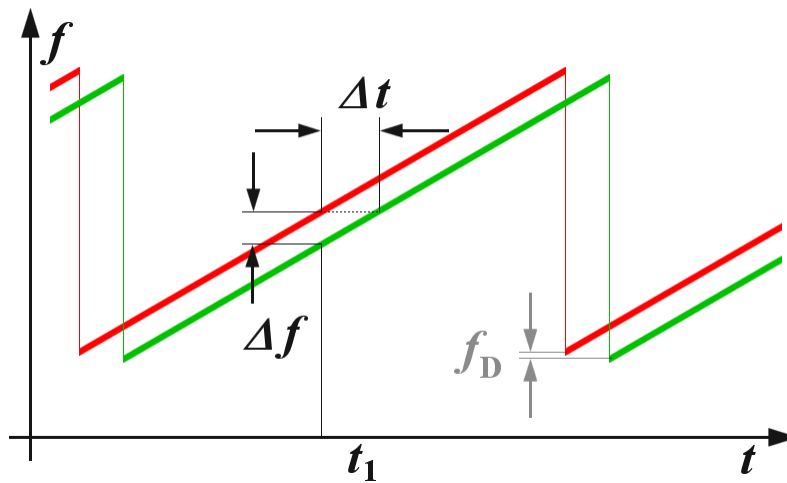1. **How does FMCW radar work?**

With an FMCW radar, a signal which linearly increases in frequency is sent out. The receiver receives a delayed version of the signal.

In the diagram above, the red line shows the transmitted signal, and the green line shows the received signal. If the two signals are mixed to get the difference, we see that the resulting signal would have a frequency of Δf, which is proportional to the distance between the radar and the object. By using the FFT, we can track which frequencies are present in the received signal and extract distance information from that. To find the velocity, we can take the 2D FFT using data from multiple sweeps.

The following presentation is a good resource for learning about the math:
https://www.ti.com/content/dam/videos/external-videos/2/3816841626001/5415528961001.mp4/subassets/mmwaveSensing-FMCW-offlineviewing_0.pdf

2. **Performance**

Frequency: 2.4 - 2.5 GHz (ISM band)
Transmit power: 26dBm (400 mW)
Antenna gain: 14dBi for both TX and RX
Sweep rate: 1kHz
Sensitivity: < -97dBm

3. **Equipment needed**

LiteVNA 62/64
Spectrum analyzer (tinySA Ultra can be used)
10/20dB attenuators (a few of each, make sure they can handle at least 1W)
Bench power supply
Red Pitaya

4. Block diagram of the radar system

(https://hforsten.com/third-version-of-homemade-6-ghz-fmcw-radar.html)
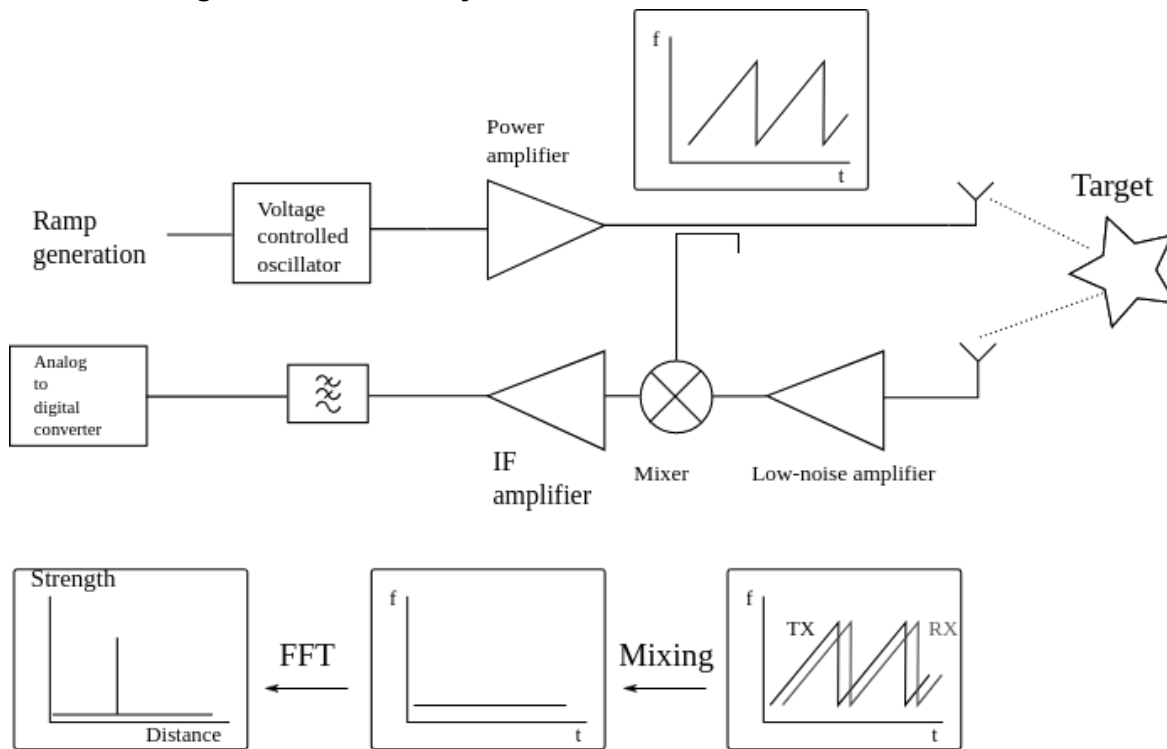
The block diagram of the radar system is shown in the picture above. A voltage controlled oscillator is used to generate the transmitted signal. The VCO is fed from an analog sawtooth wave generator. Multiple power amplifier stages are used to boost the relatively small power of the oscillator (-3dBm) to the 26dBm transmitted. (The other issue is oscillator linearity - a large pad is necessary to make the oscillator less dependent on load variations, which further limits power). On the receive side, a 15dB coupler couples part of the power amplifier signal into the IQ mixer. The received signal goes through two amplifiers to improve the noise performance of the system, before entering the mixer. The IF amplifier is designed to have a highpass response with a slope of 40dB / decade in order to equalize the power between closer and further objects. Finally, the signal goes to the ADC (Red Pitaya) and the FFT and graphics are done on the computer.

