regulator when transmitting	1. Do not send any communication over the SPI bus. Attach a voltmeter between pins 11 and ground; it should read less than 10 mV. 2. Load the test program that turns on the regulator for 1 second, then off again for 1 second. Read pin 11 (compared to ground) with a voltmeter. It should read from 3.2-3.6 V for 1 second, then less than 10 mV for 1 second.

Low Pass Filter	Verification
Successfully passes desired signals with less than 3 dB insertion loss. 1. Filter passes 1.5 kHz signal. 2. Filter passes 2.3 kHz signal.	1. Connect signal generator at input of filter, and oscilloscope set to FFT mode at output of filter. Set signal generator to 1.5 kHz at 0 dB. Verify output signal is a 1.5 kHz with magnitude between 0 and -3 dB. 2. Set signal generator to 2.3 kHz. Verify output signal is a 2.3 kHz with magnitude between 0 and -3 dB.
Filter attenuates signals past 4 kHz are attenuated by at least 30 dB.	Connect signal generator at input of filter, and oscilloscope set to FFT mode at output of filter. Set signal generator to 4 kHz at 0 dB. Sweep frequency from 4 kHz to at least 100 kHz in increments of 5 kHz. Verify output signal is attenuated by more than 30 dB for each frequency tested.

IF Mixer Requirements	Verification
Local Oscillator tank circuit can generate a proper signal F_0 - 1.5 kHz (± 0.1 kHz) signal, where F_0 is the center frequency of the IF filter. 1. SA602 chip is powered. 2. Circuit parameters are tuned to the correct values to generate a signal of frequency $F_0 - 1.5$ kHz (±0.1 kHz). 3. Local Oscillator tank circuit peak-to-peak voltage is at least 200 mV.	Insert an oscilloscope probe between GND and pin 6 on the SA602 chip. Hit MATH then FFT. Verify that the highest peak of the frequency spectrum is at F_0 - 1.5 kHz (± 0.1 kHz). 1. With a voltmeter, measure 5.0 +/- 0.1V between GND and pin 8 on the SA602 chip. 2. Insert an oscilloscope probe between GND and pin 6 on the SA602 chip. Hit MATH then FFT. Increase the capacitors to their maximum values. While looking at the oscilloscope FFT, slowly take one capacitor and decrease the capacitance of the circuit to 15.5 ± 0.5 pF. This turning action should turn one capacitor approximately 20% of the rotational range of an 8.5-40 pF variable capacitor. Stop turning when the peak is at $F_0 - 1.5$ kHz (±0.1 kHz). 3. With a voltmeter, measure at least 200 mV between pin 6 and pin 7 on the SA602 chip when the tank circuit is oscillating.

IF mixer outputs baseband signal frequency modulated by Local Oscillator frequency F_0.	Connect a function generator between TP2 and GND. Generate a 1.5 kHz sine wave with a peak-to-peak voltage of 200 mV. Insert an oscilloscope probe between GND and pin 6 on the SA602 chip. Hit MATH then FFT. Verify that the highest peaks of the frequency spectrum are located at the Fo $\pm$1.5 kHz.
1. SA602 chip is powered.	1. With a voltmeter, measure 5.0 ± 0.1 V between GND and pin 8 on the SA602 chip.
2. Local Oscillator accepts an oscillating frequency.	2. With a function generator attached to pins 6 and 7 of the SA602 chip, generate a 455 kHz sine wave with a peak-to-peak voltage of 220 mV. With another function generator attached between pin 1 and ground, generate a 1.5 kHz sine wave of peak-to-peak voltage of 200 mV. Verify that a strong peak at $455kHz \pm 5$ kHz is generated.
3. Output Impedance of previous stage > 1.5 kOhm.	3. With an Ohmmeter between TP2 and the signal source, verify the impedance measures > 1.5 kΩ.
IF Filter Requirements	**Verification**
Successfully passes desired signals with less than 8 dB insertion loss.	
1. Passes $F_0 - 0.4$ kHz, where F_0 is the center frequency of the filter.	1. Connect signal generator at input of filter, and oscilloscope set to FFT mode at output of filter. Set signal generator to a sine wave of frequency $F_0 - 0.4$ kHz at 0 dB. Verify output signal is a sine wave of $F_0 + 0.4$ kHz± 0.05 kHz with magnitude between 0 and -8 dB.
2. Passes $F_0 + 0.4$ kHz.	2. Set signal generator to F_0 kHz at 0 dB. Verify output signal is a sine wave of frequency $F_0 - 0.4$ kHz $\pm$ 0.05 kHz with magnitude between 0 and -8 dB.
Attenuates signals outside of $F_0 \pm 3$ kHz by more than 20 dB.	Connect signal generator at input of filter, and oscilloscope set to FFT mode at output of filter. Set signal generator to $F_0 - 3$ kHz at 0 dB. Verify output signal is attenuated by more than 20 dB. Repeat for F_0 kHz $+ 3$ kHz.
VHF Mixer Requirements	**Verification**
Local Oscillator tank circuit can generate a desired signal with frequency between 144-148 MHz.	Insert an oscilloscope probe between GND and pin 6 on the SA602 chip. Hit MATH then FFT. Verify that the highest peak of the frequency spectrum is at the desired signal $\pm$ 6.25 kHz.

