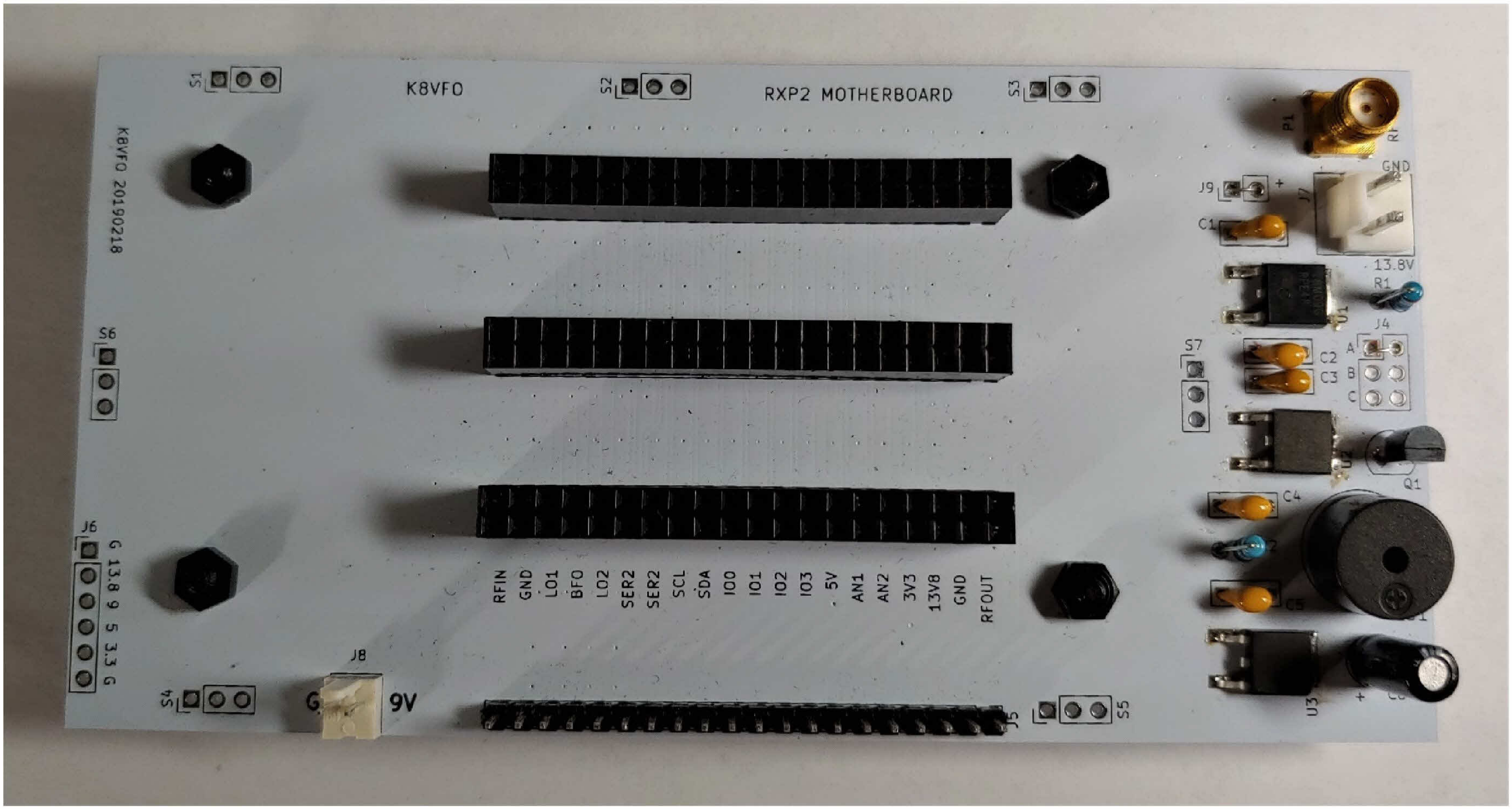
Receiver Design Fun – December 2, 2021 – W Halphen

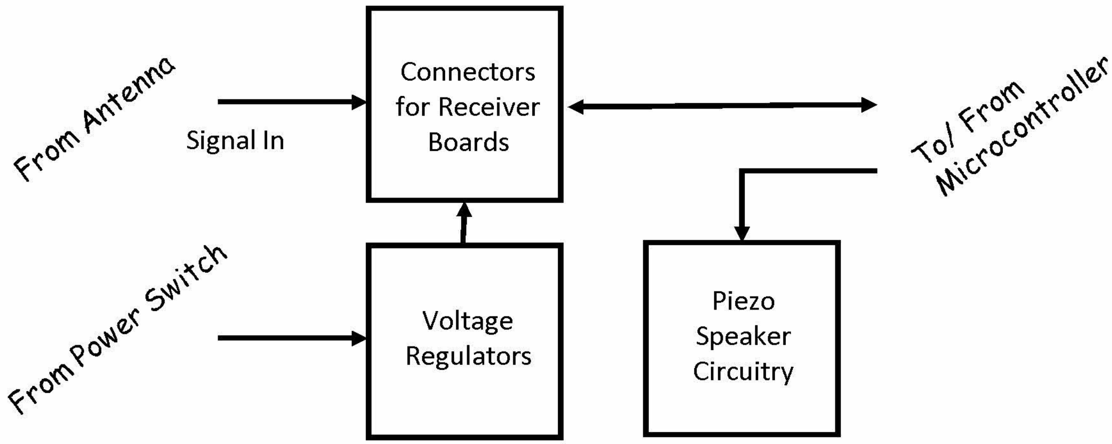
RXP2 Receiver Design Notes

- The RXP2 is a receiver experimentation platform
  - replaceable circuit boards to construct and experiment with radio receiver designs
  - backplane provides a signal bus and regulated power supplies
- user interface and radio control using a processor and display module
  - Arduino UNO (ATmega328P 16 MHz 32 bit, 32KB flash, 2KB RAM, 1KB EEPROM) with an LCD plugin
  - custom board with a more powerful processor (STM32F103 72 MHz 32 bit ARM Cortex M3, 64/128KB flash, 20KB RAM)
- designed to fit into a small metal enclosure along with a speaker
- this configuration: superheterodyne receiver
  - single sideband crystal filter
  - preselection filter for image rejection
  - attenuator
  - audio amplifier
  - reception from the 40 meter band through the 10 meter band
  - overall gain is about 90 to 100 dB

Design of the RXP2 Backplane

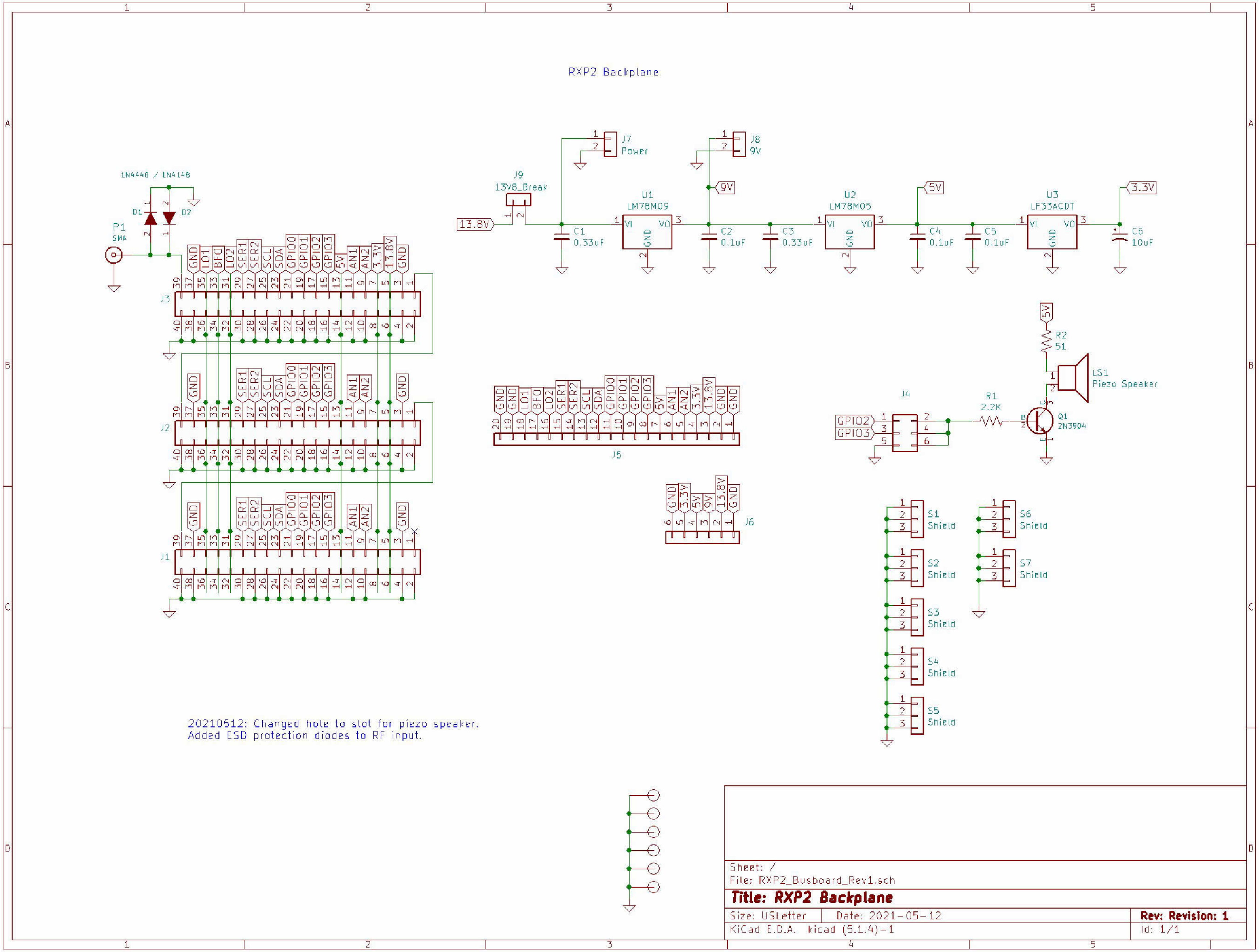


Design of the RXP2 Backplane



Operation

- provides interconnections for the various modules in the receiver
- 2x20 pin socket connectors for the RF Stage, IF Stage, and Audio Stage boards
- 1x20 pin header is used for the microcontroller
- connectors for power supplies and the antenna
- 13.8 volt supply feeds three voltage regulator circuits to provide 9 volts, 5 volts, and 3.3 volts
- a piezo speaker circuit can be connected to the microcontroller for audio feedback for the user interface
- The radio signal path travels sequentially through each receiver module from rear to front, left to right
- other lines include local oscillators, and serial, analog, and digital control signals


RXP2 Backplane
1N4448 / 1N4148
D1
D2
P1
SMA
J3
J2
J1
GND
LO1
BFO
LO2
SER1
SER2
SCL
SDA
GPIO0
GPIO1
GPIO2
GPIO3
5V
AN1
AN2
3.3V
13.8V
J9
13V8_Break
13.8V
J7
Power
J8
9V
U1
LM78M09
C1
0.33uF
C2
0.1uF
C3
0.33uF
U2
LM78M05
C4
0.1uF
C5
0.1uF
U3
LF33ACDT
C6
10uF
R2
51
LS1
Piezo Speaker
J4
GPIO2
GPIO3
R1
2.2K
Q1
2N3904
J5
J6
S1 Shield
S2 Shield
S3 Shield
S4 Shield
S5 Shield
S6 Shield
S7 Shield
20210512: Changed hole to slot for piezo speaker.
Added ESD protection diodes to RF input.
Sheet: /
File: RXP2_Busboard_Rev1.sch
Title: RXP2 Backplane
Size: USLetter
Date: 2021-05-12
Rev: Revision: 1
KiCad E.D.A. kicad (5.1.4)-1
Id: 1/1

The RXP2 Enclosure

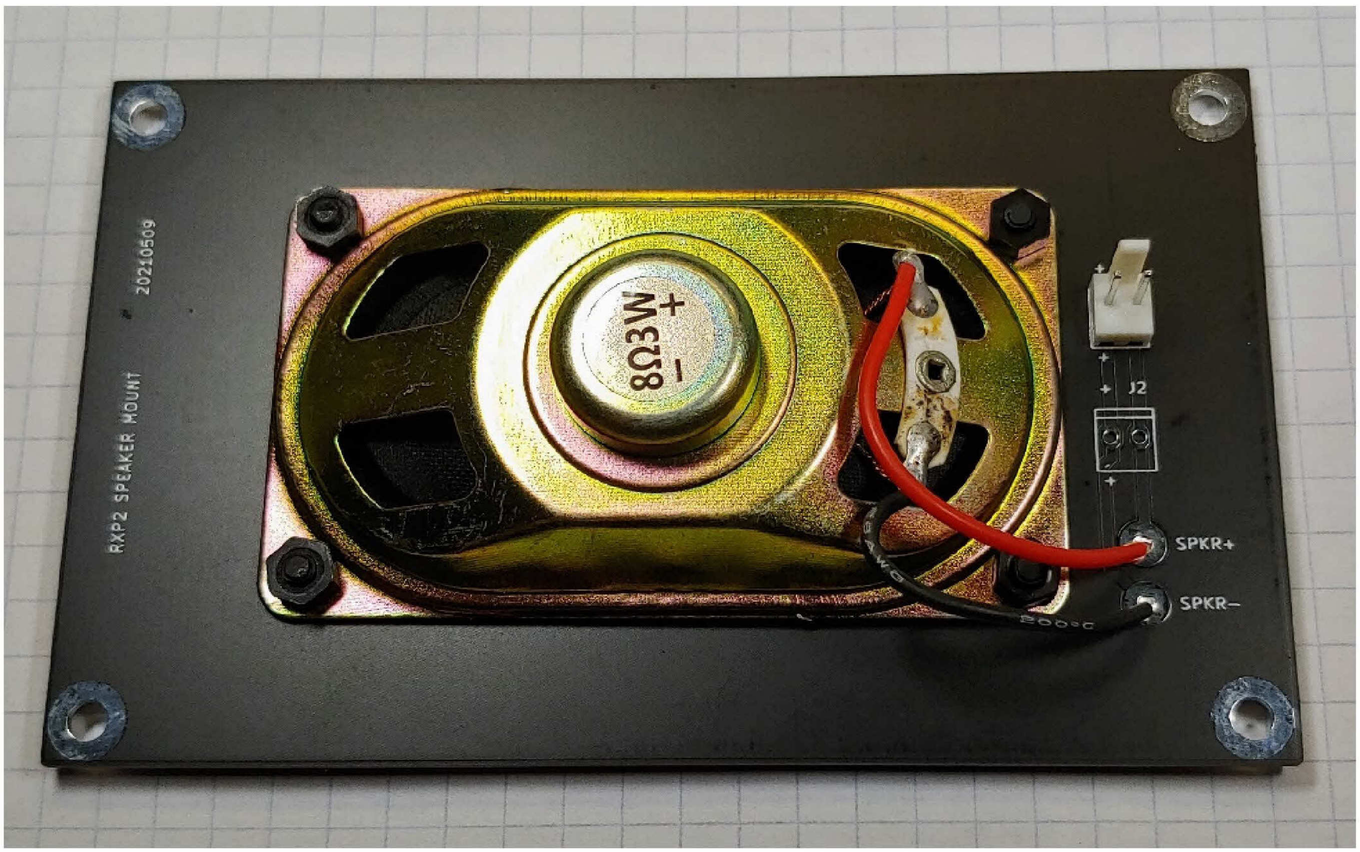
The RXP2 Enclosure

Overview

- made of steel and can provide some shielding from nearby electrical noise sources
- can be completely disassembled for ease of access during project construction
- front and rear panels are replaceable and flat so they can be replaced with precut and labeled printed circuit boards
- cover is made with slots for ventilation
- relatively inexpensive and available from several suppliers in China.
- metal panels are not touching in a way that connects them together electrically. So it's necessary to modify them slightly so they are electrically connected and provide full electrical shielding
- The manufacturing consistency is poor. The enclosure dimensions vary from box to box by as much as a couple of millimeters. And the plastic feet positions vary significantly, sometimes conflicting with the positions of the printed circuit board mounting screws.
- A few mechanical modifications are necessary for this project

