

Project Report

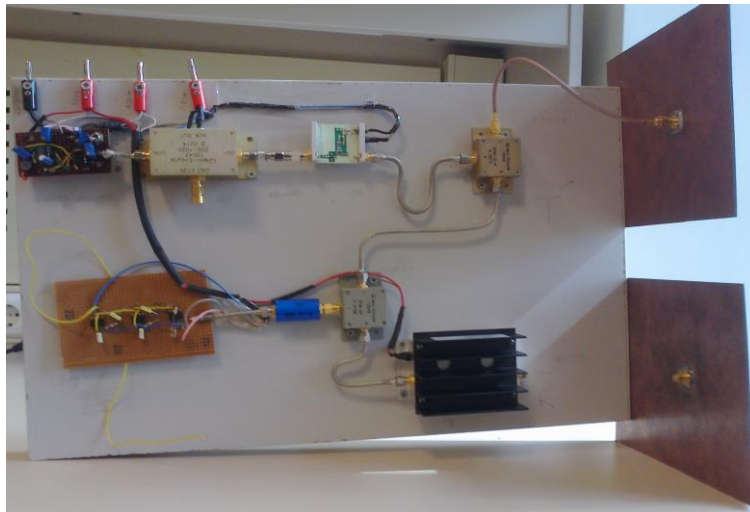
Laptop Based Radar

Selected Topics in Microelectronics I (EE 680)

(Spring Semester 2013)

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Introduction

A Frequency Modulated Continuous Wave (FMCW) RADAR has been implemented and test and measurement results are presented. The specifications of Implemented RADAR are :

Specifications

- Frequency modulated continuous wave(FMCW)
- Center frequency of 1 GHz
- Approximately 23dBm TX power
- Waveform = CW Ramp
- Max range approx. 100m for 1dBsm target
- 2 modes: Doppler(single frequency), range(FMCW)
- Data acquisition using Acquisition card and Matlab
- Signal processing in MATLAB
- DC Power < 10 Watt

Functional Decomposition

Transmitter

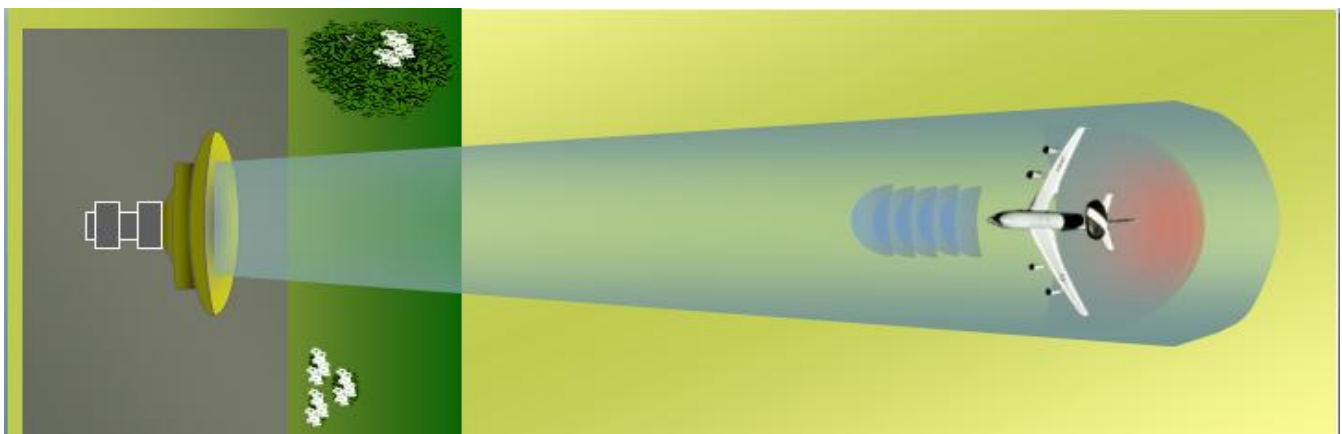
Modulated source
Amplification
Distribution
Antenna for radiation

Receiver

Antenna receive aperture
Amplification
De-modulate
Frequency Translate

Operational Mode

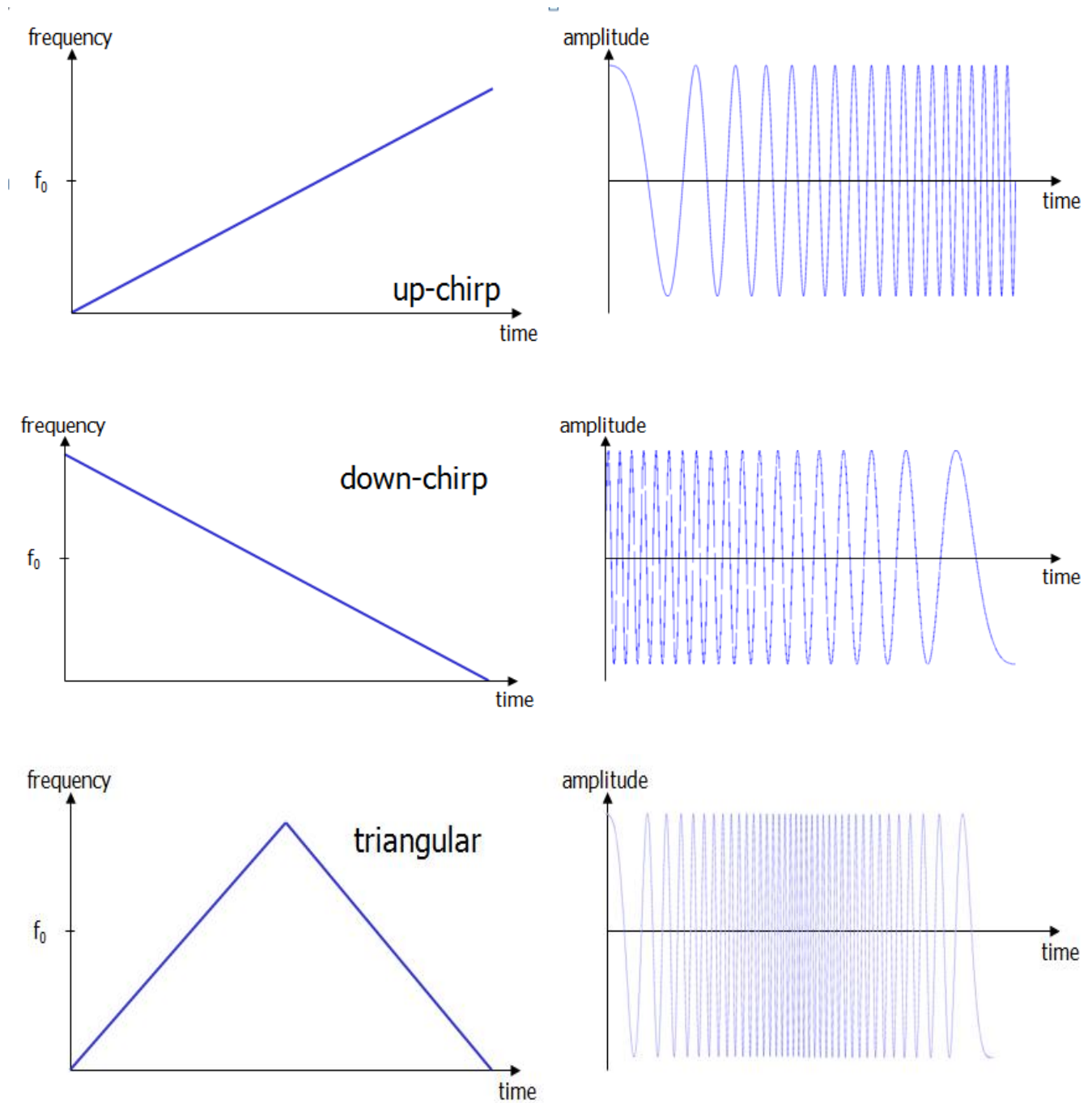
- Fixed Frequency Mode for Target Velocity/speed Measurement
- Frequency Modulated Mode for Range Measurements



