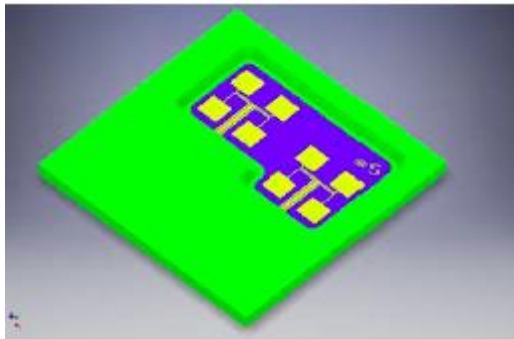# A Simple 122 GHz Transceiver

Using the Silicon Radar TRX120 Chip

Mike Lavelle, K6ML

BayCon 2018

Wait …   What ???

Did he say *122 GHz?*

Yes, there are Ham bands above 2M ...

BAND	Freq. (GHz)
2 M	0.144-0.148
1.25 M	0.222-0.225
70 cm	0.420-0.450
33 cm	0.902-0.928
23 cm	1.240-1.300
13 cm	2.300-2.310 2.390-2.450
9 cm	3.300-3.500
6 cm	5.650-5.925

| BAND	Freq. (GHz)
3 cm	10-10.5
12 mm	24-24.25
6 mm	47.0-47.2
4 mm	76-81
2.4 mm	122.25-123
2.2 mm	134 -141
1.2 mm	241-250
	All > 275

Why Operate Microwaves?

- "Because it's there"
- Satisfaction of building your own radio
- Challenge of working DX
- "Use it or lose it"
- Portable operation
- Extra points in contests
- Short haul data links
- Radars

Challenges of Microwaving

- *Above 100 MHz…*
  - the ionosphere rarely reflects signals, we are limited to line of sight propagation, with some occasional tropo enhancements
- *Above a few GHz…*
  - wires aren't wires, normal PCB traces and materials don't work
- *Above 20 GHz…*
  - the atmosphere starts fighting us (water vapor, oxygen losses)
- *Above 100 GHz…*
  - most transistors stop working
- *Other than that…*
  - no worries.

How Did Others Get on 122 GHz?
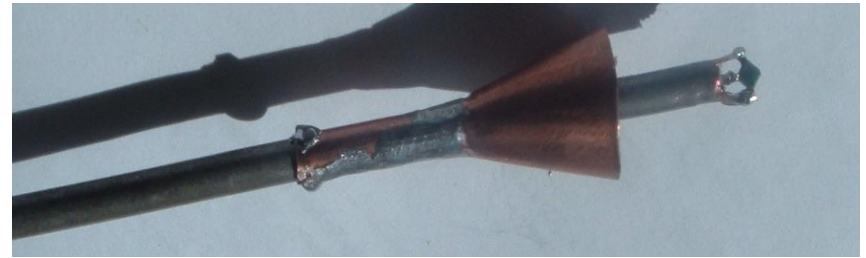
- Diode multipliers and mixers mounted in tiny waveguide pipes

- With long frequency multiplier chains for the local oscillator
  - 10 MHz X ... ->
  - ... x ... ->
  - 13.6 GHz x 3 ->   (wave-
  - 40.8 GHz x 3 ->   guides,
  - 122.5 GHz   diodes)

- Microwatts to a few milliwatts
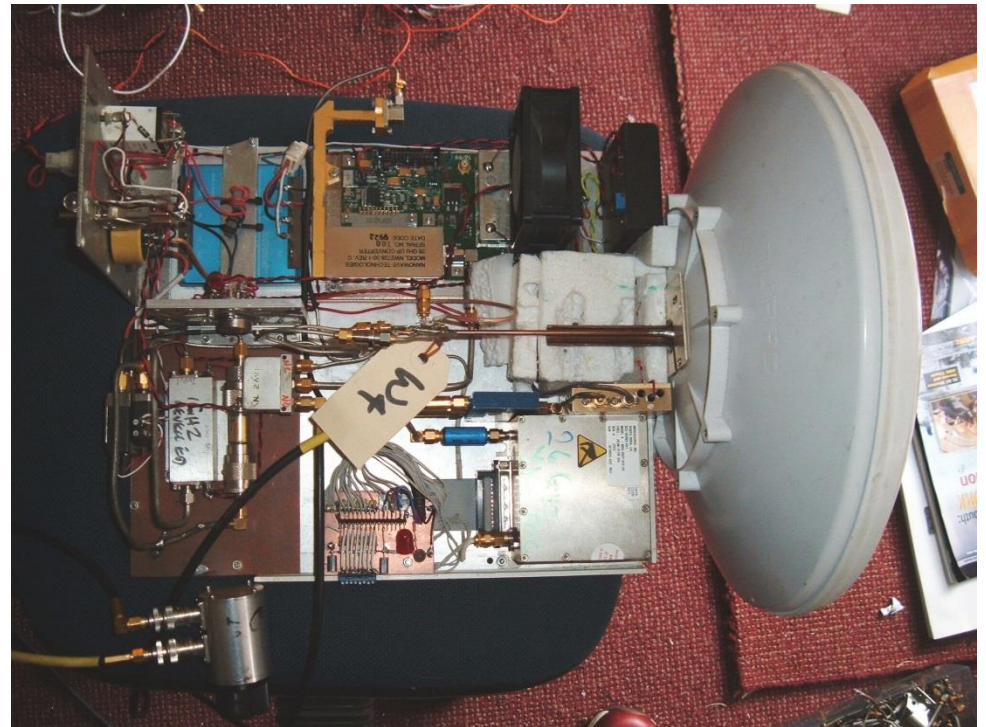
There must be an easier way …

There is!

Leverage new radar technology designed for automotive and consumer markets

Types of Radars

SRC < ————————→) TGT

- Pulse Radar
  time of flight -> range
  *transmit short pulses,
      measure echo delay*

  Classic "ping, ping, ping, ..."
  military or air traffic control radar

- Doppler (CW) Radar
  frequency shift -> velocity
  *transmit constant frequency,
      measure frequency shift
      due to (relative) motion*

  Cop's speed trap
  Ground speed (aircraft, car, ...)
  Rate of closure (cars, planes, bikes)
  Motion detector (intruder alert)
  Rainfall rate

- Chirp (FMCW) Radar
  frequency difference -> range
  *transmit varying frequency,
      measure how much frequency
      changed during echo delay*

  Target distance (cars, drones, bikes, pedestrians)
  Auto parking
  Drone landing (altimeter)
  Liquid level in tank
  Elevator in shaft
  Blind hole depth
 Golf balls, swing

Can combine CW & FMCW

Silicon Radar TRX24 and TRX120

- 24 and 122 GHz ISM (unlicensed) bands (also happen to be ham bands)
- Single Chip millimeter wave ICs
- Silicon Germanium transistors that work above 100 GHz
- Homodyne (self-mixing) architecture supports Doppler and Chirp radars

| Doppler: | Fixed Tx frequency | Mixer gives Doppler shift | (velocity) |
| Chirp: | Ramp Tx frequency | Mixer gives TOF freq change | (range) |

