S-Band 2.4GHz FMCW Radar

Iulian Rosu, YO3DAC / VA3IUL, Filip Rosu, YO3JMK, http://qsl.net/va3iul

A Radar detects the presence of objects and locates their position in space by transmitting electromagnetic energy and observing the return echo.

The most used Radars in the industry or military are the **Pulsed Radars**, which detects the range distance to a target by emitting a short pulse and observing the time of flight of the returned target echo. This type of Radar requires to have high instantaneous transmit power, which often results in a Radar with a large and expensive physical apparatus.

Other type of Radars that achieve similar results using much smaller instantaneous transmit power are the **FMCW Radars**.

Fundamentals of FMCW Radar

FMCW Radar principle was known and used at about the same time as pulsed Radar. The very first applications of FMCW Radars were measurements of the height of the ionosphere in late 1920's, and as an aircraft altimeter in mid 1930's.

FMCW Radars have a smaller physical size than pulsed Radars by emitting a continuous RF/Microwave signal that is frequency modulated (FM) by a low frequency waveform. So, the main difference between pulsed and FMCW radars is that the pulsed radars do not transmit and receive in the same time, when FMCW radars transmit and receive continuously in the same time.

- In pulsed radars the receiver is somehow protected by the high TX power, because the RX is OFF when the TX is ON.
- In FMCW Radars the isolation between TX and RX is the main concern.

At circuit level (onboard) the isolation between TX and RX is done using circulators, couplers, or splitters. The isolation provided by those circuits varies between 20dB and 60dB. FMCW Radars generally use separate antennas for TX and for RX, so another required good isolation must be between those antennas. High directive antennas can give better isolation.

- Higher distance between TX and RX antennas provides higher isolation. However, the distance between antennas cannot be too big due to limited system design requirements and losses.
- High VSWR on the TX antenna it will reduce the isolation between TX and RX, due to reflected TX power toward the receiver. For example, for a minimum TX/RX isolation of 20dB, the VSWR of the TX antenna should be better than 1:1.2 (20dB Return Loss).

- The performance of even well-designed FMCW radar system used to be degraded by 10-20dB compared to that which is achievable with pulsed systems. This limitation can be minimized by ensuring that there is good isolation between the receive and transmit antennas by separating them and by using low antenna side lobe levels and also using short range clutter cancellation techniques. Modern signal processing techniques and well-designed hardware can also be used to cancel the leakage power in real time, and good performance can be obtained.

- Lingering problem with FMCW signals is that the FMCW signal suffers from what is called ***range-Doppler coupling***. That means, a target with velocity (a moving target) will have a ***frequency shift*** due to target motion. This is called ***Doppler shift***.
  Always this frequency shift causes an error in the measurement of its distance range.

- To quantify the performance of range estimation (distance to the target), two figures of merits are used: ***range resolution*** and ***range accuracy***. Range resolution describes how close two targets can be separated such that they can be distinguished as two separate peaks in the spectral domain and hence detected as two targets.

- In FMCW radars the frequency modulation spreads the transmitted energy over a large modulation bandwidth ***B***. Large bandwidth helps to detect targets with high range resolution.

- In FMCW radars the power spectrum is nearly rectangular over the modulation bandwidth. This makes interception difficult. It is resistant to jamming because it is a deterministic signal and its form is only known to the user.

In FMCW Radars the transmitted frequency is linearly changed during the runtime to the target and back to the Radar, and the received signal is shifted by a time delay to the initial signal. By mixing the current transmitted signal with the reflected signal, the frequency difference caused by the runtime can be defined. Due to the known modulation parameters of the transmitter, the runtime of the signal can be calculated, which is proportional to the distance of the object.

Due to this indirect measurement of the runtime and by choosing adequate modulation parameters, even very nearby objects can be measured precisely and cost-efficiently.

- For a precise distance measurement, an extremely highly linear modulation of the transmitted frequency is necessary, because each nonlinearity of the modulation will decrease the accuracy of the FMCW Radar.

In the plot below (Fig. 1), the duration in time T (in seconds) it is half of the time period of the low frequency modulation waveform f_m (in Hz): $f_m = 1/(2*T)$

Generally, the duration in time ***T*** it is much greater than the return time of the echo signal t_d.

The low frequency modulation waveform signal can be ***Triangle***, ***Sawtooth, Sinusoidal***, or other periodic shape signal.

- In practical applications the frequency of the modulation signal f_m could be between 10Hz and 1kHz.