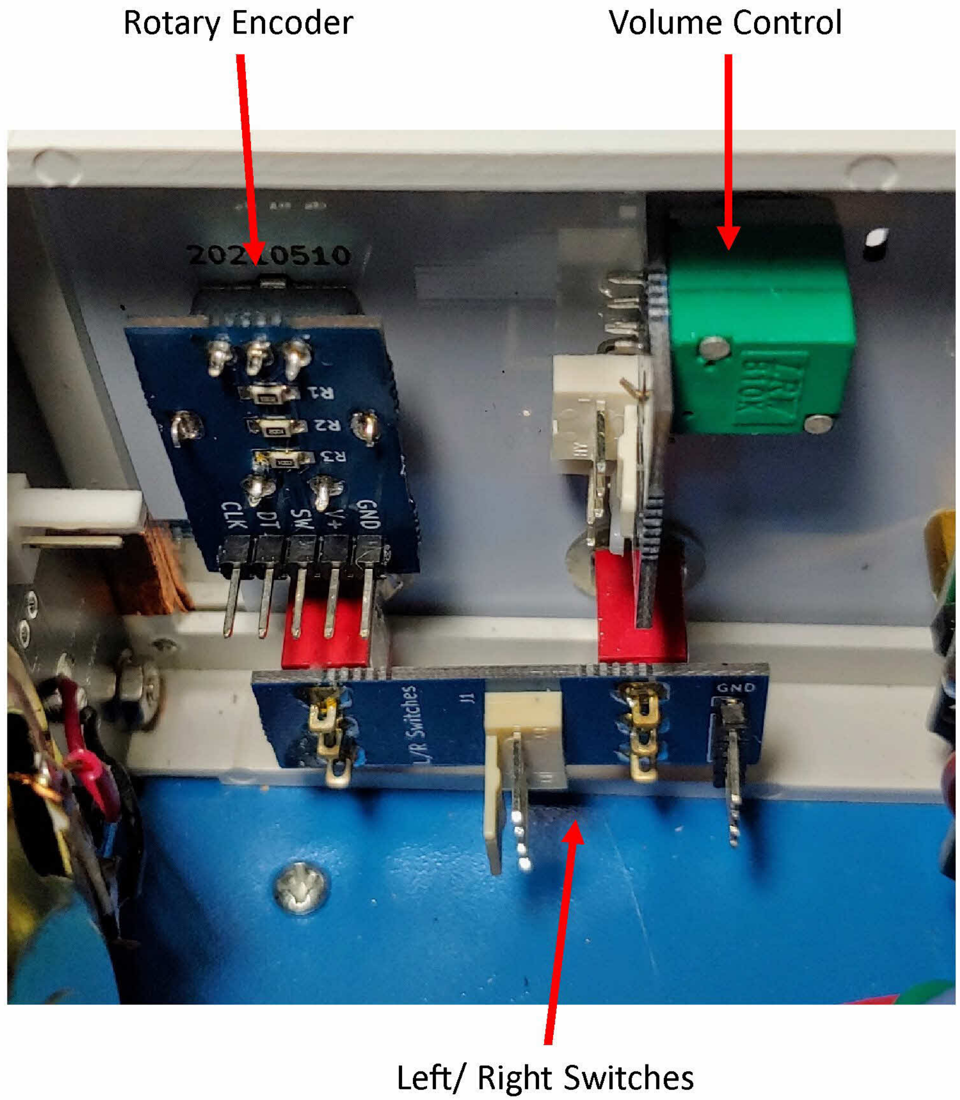
Preparing the RXP2 Enclosure

- Speaker and its mounting board



Preparing the RXP2 Enclosure

- Front Panel Controls



Front Panel Controls
after installation

Preparing the RXP2 Enclosure

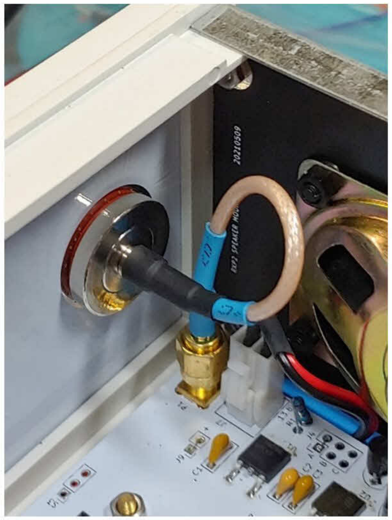
Front Panel Controls
and LCD
after installation

Preparing the RXP2 Enclosure

- Rear Panel
    1. Install the power connector and power switch
    2. Insert the antenna connector from the inside of the panel

Power connector and switch after installation.

Antenna connector after installation.



Preparing the RXP2 Enclosure

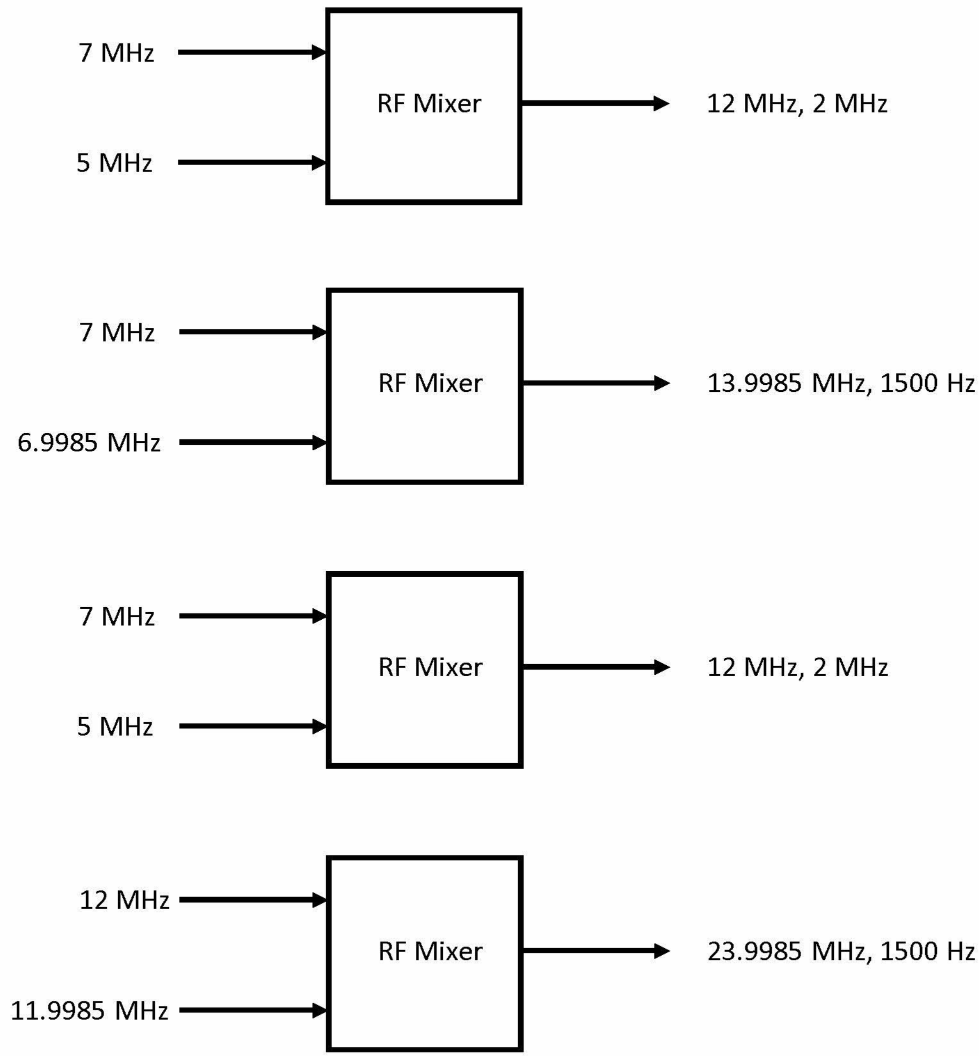
<u>Assembly</u>

- Rear Panel

Rear Panel
after installation

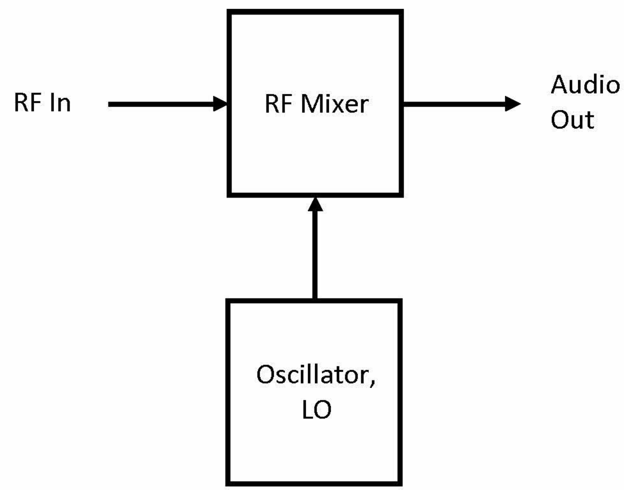
The Radio

RF Mixers



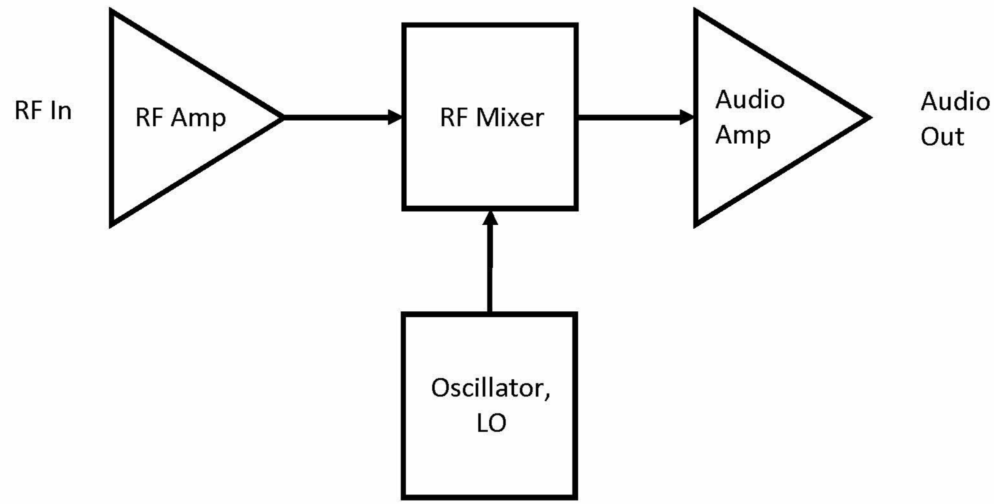
7 MHz
5 MHz
RF Mixer
12 MHz, 2 MHz
7 MHz
6.9985 MHz
RF Mixer
13.9985 MHz, 1500 Hz
7 MHz
5 MHz
RF Mixer
12 MHz, 2 MHz
12 MHz
11.9985 MHz
RF Mixer
23.9985 MHz, 1500 Hz

Direct Conversion Receiver

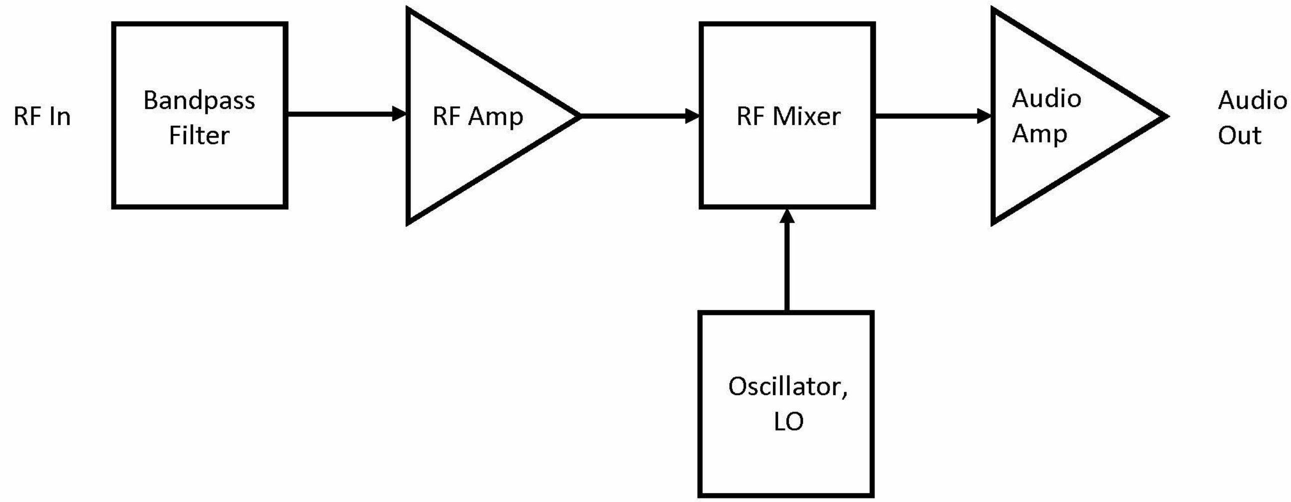


The components of a basic direct conversion receiver.