CHIRP FREQ

dF

dt
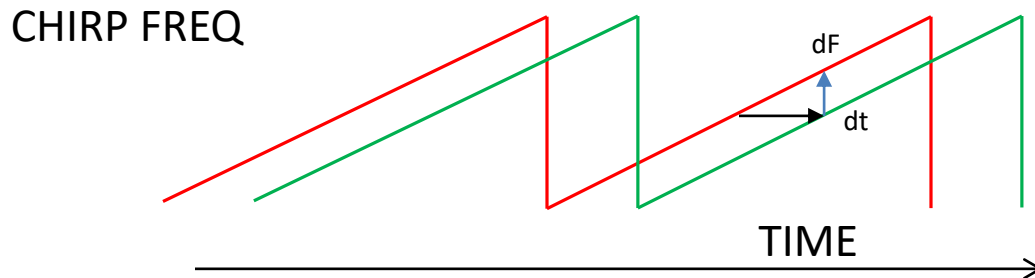
TIME

Mixer output (freq difference) tells us how much
freq ramp changed during the echo delay time.
Echo delay time is proportional to the range.
(delay time = range * speed of light)

Freq
control

Tx Ant
sends F

VCO

Rx Ant
hears echo

Receiver
IF out
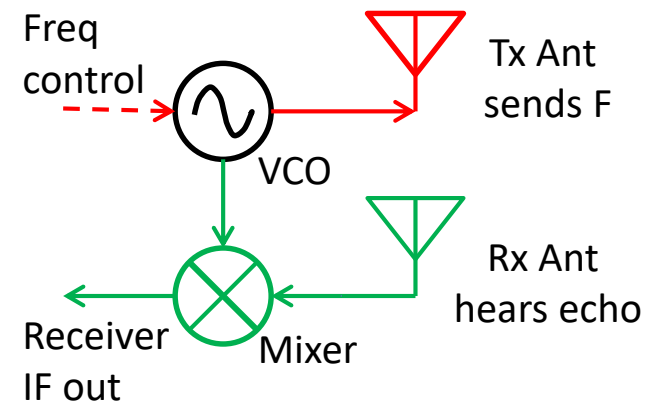
Mixer

Silicon Radar TRX120 MMIC

- Tunable 120 GHz Local Oscillator
- div64 PLL prescaler
  - 1.9 GHz to PLL
  - Can lock VCO to a stable reference

- Tx PA
  - 0.5 mW typ
- Rx LNA
  - ~10 dB DSB NF

- Phased IQ mixers
  - ~10 dB total RX Conversion Gain
  - DC-200 MHz IF out

÷ 64

120 GHz
VCO

(-90 dBc
@ 1 MHz)

PA
(-3 dBm)

90°

LNA
(~10 dB DSB NF)

I/Q Mixer
(~10 dB Rx Conv Gain)
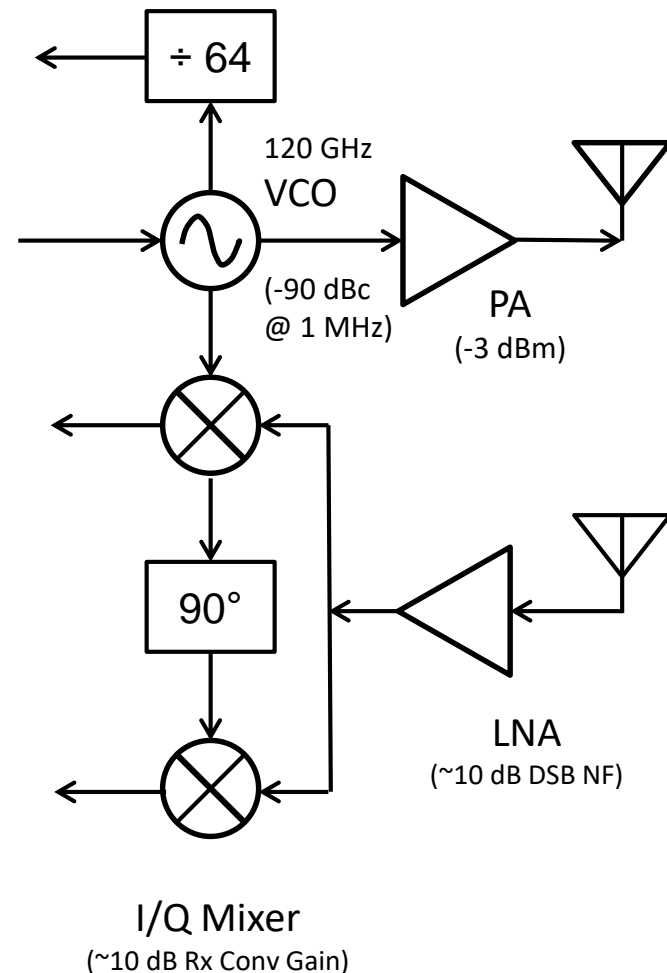
But, wait … that's not all …

- **8x8mm QFN package includes dual internal Tx and Rx antennas**

- Each is an array of 4 patch antennas
  - Each is about 2.5 mm x 2.5 mm area
  - Each has about 10 dBi gain