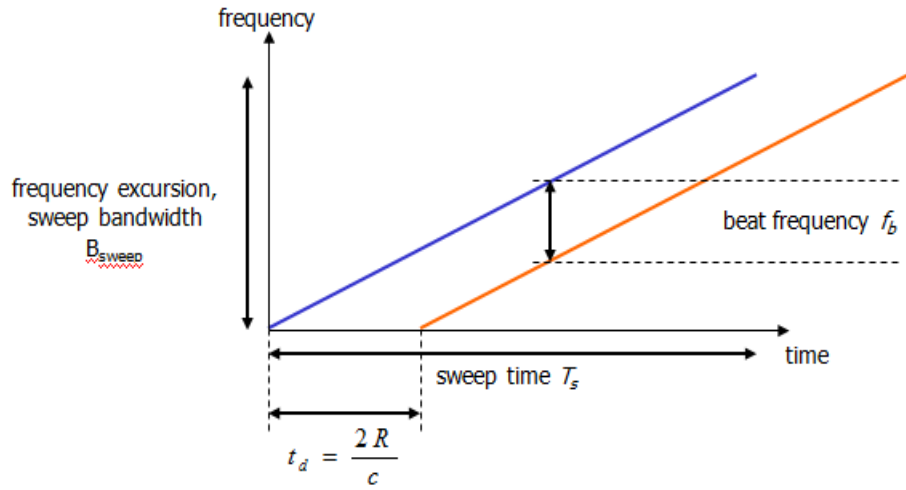
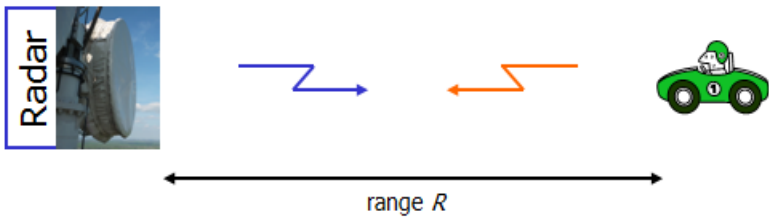
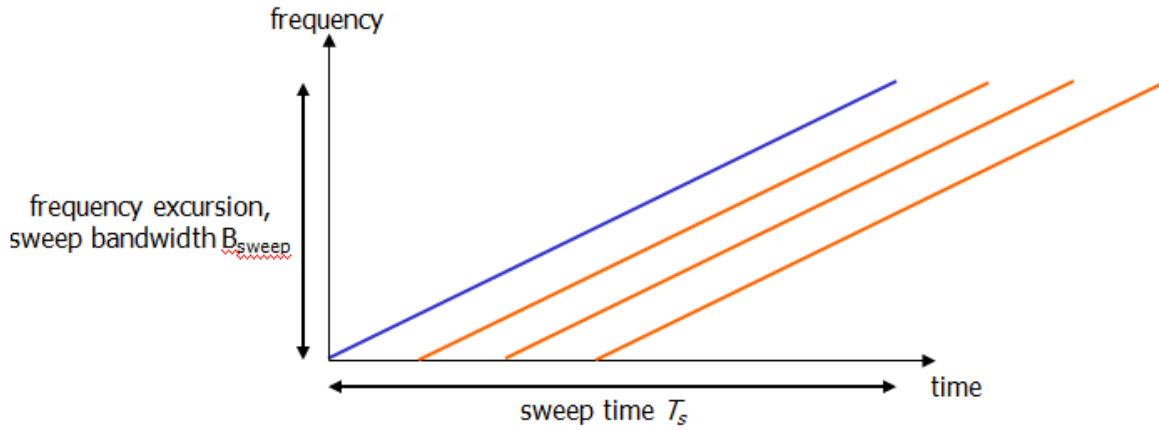
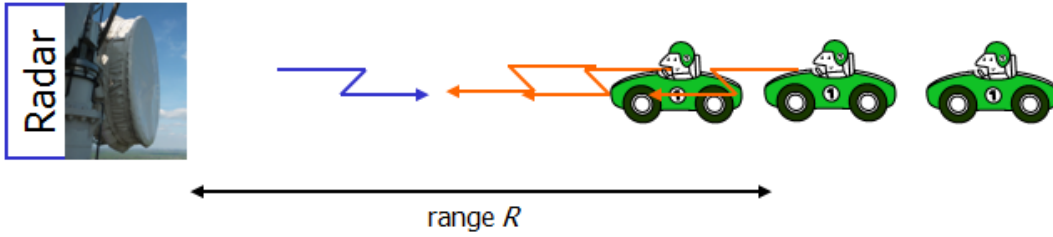
PRINCIPLE OF FMCW RADARS

Introduction

Frequency Modulated Continuous Wave (FMCW) radar is radar transmitting a continuous carrier modulated by a periodic function such as a sinusoid or saw tooth wave to provide range data (IEEE Std. 686-2008). Modulation is the keyword, since this adds the ranging capability to FMCW radars with respect to un-modulated CW radars.