The main goal of my project was to do everything from scratch. If you want to do something easier, commercial WiFi amplifiers can be used to boost the signal. An IQ mixer isn't necessary (though it does improve noise performance), and an off the shelf mixer can be used. A PLL IC + VCO IC can be used to generate a better frequency ramp (for example, the LMX2491 chip from TI).

5. Power amplifiers

Power amplifiers were designed using Keysight ADS.

I would suggest watching the Keysight ADS tutorials on Youtube here:

https://www.youtube.com/watch?v=-GLPH9BYvSo

The basic steps for doing power amplifier design:

Step 1: Set up S-parameter simulation

Step 2: Set up biasing. A radial stub + quarter wave transmission line can be used to feed DC into the transistor. Via inductance matters a lot and vias should be simulated.

Step 3: Determine the stability of the circuit using Mu and Muprime. Add resistors until the circuit is stable across ALL frequencies. You will have to test from 0 to 10 GHz. The main goal is to introduce enough loss until the circuit becomes stable again. Capacitors and inductors can be added in series/parallel to make it frequency selective. Make sure your MaxGain does not decrease too much. Place resistors on the input if possible (this hurts your P1dB less).

Step 4: Perform input matching and output matching. Using stubs is probably ideal (tiny inductors and capacitors are a huge pain to solder).

Step 5: Add microstrip lines and tees to your simulation, then create the layout and rerun simulation again with the EM solver.

IMPORTANT: PUT 10dB attenuator on port 0 and 20dB attenuator on port 1 on the LiteVNA. Calibrate with the attenuators in place. Failure to do so will lead to the LiteVNA getting damaged.

6. **Oscillator**

I used a negative resistance design
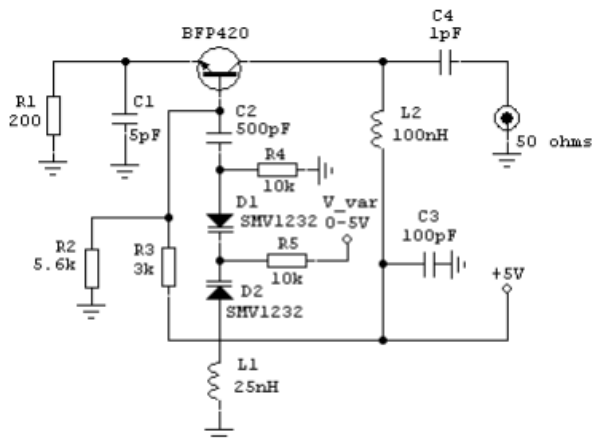
Negative Resistance VCO - 900MHz to 1.3GHz

.

Component values were varied to improve the frequency range. A harmonic balance simulation was used to evaluate performance.

https://www.qsl.net/va3iul/High_Frequency_VCO_Design_and_Schematics/High_Frequency_VCO_Design_and_Schematics.htm

7. Coupler

The coupler is just two microstrip traces close together.

The coupler should be built last since you need information about the output power of the system. Try to design the coupler so 10dBm gets coupled out. (Add 3dB if you are using an IQ mixer design).

8. LNA

Follow the same steps for designing a power amplifier, but place resistors on the output for optimal noise performance.