- **This means no wires at 122 GHz**

- **Only 2 pins operate at more a few MHz**
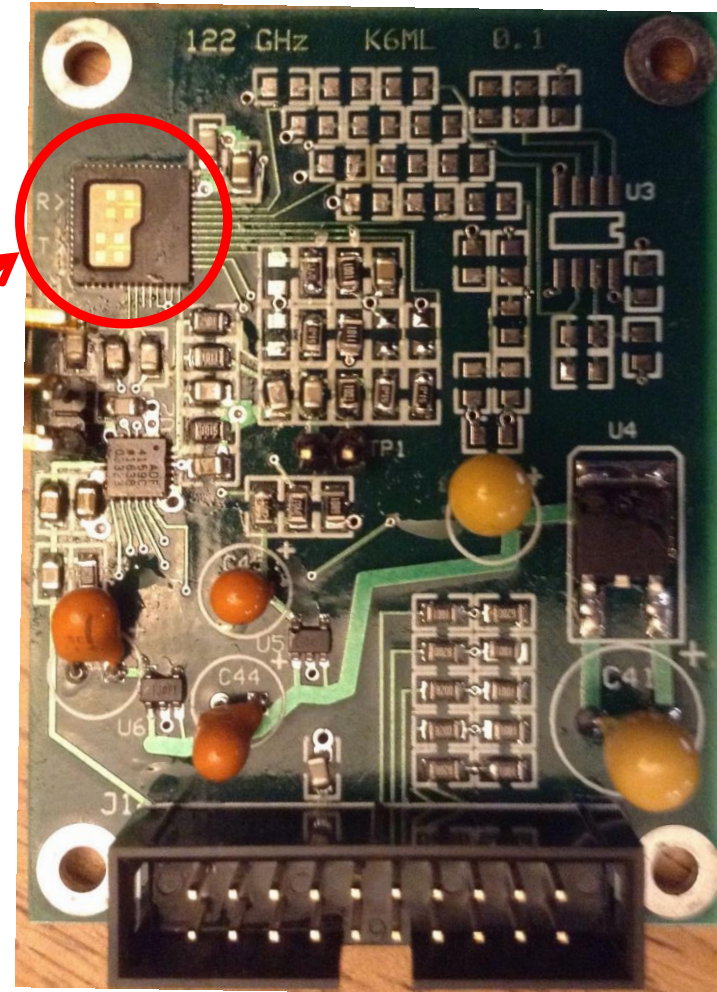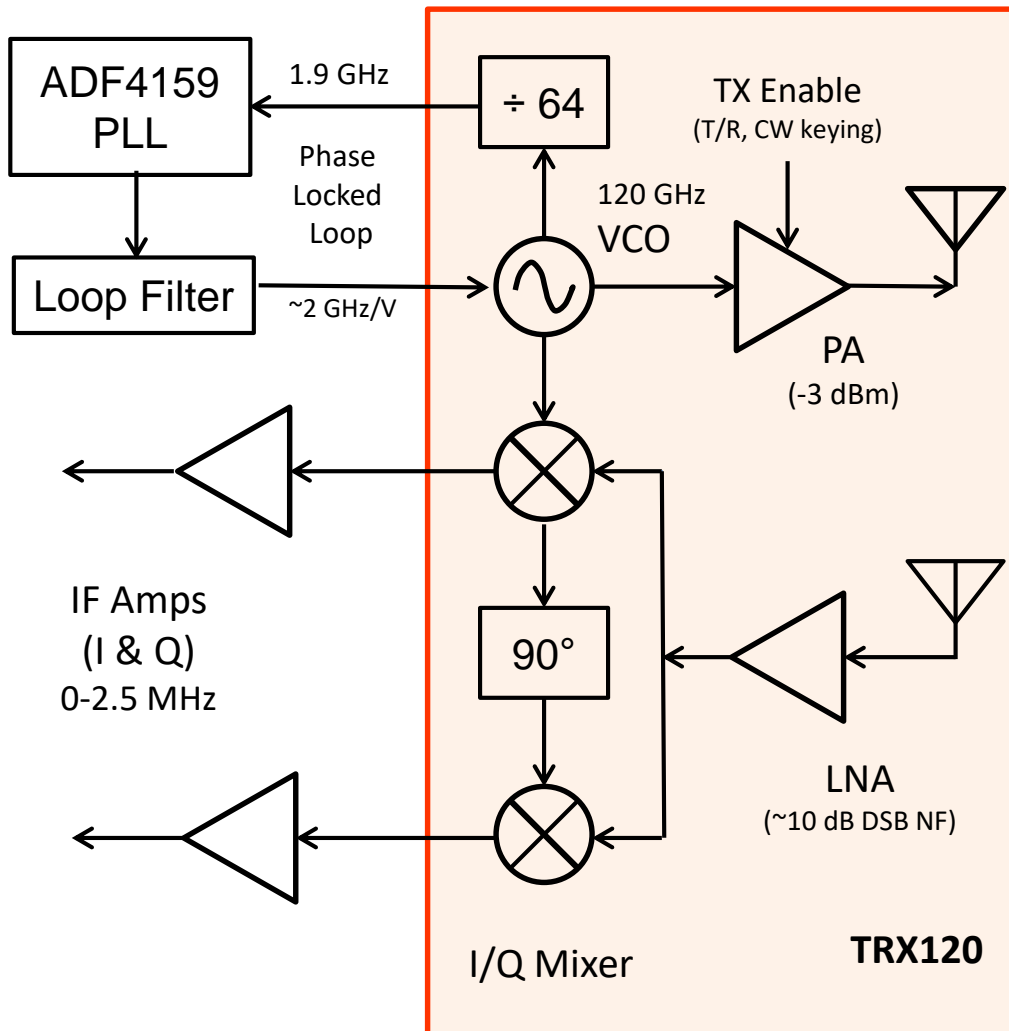 - The div64 outputs are at 1.9 GHz

It was not too difficult for me to

design and lay out my own printed circuit board …

122 GHz Front End PCB

Add PLL, IF Amp and Regulators

1.9"x2.5" FR4 PCB

ADF4159 PLL

1.9 GHz

Phase Locked Loop

Loop Filter

~2 GHz/V

÷ 64

TX Enable
(T/R, CW keying)

120 GHz VCO

PA
(-3 dBm)

IF Amps
(I & Q)
0-2.5 MHz

90°

LNA
(~10 dB DSB NF)

I/Q Mixer

TRX120

Tx Modulation

- Does not support AM, SSB
  - There is a Tx enable pin which might be used for CW OOK or T/R
- So we are left with angle modulation
  - NBFM: Audio Modulate the PLL Reference
  - PLL FSK data pin supports
    - FSK CW
    - BFSK RTTY/data
    - BPSK data link
  - PLL serial interface can support slow MFSK modes
    - WSJT modes (JT4, FT8, etc)
    - FSQ, WSQ, Domino, etc
- Can also be a Doppler or Chirp Radar

Receiver IF

- TRX120 has I and Q IF Outputs (0 – 200 MHz)

- Direct conversion (zero IF) will pick up multipath reflections …
  - ***Doppler shift at 122 GHz is 370 Hz per mph***
  - Good for a radar, not so good for a radio

- Instead, using a single conversion to a 2.5 MHz IF
  - Avoids Doppler up to 6750 mph (nothing moves that fast nearby)
  - Gets away from Tx carrier PN and leakage

- Just connect I or Q amp output to any old HF QRP receiver
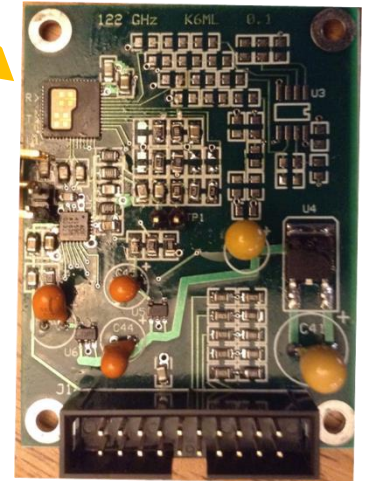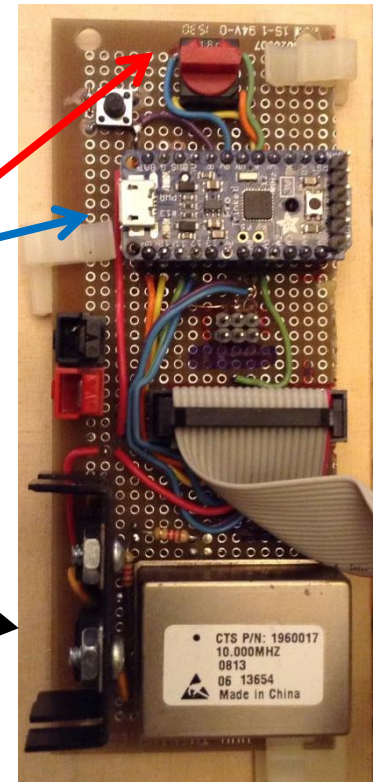
But Is It a Radio?