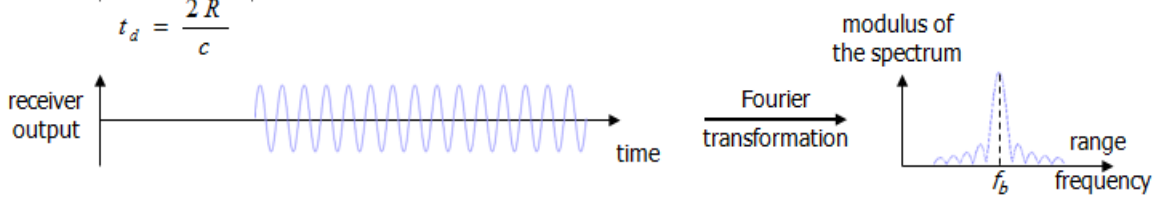


Target Distance Measurement using FMCW Radar

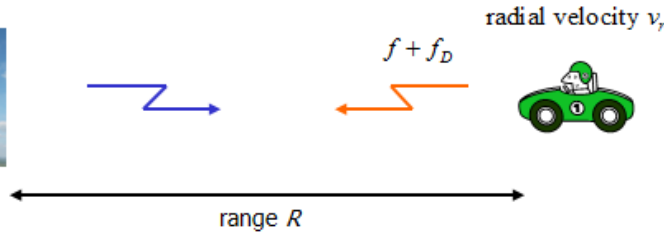


$$\frac{t_d}{T_s} = \frac{f_b}{B_{\text{sweep}}}$$

$$R = \frac{cT_s f_b}{2B_{\text{sweep}}}$$



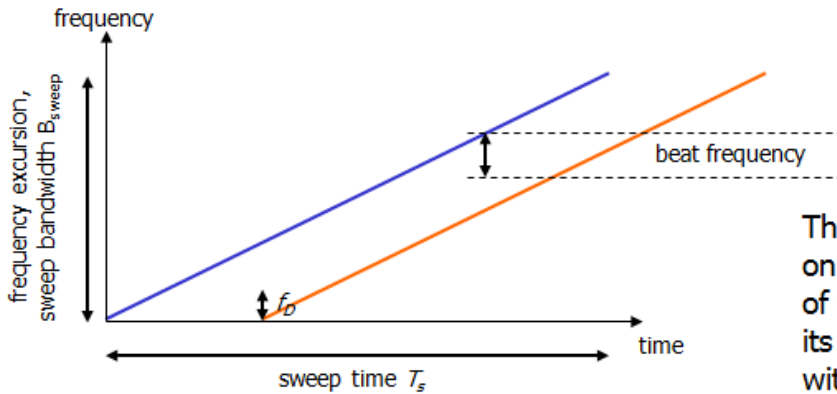
Target Velocity Measurement using FMCW Radar



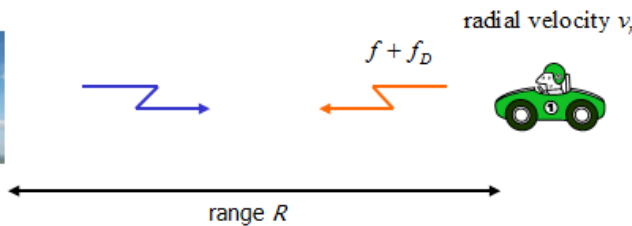
A moving target induces a Doppler frequency shift

$$f_D = \frac{2v_r}{\lambda}$$

with the radar wavelength λ .



The beat frequency is not only related to the range of the target, but also to its relative radial velocity with respect to the radar.



Beat frequency components due to range and Doppler frequency shift:

