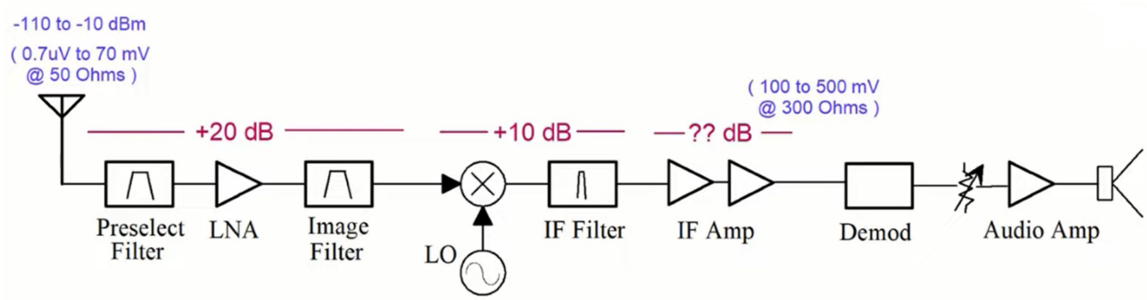
FM Receiver

Let's create and break down the circuitry of an **FM receiver (superheterodyne:** IF signals are not baseband**)**.

The design is will be based off of this Radio Design 101 video series; episodes from this series will be mentioned in this document for reference. This website is associated to the aforementioned series, and was useful for designing RF perf-boards.



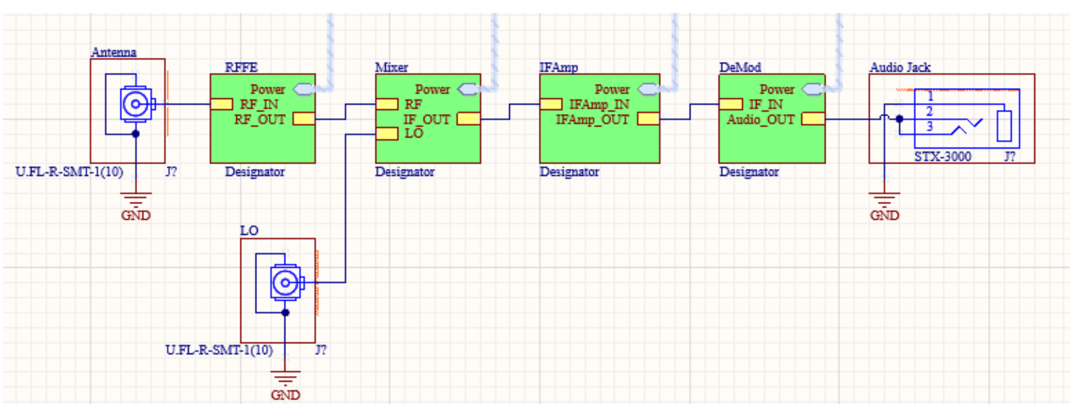
I've also referenced the following textbooks for certain design choices:

- Christopher Bowick - RF Circuit Design
- Behzad Razavi - RF Microelectronics

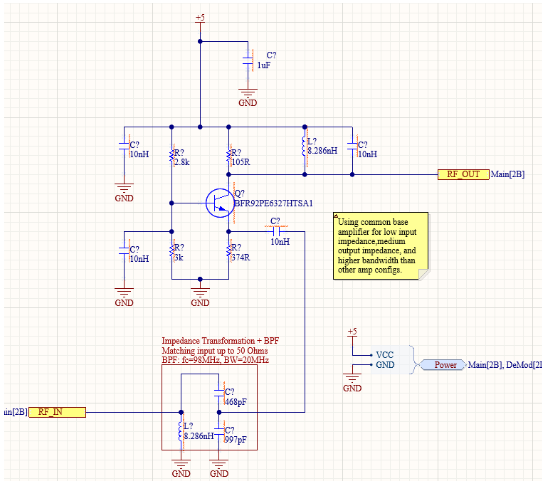
Design choice reasoning and detailed calculations are found in the following draft PDF:

A useful impedance matching Smith chart tool: Online Smith Chart Tool (will-kelsey.com)