(Demo)

- ## Tx Beacon
  - Arduino Trinket controller
    - FSK keying for beacon
    - Tuning switch: 16 channels; 160 MHz steps
  - 10.000000 MHz ovenized crystal oscillator
  - Use the TRX120 10 dBi in-package antennas
    - -3 dBm PA + 10 dBi antenna
    - = **+7 dBm EIRP**

- ## Rx
  - Same hardware plus a FT-817 as 2.5 MHz IF
    - -174 dBm + 13 dB (NF) + 35 dB (3 kHz) -10 dBi (ant)
    - = **-136 dBm MDS**

But Is It a Radio?
(Field Tests)

- ## System Gain is +143 dB with the 10 dBi antennas
  +7 Tx EIRP – (-136 Rx MDS) = +143 dB system gain

- ## Range tests:
  1   km: 135 dB path loss **works easily**,   +8 dB SNR (143-135)
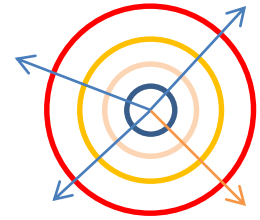
  2.1 km: 143 dB path loss **works**,   0 dB SNR (143-143)

  6.5 km: 156 dB path loss **not working**,   -13 dB SNR (143-156)

  - Observation: This is definitely a "line of sight" band
  - Doesn't see thru parked cars or around corners
  - Plenty of power and gain for short paths (radar, etc)
  - But need more gain to overcome longer path losses

Free Space Path Loss

- **Free space path loss** is the spreading loss as a signal radiates outward from its source

$$FSPL = -32.5 - 20 \log d \text{ (in km)} - 20 \log f \text{ (in MHz)}) \text{ dB}$$

- For a 10x **distance** increase, FSPL increases **100x** (20 dB)

1 km	10 km	100 km
-32.5 dB	-52.5 dB	-72.5 dB

- For a 10x **frequency** increase, FSPL increases **100x** (20 dB)

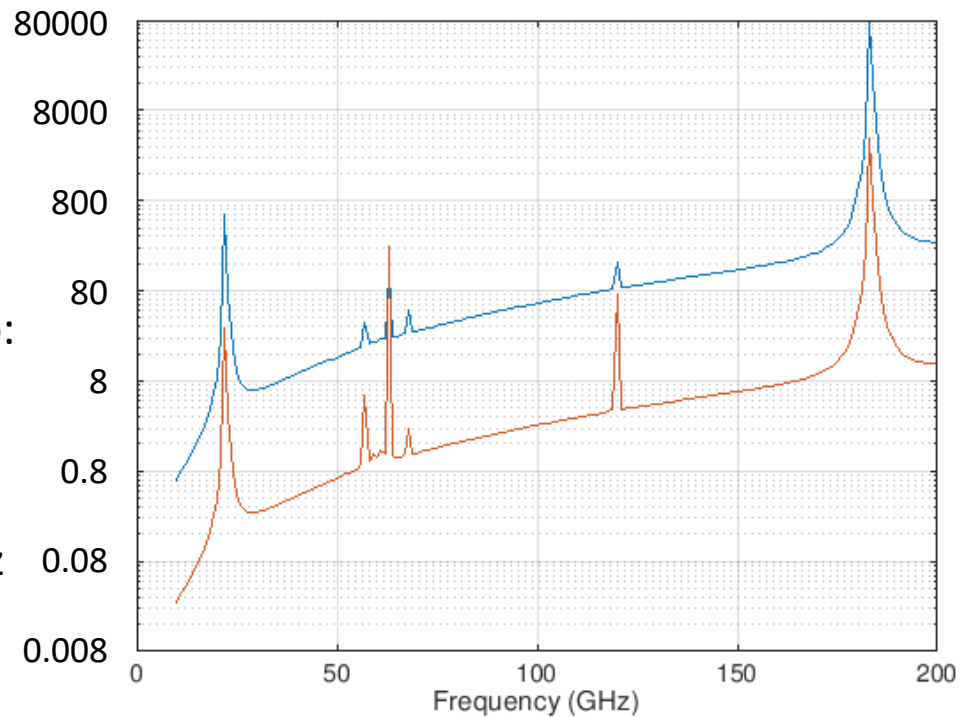| For	144 M	1.2 G	10 G	122 G
Distance loss (100 km)	**-72.5**	**-72.5**	**-72.5**	**-72.5**
Frequency loss	**-43**	**-62**	**-80**	**-102**
TOTAL FSPL (100 km)	**-115.5**	**-134.5**	**-152.5**	**-172.5**

Additional Atmospheric Loss

(dB / 100 km)

Above 20 GHz, additional losses due to:
- Water Vapor loss (humidity)
    - Steady upward trend
    - Peaks at 22 & 183 GHz
- Oxygen resonances at 60 & 119 GHz
    - Worst at sea level

➢ Blue curve for 68F, 50% RH, sea level

dB	144 M	1.2 G	10 G	122 G
TOTAL FSPL (100 km)	**-115.5**	**-134.5**	**-152.5**	**-172.5**
ATML (50%RH, at SL)	-0	-0	-0	**-80**
TOTAL PATH LOSS	**-115.5**	**-134.5**	**-152.5**	**-252.5**

For comparison, the typical 2M moon bounce (EME) path loss is -252 dB

➢ Red curve for 60F, 10% RH, 4700' ASL. It tells us "for best DX, go to the mountains in extremely dry weather"

Now for some good news …

- Gain antennas work by focusing their Rx/Tx beam into a narrow fraction of the radiating sphere

- And the amount of gain is proportional to the antenna's area, measured in wavelengths

- We get more gain per square foot at higher frequencies (shorter λ)

Freq	λ/2	0 dB	10 dB	20 dB	30 dB	40 dB	50 dB	60 dB
144M	38"	19" whip	**4 ft** **yagi**	72 ft yagi	90 ft dish	280 ft dish	**900 ft** **dish**	2800' dish
1.2G	5"	2.5" whip	**1 ft** **yagi**	8 ft yagi	10 ft dish	31 ft dish	**100 ft** **dish**	310 ft dish
10G	½"		**1.2"** **square**	4" square	15" dish	4 ft dish	**12 ft** **dish**	40 ft dish
122G	1.2 mm		**0.1"** **square**	0.34" square	1" square	4" dish	**1 ft** **dish**	3.3 ft dish
Degrees		360	**70**	15	4.5	1.4	**0.45**	0.14

- ***We must accept a very narrow beam to get very high gain (need precise aiming)***

Roughly Equivalent Antennas

← 150 foot Stanford Big Dish, operating at around 1 GHz

18" TV satellite dish, → operating at 122 GHz

Both have over 50 dB gain (and both have less than ½ degree beam)
Because both are about 200 wavelengths in diameter

Dish Antenna Feed Considerations

- ## Using the TRX120 as the dish feed
  - Place chip at focal point of parabolic reflector (like filament in a car head lamp)
  - Good match for an offset dish
  - Under-illuminates a prime focus dish.

- ## 12" dish has 49.8 dBi gain & 0.55 degree HPBW
  - Why? Because 1 foot is 123 wavelengths at 123 GHz
  - Assumes 123 GHz and 65% efficient feed

- ## 24" dish has 55.8 dBi gain & 0.27 degree HPBW
  - That's about 45 dB more than the internal patch antennas!
 - For two rigs with 2 ft dishes, an extra 90 dB system gain

TRX120 Antenna Pattern
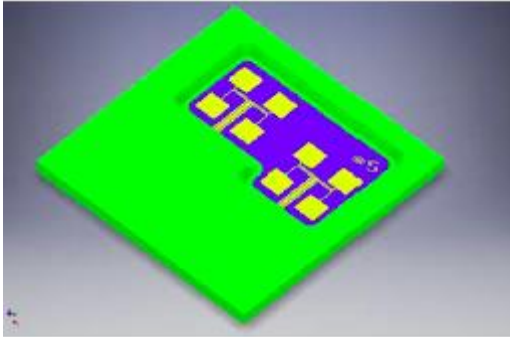
THE GOOD NEWS: Integrated antennas means highest frequency outside the package is under 2 GHz, can use ordinary PCB!