1. SA602 chip is powered. 2. Circuit parameters are tuned to the correct values to generate a signal of frequency between 144-148 MHz. 3. With a voltmeter, measure at least 200 mV between pin 6 and pin 7 on the SA602 chip when the tank circuit is oscillating.	1. With a voltmeter, measure 5.0 ± 0.1 V between GND and pin 8 on the SA602 chip. 2. Insert an oscilloscope probe between GND and pin 6 on the SA602 chip. Hit MATH then FFT. Increase the capacitors to their maximum values. While looking at the oscilloscope FFT, slowly take one capacitor and decrease the capacitance of the circuit. Stop turning when the peak is at a frequency between 144-148 MHz. 3. Local Oscillator tank circuit peak-to-peak voltage is at least 200 mV.
VHF mixer outputs baseband signal frequency modulated by Local Oscillator frequency F_0. 1. SA602 chip is powered. 2. Local Oscillator accepts an oscillating frequency. 3. Output Impedance of previous stage > 1.5 kOhm.	Connect a function generator between TP2 and GND. Generate a 455 kHz sine wave with a peak-to-peak voltage of 200 mV. Insert an oscilloscope probe between GND and pin 6 on the SA602 chip. Hit MATH then FFT. Verify that the highest peaks of the frequency spectrum are located at the $Fo \pm 455$ kHz. 1. With a voltmeter, measure 5.0 ± 0.1 V between GND and pin 8 on the SA602 chip. 2. With a function generator attached to pins 6 and 7 of the SA602 chip, generate a 146 MHz sine wave with a peak-to-peak voltage of 220 mV. With another function generator attached between pin 1 and ground, generate a 455 kHz sine wave of peak-to-peak voltage of 200 mV. Verify that a strong peak at 146.455 MHz is generated. 3. With an Ohmmeter between TP2 and the signal source, verify the impedance measures > 1.5 kOhm.
VHF Mixer is tunable from 144-148 MHz in 6.25 kHz steps.	With a function generator connected between pin 1 and GND of the SA602, generate a sine wave of frequency 455 kHz and peak-to-peak voltage of 200mV. Connect an oscilloscope to the output. With the tank circuit set to oscillate at 144 MHz, slowly tune a capacitor in the tank circuit. Verify that the spectral peak shifts from 144.45500 MHz to 144.46125 MHz.
Channel Filter Requirements	**Verification**
Successfully passes desired signals with less than 10 dB insertion loss.	