System Block Diagram



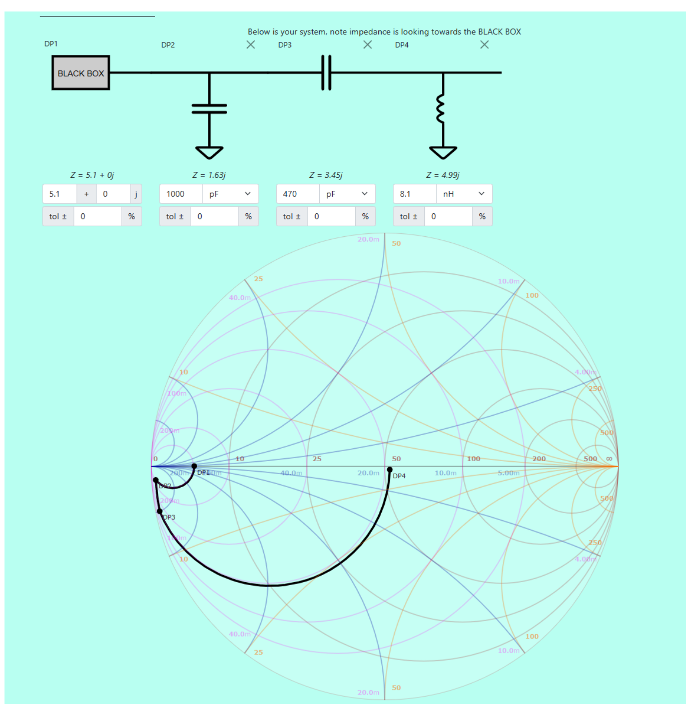
RF Front End



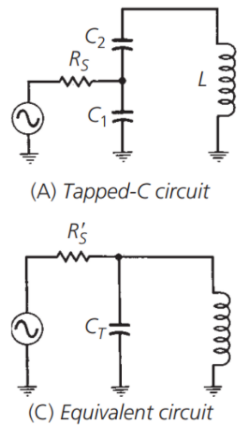
It consists of a

- **Preselect (band-pass) filter**. Its job is to filter out "out-of-band" interferers, ideally only allowing the "receive band" to pass. If this filter is missing, the rf amplifier stage will be loaded more (due to the amplification of unwanted signals), potentially causing overloading, clipping, and nonlinearity. The higher the order of the filter, the steeper the roll-off will be. However, I will be going with a first order filter as I've seen it suffice in multiple working designs and higher order filters have more parasitics, which lower the gain (produce insertion loss). Additionally, the image reject filter will work with this one to provide a 2nd-order-like roll-off on the interferers.

  This filter is also part of impedance matching circuitry, which matches the ~5.1 Ohm input impedance to ~50 Ohms (the antenna impedance). The following Smith chart shows the effectiveness of this circuit (the impedance is 52.2-1.43j, with an f_c of 98.8MHz):



The values used were based off of this impedance transformation:



$$R_s' = R_s\left(1 + \frac{C_1}{C_2}\right)^2$$

$$C_T = \frac{C_1 C_2}{C_1 + C_2}$$

RF Circuit Design, Christopher Bowick

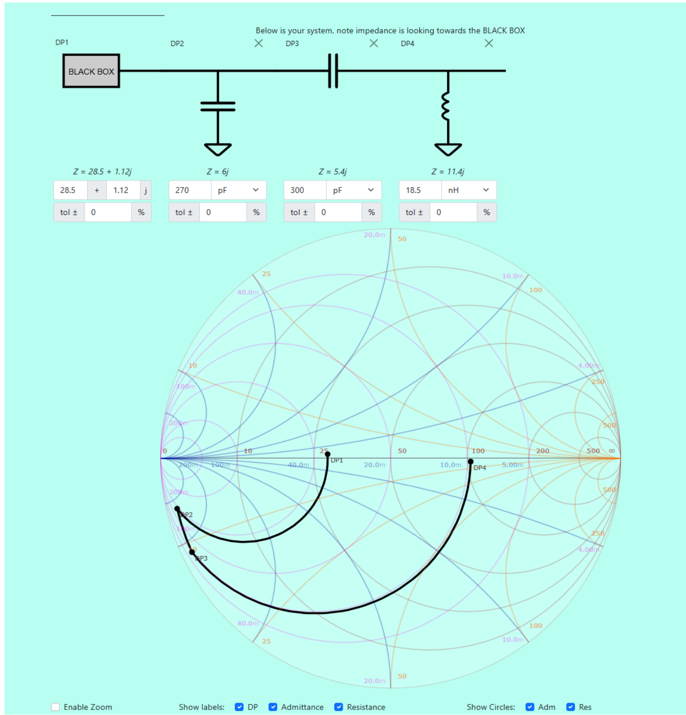
- Inductor query. IThe ideal value was, 8.28587nH, but in combination with practical capacitor values, it's best to use an 8.1nH.
  - Fixed Inductors | Electronic Components Distributor DigiKey
    - 8.2nH
    - Q = 80 @100MHz
  - LQW15AN8N3G8ZD Murata Electronics | Inductors, Coils, Chokes | DigiKey
    - 8.3nH
    - Q = 32 @250MHz
  - LQW15AN8N1G80D Murata Electronics | Inductors, Coils, Chokes | DigiKey
    - 8.1nH
    - Q = 32 @ 250 MHz
- Impedance transformation capacitors
  - GCM1885C2A102FA16D Murata Electronics | Capacitors | DigiKey
    - 1000pF
  - GCM1885C2A471FA16D Murata Electronics | Capacitors | DigiKey
    - 470pF