THE NOT SO GOOD NEWS: Antenna design is driven by radar sensor application, may not be an ideal dish feed

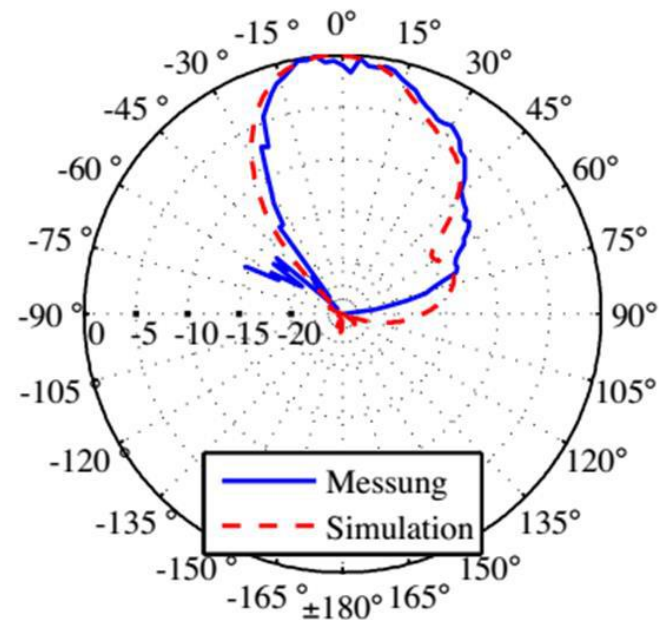***MORE NOT SO GOOD NEWS:*** Two antennas is one more than we need.

Each antenna is About 2.5mm square
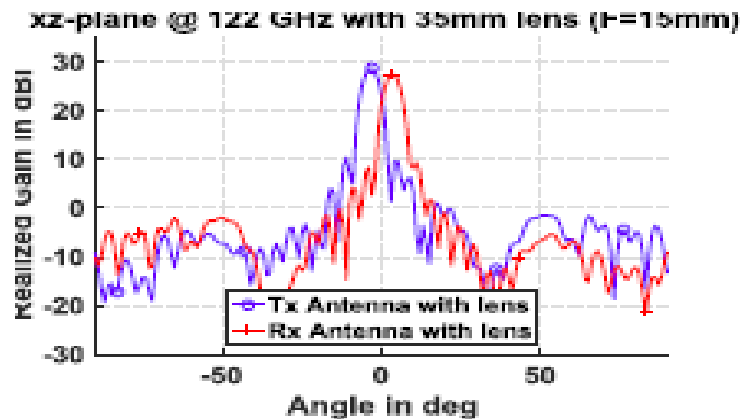
~10 dBi Gain, ~30-40 deg HPBW, ~80 deg dish illumination
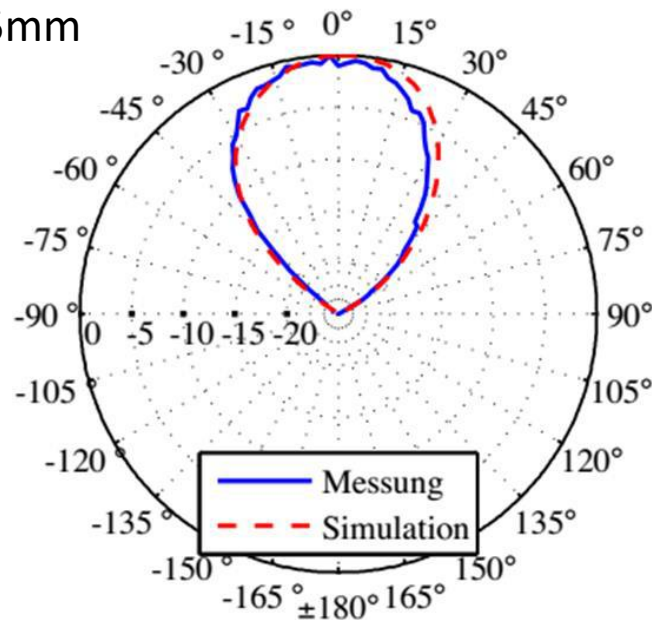
H-Plane

E-Plane

red – simulated, blue - measured

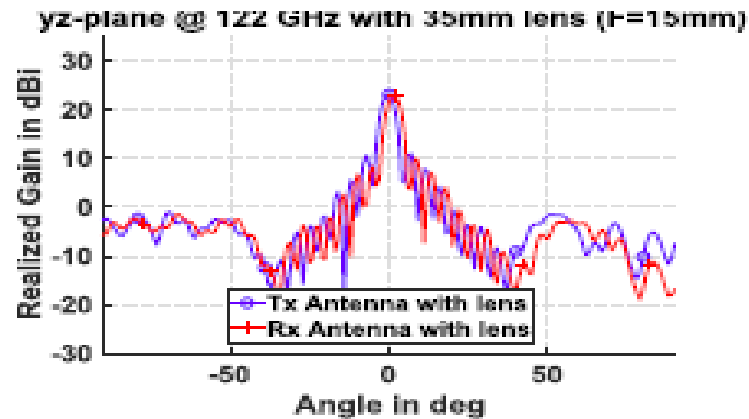# Effect of Increasing Gain on Antenna Pattern

(~20 dB extra gain from a plastic lens)

(a)

Focal point

Note that TX and RX beams are offset due to differing antenna sites, even for a low gain lens antenna

(b)

Dish Antenna Parallax / Beam Shift

- TX and RX antenna sites are offset by:

  ~ 3 mm (~ 1.23 wavelengths) vertically

  ~ 0.7 mm (~ 0.28 wavelengths) horizontally

- With a **high gain dish**, we can expect serious beam shifting between TX and RX:
  - Beam shifts by **one or more dish beam widths**
  - **Tx null** can even fall on **Rx peak**

- For correct pointing we need to either:
  - Move the dish (rotate and tilt), or
 - Move the feed (X-Y, *preferred solution*).