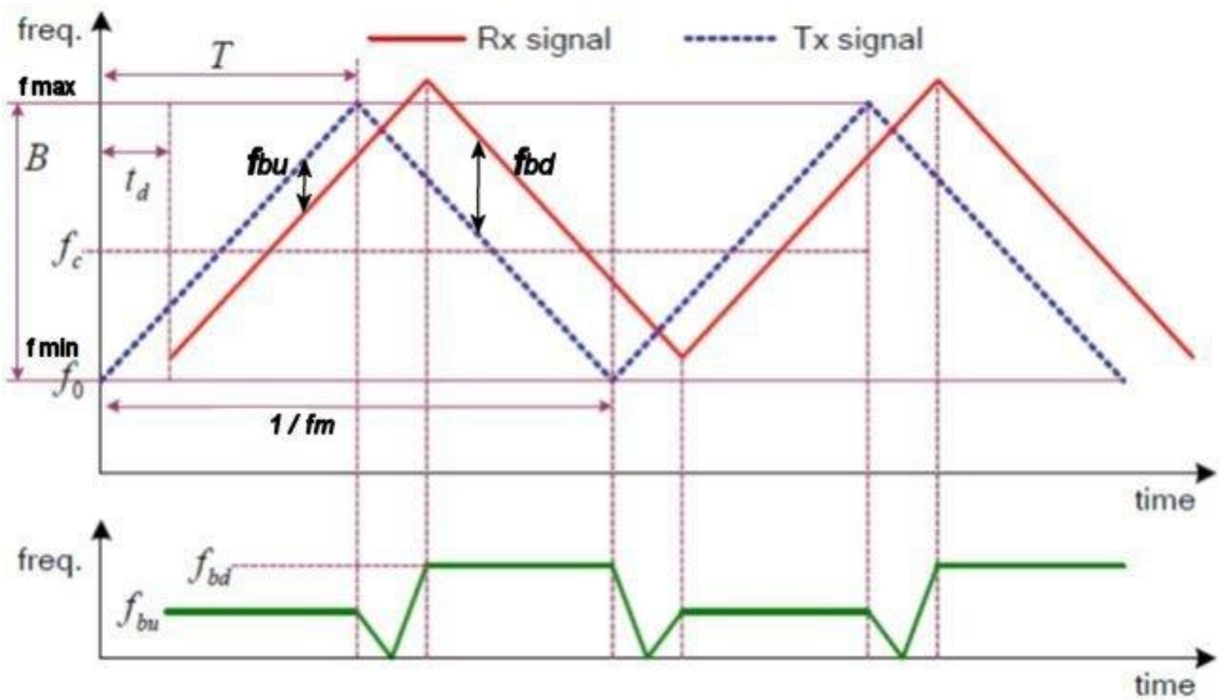


Fig. 1 - FMCW Radar signals using a triangle low frequency waveform

The transmitter emits waves of a frequency that varies linearly with time, oscillating above and below the ***mean frequency*** f_c. These waves arrive at the receiver both, by a direct connection and also by reflection from the target object. Since the trip to the target object and return takes time, the received frequency line (RX signal) is displaced along the time axis relative to the transmitted frequency (TX signal). The two frequencies (direct path and reflected path), when combined in the RX mixer, give rise to a ***beat frequency***.

- The greater the target distance, the greater the beat frequency is.

The ***Receive RX*** echo signal received after the reflection with an object is a copy of the ***Transmit TX*** signal, delayed by the propagation time t_d (in seconds):

$$t_d = (2R) / c \qquad \text{(see Fig. 1)}$$

where ***R*** is the distance (range) to the target (in meters), and ***c*** is the speed of light.

- Example: If the distance ***R*** to the target is 100m, then the total propagation time t_d (back and forth) is: 0.66 usec.

The most used system design for FMCW radars is the homodyne (direct conversion) approach, which uses the *Transmit* signal to convert the *Receive* (reflected) signal to baseband (video) frequency.

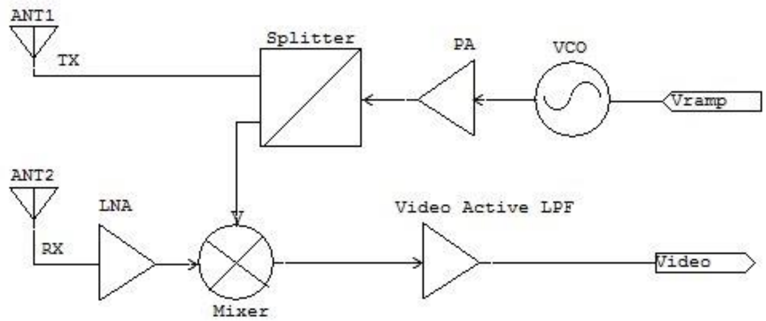


Fig.2 - Homodyne FMCW Radar Block Diagram

The down-converted frequency at the output of the mixer is then low-pass filtered to obtain an approximately sinusoidal ***video frequency*** f_W (in Hz) which is constant in the time interval $(T - t_d)$ and equals the change of the *Transmit* frequency during time t_d.

$$f_W = t_d (f_{max} - f_{min}) / T$$

where $f_{max} - f_{min}$ is the frequency deviation (the bandwidth B is the frequency range of the VCO in Hz), and t_d is the time delay in seconds (see Fig. 1).

If the target moves, the received signal will also contain a Doppler shift term (along the frequency axis), which can be used to measure the speed (velocity) of the target object.

- The difference between the transmitted signal and Doppler-shifted received signal is named ***beat frequency***.

The ***beat frequency*** is time-variant frequency and will be generated for the up-chirp (f_{bu}) and for the down-chirp (f_{bd}) (see Fig. 1).