- **Low-noise-amplifier (LNA)**.
  - Made with RF-spec'd BJTs.
  - 20dB gain from antenna output to mixer input calls for x20 open circuit gain.
  - Powered by +5V, as in episode 6 @10:37.

- BFR92PE6327HTSA1 Infineon Technologies | Discrete Semiconductor Products | DigiKey
    - BFR92PE6327HTSA1
    - Max Ic = 45mA (design will have 5mA quiescent)
    - Collector-emitter-breakdown = 15V (we're working with 5V)
    - "For broadband amplifiers up to 2GHz" (we go up to 108MHz)
- Resistors
    - 2.8k
    - 3k
    - 105R
    - 374R
- AC-Short Cap (for common-base design)
    - 10nH
- DC-Blocking Cap
    - 10nH
- Bypass & Decoupling Caps
    - 10nH (provide quick return path for AC signals from 5V to GND)
    - 1uF (decoupling cap)

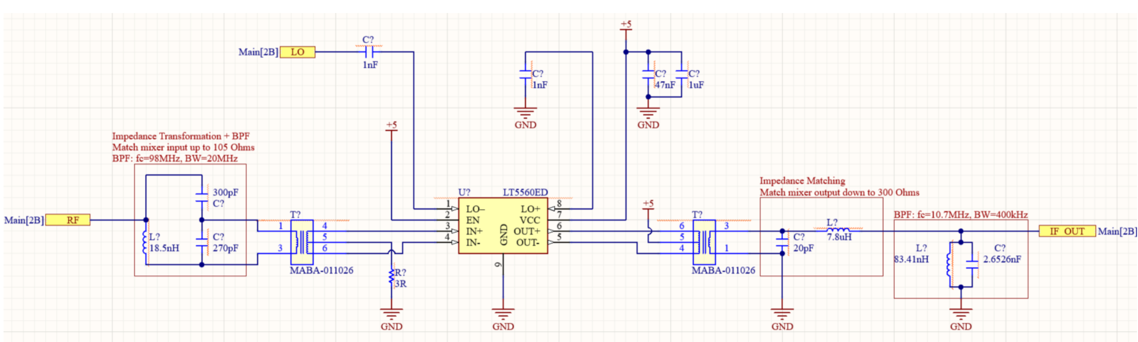
- Image reject (band-pass) filter. It filters out the out-of-band noise/noise-floor before it enters the mixer (Razavi pg.166 mentions this). Also, the image frequency (which, like the target frequency, differ from the LO by 10.7MHz) get's filtered out (pre-select filter contributes to this).
    - This forum post discusses the reasoning behind IF being 10.7MHz in FM radio receivers. In short, it makes all image frequencies be out of the 20MHz-wide broadcast band.

  It is incorporated in the impedance matching circuitry of the Downconversion Mixer input, which transforms the mixer input impedance to 105 Ohms (amp output Z). It has an ideal center frequency of 98MHz (using practical component values shifts it to 104MHz) and bandwidth of 20MHz (shifted to 22.6MHz). Here is a smith chart of the circuit (resulting impedance is 103 - 3.24j).



- [744913118 Würth Elektronik | Inductors, Coils, Chokes | DigiKey]()
  - 18.5nH Inductor
  - Q = 132 @ 150MHz
- [GCM1885C2A301FA16J Murata Electronics | Capacitors | DigiKey]()
  - 300pF Capacitor
- [GCM1885C2A271FA16D Murata Electronics | Capacitors | DigiKey]()
  - 270pF Capacitor

Downconversion Mixer



This device multiplies the LO waveform with the RF input waveform (at the LNA output), resulting in waveforms (at the mixer output) carrying all of the modulating “data” that was present at the input, but at downconverted & upconverted frequencies ($\pm(w_{in} \pm w_{LO})$), the latter of which gets filtered out.