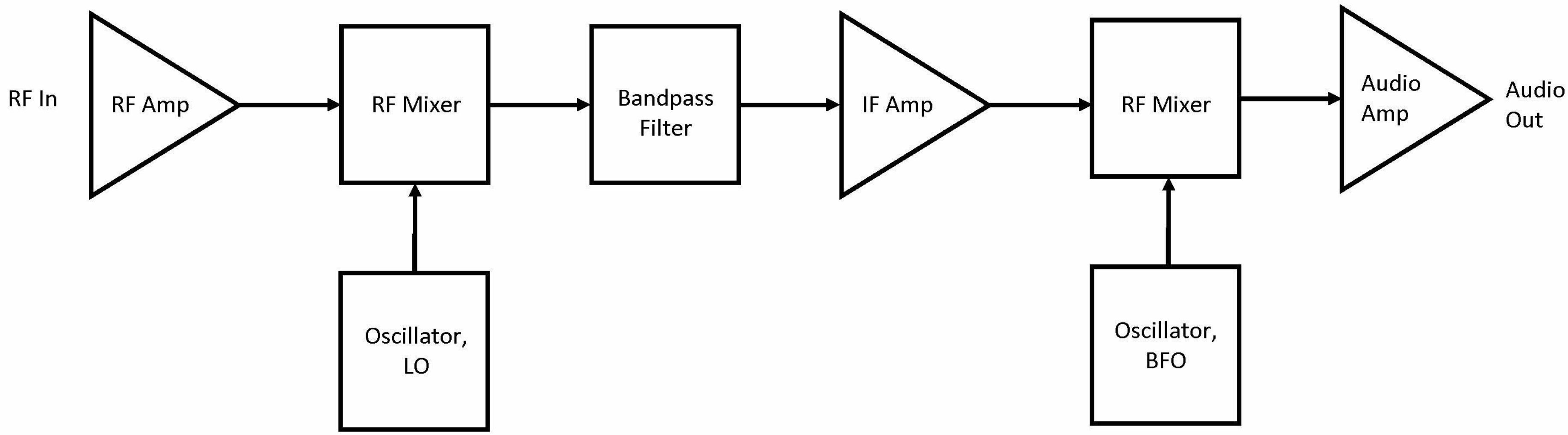
Direct Conversion Receiver, Improved



Selective Direct Conversion Receiver

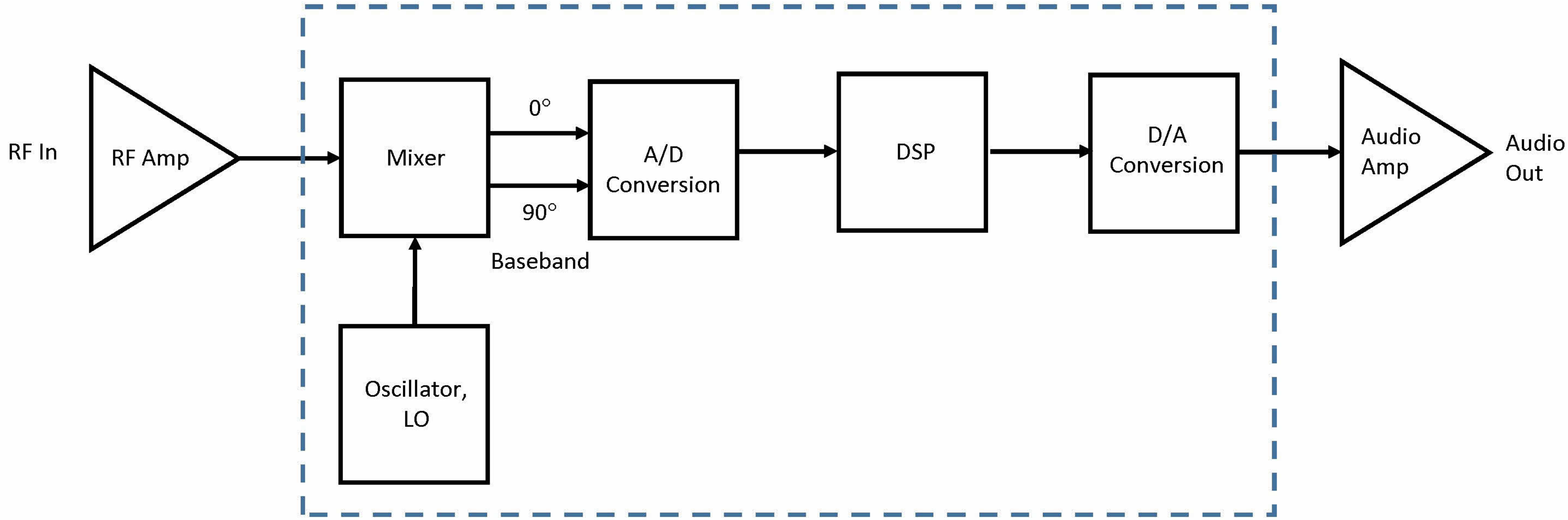


Superheterodyne Receiver



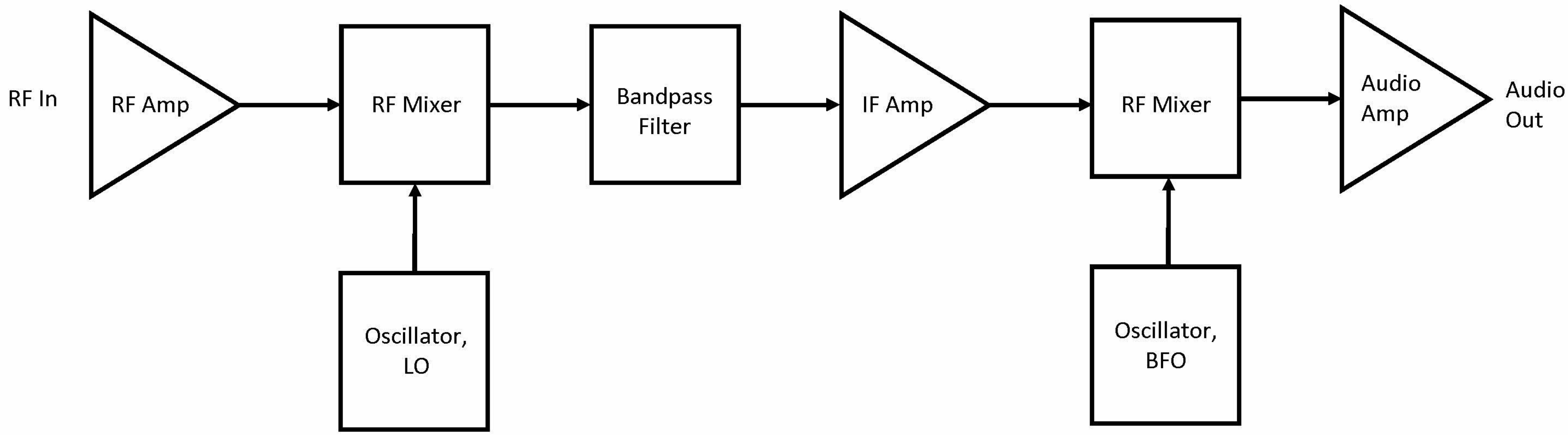
The components of a basic superheterodyne receiver for single sideband signals. In our construction, there are additional amplification and filtering stages not shown in this diagram.

Direct Conversion Software Defined Receiver

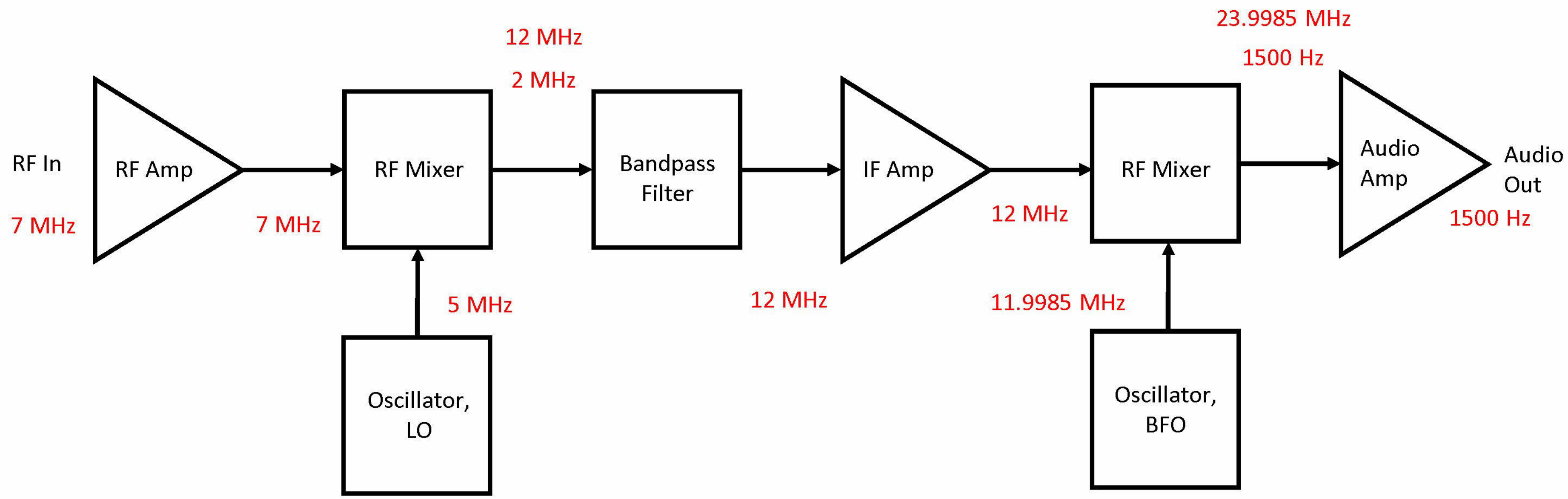


Direct conversion SDRs have become typical in modern radio equipment, such as cell phones.

Superheterodyne Receiver

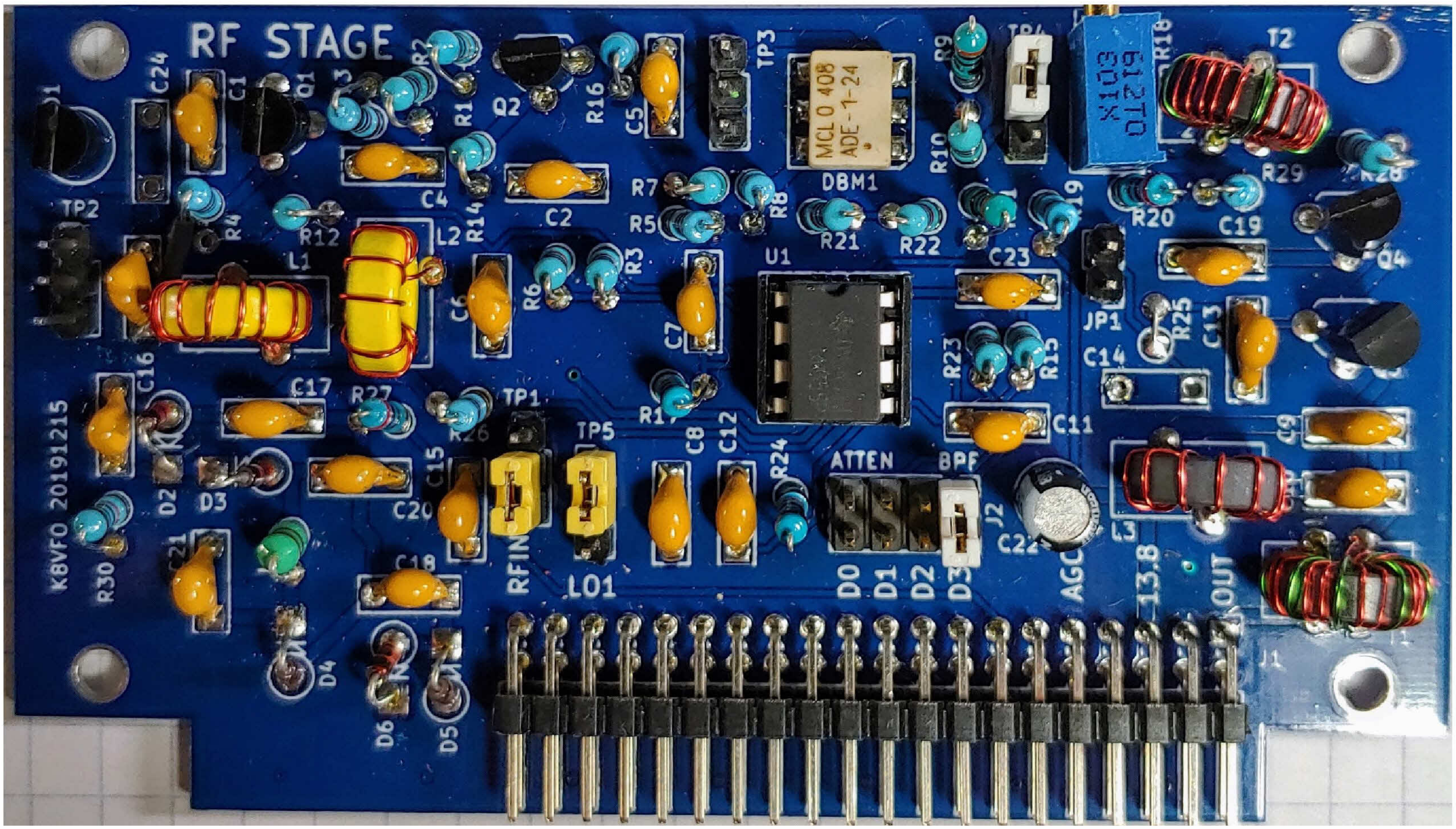


Superheterodyne Receiver -- Example

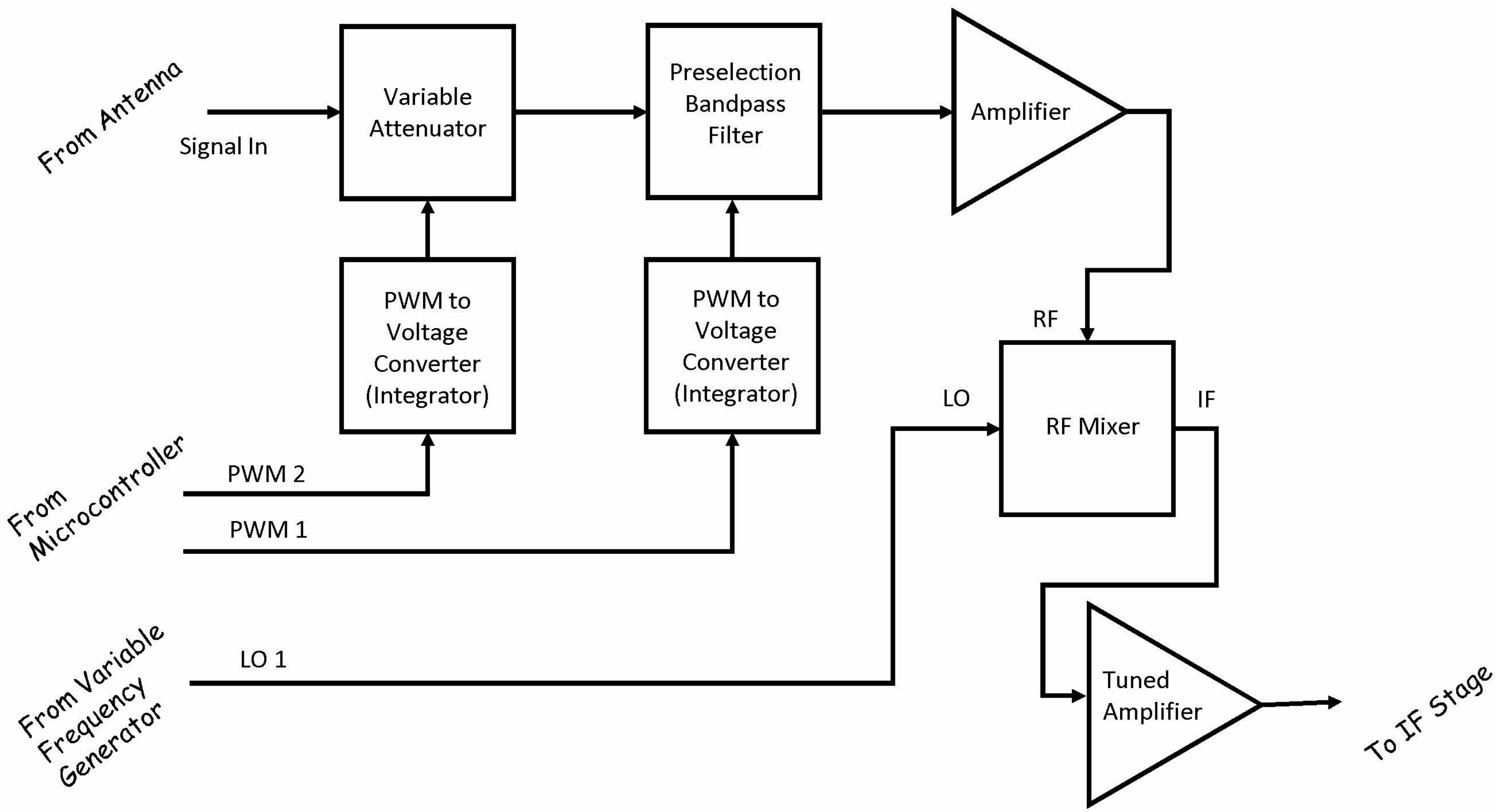


Example of major frequency components at each step when tuned to 7 MHz.