$$f_b = \frac{B_{sweep}}{T_s} \cdot \frac{2R}{c}$$

$$f_D = \frac{2v_r}{\lambda}$$

that are superimposed as

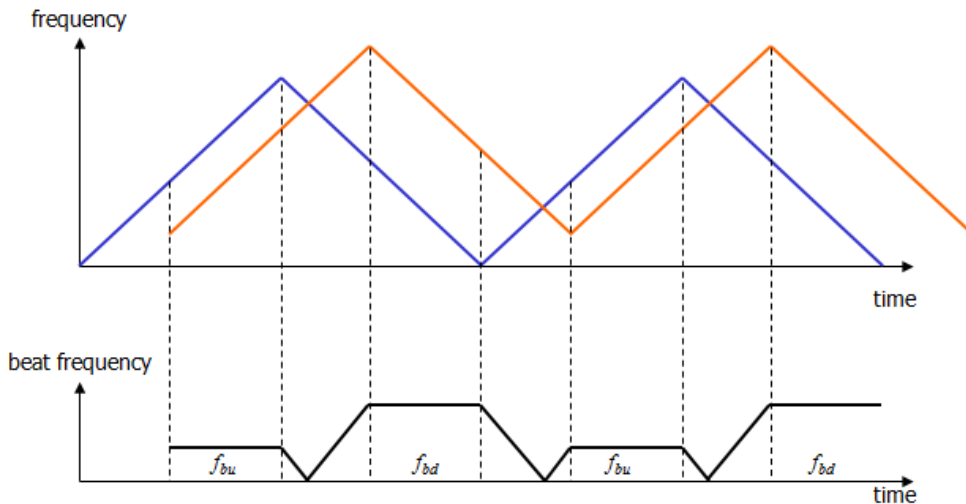
$$f_{bu} = f_b - f_D$$

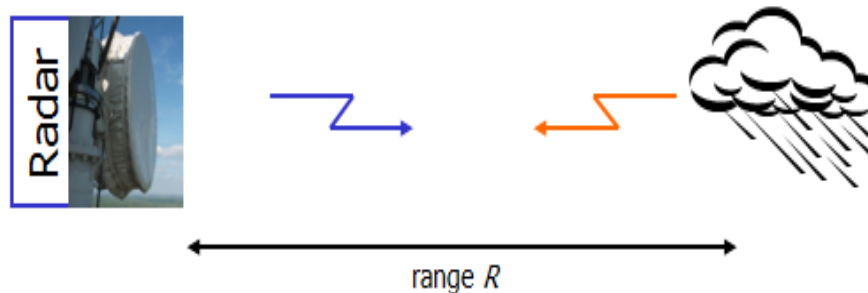
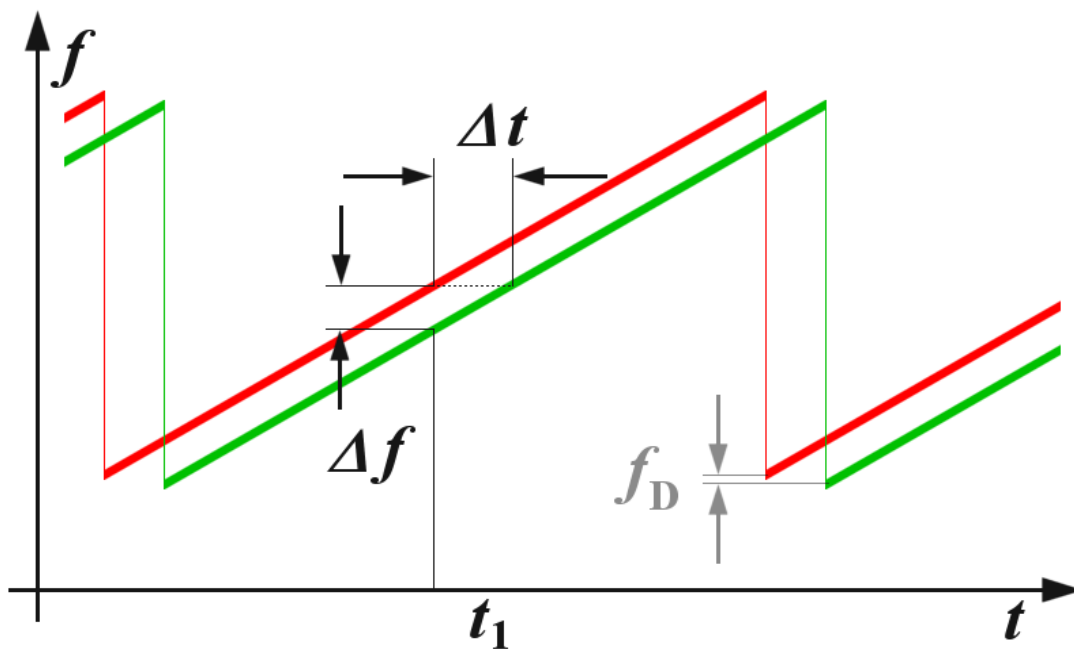
$$f_{bd} = f_b + f_D$$

so range and radial velocity can be obtained as

$$R = \frac{cT_s}{4B_{sweep}} (f_{bd} + f_{bu})$$

$$v_r = \frac{\lambda}{4} (f_{bd} - f_{bu})$$





When the expected Doppler frequency shift of the target has a negligible effect on the range extraction from the beat frequency, it can be estimated by comparing the phase of the echoes of successive sweeps, e.g. for meteorological applications.

the phase of the received signal is $\Phi_r = \Phi_t + 2R \frac{2\pi}{\lambda}$

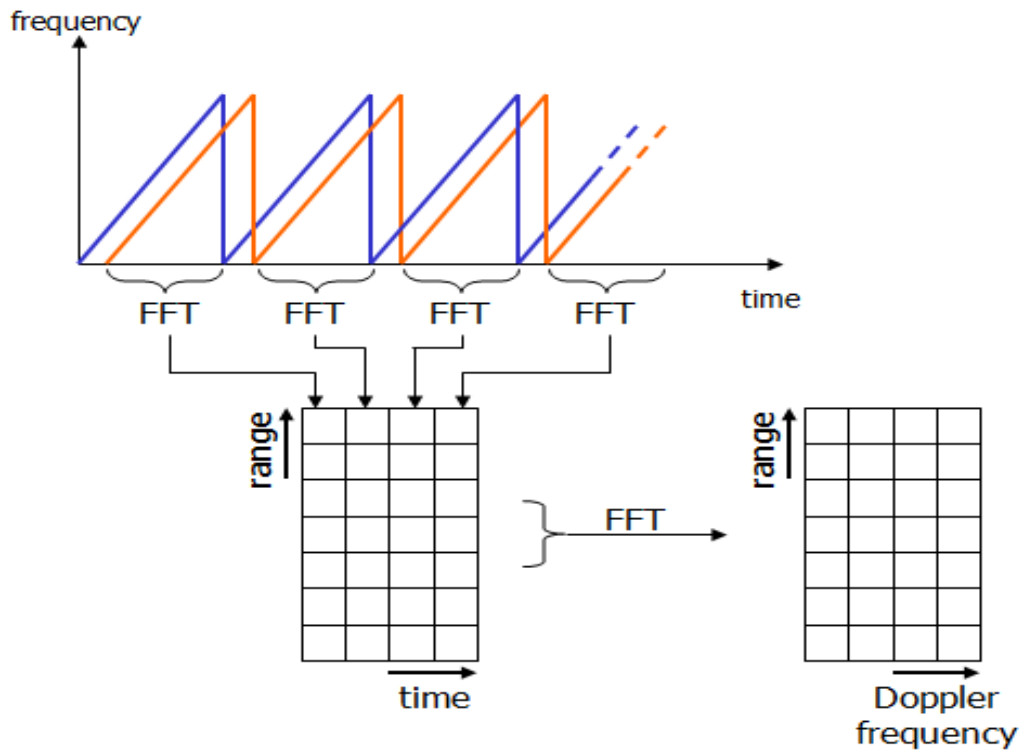
the change of the phase of the received signal with time is given by

$$\frac{d\Phi_r}{dt} = \frac{4\pi}{\lambda} \frac{dR}{dt} = \frac{4\pi}{\lambda} v_r$$