Still to Do

- Test various surplus dish antennas
  - Feed vs. F/D, feed focus, beam pattern, gain
  - Use 10 dBi beacon as antenna range source
  - *Find max range using one dish*

- T/R (and band) switching
  - Mount front end PCB on a X-Y slider stage with linear actuators to maintain focus
  - Firmware calibrates, remembers and applies feed X-Y offsets when band or T/R switching
  - *Find max range for 2 way QSOs, dishes on both ends*

More to Do: Dual Band Rig

- Add a 24 GHz front end that shares the dish & IF Rx
  - Make a copy of 122 GHz design using the 24 GHz chip
  - Use the slider stage to focus on either band's front end
- Has several operational advantages:
  - Higher power & lower NF at 24 GHz using TRX024 in similar design
  - 5x easier to point the dish in both azimuth and elevation at 24 GHz
  - 5x easier to establish operating frequency at 24 GHz
  - Much lower path loss at 24 GHz
    - 24 GHz link budget is ~60 dB better at 100 km
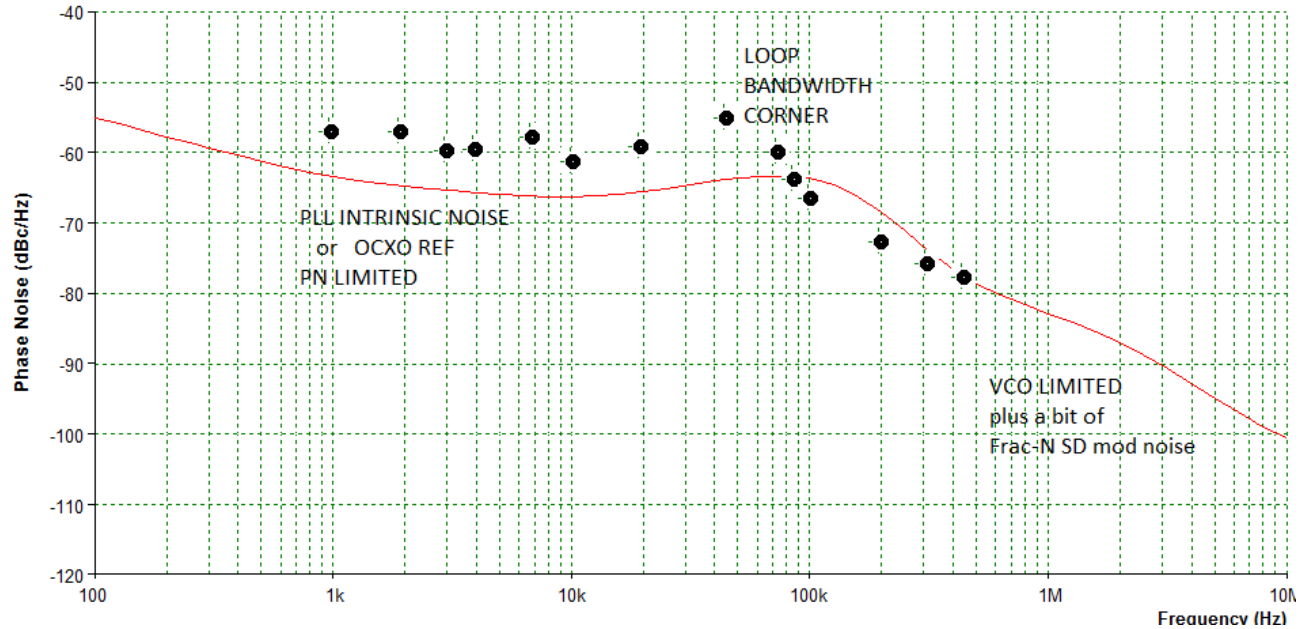 - QSY up to 122 GHz when 24 GHz path approaches S9 signals

Thank You
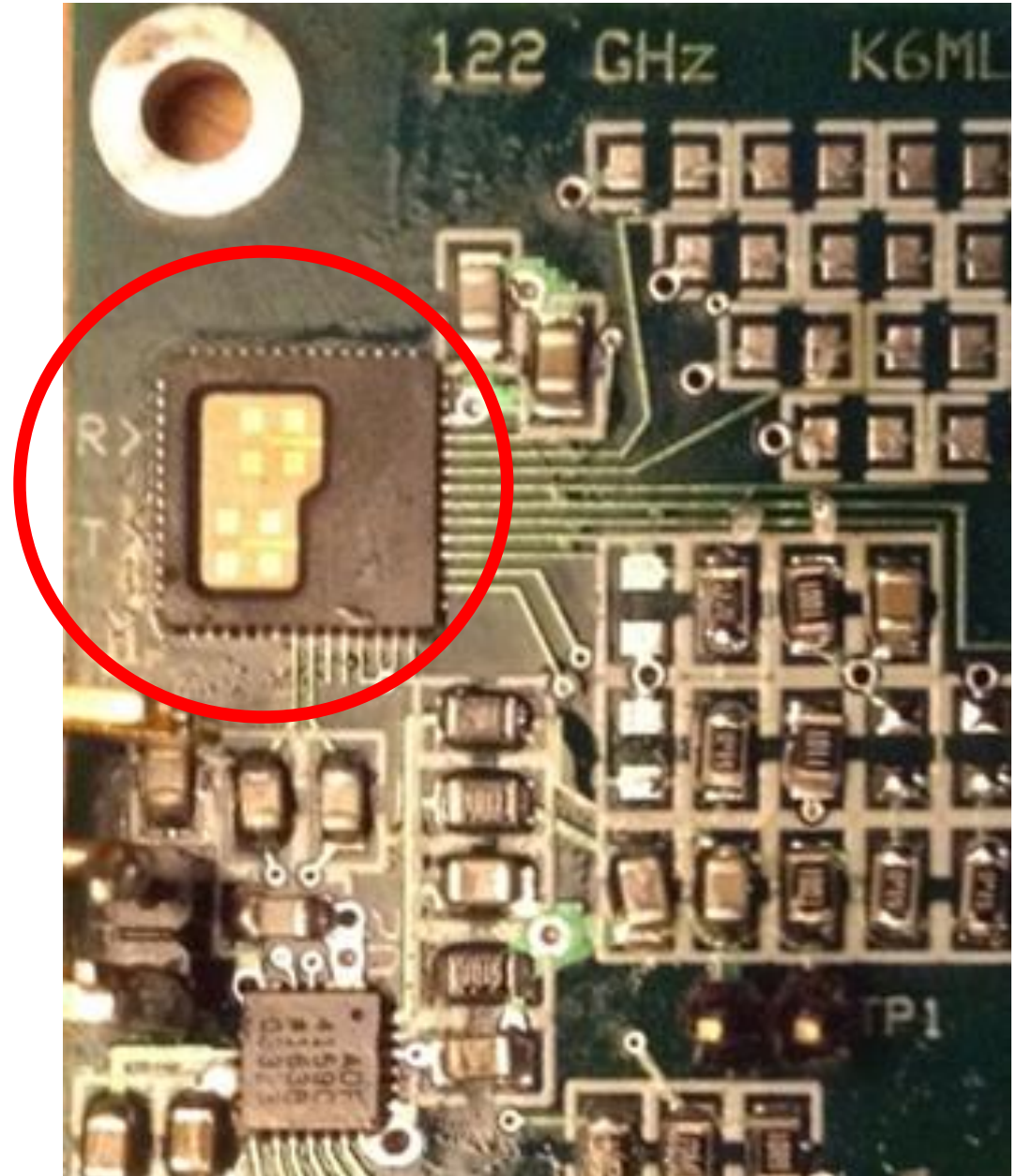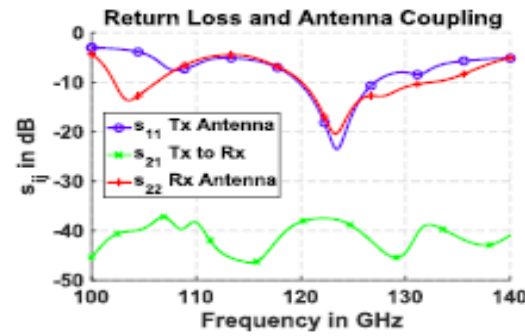
Any Questions?