RXP2 RF Stage



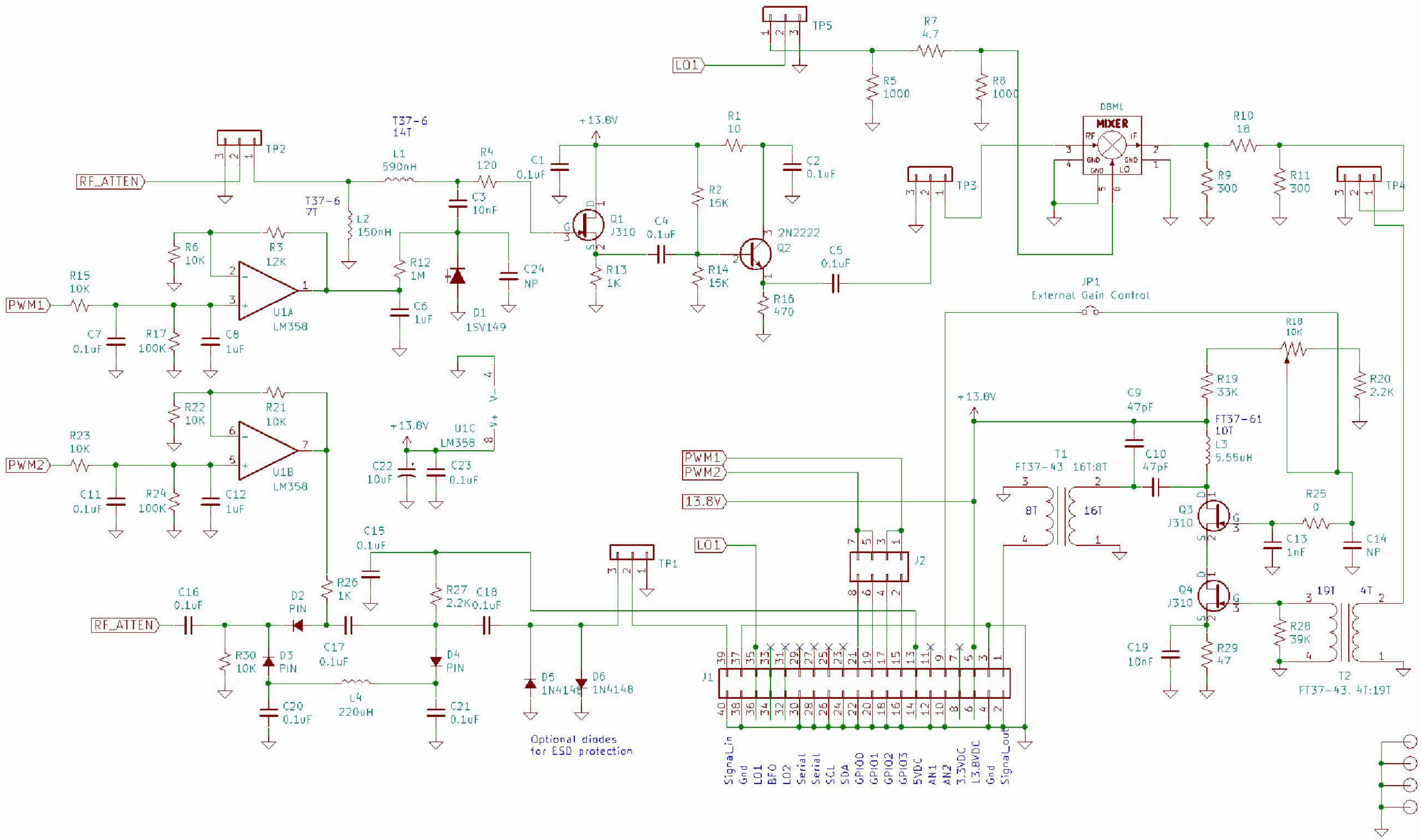
Design and Construction of the RXP2 RF Stage



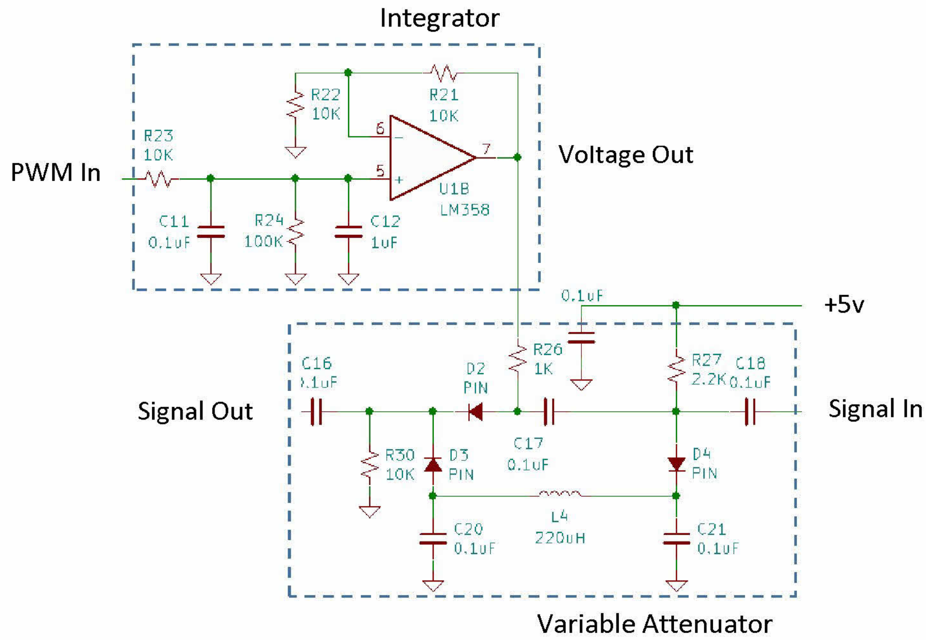
<u>Operation</u>

- The input signal is adjusted by the attenuator and the preselection filter to limit the amplitude and bandwidth and reduce interference from undesired or overloading signals.
- The attenuator and preselection filter are both voltage controlled. The microcontroller controls these stages using digital pulse width modulated outputs which have to be integrated to convert them to voltage levels.
- The signal is then amplified and mixed with the local oscillator frequency (also controlled by the microcontroller) to produce the intermediate frequency, which is then amplified again.

Design and Construction of the RXP2 RF Stage



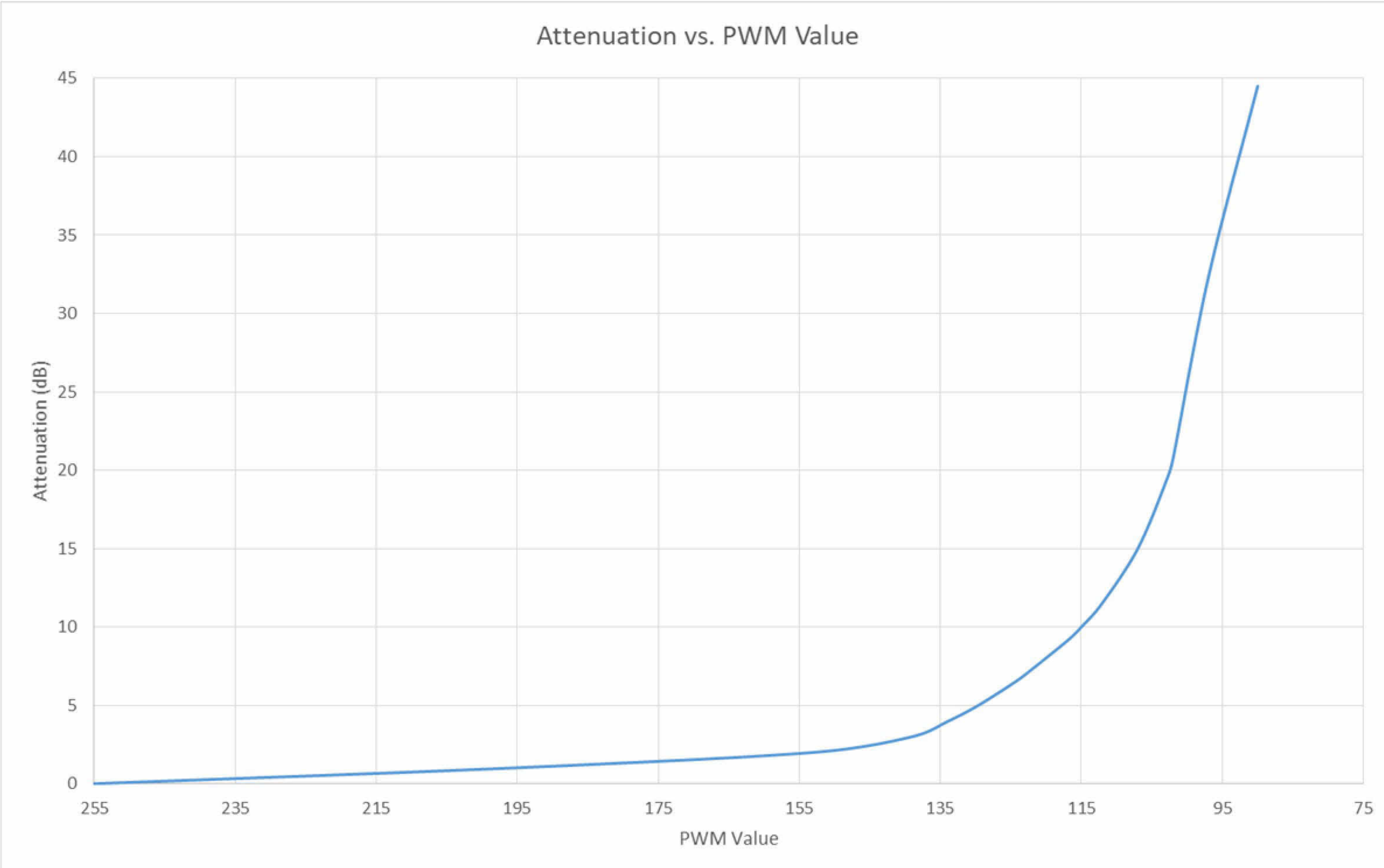
Design of the RXP2 RF Stage – Variable Attenuator



<u>Operation</u>

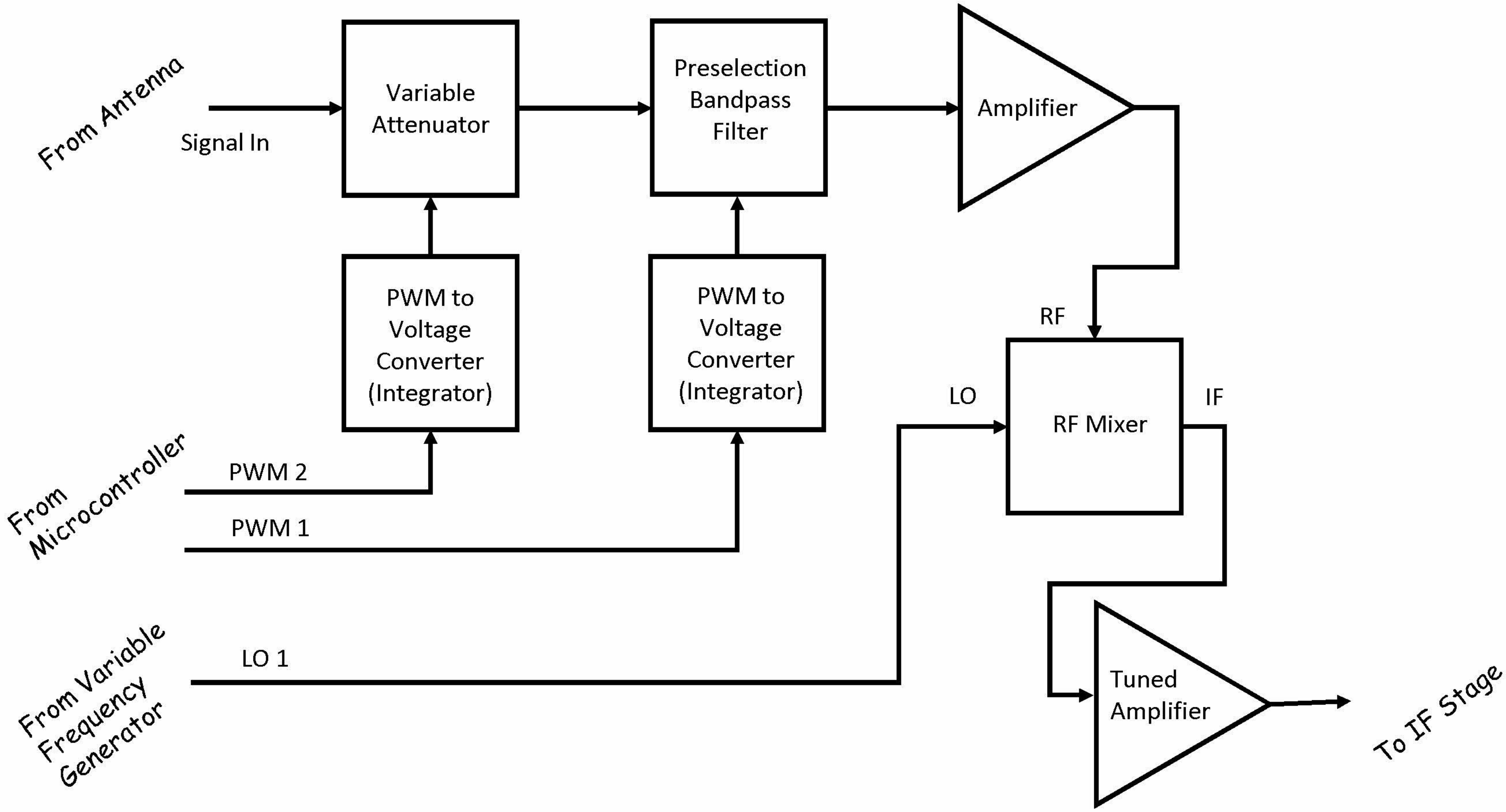
- U1 is a LM358 dual operational amplifier (op amp) which forms the basis for each of the two integrators. The pulse width modulated (PWM) input is a train of 5 volt pulses with a duty cycle ranging from 0% to 100% and controlled by the microcontroller. These pulses charge C12 with a time constant determined by R24. The result is that C12 charges up to a voltage level which is a trailing average of the PWM duty cycle. U1, R21, and R22 form an amplifier which amplifies the voltage at C12 and isolates (buffers) it before feeding it to the Variable Attenuator.
- (U1 also contains a second op amp which integrates another PWM signal that controls the Variable Preselect Filter used in the next step of the receiver signal processing.)
- The 5 volt supply forward biases D4 and D3 allowing a current to flow and producing a voltage drop across R30. When the voltage from the integrator is less than the voltage drop across R30, D2 is reverse biased, thus it is turned off and the RF signal cannot travel down the path of C18, C17, D2, and C16 to the output. D4 and D3 are forward biased, shorting the AC signal to ground.
- As the voltage level from the integrator is gradually increased, D2 gradually becomes forward biased, allowing more signal to pass through. D4 and D3 become reverse biased, blocking the AC path to ground. The capacitors all are used to block the DC current and allow only the AC signal to pass. The inductor is used to allow DC current to pass and block the AC signal. In this way, the design directs the DC current to bias the diodes and also controls the flow of AC signal along the proper signal path.

