Clackamas Superheterodyne CW Transceiver

FDIM 2010 QRP Challenge Entry by Jason Milldrum, NT7S

Introduction

When I heard in January 2010 that QRP ARCI would be sponsoring a new design challenge at Four Days In May, I got more excited about designing a new radio than I have in a long time. I commend the creation of this 72 part challenge, as it was one of the most difficult yet rewarding experiences that I've ever had in my homebrewing and radio design career. I'm pleased to present my entry into the contest: the Clackamas superheterodyne transceiver.

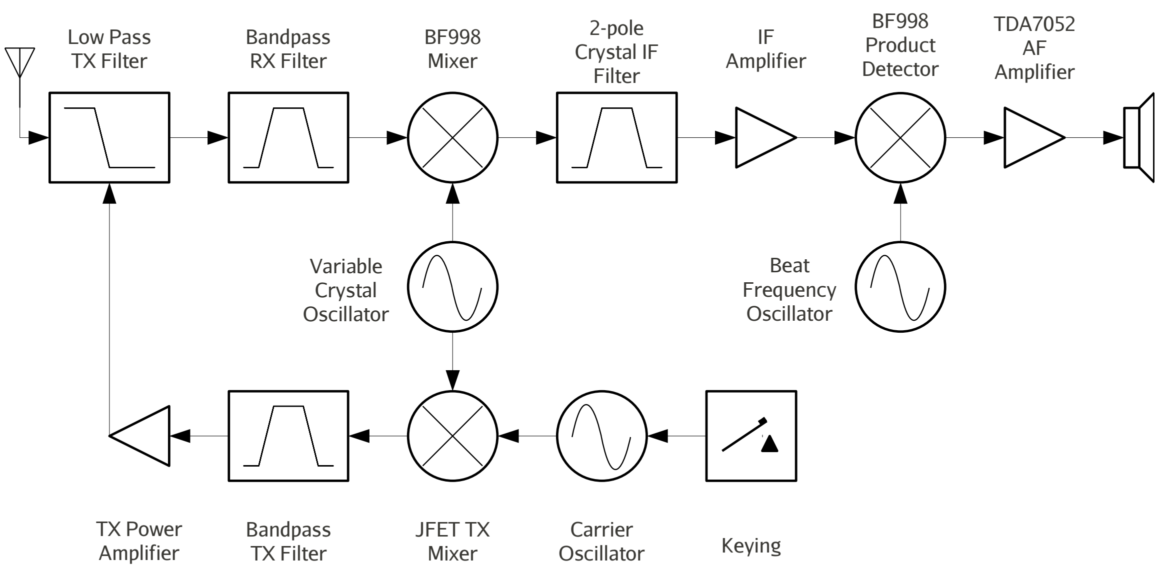
Block Diagram

The topology of the Clackamas follows that of a typical single-conversion superheterodyne. The signal coming into the receiver front end passes through the transmitter low pass filter and a DPDT T/R switch. A single-tuned circuit provides bandpass filtering to knock down strong out-of-band signals. The desired 40 meter signal is then downconverted to the 4.032 MHz intermediate frequency and amplified by approximately 8 dB. A simple Colpitts crystal oscillator running at 11.059 MHz provides the local oscillator signal to both the receive and transmit mixers. Intermediate frequency filtering is provided by a 2-pole 4.032 MHz crystal ladder filter with a nominal bandwidth of 450 Hz. This filter is coupled via L-network to a simple bipolar IF amplifier with approximately 27 dB of gain. The combination product detector/beat frequency oscillator downconverts the IF signal to audio frequencies while amplifying it by 10 dB. The audio signal is then fed into a TDA7052 audio amplifier, which provides ample gain to drive headphones.

The heart of the transmitter is a N-channel JFET active mixer, which takes the LO signal and mixes it with a Colpitts carrier oscillator coupled to the gate. The output of the active mixer is filtered with a double-tuned circuit before being lightly coupled to the BS170 power amplifier. Transmitter filtering is provided by a standard 5-element low pass filter.