PLL Design
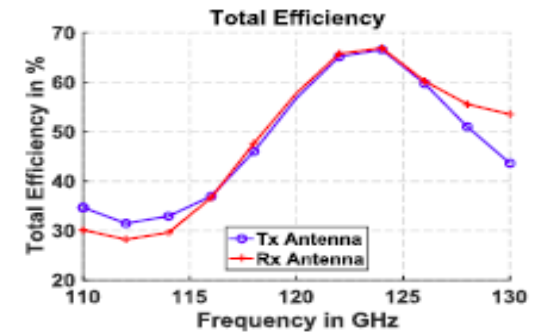
Phase Noise at 123GHz

- Frac-N PLL provides radio tuner (38 Hz steps) & mFSK deviations as small as 38 Hz
  - Supports FSK and PSK, as well FMCW chirp radar
- ~100 kHz loop bandwidth filters out LF VCO PN and allows ~20 kbaud max FSK

TRX120 Antenna Measurements
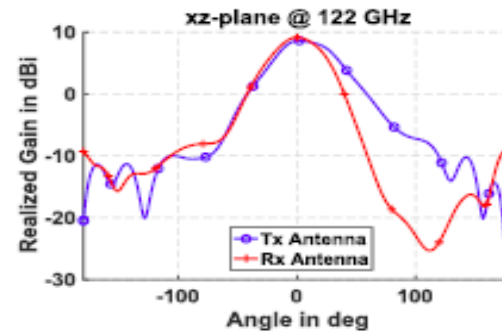
Focal point

Return Loss and Antenna Coupling

s_{11} Tx Antenna
s_{21} Tx to Rx
s_{22} Rx Antenna

(a)

Total Efficiency

Tx Antenna
Rx Antenna

(b)

xz-plane @ 122 GHz

Tx Antenna
Rx Antenna

(c)

yz-plane @ 122 GHz

Tx Antenna
Rx Antenna

(d)

Note that TX and RX beams are offset due to differing antenna sites, even for a low gain lens antenna →

xz-plane @ 122 GHz with 35mm lens (F=15mm)

Tx Antenna with lens
Rx Antenna with lens

(a)

yz-plane @ 122 GHz with 35mm lens (F=15mm)

Tx Antenna with lens
Rx Antenna with lens
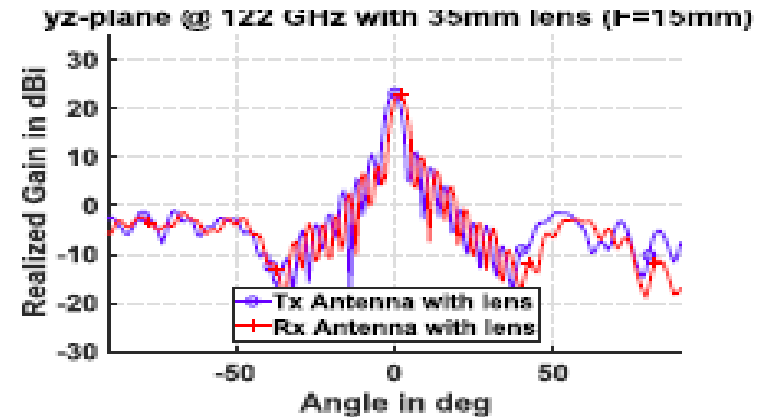
(b)

24 GHz Front End PCB

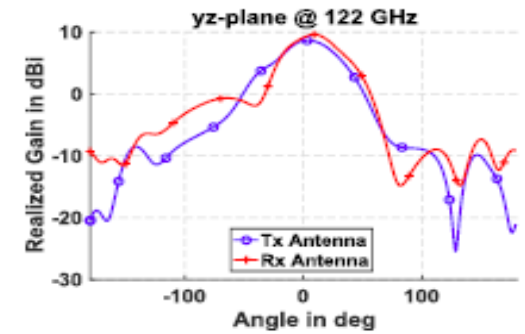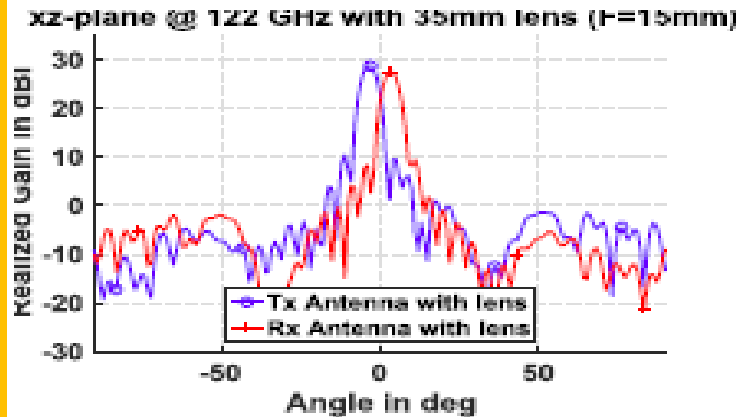Only significant difference: TRX024 does not have on chip antenna

Lock Detect

10 MHz ref

FSK TXD

Serial programming & tuning

ADF4159 PLL

I_{cp}

Loop Filter

756 MHz

÷ 32

Coarse Tune
(preset, temp adj)

24 GHz
VCO

Fine Tune
220 MHz/V

TX Enable
(T/R, CW keying)

PA
(+4 dBm)

Circular Horn Feed

(on back of PCB)

LNA
(4 dB DSB NF)

90°

I/Q Mixer
(11 or 18 dB Rx Conv Gain, pin programmable)

IF Outputs
(I & Q)
0-2.5 MHz

1V8
LN LDO

PLL (dig)

3V3
LN LDO

PLL (ana)