Design of the RXP2 RF Stage – Variable Attenuator



This graph shows actual measured attenuation level versus the pulse width modulation output from an Arduino, which controls the duty cycle based on software value ranging from 0 to 255 (corresponding to a duty cycle of 0 to 100%). This variable attenuator circuit increases the attenuation as the PWM value (and duty cycle) decreases.

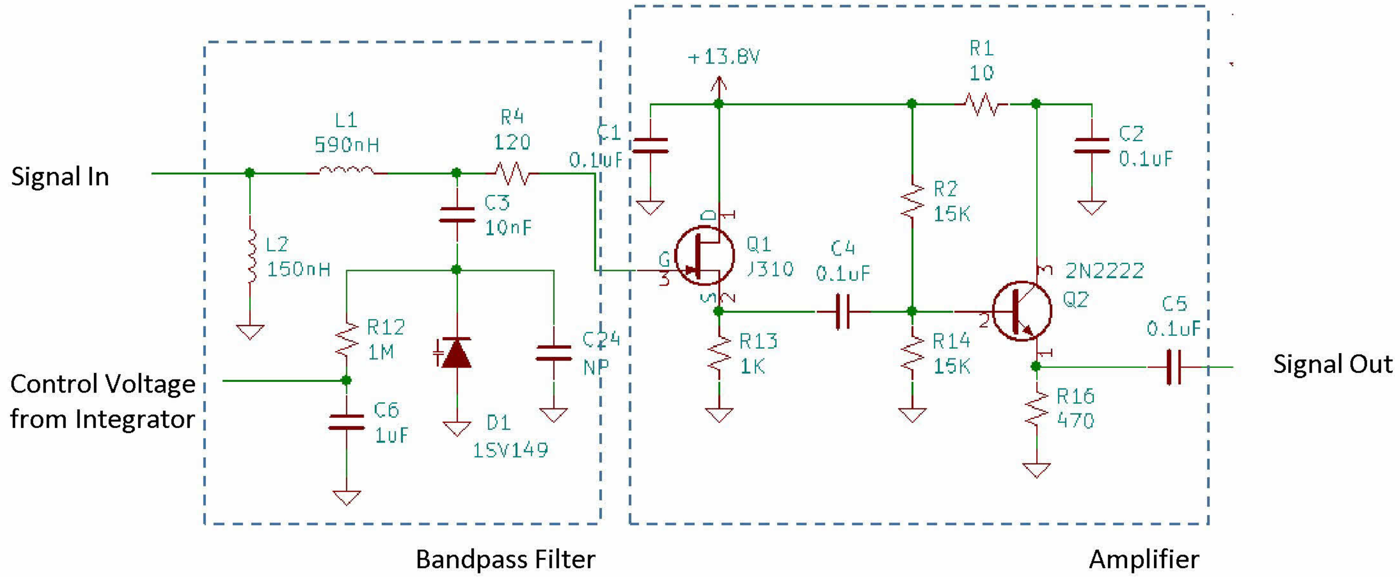
Design and Construction of the RXP2 RF Stage



<u>Operation</u>

- The input signal is adjusted by the attenuator and the preselection filter to limit the amplitude and bandwidth and reduce interference from undesired or overloading signals.
- The attenuator and preselection filter are both voltage controlled. The microcontroller controls these stages using digital pulse width modulated outputs which have to be integrated to convert them to voltage levels.
- The signal is then amplified and mixed with the local oscillator frequency (also controlled by the microcontroller) to produce the intermediate frequency, which is then amplified again.

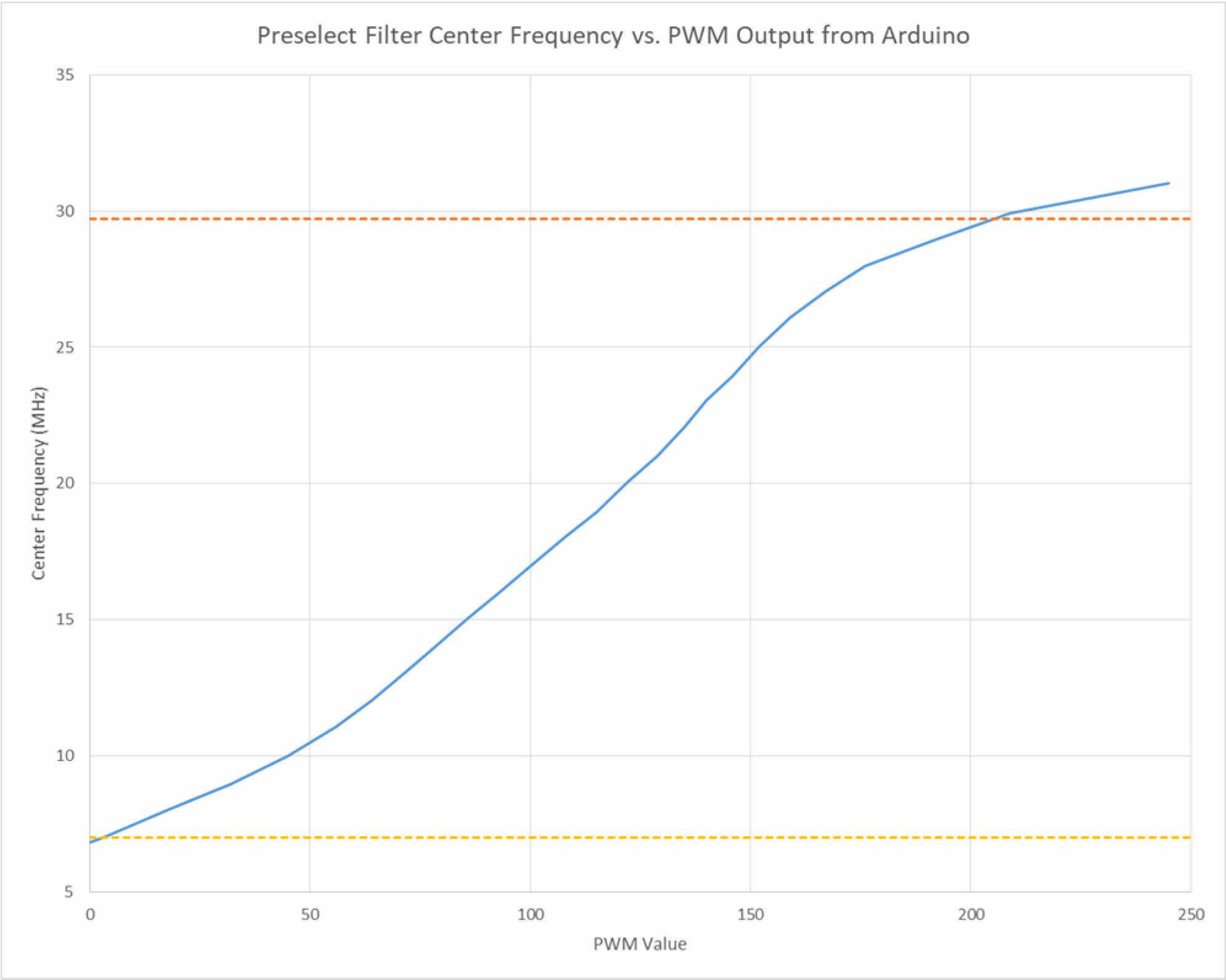
Design of the RXP2 RF Stage – Variable Preselect Filter



<u>Operation</u>

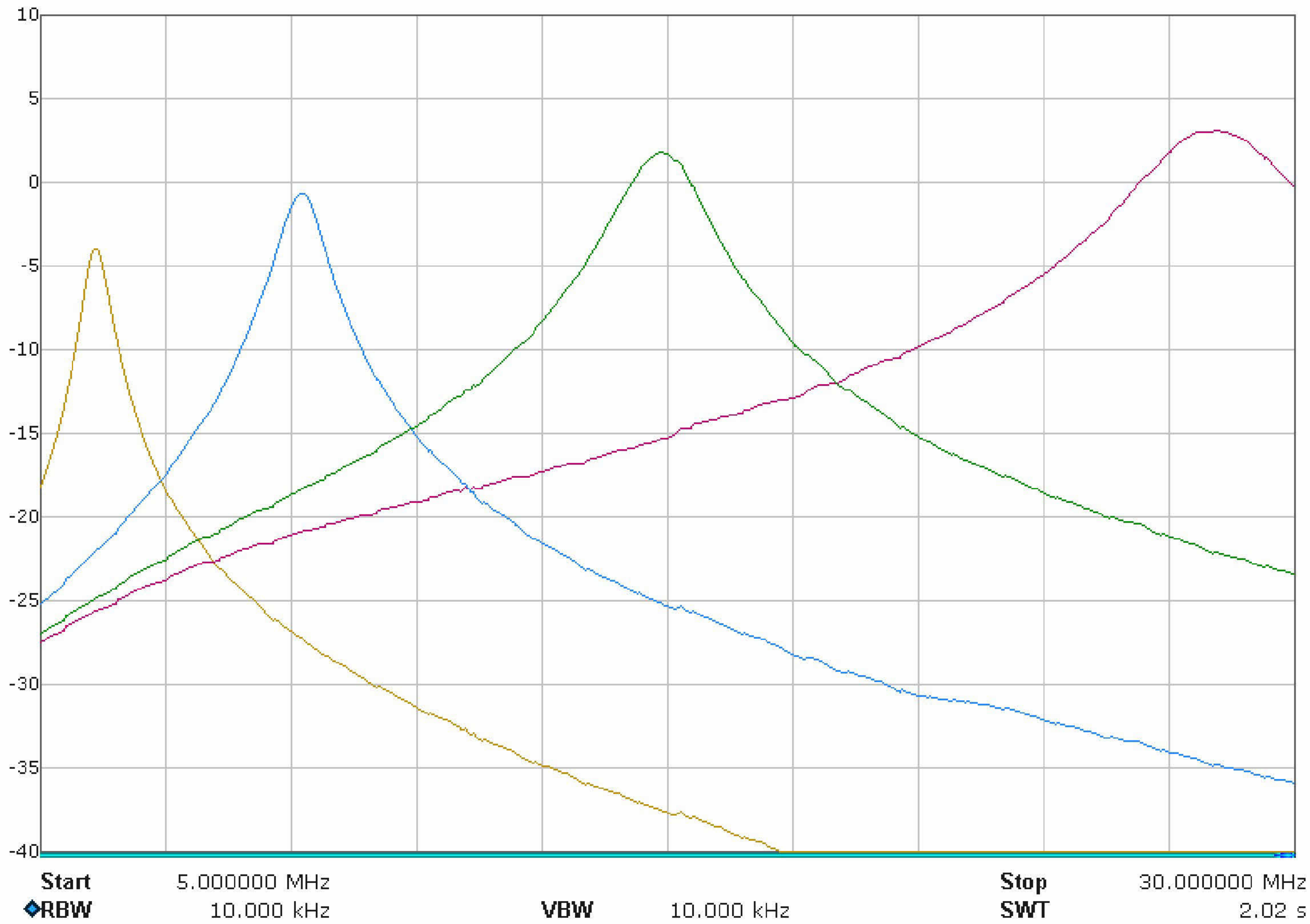
- The control voltage from the Integrator applies a reverse bias to D1. This diode is a varactor diode which is manufactured to have a controlled capacitance which is a function of the reverse bias voltage. So, effectively, D1 provides a variable capacitance in series with C3 and the total capacitance of the two is determined by the control voltage from the Integrator.
- L2, L1, and the variable capacitance form a bandpass filter with a center frequency that is a function of the inductor values and the variable capacitance. Thus, by changing the voltage from the Integrator, the center frequency of the filter can be controlled.
- The filter output drives R4, Q1, and R13 which form a buffer with a high impedance input. The purpose of this buffer is to provide isolation between the bandpass filter and the amplifier composed of R2, R14, Q2, and R16. C4 provides blocking of the DC bias voltage for Q2, while allowing the AC signal to pass from the buffer to the amplifier. C5 provides blocking of the DC bias voltage at the output of the circuit while the AC signal passes through to the next step in the processing.
- C1, R1, and C2 are intended to eliminate unwanted radio frequency leakage to or from the power supply.
- This circuit is from a design published by George Steber, WB9LVI, in QEX in 2018. His article gives a good description of the design. http://www.arrl.org/files/file/QEX_Next_Issue/Jan-Feb2018/Steber.pdf

Design of the RXP2 RF Stage – Variable Preselect Filter



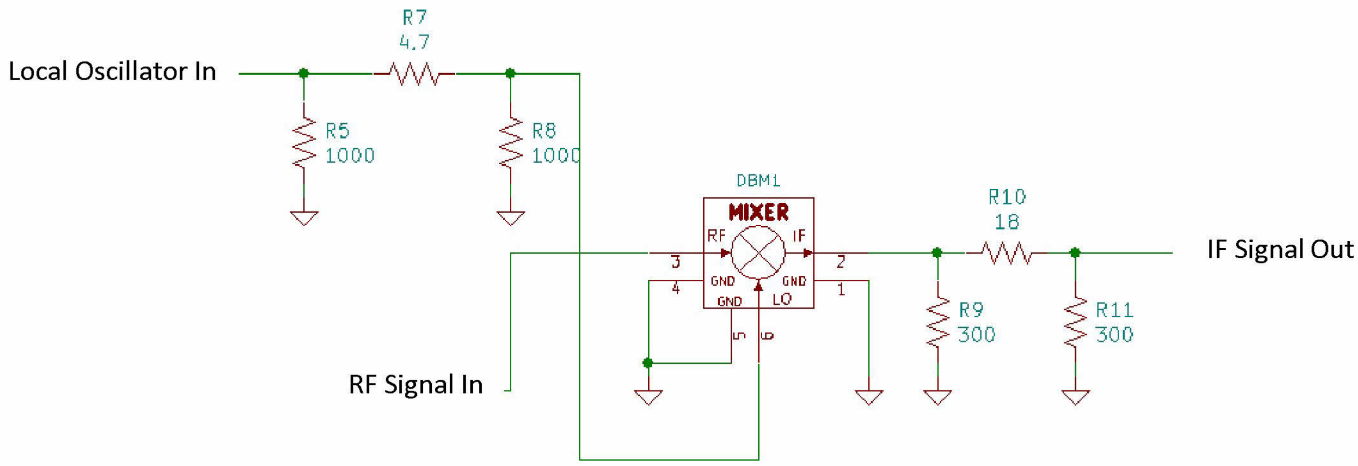
This graph shows the preselect filter center frequency resulting from a pulse width modulation (PWM) output from an Arduino. The PWM output value can range from 0 to 255, producing a duty cycle of 0 to 100%. The horizontal lines indicate center frequencies of 7 MHz and 29.7 MHz (40 meter thru 10 meter bands), which covers the range of frequencies tuned by the receiver.

Design of the RXP2 RF Stage – Variable Preselect Filter



This screenshot from a spectrum analyzer shows the preselect filter bandpass performance at four different frequencies across the range of the receiver.