Design Strategy

Even though the rules of the Challenge limited us to one integrated circuit (without penalty), I knew that I would need to find a way to include circuits that resembled ICs, in the sense that they would need to be able to perform or combine functions in as few parts as possible. Immediately, it seemed to make the most sense to try to work with dual-gate MOSFETs. I've had a large store of BF998 dual-gate



MOSFETs in my junkbox for many years, courtesy of KE6F (via W7ZOI's website).

Over the last few years, I had experimented with the BF998 and was able to successfully use them as amplifiers but never had much luck getting them to work correctly as active mixers. Going back to many of my reference books published in the 70s and 80s, it was easy to find lots of dual-gate MOSFET circuits, but the biasing schemes presented never worked correctly with the BF998.

To make a very long story short, after much pain and suffering I was able to tackle the two main impediments to implementing my dual-gate MOSFET strategy: biasing the BF998 for use as a decent performing mixer and figuring out how to configure the BF998 to function as a combination product detector and BFO. Once these challenges were tackled, the rest of the transceiver fell into place with only a moderate amount of difficulty. It should be noted that I scrapped the whole idea of using dual-gate MOSFETs twice so that I could try different design avenues, but none of the alternative strategies could yield a parts count even close to 72. Eventually perseverance paid off, and I was able to get my original design idea to work after a lot of experimentation.

One of the greatest advantages of using FETs is the relaxation of the need for high oscillator drive levels. This allowed me to cut all of the oscillators to bare-minimum functional units, with no buffering necessary due to the very light loading from high input impedances of the FETs.

I would have liked to have used FETs throughout the entire rig, but the parts count limitation demanded that I use a bipolar transistor amplifier in the IF, so I also stuck with bipolar oscillator circuits since they are cheap and nearly bulletproof.

Pedigree

It is very clear that the Clackamas can draw its lineage from the series of minimalist superhet receivers that Doug DeMaw, W1FB published in the late 70s. While I did not strive to copy these designs, there is only a small number of ways that one can configure a minimal parts count superhet using dual-gate MOSFETs. Let there be no doubt that the Clackamas was not a simple cut-and-paste job. While its design may be similar to the W1FB classics, it took quite a bit of work to modernize the circuits and pare them down to an absolute minimum of parts.

Perhaps the greatest inspiration for the Clackamas came from the W1FB combination product detector and BFO. Without this critical bit of parts-saving circuitry, I think that my task would have been nearly impossible to achieve.

Much credit also goes to the wonderful work of Wes Hayward, W7ZOI. His work in the homebrewer classics such as *Solid State Design for the Radio Amateur* and *Experimental Methods in RF Design* have provided me with an invaluable education in practical circuits that can get the job done. His S7C design was especially influential in the design of the Clackamas.

Specifications

General

Frequency Range:	7.029 – 7.0325 MHz

Receiver

IF Bandwidth:	462 Hz
MDS:	-126 dBm
3rd Order DR (20 kHz):	80.5 dB
IIP3 (20 kHz):	-5.2 dBm
Blocking DR (20 kHz):	102.6 dB
IF Rejection:	23 dB
Image Rejection:	48 dB
Current Consumption (13.8 VDC):	50 mA

Transmitter

Power Output (13.8 VDC):	1.7 W
Current Consumption (13.8 VDC):	260 mA
Spectral Purity:	<-40 dBc

Design Commentary

Front End

A light bit of bandpass filtering is provided by a single-tuned circuit in the receiver front end. I was a bit concerned about the ability of a single-tuned circuit to provide any meaningful filtering of the very strong adjacent signals one generally encounters in the 40 meter band, but the filter worked surprisingly well. Of course, the conditions on 40 meters tends to be easier here on the West Coast of the United States than they are in other places, so this design may not be as suitable in those areas.