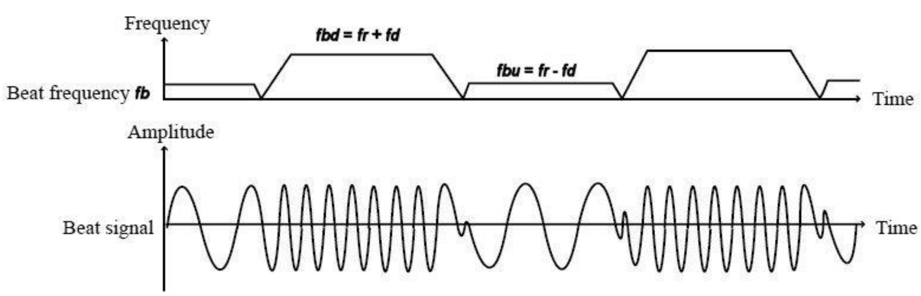


Fig. 3 - FMCW beat frequency signals using Triangular waveform

- The maximum ***beat frequency*** f_r (beat frequency distance range) is given by:

$$f_r = |f_{bu} + f_{bd}| / 2$$

- If the RF frequency is modulated at a frequency rate f_m than ***beat frequency*** f_r is:

$$f_r = (4RB f_m) / c$$

- Example: If the distance range ***R*** is 100m, the sweep range ***B*** (bandwidth of the VCO) is 100MHz ($100*10^6$Hz), the frequency of the modulation signal f_m (triangle signal) is 100Hz, then the beat frequency distance range f_r is: 13333Hz (13.333kHz).

The maximum ***Doppler frequency*** (Doppler frequency velocity range) f_d is given by:

$$f_d = |f_{bu} - f_{bd}| / 2$$

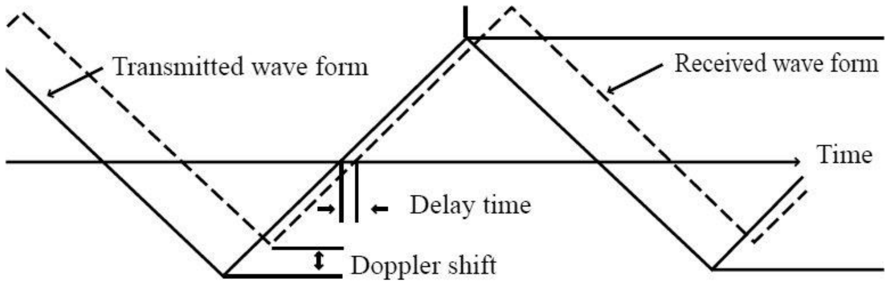


Fig. 4 - FMCW Doppler shifted received signal using Triangular waveform

- The distance ***R*** (range, in meters) to the target can be calculated with:

$$R = (cTf_r) / 2B$$

where ***B*** is the RF frequency bandwidth (in Hz), which is the sweep frequency range of the VCO:

$$B = f_{max} – f_{min} \qquad \text{(see Fig. 1)}$$

The accuracy of distance measurement it is related to the bandwidth ***B*** of the radar.

- Example: If the duration in time ***T*** is 5 msec (which corresponds to a modulation signal f_m=100Hz), the beat frequency distance range f_r is 13333 Hz, and the sweep bandwidth ***B*** is 100MHz ($100*10^6$Hz), then the distance to the target ***R*** is: 100m.

- By using higher transmit frequencies, higher bandwidths are possible. In this project the bandwidth ***B*** is 100MHz.

- f_c represents the mean (center) of the RF frequency and is given by:

$$f_c = f_{max} – (B / 2) \qquad \text{(see Fig. 1)}$$

- The speed (velocity) ***V*** of the target object can be calculated in m/sec with:

$$V = cf_d / 2f_c$$

- Example: If the center of the RF frequency f_c is 2400MHz ($2400*10^6$ Hz) and the Doppler frequency velocity range f_r is 100Hz, then the speed (velocity) ***V*** of the target object is: 6.25 m/sec (or 22.5 km/h).

- The **range resolution** in meters S_r which is the ability of the Radar to distinguish between two target objects, is:

$$S_r = c / (2B)$$

If the spacing between two target objects is too small, then the Radar "see" only one target.

- If the bandwidth ***B*** is higher, the range resolution S_r is smaller, which means the resolution is better.
- The velocity range resolution V_r in m/sec is given by:

$$V_r = (2f_m)/ f_c$$

The beat frequency is amplified, amplitude-limited, and low-pass filtered at the output of the RX mixer. If the target object is stationary, the beat frequency note can be measured with a simple frequency meter calibrated in distance.

If the target object is moving, the above assumption is not applicable, a Doppler frequency shift will be superimposed on the FM distance range beat note and an erroneous distance measurement result.

The Doppler frequency shift causes the frequency-time plot of the received echo signal to be shifted up (f_{bu}) or down (f_{bd}).

- If the target is approaching the Radar, the beat (up) frequency will be:

$$f_{bu} = f_r - f_d$$

- If the target object is moving away from the Radar, the beat (down) frequency will be:

$$f_{bd} = f_r + f_d$$

- The beat frequency f_r (distance range) can be extracted by measuring the average beat frequency:

$$f_r = (f_{bu} + f_{bd}) / 2$$

- If f_{bu} and f_{bd} frequencies are measured separately (by switching the frequency meter every half modulation cycle), the Doppler frequency (velocity) can be measured:

$$f_d = (f_{bu} - f_{bd}) / 2$$

The above statements for distance and velocity measurements assume that: $f_r > f_d$

If the target is at short range from the Radar and have very high-speed, then: $f_r < f_d$

In this situation the roles of the averaging and the difference-frequency measurements are reversed. The averaging meter will measure the Doppler velocity, and the difference-frequency meter will measure the distance.