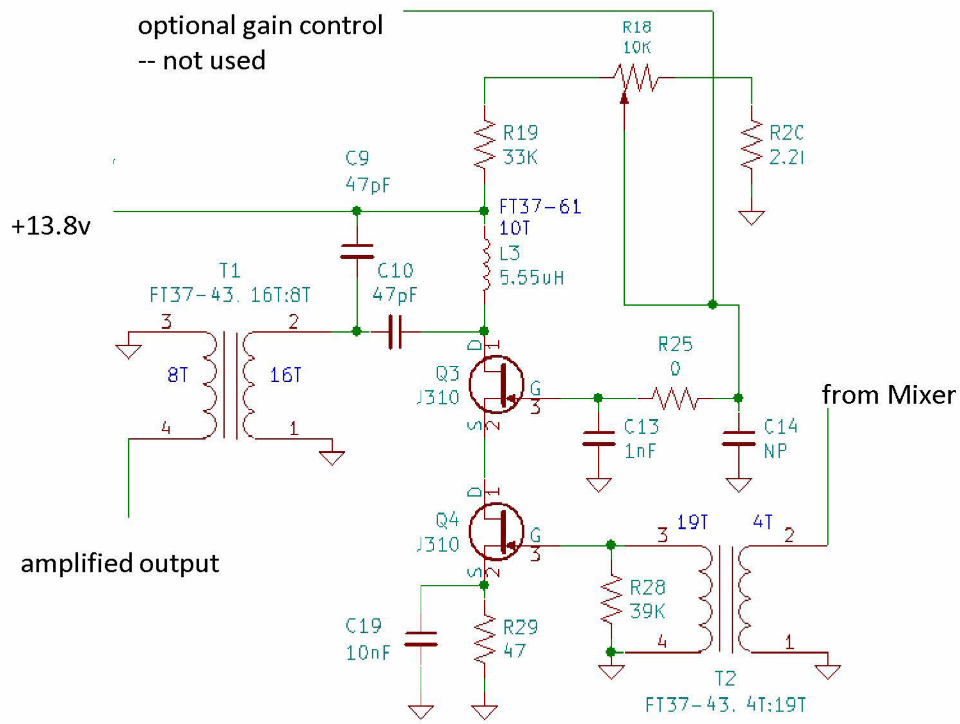
Design of the RXP2 RF Stage – Mixer



<u>Operation</u>

- The RF mixing is done in DBM1, which is a double balanced mixer.
- The resistors, R5, R7, and R8, form an attenuator to reduce the output of the local oscillator to a level required by the mixer. The resistors, R9, R10, and R11 form a 3 dB attenuator with a 50 ohm input. This mixer works best with a 50 ohm load. This attenuator ensures that the mixer sees a load which is always at or near 50 ohms – even as the input of the next circuit varies away from 50 ohms at the frequencies of some of the output frequency components.

Design of the RXP2 RF Stage – Tuned Amplifier

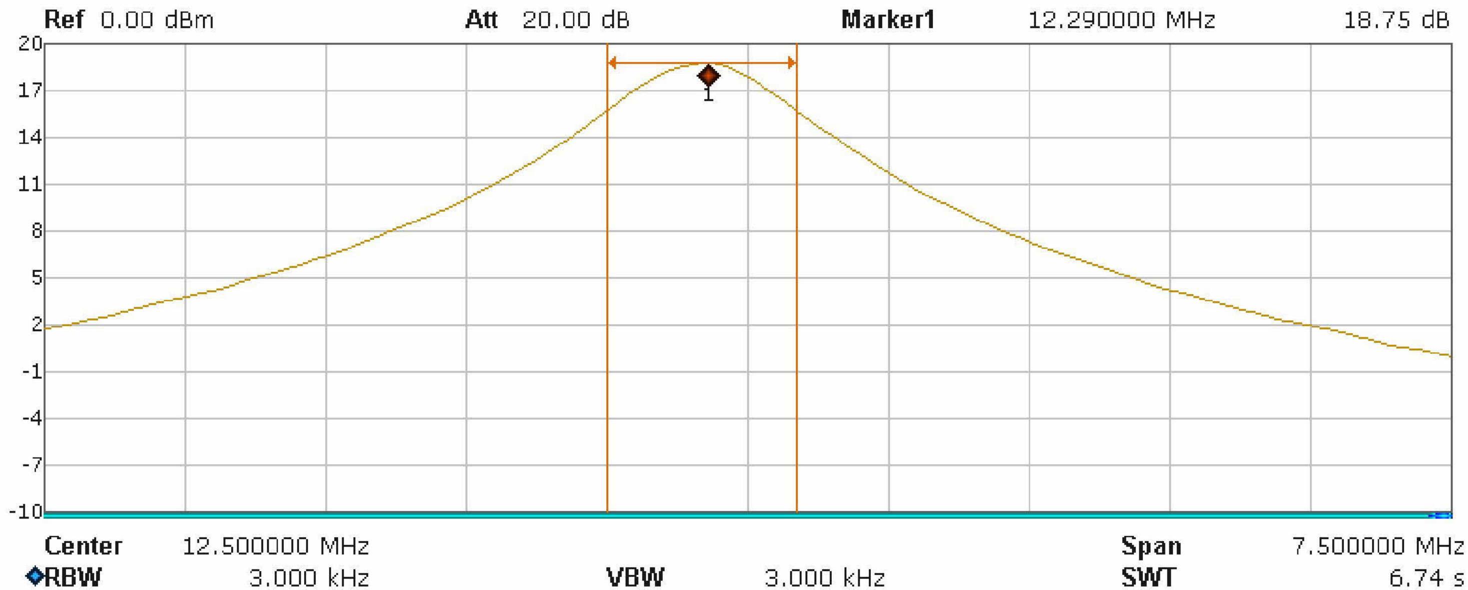


Operation

- The output of the mixer is at a reduced level compared to the input to the mixer. So, it's helpful to amplify it before feeding it to the IF stage.
- We want the mixer to see a 50 ohm load. So T2 is used to transform the high impedance input of the amplifier to about a 50 ohm load for the mixer.
- The two field effect transistors and their associated resistors and capacitors are configured as a cascode amplifier. A cascode design has particular benefits of having high gain and working well at high frequencies.
- Notice that C9, C10, and L3 form an LC resonant tank circuit. These tune the amplifier to provide higher gain at the resonant frequency, as well as to attenuate frequencies away from the resonance frequency. This tank is tuned to resonate at the IF frequency. C9 and C10 also form a capacitive transformer to shift the impedance.
- T1 is used to transform the high impedance output of the amplifier to 50 ohms before it leaves the circuit board.
- R19, R18, and R20 provide an adjustable bias voltage which can be used to adjust the gain of the amplifier, if necessary. The gain can also be controlled by an external voltage, though this is not used in our project.

Tuned RF Amplifier

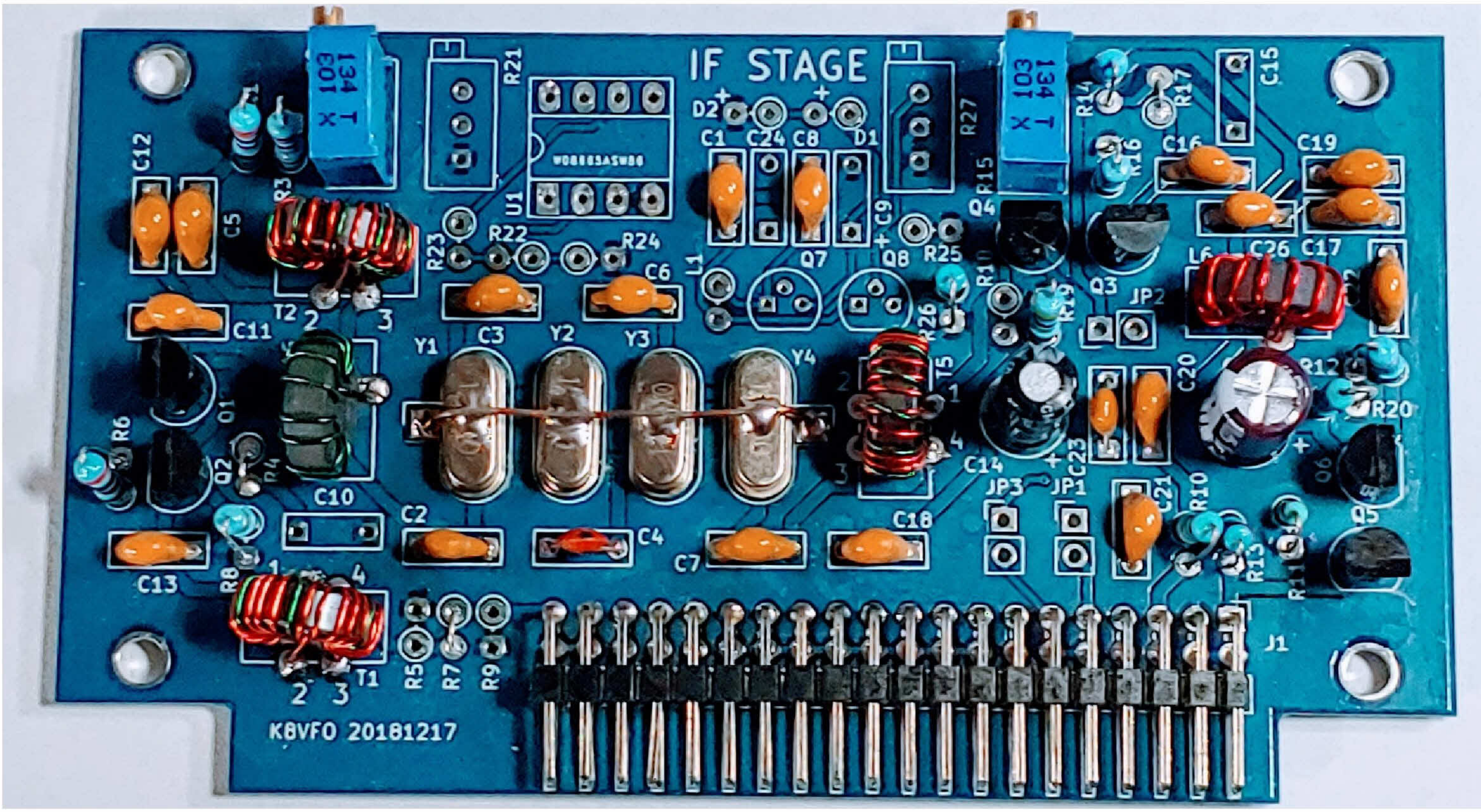
Tuned Amplifier



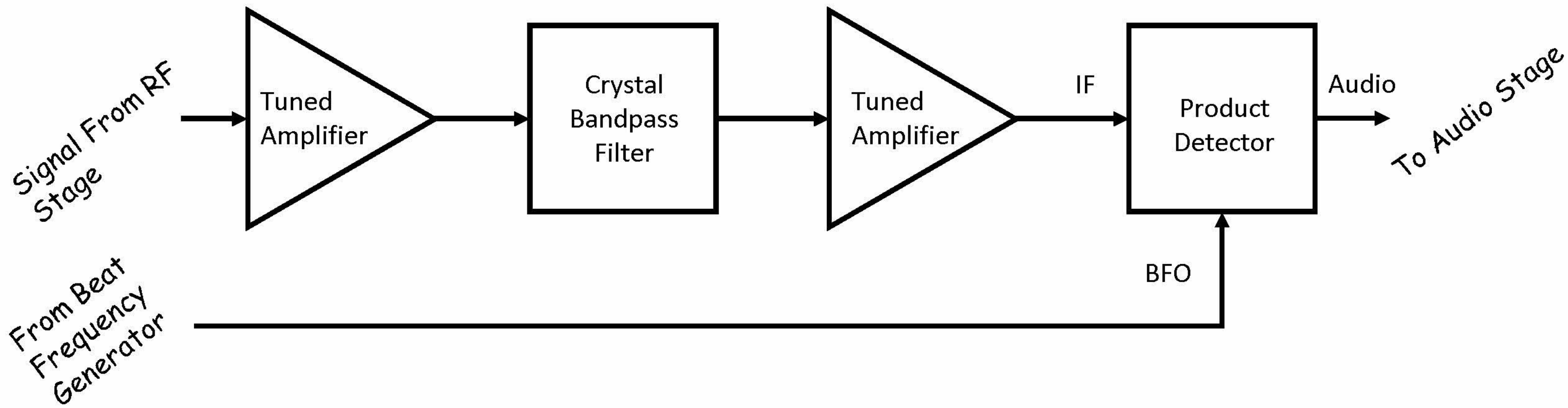
Occupied BW

Occupied BW	DBC
1.010000 MHz	3.00 dB

Construction of the RXP2 IF Stage



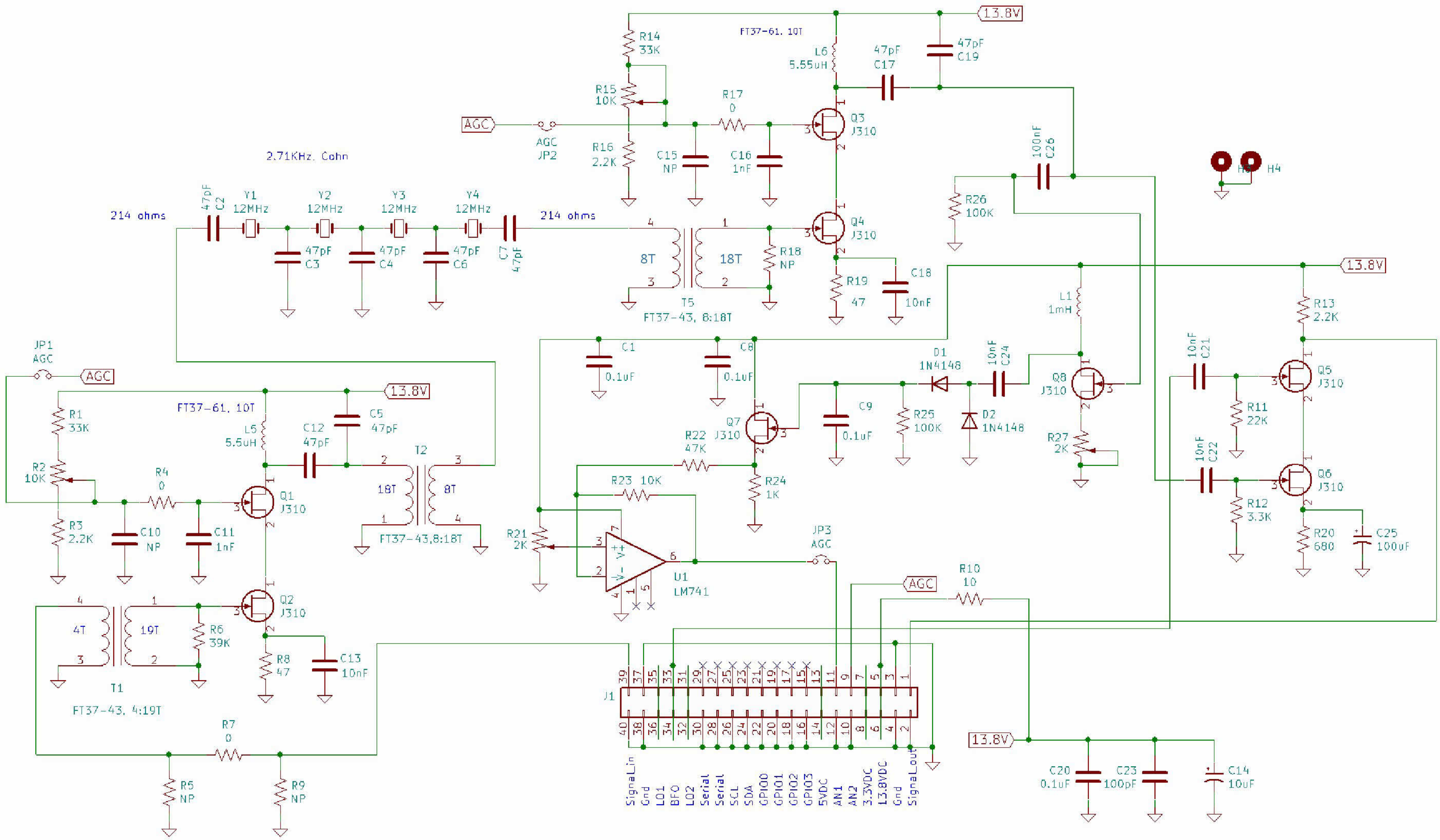
Design and Construction of the RXP2 IF Stage