1. Passes 144.456 MHz. 2. Passes 144.457 MHz.	1. Connect signal generator at input of filter, and oscilloscope set to FFT mode at output of filter. Set signal generator to 144.456 MHz at 0 dB. Verify output signal is a 144.456 $\pm$ 0.05 MHz with magnitude between 0 and -10 dB. 2. Set signal generator to 144.457 MHz at 0 dB. Verify output signal is a 144.457$\pm$0.5 MHz with magnitude between 0 and -10 dB.
Signals 2 MHz outside of desired signal are attenuated by at least 30 dB.	Connect signal generator at input of filter, and oscilloscope set to FFT mode at output of filter. Set signal generator to 146.456 MHz at 0 dB. Verify output signal is attenuated by more than 30 dB for each frequency tested. Repeat for 142.456 MHz.
Amplifier Requirements	Verification
Amplifies the input signal to more than 20 dBm. 1. Amplifier is powered 2. Output impedance of previous stage is 50 $\Omega \pm 10\ \Omega$.	Connect a function generator between the input of the amplifier and GND. Generate a 146 MHz sine wave with peak-to-peak voltage of 200 mV. Connect an oscilloscope with an attenuator between the output of the amplifier and GND.Verify the signal output is at least 20 dBm. 1. With a voltmeter, verify that the amplifier is receiving 5.0$\pm$0.1 V between V_{cc} and GND. 2. With an ohmmeter, verify that the output impedance of the previous stage is 50 $\Omega \pm 10\ \Omega$.
Output Filter Requirements	Verification
Successfully passes desired signals (144-148 MHz).	Connect signal generator at input of filter, and oscilloscope set to FFT mode at output of filter. 1. Set signal generator to 144 MHz at 0 dB. Verify output signal is a 144 $\pm$ 0.05 kHz with magnitude between 0 and -10 dB. 2. Set signal generator to 148 kHz at 0 dB. Verify output signal is a 148 $\pm$ 0.05 kHz with magnitude between 0 and -10 dB.
Attenuates signals outside of 144 - 148 $\pm$ 1 MHz by 30 dB.	Connect signal generator at input of filter, and oscilloscope set to FFT mode at output of filter. Set signal generator to 143 MHz at 0 dB. Verify output signal is attenuated by more than 30 dB for each frequency tested. Repeat for 149 MHz.
Voltage Regulator Requirements	Verification
The voltage regulator is enabled by the enable pin.	Power the regulator with 6-9 V.

1. The voltage regulator turns off when enable is low. 2. The voltage regulator turns on when enable is high.	1. Ground the enable pin, it should output less than 0.1 V. 2. Use a power supply to send 3.3 V to the enable pin of the regulator. It should output 5 ± 0.1 V.
Outputs a 5 ± 0.1 V when a 6-9 V voltage is applied.	Attach the input of the regulator to a power supply. Attach the output to a voltmeter. Move the power supplys voltage from 6 volts to 9 volts and back again. The output should stay within 0.1 volts of 5V.

4 Tolerance Analysis

Capacitance is also a critical part of most RF systems, not to mention this one. A simple parts search can show that typical capacitor and inductor values can vary as much as ±10%. This deviation would yield unacceptable results should standard, unadjustable capacitors be used in an example resonant circuit below. For the IF Colpitts tank oscillator that is utilized in the beacon, if standard parts were used, the maximum frequency deviation is shown below.

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{12}$$

$$\Delta f_0 = \frac{1}{2\pi\sqrt{L(C+0.1C)}} \tag{13}$$

$$C = \frac{(C_1+\Delta C_1)(C_2+\Delta C_2)}{C_1+C_2+\Delta C_1+\Delta C_2} \tag{14}$$

Choosing the intended value of 2.44 pF, but including a 10

$$C = \frac{(2.44 \text{ pF} + 0.244 \text{ pF})^2}{2(2.44 \text{ pF} + 0.244 \text{ pF})} \tag{15}$$

$$C = 1.34 \text{ pF} \tag{16}$$

So, our frequency could be as low as:

$$f = \frac{1}{2\pi\sqrt{1\ \mu\text{H}(1.34 \text{ pF})}} = 137 \text{ MHz} \tag{17}$$

$$\Delta f = 144 - 137 = 7 \text{ MHz} \tag{18}$$

Thus, it is easy to see that precison that only variable capacitors can offer are necessary for a robust design of the beacon.

5 Ethics and Safety

5.1 Ethics

The IEEE code of the ethics set the guidelines for all engineers to follow, and during the design of this project potential dishonorable situations may arise. We propose the following to address this matter.

The operation of our device will use voltages and emit radiation, thus proper documentation and warning is important to anyone who might handle our device in the implementation to the CubeSAT, adhering to code 1.

1. "to accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment.'[4]

During the design of the VHF beacon we will ensure our device does not leak into other bands. Our beacon will only transmit in the desired 2M band of 144 MHz to 148 MHz. This adheres to IEEE code 2.

2. "to avoid real or perceived conflicts of interest whenever possible, and to disclose them to affected parties when they do exist." [4]

During testing, we will not falsify any results that may affect the VHF beacon while in space and not provide false labeling of the beacon intended operations, adhering to code 3.

3. “to be honest and realistic in stating claims or estimates based on available data.” [4]

In order to provide the cubeSAT team with an understanding of how to implement our device into their system, we must also document in a proper and informative manner, adhering to codes 5 and 10.