- So, it is very important at any time that the system should know the roles of the frequency meters (to know the inequality sign **< >** between f_r and f_d), otherwise incorrect interpretation of the measurement may result.

Effect of Target Motion – A moving target will impose a Doppler frequency shift ***(f_d)*** on the beat frequency distance range ***(f_r)*** as shown in Fig. 5.

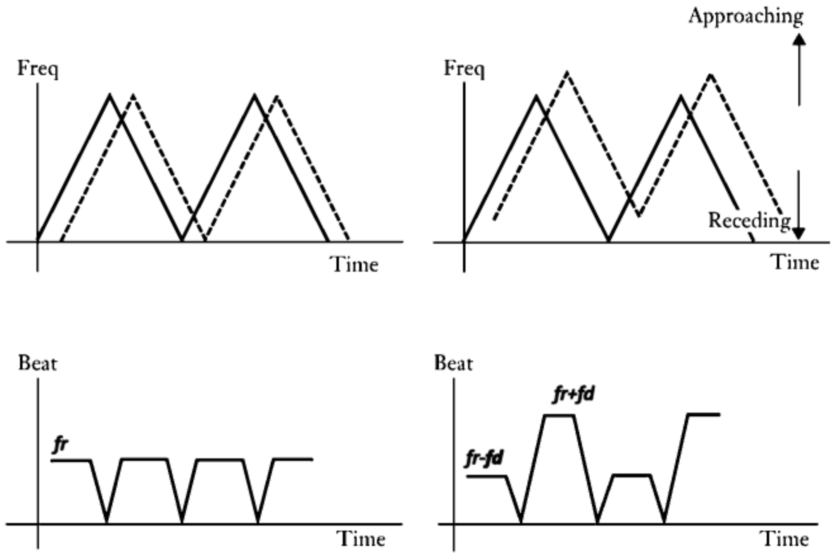


Fig. 5 – Effects of Doppler shift (f_d) on beat frequency distance range (f_r)

One portion of the beat frequency ***(f_r)*** will be increased and one portion will be decreased. For a target approaching the Radar, the received signal frequency is increased (shifted up in the diagram) decreasing the up-sweep beat frequency (f_{bu}) and increasing the down-sweep beat frequency (f_{bd}).

When more than one target is present within the view of the Radar, the mixer output will contain more than one difference frequency. If the system is linear, there will be a frequency component corresponding to each target. In general, the ***distance range*** to each target may be determined by measuring the individual frequency components and applying to each the equation:

$$f_r = (4RB\, f_m)/c$$

To measure the frequencies, they must be separated from one another. In an analog system processing, this can be accomplished with a bank of narrowband filters. Alternatively, a single frequency corresponding to a single target object may be tracked and observed using a narrowband tunable filter.

The measuring of range distance of multiple targets become more complicated if they are moving, or if the FM waveform is nonlinear, or if the entire receiving chain is not operated in the linear region.

If the FMCW Radar is used to detect single targets only, such as in the radio altimeter, it is not necessary to employ a linear modulation waveform, and a ***Sinusoidal*** FM signal can be used. The beat frequency obtained with sinusoidal modulation is not constant over modulation cycle (as in linear modulation), but the average beat frequency yields the correct value of the target distance range.

If a ***Sawtooth*** sweeping signal is used instead of a ***Triangle*** signal, the Radar system can measure the distance to the target but cannot measure the velocity of the target, because to extract the Doppler frequency f_d the modulation waveform must have equal up-sweep and down-sweep intervals.

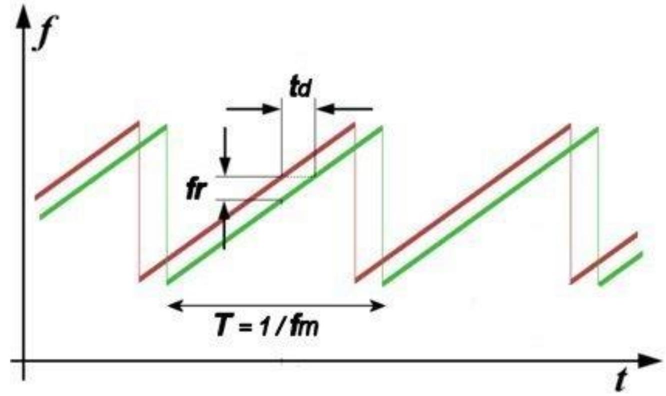


Fig. 6 - FMCW signals using Sawtooth waveform

Schematic Description of the FMCW Radar

There are many published FMCW Radar projects which claims that they are Low Cost. But all of them use either already built RF/Microwave blocks (mainly from Minicircuits), or using integrated RF/Microwave MMICs from various manufacturers as Hittite, Analog Devices, Maxim, LinearTech, Minicircuits, or others.

The presented project uses only discrete RF components as SiGe transistors, Schottky diodes, varicap diodes, and onboard planar RF mixer and Wilkinson splitter, which are built directly on the main 1mm thick FR4 PCB. The schematic use only few common analog OpAmps ICs necessary to build the triangle wave generator and the output Low Pass Filter. Total cost of the discrete components bought in low volume is less than $10.

One of the most important components of an FMCW Radar is the frequency sweep Voltage Controlled Oscillator (VCO).