<u>Overview of IF Stage</u>

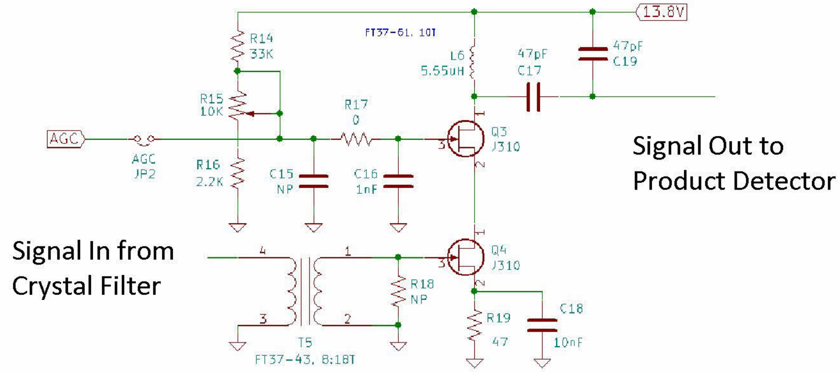
- The purpose of the Intermediate Frequency (IF) stage is to process the signal from the RF stage (which has been shifted to the intermediate frequency) and filter it to eliminate all except the specific slice of radio spectrum that we are interested in. Since the range of frequencies used for human speech is a slice of only about 3000 Hertz, we will use a bandpass filter with a bandwidth of about 3000 Hz.
- Using only inductors and capacitors, it would not be practical to build such a narrow bandwidth filter at the frequency we are processing. So this design uses a filter based on quartz crystals which have been cut to have a resonance over only a few hundred Hertz. By using four crystals and slightly shifting the resonance frequency of each by using capacitors, we can combine them into a bandpass filter with a 3000 Hz bandwidth and the ability to greatly attenuate anything outside of this band.
- Although quartz crystals have excellent ability to act as filters, they also attenuate the desired signals to some degree. To overcome that attenuation, and to provide further boost to the low level signal coming from the RF stage, we need to add amplification to the signal path. In the design of this stage, an amplifier is used before the filter and another after the filter.
- At the end of the IF stage, a mixer is used to shift the signal from the 12 MHz intermediate frequency down to the audio range so it's ready for the audio stage processing. In this type of application, where we are recovering the audio information from the RF signal, the mixer is typically called a *product detector*.
- Additionally, this board has provisions for a peak detector. The peak detector simply tracks the level of the signal so that if a weak signal is detected, more amplification can be applied to boost the level. Or, in the case of a signal level that's too high, the amplification can be reduced. However, in our project, we will not be using this *automatic gain control* (AGC) circuitry.

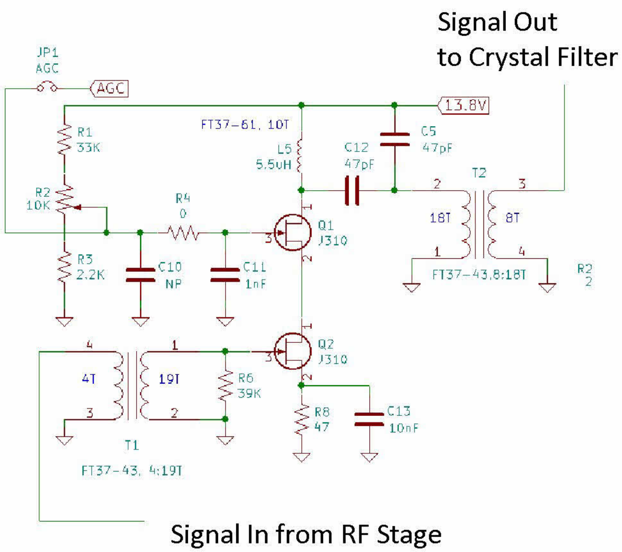
Design and Construction of the RXP2 IF Stage



Design and Construction of the RXP2 IF Stage

Tuned Amplifiers



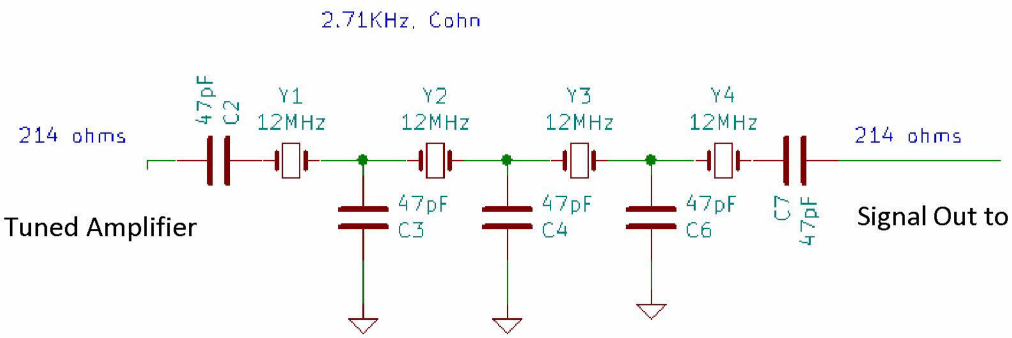


Operation

- The IF Stage contains two tuned amplifiers. One provides amplification before the signal enters the crystal filter. The other provides amplification to the signal coming out of the crystal filter.
- The operation of these amplifiers is the same as the tuned amplifier described for the RF Stage.
- The transformer, T1, is used to transform the 50 ohm impedance on the signal path from the RF Stage to a higher impedance expected by the amplifier.
- Transformers, T2 and T5, match the amplifier impedance levels to the 200 ohm impedance needed for the crystal filter to properly operate.
- The AGC lines can be used to change the amplification (gain) of the amplifiers by an automatic gain control circuit. However, the AGC circuit is not installed for this project.

Design and Construction of the RXP2 IF Stage

Crystal Filter



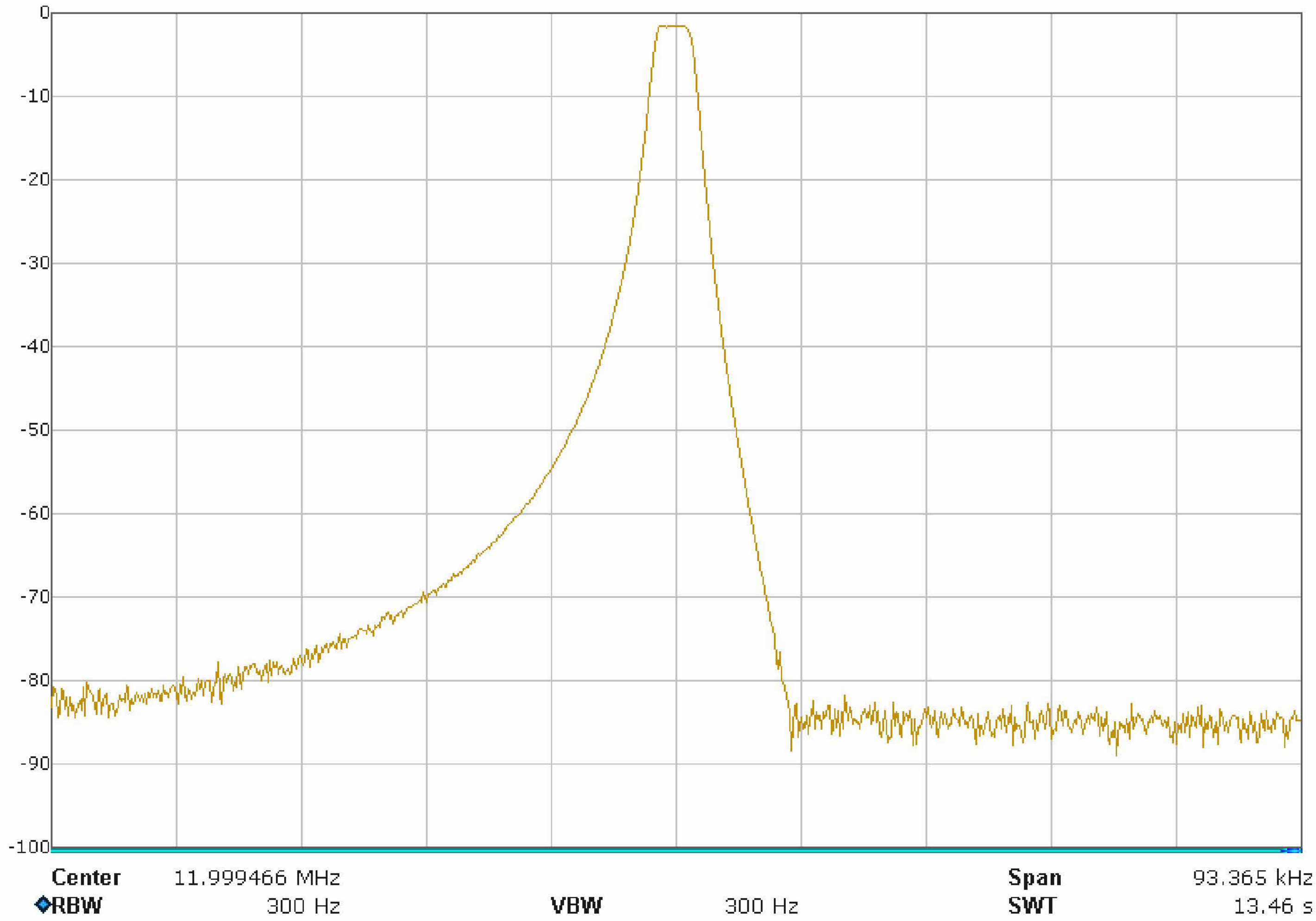
Signal In from Tuned Amplifier

Signal Out to Tuned Amplifier

<u>Operation</u>

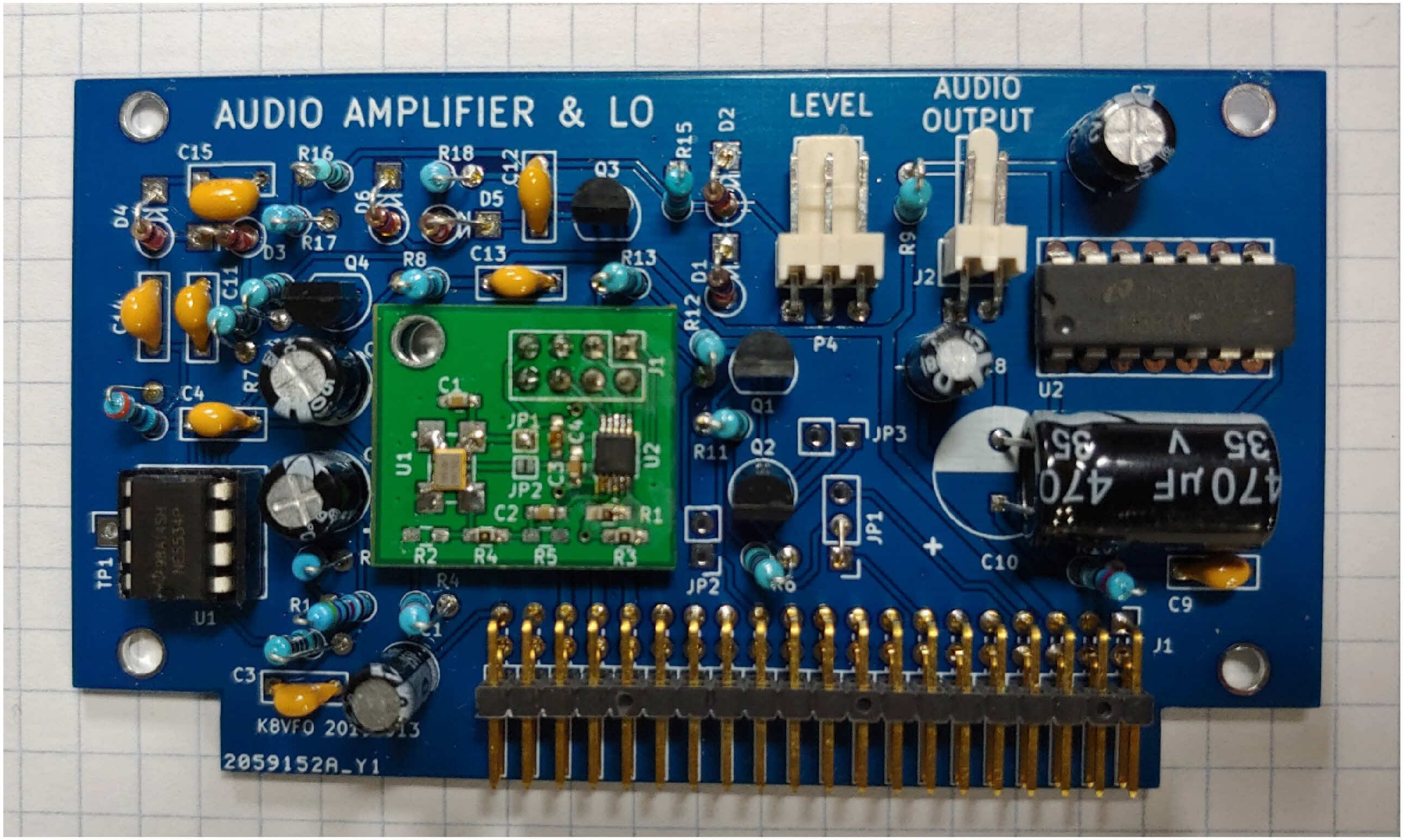
- Y1, Y2, Y3, and Y4 are quartz crystals manufactured to resonate at 12MHz. The surrounding capacitors cause the resonance frequencies of the crystals to each shift slightly so that the bandwidth of each crystal (which is a few hundred Hertz) overlaps the others such that the combination results in the desired wider bandwidth.
- The filter uses a design approach published by Seymour Cohn in 1957, so it's commonly called a Cohn filter. This one has been designed to have a 2700 Hz bandwidth to accommodate the 300 Hz to 3000 Hz speech frequency range typically found in a single sideband voice transmission.
- Because of the variations in parameter values that are typical for crystals and the adjacent capacitors, the performance of crystal filters may vary. However, the Cohn design is quite forgiving and will work well. The key objective is to have a bandwidth of about 3000 Hz and sharp attenuation outside of this band. If the center frequency is not quite 12 MHz, this can be accommodated by adjusting the intermediate frequency to match the performance of the filter.
- The crystal filter performs best when connected to specific source and load impedances. The impedance values resulting from the design calculations in this case specify a 214 ohm impedance match. So transformers are used to provide a 200 ohm match to the input and output amplifiers.