This “translation” makes it easier to have a high Q (center frequency to bandwidth ratio) channel-select filter due to the center frequency of the downconverted (**IF**) waveform being much lower than the input’s (in FM radios, a standard 10.7MHz is used). Also, if the LO frequency can be varied, the channel-select filter can have a single center-frequency, making its design simple (i.e. non-variable) yet allowing the receiver to demodulate different radio channels!

Query: RF Mixers | Electronic Components Distributor DigiKey

Ended up using the LT5560 as it has lots of documentation and application examples. The only problem is it operates at frequencies above 10kHz, so the first version of this project will involve tests on inaudible modulating signals (not FM radio.. quite yet!)

- To convert the single-ended output signal from the LNA to a differential input (for low losses at the mixer input stage), a balun is used. Additionally, the output stage is differential by default, which needs to be transformed as well.

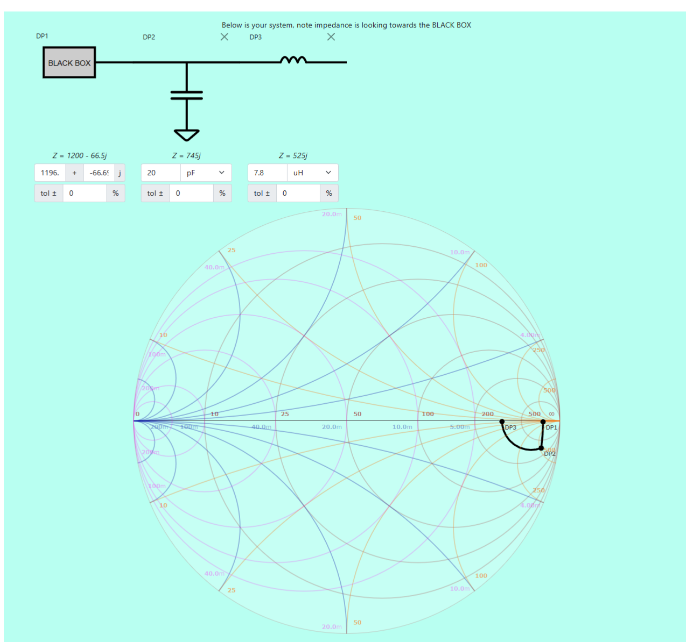
  Balun query, we want 1:1; for the FM band.

  - MABA-011026 MACOM Technology Solutions | RF and Wireless | DigiKey

Mixer input Impedance Matching is mentioned above.

Mixer output Impedance Matching:

- Mixer output gets matched to 300 Ohms (input Z of IF amp) with an LC network. The Smith chart below involves practical R & C values, which result in an impedance of 317 - j4.33.
  - The benefit of this step is uncertain for me. At this point in the receiver, since we are not concerned much with reflections due to the trace lengths being smaller than a tenth of the wavelength of the IF frequency, it’s probably best to prioritize voltage gain over maximum power transfer. Though, the mixer output impedance is fairly high, so transforming it down might be beneficial.



- Query Fixed Inductors | Electronic Components Distributor DigiKey
    - PA2050.782NL Pulse Electronics | Inductors, Coils, Chokes | DigiKey
        - 7.8uH Inductor
        - 10% Tolerance (lowest that was available)
        - DC resistance 5.1mOhms.
    - GCM1885C2A200FA16D Murata Electronics | Capacitors | DigiKey
        - 20pF Capacitor

The output stage of this mixer employs a **Channel Select Filter**:

- 10.7MHz center frequency, 400kHz bandwidth, as per the video series. Uses practical values insignificantly changes fc, and BW goes to 392KHz. High Q inductor is used to keep BW minimal.
    - LQW2BAS82NJ00L Murata Electronics | Inductors, Coils, Chokes | DigiKey
        - 82nH
        - Q = 70 @500MHz
            - Calculated Rp = 18k
    - GCM1885C1H272FA16J Murata Electronics | Capacitors | DigiKey
        - 2700pF
        - Murata (good documentation)