- In a FMCW Radar the VCO linearity and VCO phase stability affects directly the accuracy of the distance and of the velocity measurements.

The chosen VCO type for this project is a **Negative Resistance oscillator**.

This is a circuit with low count of components. High number of components may affect indirectly the linearity MHz/V of the VCO. A high frequency SiGe transistor (BFP420) is used as an oscillator (Q1). The transistor has the collector supplied to the +Vcc through a 1nH (*) inductor. Adjusting the value of this inductor helps for tuning the central frequency f_c of the VCO. The output of the VCO is taken from the emitter using a 2.2pF (*) capacitor. Its value may be adjusted for getting the desired frequency fc, the frequency sweep range, and the MHz/V linearity.

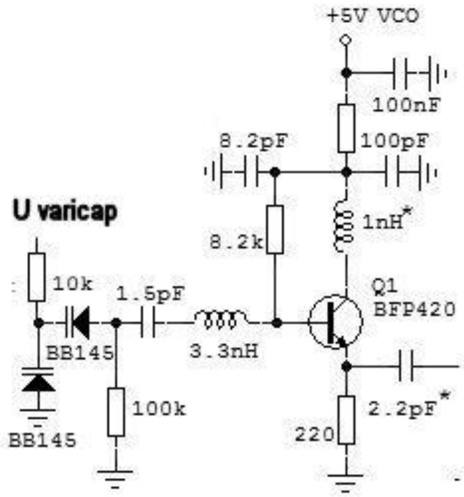
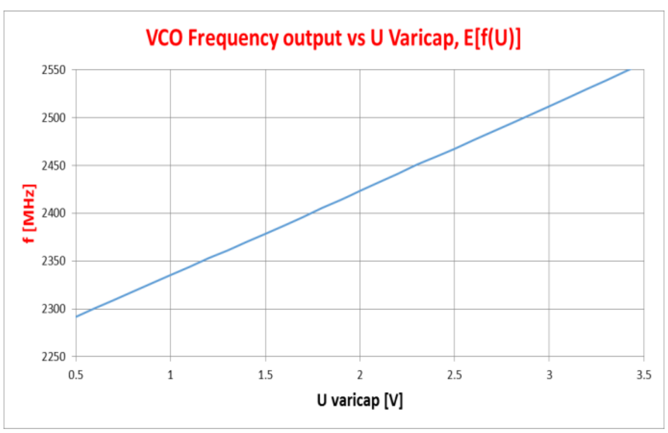
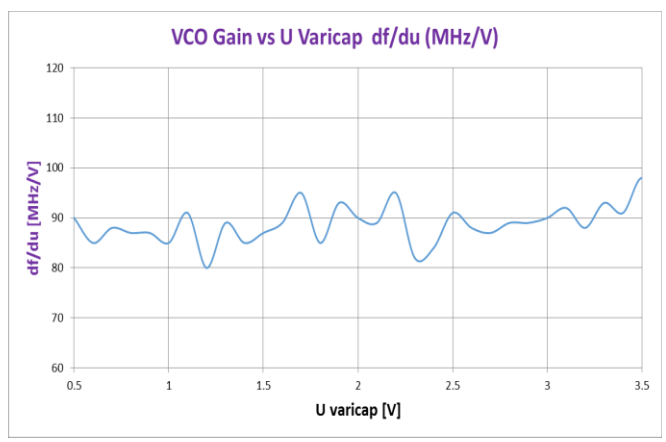


Fig. 7 - VCO Schematic

In a Negative Resistance VCO the parasitic capacitance from the emitter to the ground is very critical in obtaining a good MHz/V linearity, so careful PCB design is required.

The varicap diode capacitance characteristic as a function of the reverse voltage (U varicap), have a one-to-one impact on the VCO linearity. Should be chosen varicap diodes with linear characteristic. For the project was chosen BB145 varicap diode which has a pretty linear capacitance characteristic between 0.4V and 4V. Other newer varicap models may work as well. Back-to-back varicap diode configuration is used to improved balance and to minimize even-order varacap nonlinearities.





We can see from the above measurement's plots that the VCO which was built has more than 250MHz frequency range for a varicap voltage sweep between 0.5V and 3.5V. The actual project uses only 100MHz from this 250MHz frequency range. The chosen frequency range is between 2300MHz and 2400MHz (U varicap = 0.5V to 1.7V), region where the linearity characteristic of the VCO is reasonable, and also because this is a frequency band with less number of external interferers.

The triangle sweep generator was made using three OpAmps, all part of a LM324 IC. There are two sweep options of U varicap (using the switch S1). One option is to connect U varicap to the triangle generator (auto sweep) and second option, to do a manual frequency sweep using a multi-turn 10k potentiometer. The second option is useful for evaluating the MHz/V characteristic of the VCO. The chosen ramp sweep having an amplitude between 0.5V and 1.7V can be easily adjusted using the trimming potentiometers.