5. “to improve the understanding of technology; its appropriate application, and potential consequences.” [4]
10. “to assist colleagues and co-workers in their professional development and to support them in following this code of ethics.” [4]

While building the physical device we will be safe in all lab procedures for both colleagues and ourselves ensuring that nobody gets injured, adhering to code 9.

9. “to avoid injuring others, their property, reputation, or employment by false or malicious action.” [4]

5.2 Safety

In any project involving electricity it is important to ensure that all the equipment we use is working properly and we do not create any electrical hazards. Our final product will operate at a low voltage, and thus should not be very dangerous to the cubeSAT team that will be using it. It is important, though, that we ensure that our circuit will not have any short circuits, which could overheat and burn someone handling it. It is also important that we follow FCC regulations, so our satellite will not interfere with important communications in other frequency bands.

6 Parts and Labor

<table>
<tr><th colspan="2">Part</th><th>Part Number</th><th>Cost</th></tr>
<tr><td colspan="2">PIC Microcontroller</td><td>PIC16F1508</td><td>$3.36</td></tr>
<tr><td colspan="2">RF Mixer</td><td>SA602</td><td>$1.13</td></tr>
<tr><td colspan="2">RF amplifier-15dB gain</td><td>THS9001</td><td>$1.78</td></tr>
<tr><td colspan="2">Voltage Regulator</td><td>TPS773</td><td>$2.37</td></tr>
<tr><td colspan="2">Miscellaneous Resistors, Capacitors, Inductors</td><td>N/A</td><td>$15.00</td></tr>
<tr><td colspan="2">4 Layer PCB</td><td>N/A</td><td>$125.00</td></tr>
<tr><td colspan="3">Total</td><td>$150.75</td></tr>
<tr><th>Laborer</th><th>Rate ($/hour)</th><th>Hours</th><th>Total (Rate*2.5*hours)</th></tr>
<tr><td>Russell</td><td>$40.00</td><td>145</td><td>$14500.00</td></tr>
<tr><td>Neal</td><td>$40.00</td><td>145</td><td>$14500.00</td></tr>
<tr><td>Jeff</td><td>$40.00</td><td>145</td><td>$14500.00</td></tr>
<tr><td>Total</td><td>$120.00</td><td>435</td><td>$43500.00</td></tr>
<tr><td colspan="3">Grand Total</td><td>$43650.75</td></tr>
</table>

7 Calendar

Week	Neal	Jeff	Russell
Feb 4	Finish the Proposal Find power regulation ICs Register for Design contest	Start Designing FM modulator and filter Decide on filter-amplifier design approach	Polish Proposal Write some PIC code Get access to CubeSAT computer lab
Feb 11	Begin ordering parts Start first state schematic	Design Amplifier Stage	Write working output code for PIC
Feb 18	Begin breadboarding Finish first state schematic	Simulate FM modulator to Amplifier Stage Find TI parts for application	Finish and test input/output code for PIC
Feb 25	Revise schematic	Breadboard and verify the FM modulator to Amplifier Stages	Verify breadboarded circuit works
Mar 4	Begin PCB layout	Add amplifier stage Add filter if needed	Write power management code for PIC
Mar 11	Order PCBs	Continue PCB design	Design Mock-up Demo
Mar 18	Spring Break	Spring Break	Spring Break
Apr 25	Solder PCB	Assemble Filter, amplifier, FM modulator	Make Mockup-up Presentation
Apr 1	Finish PCB layout	Finish building circuit	Verify functionality of subsystems
Apr 8	Thermal testing	Finalize Iteration of PCB design (if needed)	Make programs and devices needed for demo
Apr 15	Vibration testing	Maintain functionality for demo	Testing of Final Device Testing of Final Device
Apr 22	Begin compiling final paper	Demo preparation	Finalize Code
Apr 29	Return Equipment	Compile Documentation	Polish Final Paper

8 Contingency Plan

Components with noisy output

In the event that one of our components has a noisy output, we can add additional filters. To this end, we will have places on our PCB for filters, which, if unneeded, we can fill with 0Ω resistors.

Amplifier lacks sufficient gain

If our amplified does not have enough gain to boost our signal to 100 mW, then we can cascade amplifiers stages to make a stronger amplifier.

PIC fails to produce AFSK signal

If the PIC's output is not good enough to be transmitted, we can add a separate block that generates the needed frequencies for our AFSK. This block will then be controlled by the microcontroller.

Local oscillator does not generate a frequency

Try the following:

1. Pick a different local oscillator topology.
2. Add a frequency generator circuit
3. Change the frequency modulation scheme

References

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