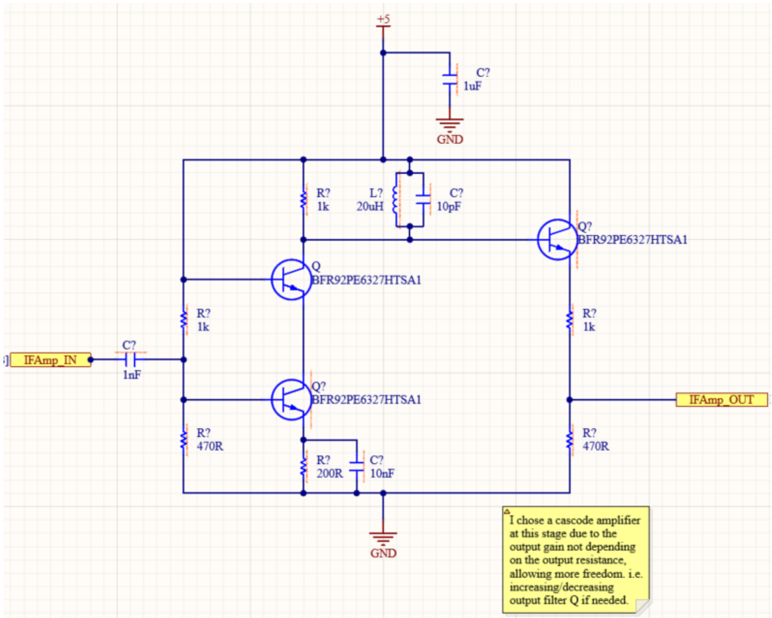
Decoupling and Bypass Caps

- 2× 1nF
- 47nF
- 1uF

Current Limiting Resistor

- 3 Ohms

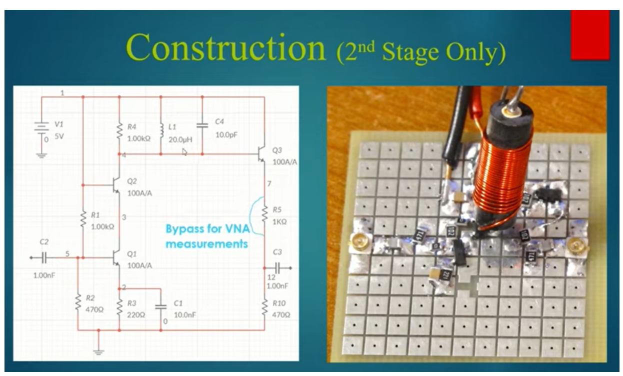
IF Amplifier



Provides gain to the IF signal.

- How much gain? Enough for the powered speakers to pick it up.

Will use a cascode amplifier. The biasing and overall amplifier setup is pretty involved, so I've copied a setup from the video series I've followed to get a practically working FM receiver IF-stage cascode amplifier:



[Radio Design 101 - Finishing the Receiver (Episode 6) - YouTube]

Transistors

- 3x [BFR92PE6327HTSA1 Infineon Technologies | Discrete Semiconductor Products | DigiKey]