Looking in the time domain, the RF signal (2.3GHz to 2.4GHz) at the output of the VCO (using for U varicap the triangular modulation waveform), shows to be as in the plot below:

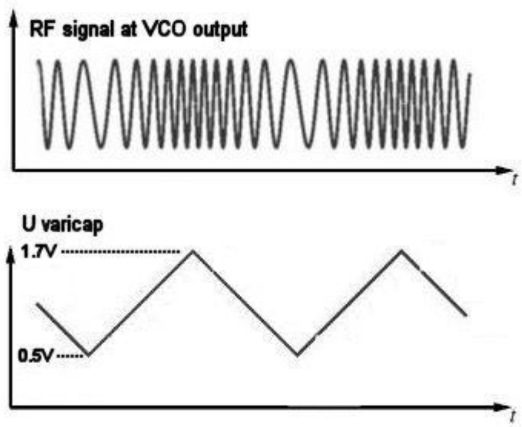


Fig. 8 - RF modulated signal at VCO output vs U varicap

According to the beat frequency equation $f_r = (4RB\, f_m)/c$, the f_r value is function of the: distance range R, of the frequency bandwidth B (100MHz in our case), and also is function of the frequency (period) of the triangular modulation signal f_m.

- Higher frequency bandwidth B and higher modulation frequency f_m, gives a higher beat frequency f_r, which means higher distance resolution.

For example, if the target object is at 3m, and the triangular modulation frequency is 50Hz, the beat frequency is 200Hz. In the same system if we change only the triangular frequency to 1kHz, the beat frequency become 4kHz.

However, according to the velocity (speed) resolution equation $V_r = 2f_m/f_c$:

- Lower modulation frequency f_m and higher mean RF frequency f_c, gives higher velocity resolution (less meters per second, which means better speed resolution).

The output power of the VCO is just above 0dBm. At the output of the VCO was placed a 6dB pad attenuator instead of a buffer transistor. This improves the VCO phase noise and load pulling, caused by the impedance changes on the next stage.

The Power Amplifier driver (Q2) and the Power Amplifier final stage (Q3, Q4) use high IP3 SiGe transistors BFU790F. To increase the output power the final stage use two transistors in parallel, with 0.2 ohms ballast resistors in emitters. The output power of the Power Amplifier is about +23dBm.

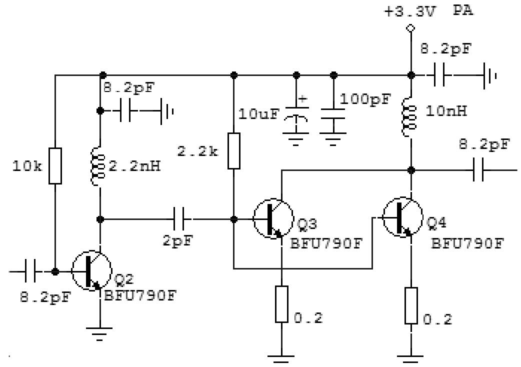


Fig. 9 - Power Amplifier schematic

A printed Wilkinson splitter is used to distribute the output signal to the TX antenna and also to the receive mixer. Counting the 3dB insertion loss through the Wilkinson splitter, the output power at the connector of the TX antenna is about +20dBm.

The received reflected signal is collected by the RX antenna and routed to the Low Noise Amplifier (Q5) made also with a SiGe transistor BFU790F, transistor which have 0.5dB noise figure and 16dB of gain at 2.4GHz. This LNA placed in front of the mixer improves the Signal to Noise Ratio of the receiver system. The input of the LNA was impedance matched for best noise figure and highest gain, using a shunt 5.6nH inductor and a 5.6pF series capacitor.

The emitter 0.5nH inductor, named inductive degeneration, helps to improve input and output match, noise figure, stability, and the linearity of the LNA.

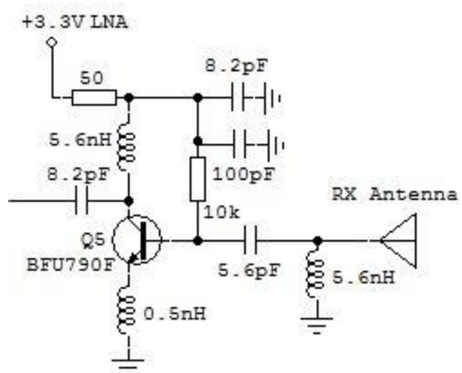


Fig. 10 - LNA schematic

The planar Double Balanced mixer (used in this FMCW Radar project), was invented and patented by [Rod Kirkhart](#) in 2007.

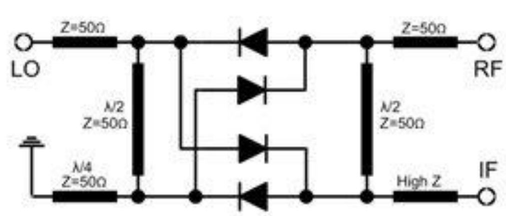


Fig. 11 - Planar Double-Balanced Mixer schematic

This Double Balanced Mixer it has low insertion loss (~4dB), is using four Schottky diodes [BAT17](#) cross connected, and it has planar BALUNs at the RF and LO ports.

The mixer provides about 45dB isolation between LO-RF ports and about 50dB isolation between LO-IF ports.

For the best space economy and minimum layout losses, the footprint layout of the planar mixer could be implemented as in the picture below:

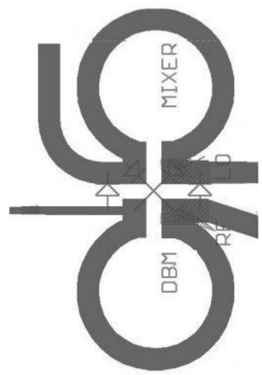


Fig. 12 - Planar Double-Balanced Mixer footprint layout

The two 50 ohms microstrip circle lines represents the λ/2 transmission lines, and the 50 ohms microstrip arc represents the λ/4 transmission line.