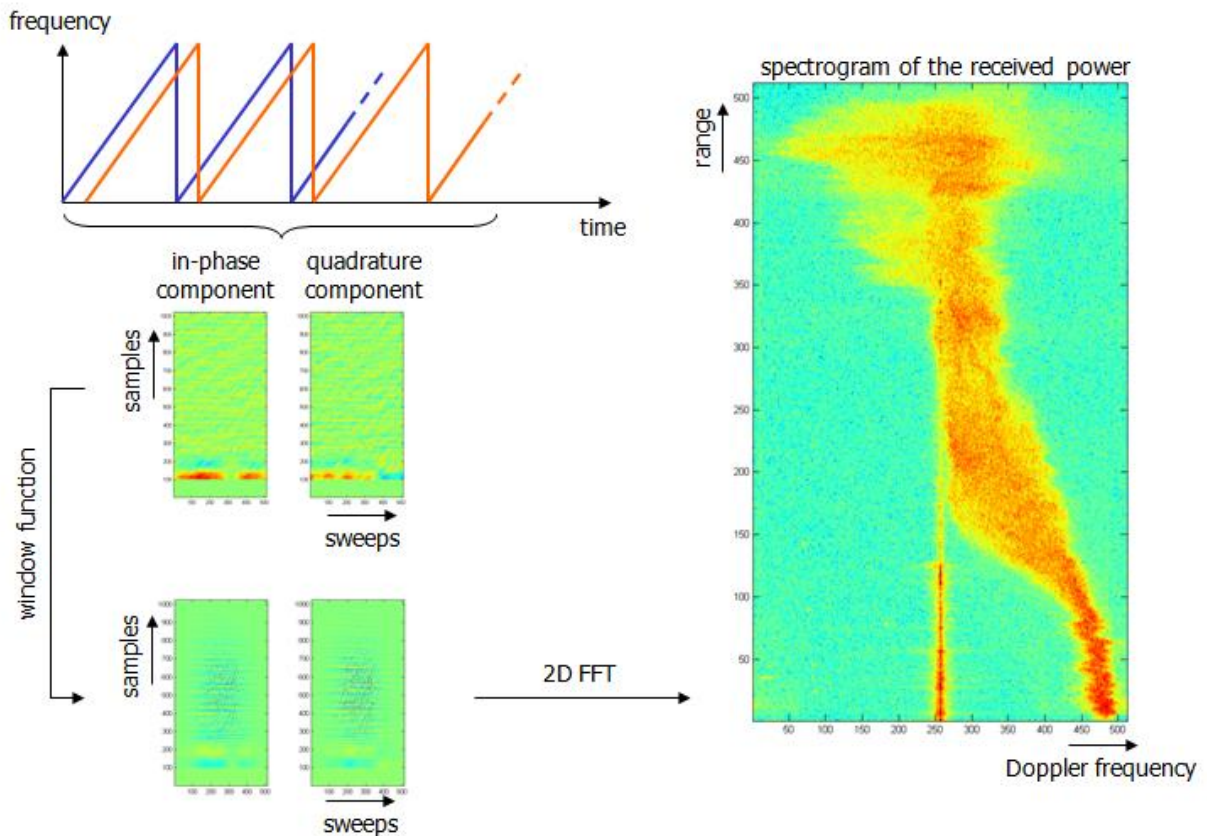
and the change of the phase of the received signal from sweep to sweep is given as

$$\frac{\Delta\Phi_r}{T_s} = \frac{4\pi}{\lambda} v_r \longrightarrow v_r = \frac{\Delta\Phi_r}{T_s} \cdot \frac{\lambda}{4\pi}$$

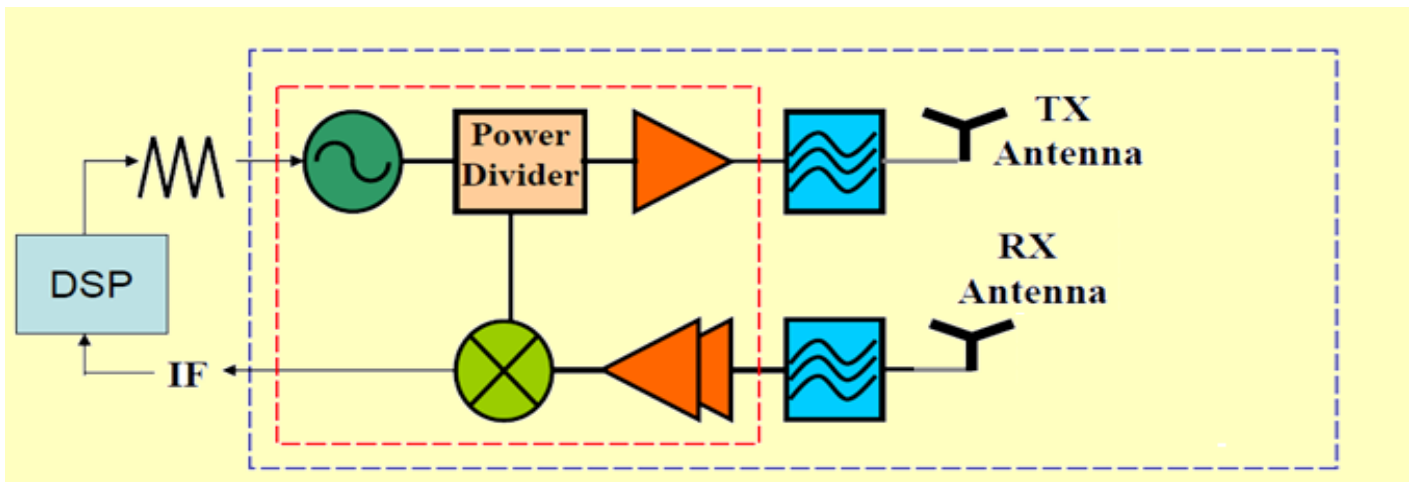
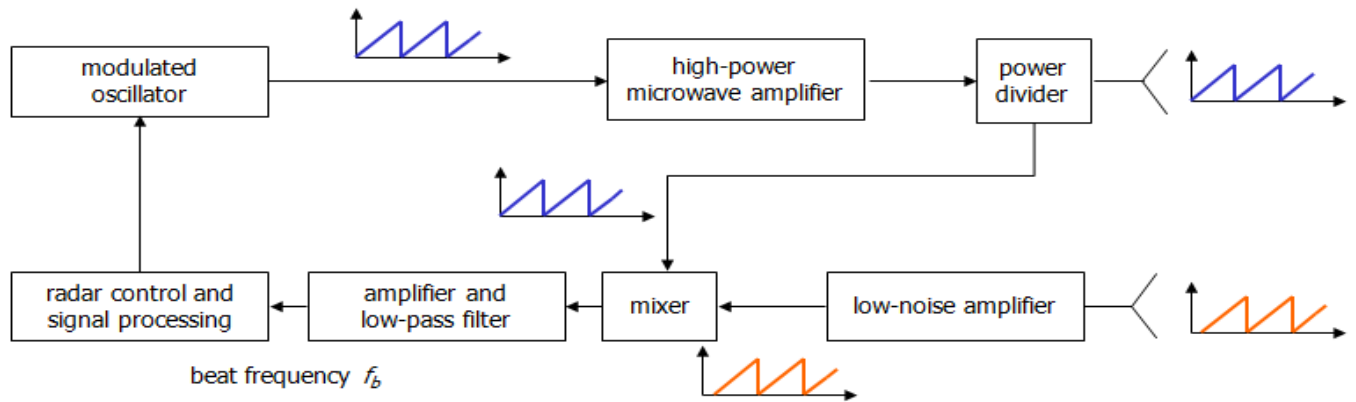
FMCW radar signal processing