Resistors

- 3× 1k
- 2× 470R
- 200R

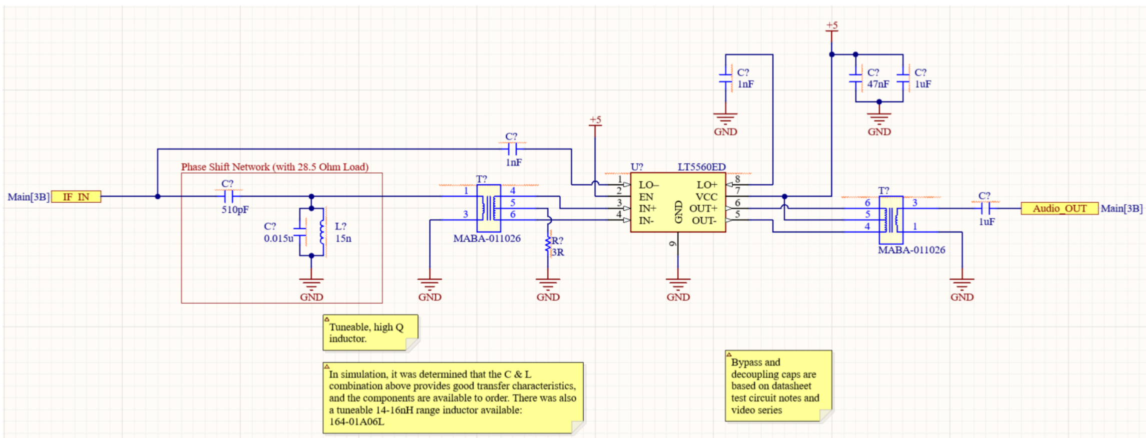
Capacitors

- 1uF Decoupling
- 10nF common-source cap

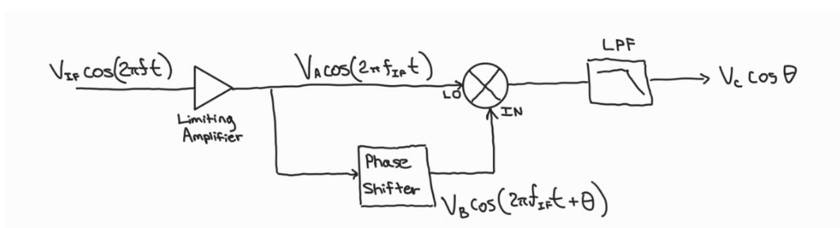
Filter

- 744772200 Würth Elektronik | Inductors, Coils, Chokes | DigiKey; 20uH inductor
- 06035A100BAT2A KYOCERA AVX | Capacitors | DigiKey; 10pF capacitor

Demod

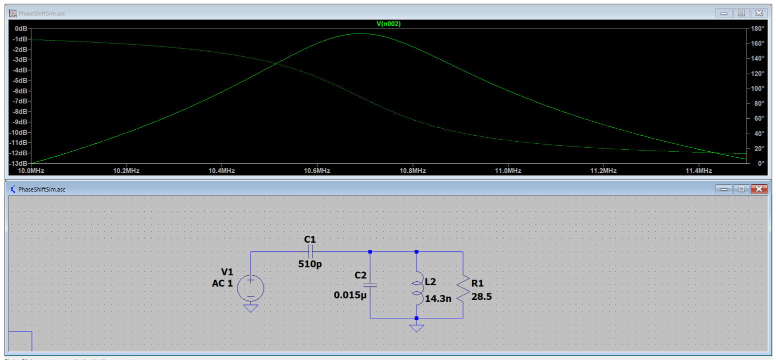


The De-Mod stage consists of a simplified frequency-discriminator circuit. It’s working principle is to create a phase shift on the IF signal, and multiply (with a mixer) the original and the phase shifted signals. The output will be a signal that has a phase equal to the phase shift angle (since the frequencies of the multiplied signals are equal, the multiplication cancels them out, resulting in a baseband signal). The phase shift applied to the IF signal should be applied by a phase shift network whose phase frequency response is linear in the range of the desired FM channel (10.7MHz +- 75kHz).



Note: the schematic doesn’t include a limiting amp

The phase shift network has the following transfer characteristic:



- The component values are based off:
  - C1 having reactance of 28.5 Ohms (to match the load: not sure why but it worked in another design),
  - C2 (fixed) and L2 (variable 14nH-16nH: mouser link) both being available components and L2 having available “fixed” counterparts (i.e. 15nH).
- CC0603FRNPO9BN511 YAGEO | Capacitors | DigiKey
  - 510pF Cap
- C0603C153F3GAC7867 KEMET | Capacitors | DigiKey
  - 0.015uF
  - 0603
  - 1% Tolerance, $2/unit
- C0603C153G3GEC7867 KEMET | Capacitors | DigiKey
  - 0.015uF
  - 0603
  - 2% Tolerance, $0.67/unit
- 0603B153J500CT Walsin Technology Corporation | Capacitors | DigiKey
  - 0.015uF
  - 0603
  - 5% Tolerance, $0.15/unit

The LT5560 Mixer is used again for multiplying the out of phase signals. 2× 1:1 Baluns are used for converting single ended amplifier signals to balanced mixer input, and balanced mixer output to single ended audio input.

Decoupling, Bypass and DC blocking Capitors

- 2× 1nF
- 47nF
- 2× 1uF

Current Limiting Resistor

- 3 Ohms

Audio Output

STX-3000 Audio jack connected to a powered speaker.

Can use an Op-Amp circuit with adjustable gain to be able to amplify the output signal.

Local Oscillator

This variable frequency oscillator is essential for allowing the user to select different channels.

If we want an IF of 10.7MHz, then $f_{RF} = f_{LO} + 10.7 * 10^6$. f_{LO} can be precisely tuned by the user to select an f_{RF}. However, this is tricky.

(chapters 9-11 “frequency synthesizer”, chapter 4.2.1 pg 161, chapter 8 “Oscillators”).

This is a pretty involved topic. I will just use a function generator for this purpose, for now.