The Schottky diodes are soldered on the top of the structure, in a cross connection. The internal configuration of two BAT17-4 allow for an easy soldering handwork.

The LO input level, which actually is the TX output power routed through the Wilkinson splitter, should be adjusted with a pad attenuator to get the minimum mixer insertion loss (which mean better receive sensitivity) but also avoiding any unwanted TX leakage directly into the RX chain, especially at the LNA input, or mixer RF input.

The DC offset, which is a major issue in Direct Conversion receivers, is minimized by the topology of this mixer.

To avoid other TX to RX leakages, should be done: a careful design of the PCB, a careful placement of the components, a good shielding, and a good TX / RX antenna isolation.

The IF output of the mixer is the video signal (baseband) which is routed further to an active low-pass filter.

To get the best performances of the active low-pass filter should be used OpAmps which have a Bandwidth Product at least 1MHz. The project use the low-noise, 16MHz BW MC33078 which gives about 32dB of gain.

The cut-off frequency of the active low-pass filter should allow to pass the highest beat frequency of interest (corresponding to the desired maximum distance).

At the input of the active low pass filter was used a series 100nF capacitor and a shunt 10k resistor, which form a basic RC high-pass filter with cut-off at about 1kHz. This high-pass filter helps attenuating the inevitable ground reflection seen by the radar receiver.

The PCB layout was designed on a low-cost, dual-layer, 1mm thick, FR4 laminate.

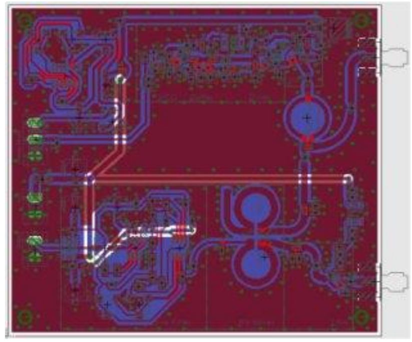


Fig. 13 - PCB Layout

For the final FMCW Radar System were built experimentally two sets of antennas.
One set using two Coffee-Can antennas, and one set using two Helical antennas.
The seven turns Helical antenna have about 3dB higher gain than Coffee-Can (11dB compared to 8dB), but Coffee-Can antenna provide better TX to RX isolation.
Lower TX to RX isolation reduce the receiver SNR, and so, the receiver sensitivity.
Also, due to the nature of the antenna type, the Coffee-Can antenna have lower input VSWR than the Helical antenna.
Helical antenna needs a specific triangle shape transmission line to get the 50 ohms input impedance.

Fig. 14 - Coffee-Can Antennas

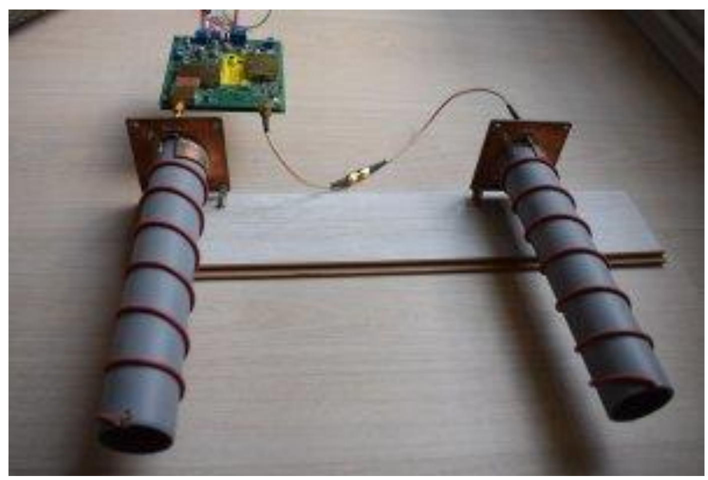


Fig. 15 - Helical Antennas

The Radar circuit was practically built on a 1mm thick FR4 PCB using 0805 SMD inductors and capacitors.

The SRF (Series Resonant Frequency) of the 8.2pF capacitors in SMD-0805 package, appears at about 2.4GHz. At that point the capacitor has the lowest reactance, and so they are good to be used as RF decoupling or DC blocking capacitors in a 2.4GHz RF system.

One method to measure the initial performances of the FMCW Radar is to do not use the TX and RX antennas, and use instead a 50 ohms coaxial cable with known length and dielectric properties, connected between TX and RX antenna connectors.

- The beat frequency equation using a coaxial cable is given by:

$$f_r = [(4RB\ f_m)/c]*[\sqrt{E_r}/2]$$

resulting that the cable length is: $R = (2cf_r) / (4Bf_m\sqrt{E_r})$

where f_r is the beat frequency in Hz, f_m is the modulation frequency (***1/2T***) in Hz, E_r is the dielectric constant of the coaxial cable, ***R*** in this case is the cable length in meters, and ***B*** is the sweep frequency bandwidth in Hz.

  - **Example**: If the beat frequency f_r is 1kHz, the modulation frequency f_m is 50Hz, the dielectric constant E_r of the coaxial cable is 2.2, and the sweep frequency bandwidth ***B*** is 100MHz, results a coaxial cable length of 20.23 meters.