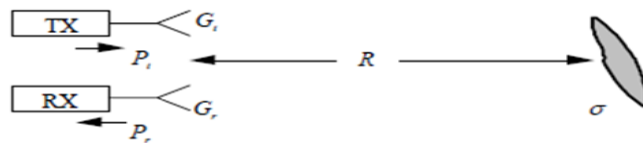
FFT .. fast Fourier transformation



Block diagram of an FMCW RADAR



RADAR Range Equation



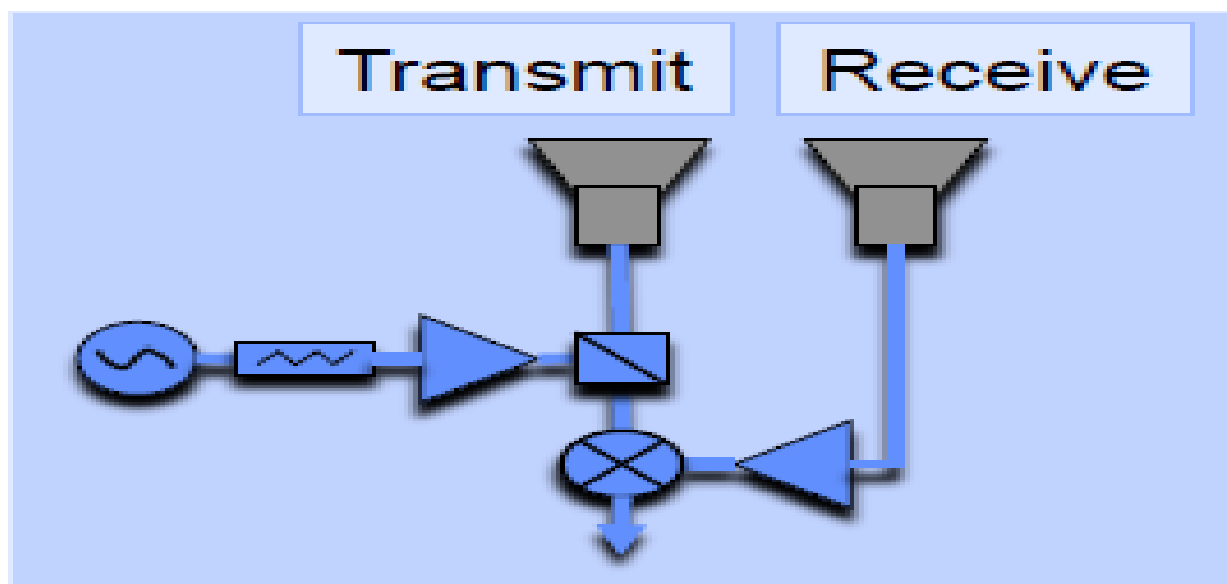
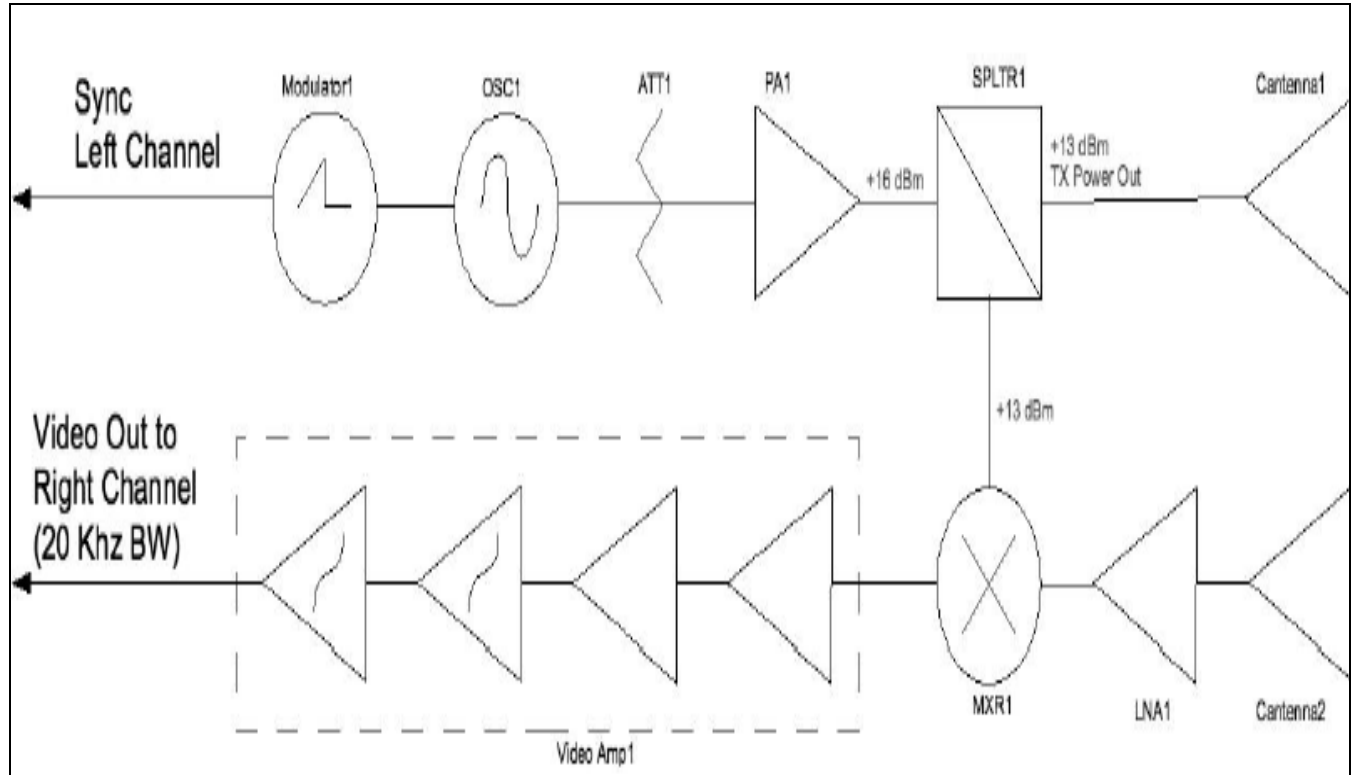
- P_t = transmit power (W)
- P_r = received power (W)
- G_t = transmit antenna gain
- G_r = receive antenna gain
- σ = radar cross section (RCS, m^2)
- A_{er} = effective aperture area of receive antenna