The standing current in Q6 (the BF998 mixer) is very small; only a few hundred microamps. When I was working on the development of the mixer, I tried to increase the standing current by reducing R9 and providing bias to gate 1. It wasn't difficult to get the standing current to a few milliamps, but a large problem manifested itself. Increasing the standing current also triggered a very significant degradation in the noise figure (especially if bias was added to gate 1). Reducing the standing current made the receiver quite deaf. By quite a bit of trial and error, I was able to find a value of R9 that provided the sweet spot between excessive noise and insufficient gain. This is not my favorite way to design circuits, but I still don't have a firm grasp on all of the nuances of using the BF998 as a mixer, so using a purely experimental method is the best that I could do under the circumstances.

Crystal Ladder Filter

There is nothing particularly interesting about the 2-pole crystal IF filter. The filter was designed for a 450 Hz bandwidth with the *xlad* program from the *Experimental Methods in RF Design* supplementary CD using common 4.032 MHz crystals. The terminating impedance of the filter ended up being about 225 Ω. T2 provides the impedance transformation from the Q6 drain impedance of approximately 1.2 kΩ, while an L-network formed from C10 and L2 match the filter to the 50 Ω input impedance of the IF amplifier.

Product Detector/Beat Frequency Oscillator

In my view, the greatest breakthrough in the design of this radio was the completion of the combination product detector/BFO. As I found though experimentation, the only reason that this circuit can work is because the IF signal at RF frequencies is converted down to baseband. In order for Q7 to be able to oscillate at 4.032 MHz, the drain has to be bypassed to ground at that frequency (just as you would expect a Colpitts to be configured) while allowing the AF signals to remain on the drain. As far as I can tell, there is no way to configure this circuit to work as a front end mixer (where you would move a RF signal to another RF frequency).

Audio Amplifier

The audio amplifier is so dead simple there is very little to say about it. The selection of the TDA7052 was a virtual no-brainer, since I knew that it needed very little supporting circuitry in order work. It turns out that I was able to get it to function reasonably well completely on its own, with no decoupling on the V_{CC} rail. There's more than enough audio gain from this amplifier. You can't beat 40 dB of audio amplification and 1 watt of available AF power for a grand total of 1 part.

Variable Crystal Oscillator

There's nothing particularly interesting about the VXO. It is a standard Colpitts VXO with polyvaricon tuning. Because it only needs to drive high impedance FET gates, there's no need for buffering. Drive levels to the receiver and transmitter mixers were set by experimentally changing the coupling capacitors (C20 and C29)

Carrier Oscillator and Transmit Mixer

The carrier oscillator is nearly an exact copy of the VXO, with two important exceptions. A large inductor was needed in series with the crystal in order to pull the oscillator onto the right side of the IF filter skirt. Since I ran low on parts, I found that I was able to leave the normal 100 nF decoupling capacitor off of the collector. Once again, due to the fact that the CO is driving a FET gate, no buffering was necessary.

Transmitter keying is provided by grounding the emitter leg of the carrier oscillator. Normally, directly keying an oscillator is a big faux pas. However, the CO is so lightly loaded by the transmit mixer that no noticeable chirp is detectable during keying.

It took a bit of work to find a workable transmit mixer. It was always my desire to use an active device as a mixer, but I encountered quite a bit of difficulty in taming the mixers that I initially tried. Passive mixers were found to be unsuitable because they provided conversion loss instead of conversion gain and could not directly drive the following stages. After quite a bit of experimentation, I found that a J310 was the ideal choice for this application. I was a bit concerned that the unbuffered VXO could not drive the source of Q4, but it turned out to not be a problem at all. The necessary bandpass filter is incorporated into the drain of the transmit mix JFET.

Transmit Power Amplifier

I initially knew that I wanted to use a simple MOSFET PA such as a 2N7000, BS170, or IRF510. The IRF510 was ruled out almost immediately because the simple transmit mixer could not drive the relatively large gate capacitance. The 2N7000 and the BS170 are nearly identical, but the BS170 can handle quite a bit more current than then 2N7000, so it made more sense to use the BS170 as a PA (as evidenced by many of the new QRP kits coming on to the market place).