9. Mixer

You can either do a single mixer or you can do two mixers. In the two mixer case, a Wilkinson divider and branchline coupler are used to generate the LO and RF.
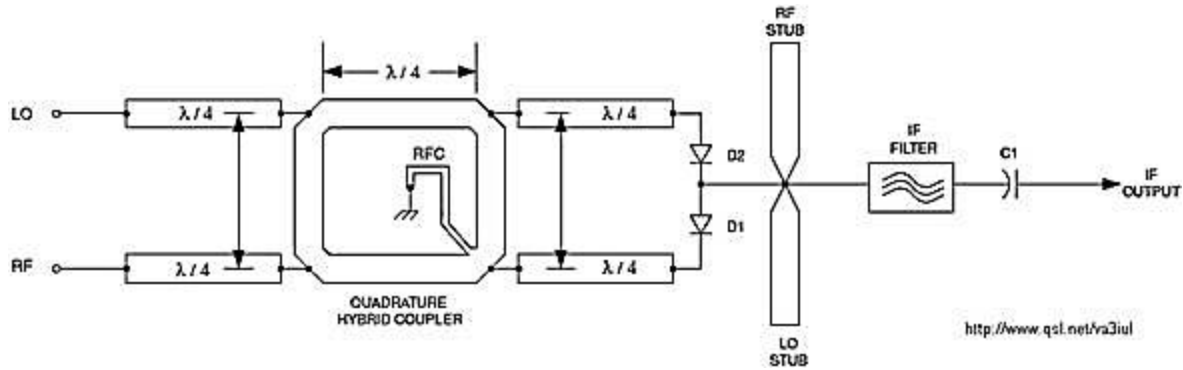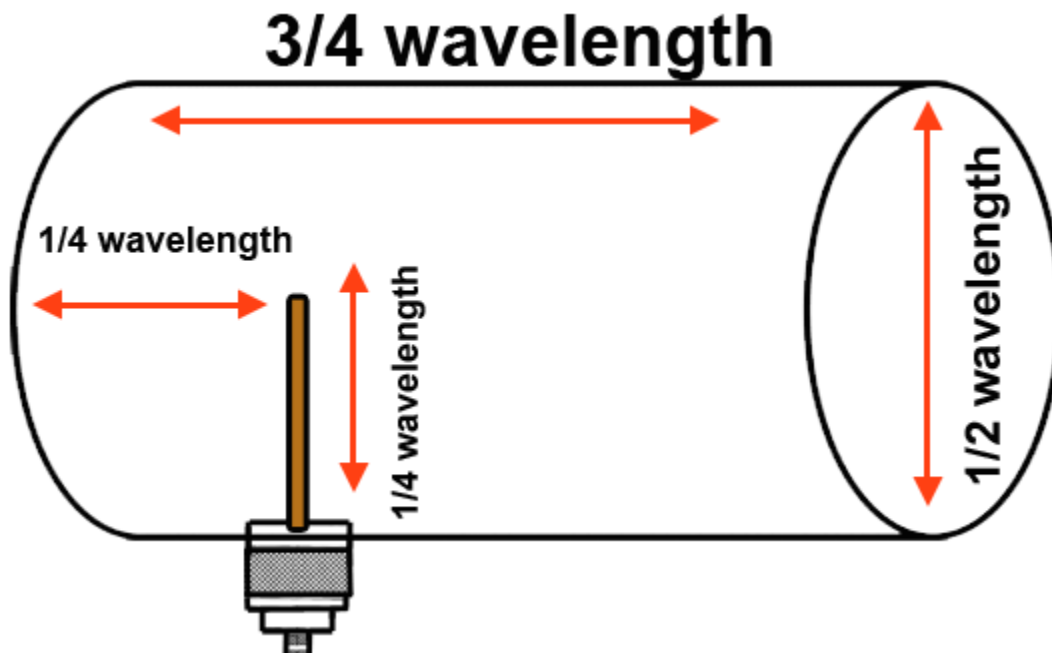
The following design was used by me. The RF stubs must be placed as close to the diodes as possible.

10. IF amplifier

A transformer is used to boost the voltage. A 4th order highpass filter was used to do equalization. Then low noise op-amps were used to amplify the signal.

11. Antennas

A cantenna design was used for the antennas.

The diameter of my antenna was 4 inches (which is significantly larger than the diameter in the diagram). A 4 to 6 inch drain pipe reducer was put on the end to further increase the gain.

12. Software

A CIC filter was used to downsample from 125 MSPS to ~4 MSPS (a factor of 32). Then, a FIR filter compensator was designed to further downsample to 1 MSPS and correct for any amplitude errors introduced by the CIC filter.

A compensator can be designed with Matlab:
https://www.mathworks.com/help/dsp/ref/dsp.ciccompensationdecimator-system-object.html

The software can be found on my Github:
https://github.com/enpassant123

Credit to Pavel Demin:
https://github.com/pavel-demin/red-pitaya-notes

13. Useful resources

Similar projects:
https://www.qsl.net/va3iul/Radar/S-Band_2.4GHz_FMCW_Radar/S-Band_2.4GHz_FMCW_Radar.pdf

https://www.qsl.net/va3iul/Radar/C-Band_5.6GHz_FMCW_Radar/C-Band_5.6GHz_FMCW_Radar.pdf

https://hforsten.com/third-version-of-homemade-6-ghz-fmcw-radar.html

https://rickettslab.org/rabbit-radar/

Other helpful links:

https://www.microwaves101.com/

https://www.youtube.com/watch?v=xa6dqx9udcg

https://www.radartutorial.eu/02.basics/Frequency%20Modulated%20Continuous%20Wave%20Radar.en.html

If you want to ask questions, please send an email to davidzheng@g.ucla.edu