TRX 120

+8V

5V LDO

IF amps
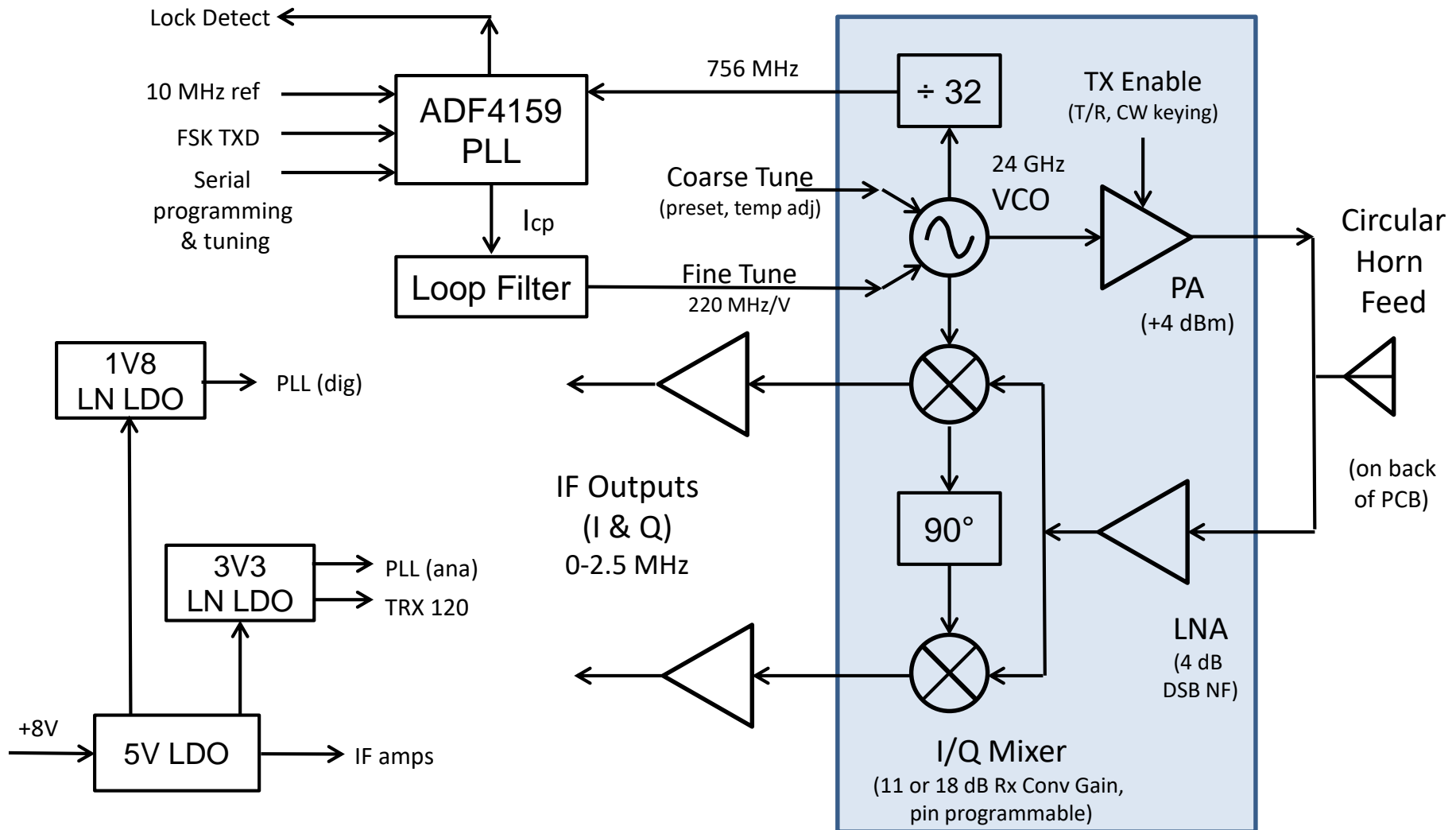
Common IF Board (in design)
Reference buffers, band switch, downconverter
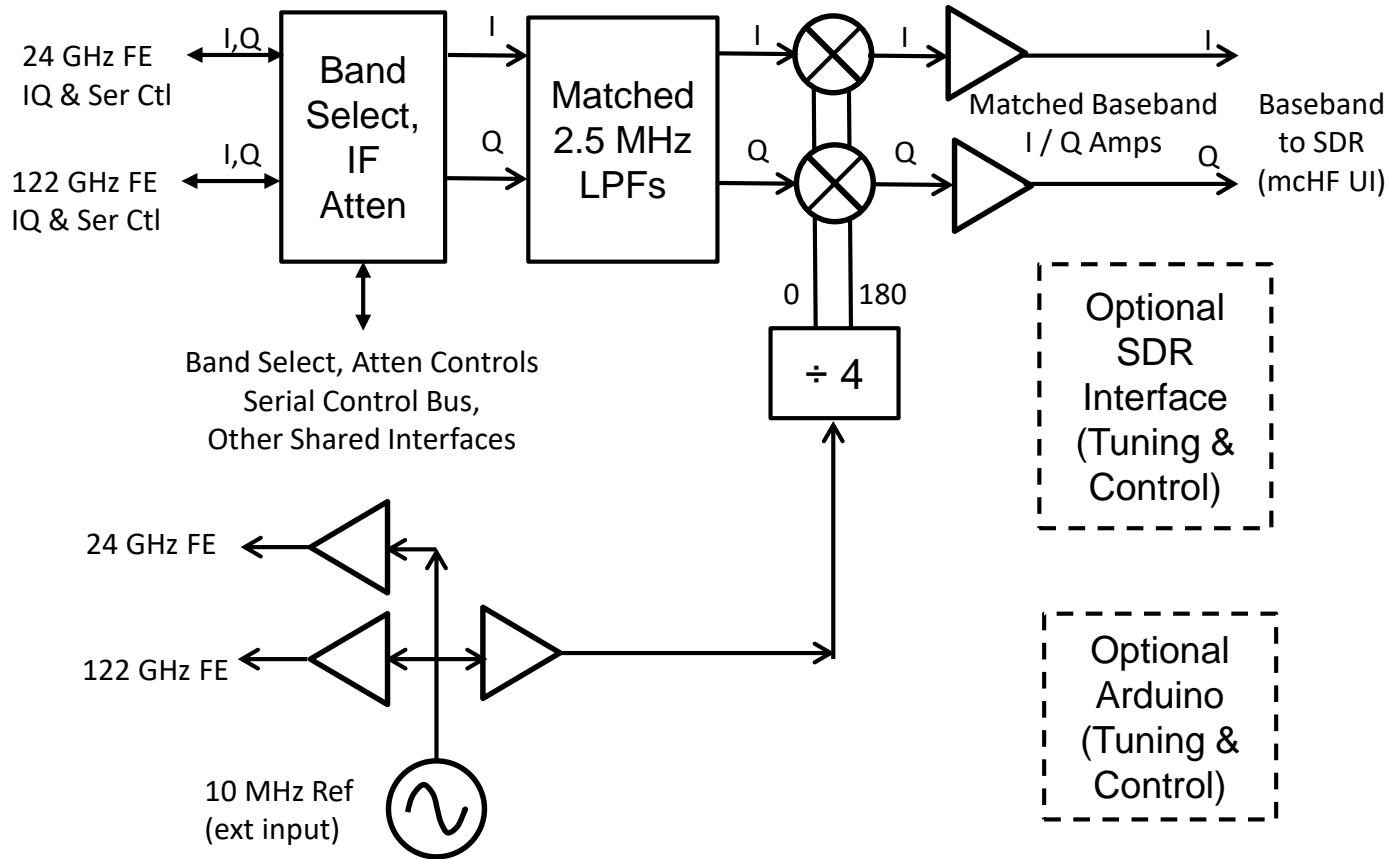
Matched LPFs, sampling downconverter and matched BB amps preserve IQ
phase & amplitude so that a Weaver method SDR can be used to reject SSB image noise

Duplex vs Simplex

- Full Duplex "SiGePlexer"
  - Along the lines of the venerable Gunnplexer:
  - Can talk and listen at same time
  - **Station A: LO at F,   transmits at F,   listens   at F+IF**
    vvvvvvvvvvvvvvvv   ^^^^^^^^^^^^^^^^^^^^^^^
  - **Station B: LO at F+IF, listens   at F,   transmits at F+IF**
  - A 455 kHz or 10.7 MHz FM IF strip/chip could hook up directly to RX IF out

- Simplex
  - Tx enable pin supports simplex T/R
  - When T/R switching, shift PLL/VCO frequency up by the IF frequency
  - Lower desense floor should enable better DX
  - Current efforts are simplex