Using a coaxial cable instead of TX/RX antennas, when visualizing the output signal with an oscilloscope, the beat frequency note is very stable compared to the radiated mode (using TX/RX antennas), because the measurement is not affected by parasitic reflections or external interferers.

Depending by the cable length and also depending by the cable insertion loss at 2.4GHz, may need to add some attenuators in series with the coaxial cable, to do not saturate the RX LNA and the RX mixer, saturation which would be translated into erroneous measurements.

A digital oscilloscope placed at the video output may help to visualize the beat frequency and also to capture the waveform in the sight of doing an initial signal processing in Matlab. Using the Radar signals, the object target range and velocity can be quickly calculated using Fast Fourier Transforms (FFT). FFT is a commonly used signal-processing technique that converts time-varying signals to their frequency component.

The video output also can be connected to a PC (microphone input or line input), and using a simple freeware audio spectrum analyzer software, you can visualize on the PC screen the beat frequency vs target distance (real-time in the frequency domain). The program samples an audio input stream, and then uses a Fast Fourier Transform to yield the spectral analysis in real-time.

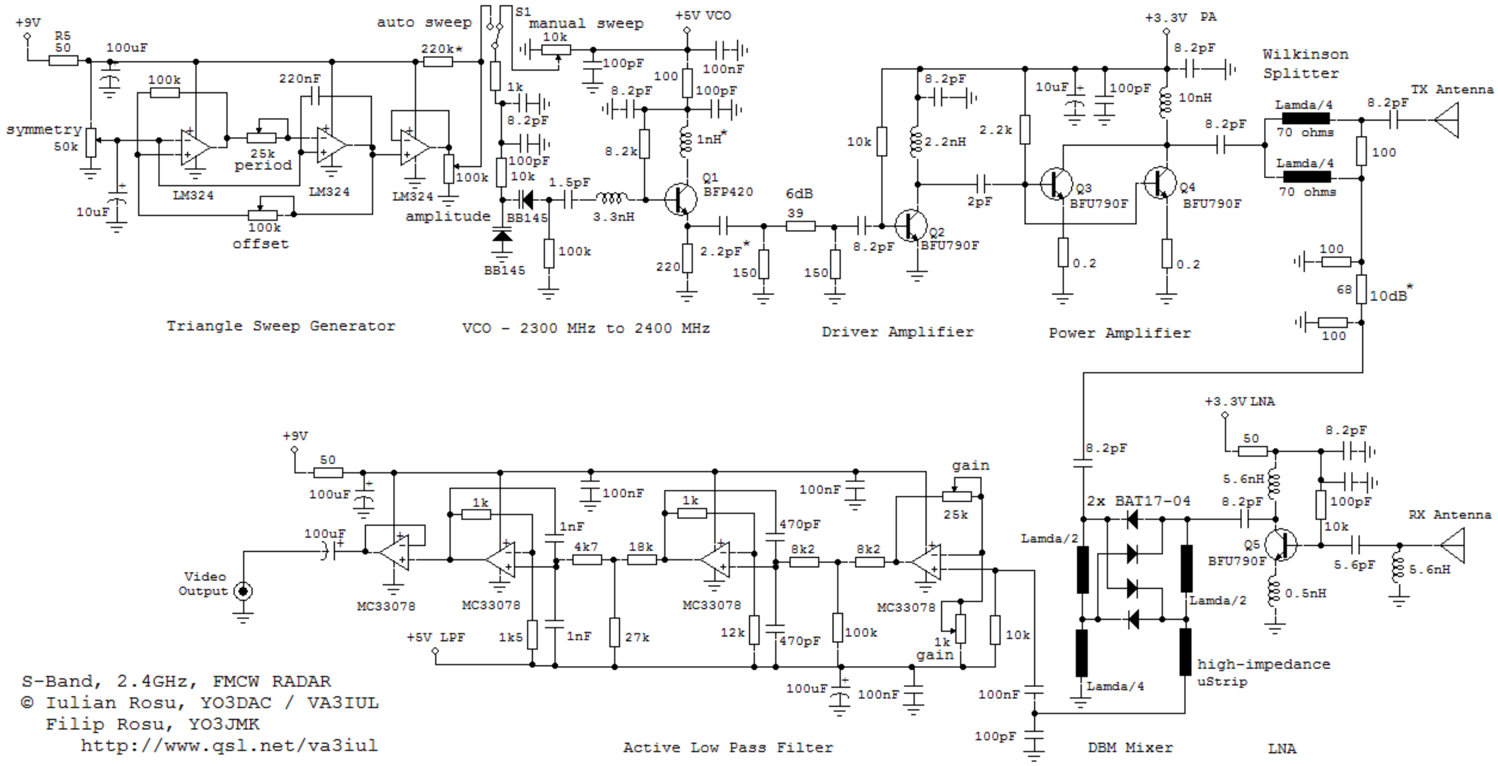


Fig. 16 - Schematic of the S-Band, 2.4GHz, FMCW Radar

References:

1. *Radar System Engineering (1948) – Ridenour*
2. *Introduction to Radar Systems 2nd ed. – Skolnik*
3. *Small and Short Range Radar Systems – Charvat*
4. *Design of Multi-Frequency CW Radars - Jankiraman*