Although I wanted to drive the PA in class C mode, I found that I could not extract much power from the amplifier configured in class C in this circuit. Through some more experimentation, I found that PA required a bit of gate bias in order to produce a reasonable amount of power output. Blue LED D1 provides a stable gate bias voltage under varying power supply voltage changes. In order to achieve maximum power transfer, the double-tuned transmit mixer bandpass filter also needed to be adjusted to compensate for the input capacitance of Q2 by reducing the value of C22.

T/R Switching and Sidetone

It would be nice to have QSK, but realistically I knew that wasn't likely in a minimal parts rig. Therefore, the T/R switching is a simple DPDT switch. One pole switches the receiver path to the antenna out during transmit. The other pole switches power to the transmitter and receiver sections appropriately.

The sidetone is a pure hack but it works surprisingly well. Quite a bit of time was spent trying out different muting schemes where I would attempt to let a small bit of the transmitted signal back into the front end so the actual signal could me monitored as the sidetone. I never could get this level to anything lower than a roar, so I had to approach the problem differently. In a brainstorm, I figured out that I could just cut power to all of the receiver stages except for the product detector/BFO and audio amplifier. Now, the product detector picks up the stray carrier oscillator signal and downconverts it to a nice sidetone which accurately reflects the offset between the transmitted and received signal frequencies.

Attaining Zen

Not surprisingly, I was forced to evaluate the necessity of every single part in the rig. Sometimes as designers we will do this exercise on a circuit block, but rarely is it necessary to perform it on the entire radio. One excellent side effect of the requirement to do this is that I have learned much about what is really absolutely vital to include in each circuit, what provides nice but marginal performance improvements, and what is superfluous. I have no doubt that this hard won knowledge will be very useful in the future.

What Would I Put Back In?

Now that the Clackamas is cut down to the bare bones, there are some things I might add back in if I wanted to increase the operating conveniences and improve the performance.

- More effective decoupling would be one of the first things on my list. I was able to remove quite a bit of the decoupling with a minimal performance hit, but I would feel much more comfortable with the proper decoupling in the radio.
- It would be great to stick with using the BF998 throughout the Clackamas. If the IF amplifier was replaced with a BF998-based version, the receive current consumption could be reduced below 10 mA.
- Two poles of crystal filtering is a bit light for my taste. The biggest problem with the 2-pole filter is that the ultimate attenuation is only about 50 dB, so you can hear strong nearby signals. A 4-pole filter would be an excellent substitution.
- Due to the very light bandpass filtering on the front end and the fact that the mixer amplifies everything that gets to gate 1, the IF and image rejection is pretty poor. In order to fix this, I would change this filter to at least a double-tuned circuit, perhaps even triple-tuned.
- The simple keying and muting in the Clackamas works very well for the parts count, but semi-QSK keying and muting would be a nice convenience feature.
- The tuning range of the VXO is a bit restricted, so the addition of a second parallel 11.059 MHz crystal, plus perhaps a series inductor, would give a much greater tuning range.

A Suggestion

I really enjoyed the FDIM QRP challenge, but would like to suggest one rule change if QRP ARCI decides to conduct a similar restricted parts count contest in the future. Please allow for any tuned network in a transmitter output stage to count for a maximum of three parts, no matter the actual parts count. This rule comes from the Minimal Art Session in Germany, and would allow the designer to not have to worry about trading off spectral purity for a critical feature elsewhere in the radio.

Finally…

I wanted to spend a few moments to praise all of the wonderful design tools that I used in the creation of the Clackamas. All of the major tools that I used are free, open source software. This includes the Ubuntu 10.04 operating system, the wonderful OpenOffice.org suite, and TinyCad schematic capture. Where I didn't have open source software, I was able to run programs such as the extremely useful *EMRFD* tools under *WINE* Windows emulation. It is truly amazing how today's designer and builder has access to professional quality tools for little or no money.