Design and Construction of the RXP2 IF Stage

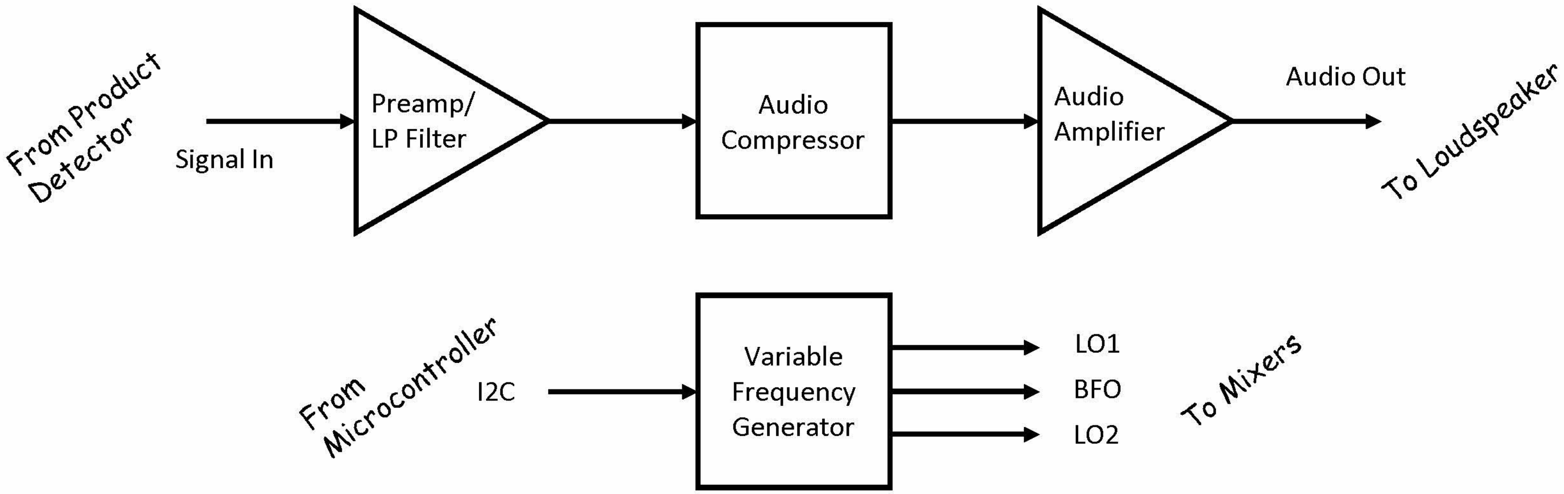


Crystal Filter, 3dB Bandwidth: 2.998 kHz

Design and Construction of the RXP2 Audio Stage and Local Oscillators

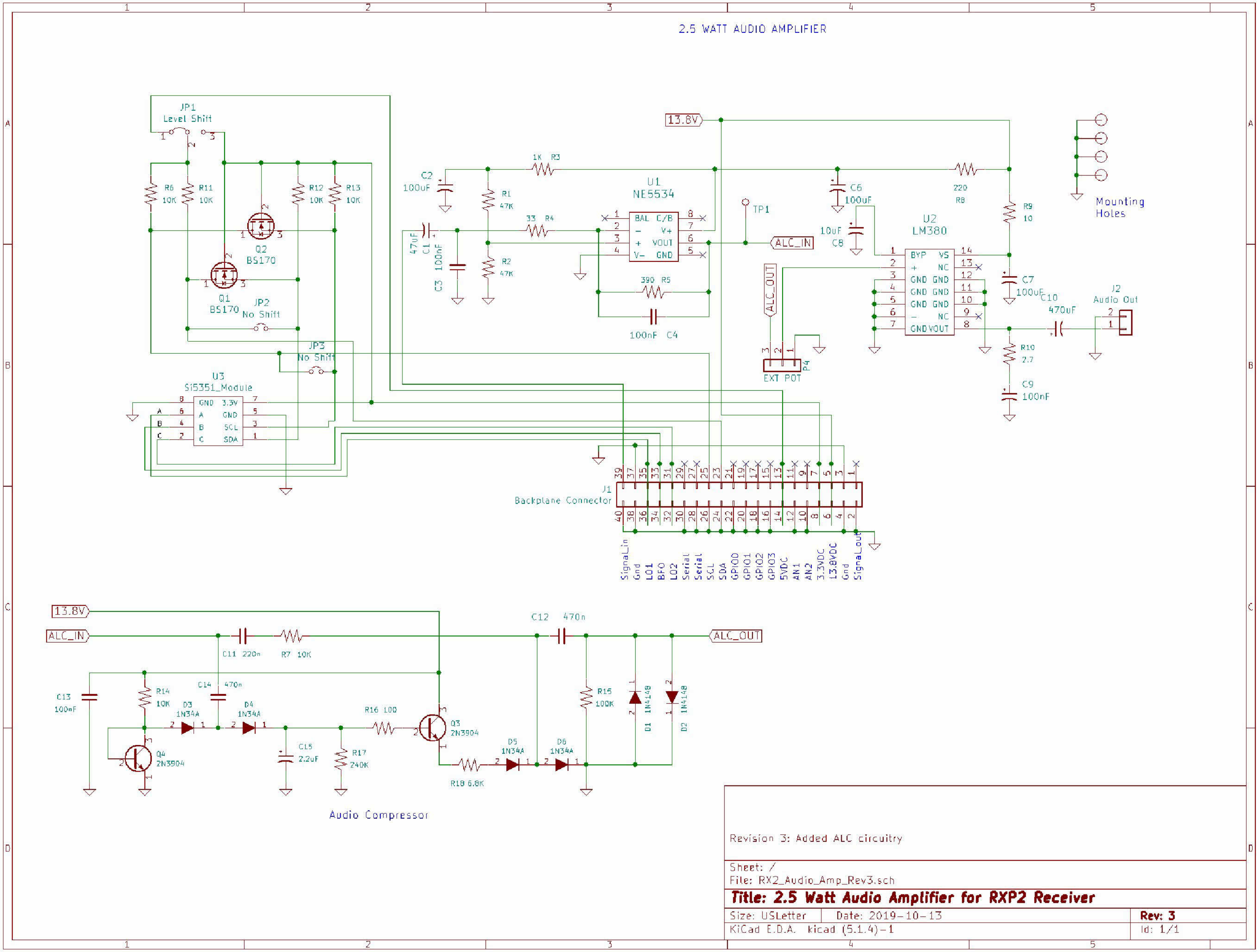


Design and Construction of the RXP2 Audio Stage and Local Oscillators



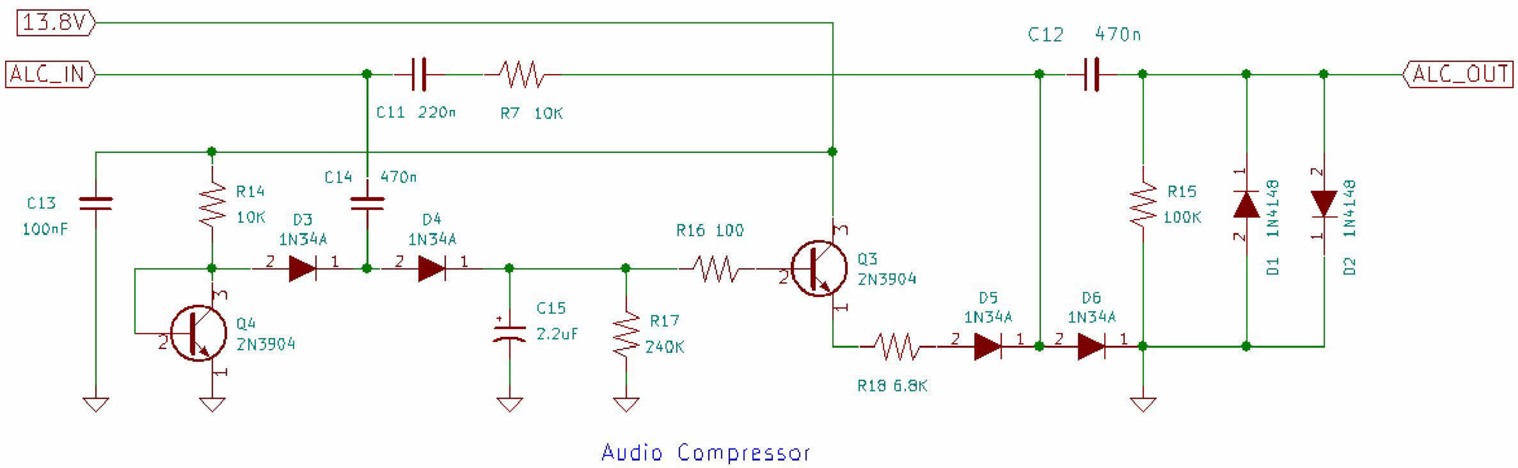
Operation

- The output of the product detector on the IF stage contains mixing products which, in addition to various radio frequency components, includes the desired signal shifted down to the audio range. This feeds into the input of the audio stage. The input is amplified and filtered. The filter is a Low Pass filter which blocks the radio frequency components and allows the audio components to pass.
- This board also holds the radio frequency generator module which produces specific output frequencies which are fed into the mixers.
- LO1 is the local oscillator #1 and is used to shift the signal from the antenna to the intermediate frequency used in the radio.
- BFO is the beat frequency oscillator and is used to shift the intermediate frequency down to the audio range.
- LO2 is currently not used in the design.
- The radio frequency generator is based on a programmable clock chip and is controlled by the microcontroller via an Inter Integrated Circuit (I2C) serial communication channel.


2.5 WATT AUDIO AMPLIFIER
JP1
Level Shift
R6 10K
R11 10K
R12 10K
R13 10K
Q1 BS170
Q2 BS170
JP2 No Shift
JP3 No Shift
U3
Si5351_Module
GND 3.3V
A GND
B SCL
C SDA
13.8V
C2 100uF
1K R3
R1 47K
R2 47K
33 R4
47uF C1
C3 100nF
U1
NE5534
BAL C/B
V+
VOUT
V- GND
390 R5
100nF C4
TP1
ALC_IN
ALC_OUT
C6 100uF
10uF C8
220 R8
R9 10
U2
LM380
BYP VS
GND
GND VOUT
C7 100uF
C10 470uF
J2 Audio Out
R10 2.7
C9 100nF
EXT POT
P4
Mounting Holes
J1
Backplane Connector
Signal_in
Gnd
LO1
BFO
LO2
Serial
Serial
SCL
SDA
GPIO0
GPIO1
GPIO2
GPIO3
5VDC
AN1
AN2
3.3VDC
13.8VDC
Gnd
Signal_out
13.8V
ALC_IN
C11 220n
R7 10K
C12 470n
ALC_OUT
C13 100nF
R14 10K
C14 470n
D3 1N34A
D4 1N34A
C15 2.2uF
R17 240K
R16 100
Q3 2N3904
Q4 2N3904
R18 6.8K
D5 1N34A
D6 1N34A
R15 100K
D1 1N4148
D2 1N4148
Audio Compressor
Revision 3: Added ALC circuitry
Sheet: /
File: RX2_Audio_Amp_Rev3.sch
Title: 2.5 Watt Audio Amplifier for RXP2 Receiver
Size: USLetter
Date: 2019-10-13
Rev: 3
KiCad E.D.A. kicad (5.1.4)-1
Id: 1/1

Design and Construction of the RXP2 Audio Stage

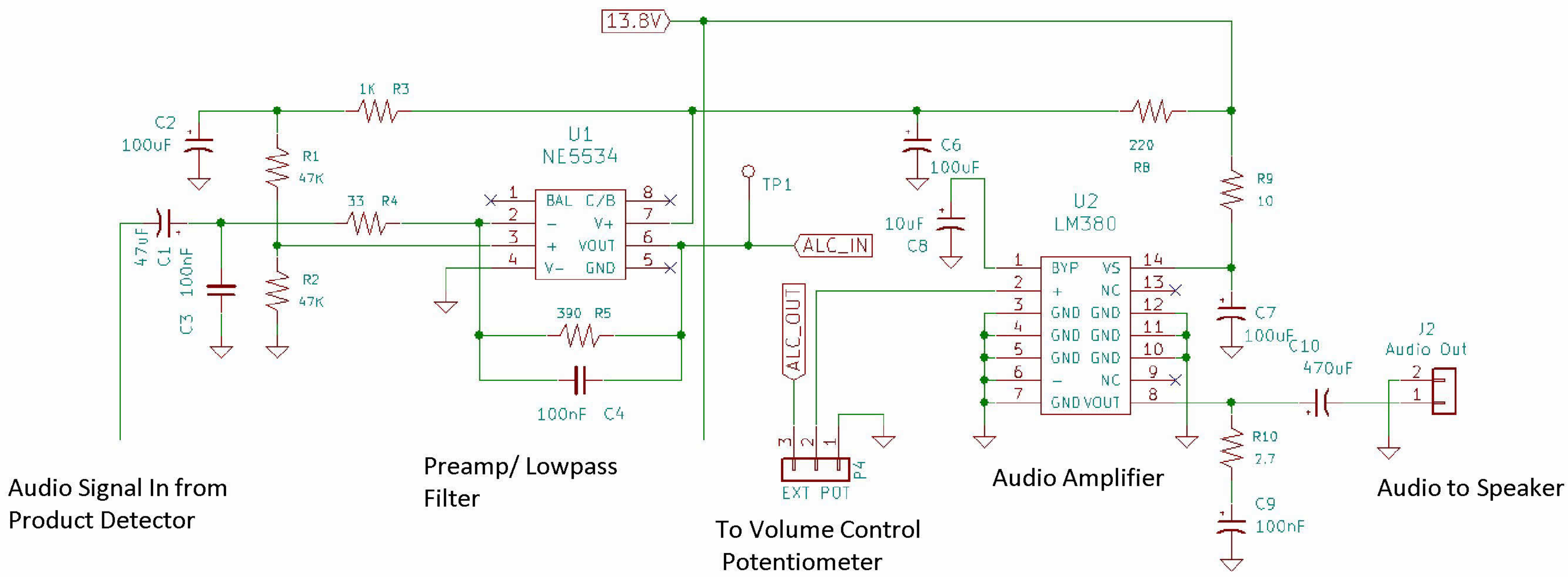
Audio Compressor



This audio compressor circuit was designed by W2AEW. D4 and C15 form a peak detector which tracks the peak level of the audio, using Q3 to adjust the voltage drop in the voltage divider composed of R7 and R15 by controlling the effective resistance of D6, which is in parallel with R15.

The latest builds of the receiver added a tap at C15 and feeds it into the A/D convertor on the Arduino, using it to control the RF attenuator. This provides AGC for the receiver. Consequently, the audio compressor is no longer necessary and will be replaced with only a peak detector.

Design of the RXP2 Audio Stage



U1 is a low noise operational amplifier chip configured as a preamp with a frequency roll off above 3 kHz to eliminate any extraneous mixing products from the product detector.

U2 is a common LM380 audio amplifier chip with a 2 watt maximum output.

What's next?

This is an experimental platform! Here's other experimentation underway:

- custom processor board with a more powerful processor

  (STM32F103 72 MHz 32 bit ARM Cortex M3, 64/128KB flash, 20KB RAM)
- variable bandwidth crystal filter
- RF amplifiers using common BJTs instead of FETs
- replace IF stage board with DSP stage
- extend range to include 60, 80, and 160 meters

- And a few ideas I would like to try:
  - add socket on baseboard for processor/ display
  - use TFT graphic display
  - use single ARM Cortex M4 processor for DSP and user interface
  - miscellaneous:

    audio output for headphones, digital decoding

    PTT muting