Bill of Materials

Resistors
(all 0.25 W)

R1,R8,R13	3	10k
R2	1	1.2k
R3	1	2.2k
R4	1	22k
R5	1	100k
R6	1	150
R7,R11,R15	3	1k
R9	1	470
R10,R14	2	150k
R12	1	100
R16	1	220

Subtotal	16	

Capacitors
(all 25 WVDC min. unless specified, all values pF unless specified)

C1	1	1u
C2	1	220u
C3	1	10n
C4,C5,C13,C23,C25,C27	6	100
C6,C26	2	65 trimmer
C7,C8,C9,C14,C15,C19,C30	7	100n
C10	1	180
C11	1	150
C12	1	22
C16,C18	2	220 (50 WVDC)
C17	1	560 (50 WVDC)
C20,C22	2	68
C21	1	270 polyvaricon
C24	1	4.7
C28	1	33
C29	1	47

Subtotal	30	

Transistors

Q1,Q3,Q5	3	2N4401
Q2	1	BS170
Q4	1	J310
Q6,Q7	2	BF998

Subtotal	7	

Inductors

L1	1	220u (molded)
L2	1	T37-2 30T
L3,L4	2	T37-2 17T
L5	1	FT37-43 10T
L6	1	100u (molded)

Subtotal	6	

Transformers

T1	1	FT37-61 6:20
T2	1	FT37-61 16:7
T3,T4,T5	3	Toko 42IF123

Subtotal	5	

ICs

U1	1	TDA7052

Subtotal	1	

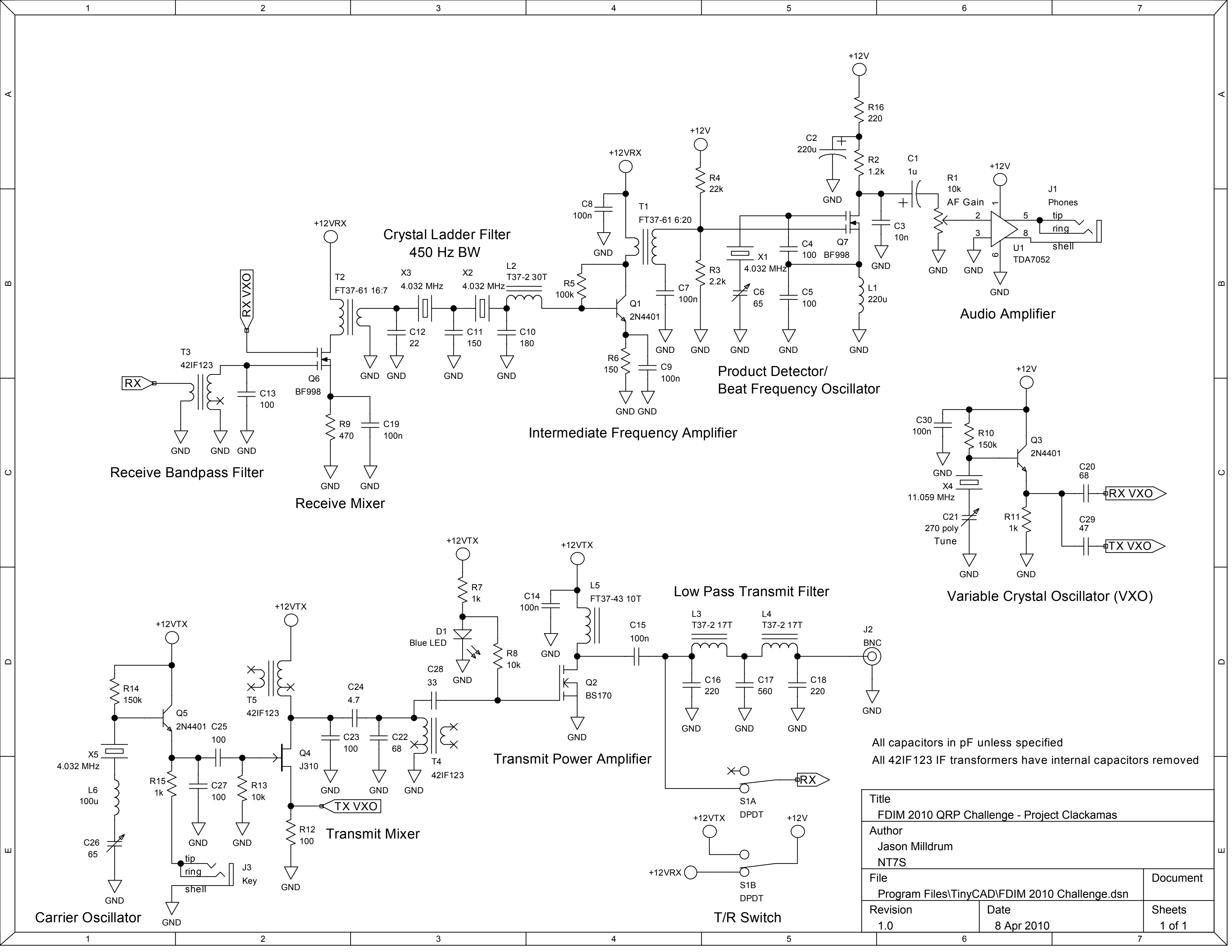
Miscellaneous

X1,X2,X3,X5	4	4.032 MHz (HC-49)
X4	1	11.059 MHz (HC-49)
D1	1	Blue LED
S1	1	DPDT

Subtotal	7	
	===	
Total	72	

Not included in parts count

J1	1	Phones (3.5 mm stereo)
J2	1	BNC
J3	1	Key (3.5 mm stereo)


Crystal Ladder Filter
450 Hz BW
Receive Bandpass Filter
Receive Mixer
Intermediate Frequency Amplifier
Product Detector/
Beat Frequency Oscillator
Audio Amplifier
Variable Crystal Oscillator (VXO)
Low Pass Transmit Filter
Transmit Power Amplifier
Transmit Mixer
Carrier Oscillator
T/R Switch
RX
T3
42IF123
C13
100
Q6
BF998
R9
470
C19
100n
RX VXO
T2
FT37-61 16:7
X3
4.032 MHz
X2
4.032 MHz
L2
T37-2 30T
C12
22
C11
150
C10
180
+12VRX
C8
100n
T1
FT37-61 6:20
R5
100k
Q1
2N4401
R6
150
C9
100n
C7
100n
+12V
R4
22k
R3
2.2k
X1
4.032 MHz
C6
65
C4
100
C5
100
Q7
BF998
L1
220u
R16
220
C2
220u
R2
1.2k
C3
10n
C1
1u
R1
10k
AF Gain
U1
TDA7052
J1
Phones
tip
ring
shell
GND
C30
100n
R10
150k
Q3
2N4401
X4
11.059 MHz
C21
270 poly
Tune
R11
1k
C20
68
C29
47
TX VXO
+12VTX
R7
1k
D1
Blue LED
R8
10k
C14
100n
L5
FT37-43 10T
Q2
BS170
C15
100n
L3
T37-2 17T
L4
T37-2 17T
C16
220
C17
560
C18
220
J2
BNC
R14
150k
Q5
2N4401
X5
4.032 MHz
L6
100u
C26
65
R15
1k
C27
100
C25
100
R13
10k
T5
42IF123
Q4
J310
R12
100
C24
4.7
C23
100
C22
68
C28
33
T4
42IF123
J3
Key
S1A
DPDT
S1B
DPDT
All capacitors in pF unless specified
All 42IF123 IF transformers have internal capacitors removed
Title
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Sheets
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