$$P_r = \frac{P_t G_t \sigma A_{er}}{(4\pi R^2)^2} = \frac{P_t G_t G_r \sigma \lambda^2}{(4\pi)^3 R^4}$$

Hardware Implementation Details of our RADAR

Block Diagram

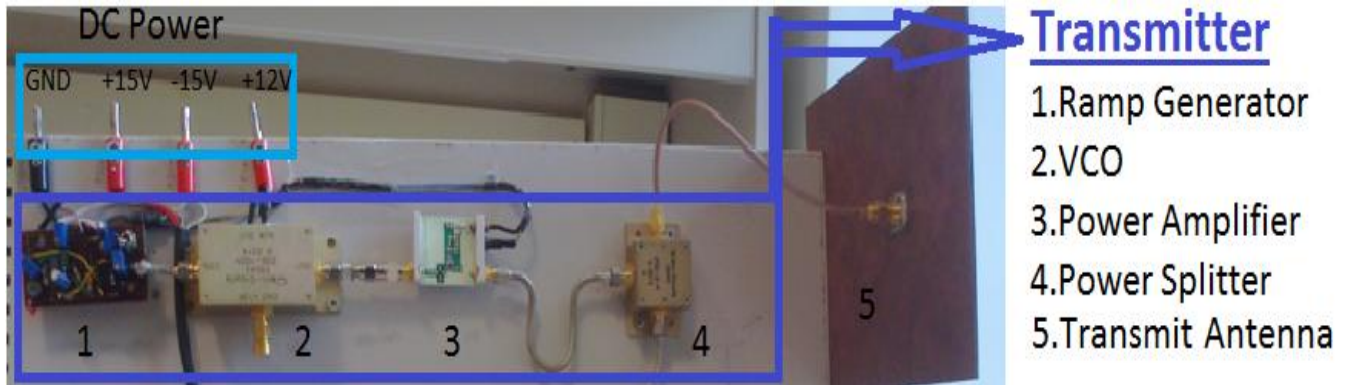
The Block diagram of our RADAR is shown below.



RADAR Transmitter

RADAR Transmitter is comprised of following subsystems.

- Ramp Generator
- Voltage Controlled Oscillator
- RF Power Amplifier
- Power Splitter
- Transmit Antenna



The description of each one is given below.

1. Ramp Generator

The main use of the ramp waveform is to sweep the VCO through the desired frequency range. The 555 timer is the best option that I got which is easily available and easy to implement.

For Ramp Generation the 555 timer is configured in Astable mode. The output frequency depends on the charging and discharging of the capacitor, resistors values and the power supply for the IC.

The charging time for the capacitor can be found as follows:

$$T_C = .693(R_a + R_b)C$$

For discharging time, the following equation can be used:

$$T_D = .693R_b C$$

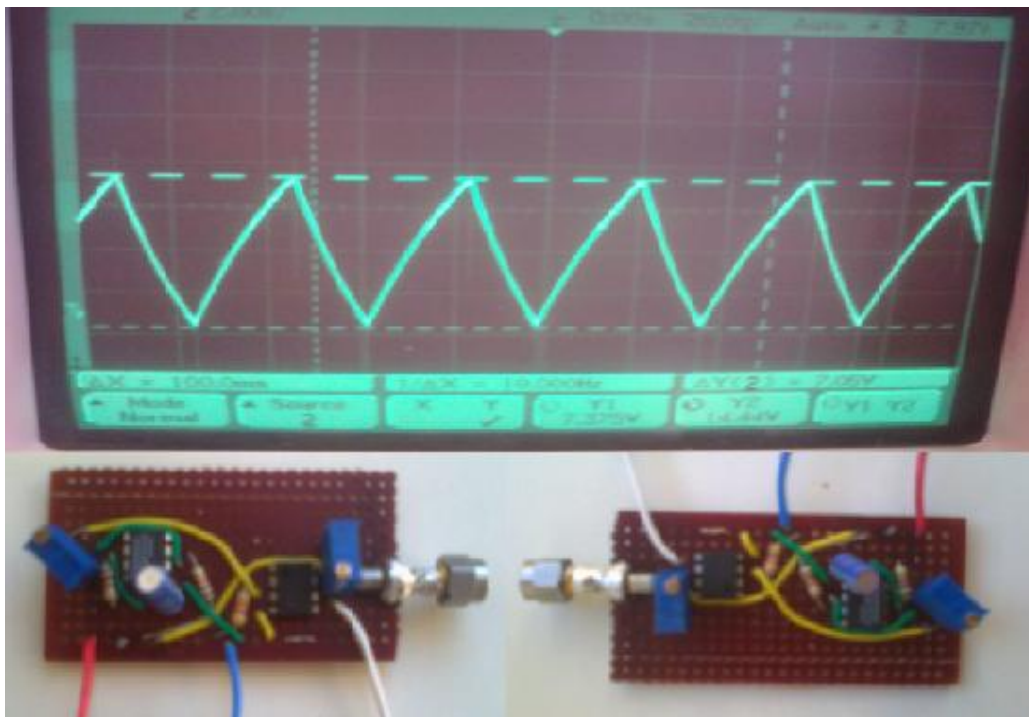
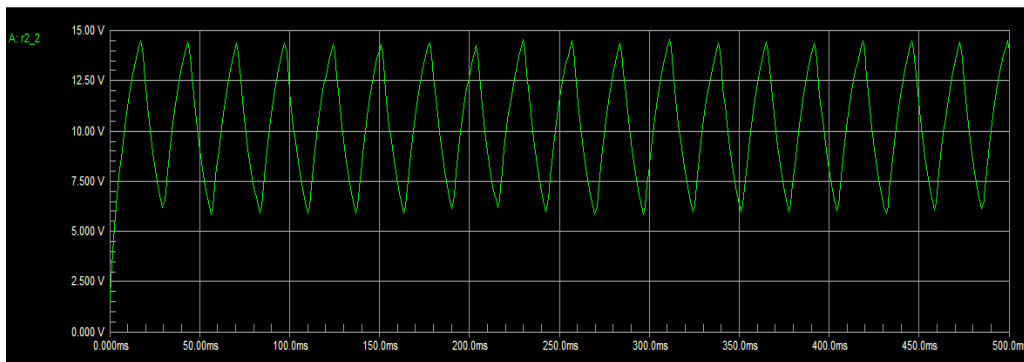
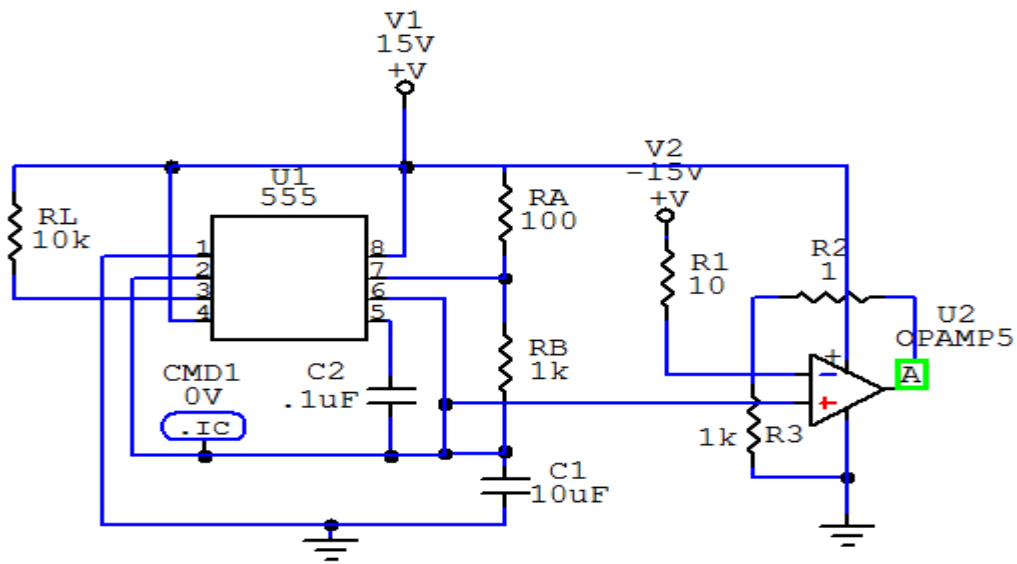
The output frequency can be calculated as follows:

$$f = \frac{1.44}{(R_a + 2R_b)C}$$

The 555 timer in Astable mode as used to generate Ramp Voltage. The generated Ramp has:

Frequency=25-80 Hz and Amplitude=8-13 Volts

The schematic and the simulation using Circuit Maker 2000 software are shown below.



2. Voltage control Oscillator (VCO)

It is the device that generates the RF signal which will interfere with the cell phone. The output of the VCO has a frequency which is proportional to the input voltage, thus, we can control the output frequency by changing the input voltage. When the input voltage is DC, the output is a specific frequency, while if the input is a saw tooth waveform, the output will span a specific frequency range.

By varying the parameters of the saw-tooth waveform, the changes in VCOs output is:

- When the DC offset in the saw-tooth waveform is changed, then the centre frequency of VCOs is shifted.
- When the peak amplitude of saw-tooth waveform is changed, then its output Bandwidth is changed.
- By varying the frequency of saw-tooth waveform, the VCOs sweep rate varies.

In our design ZOS-1025 from Mini Circuits was used.

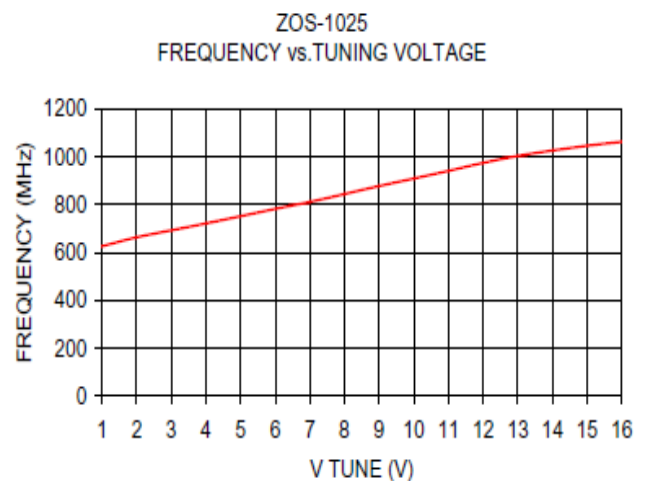
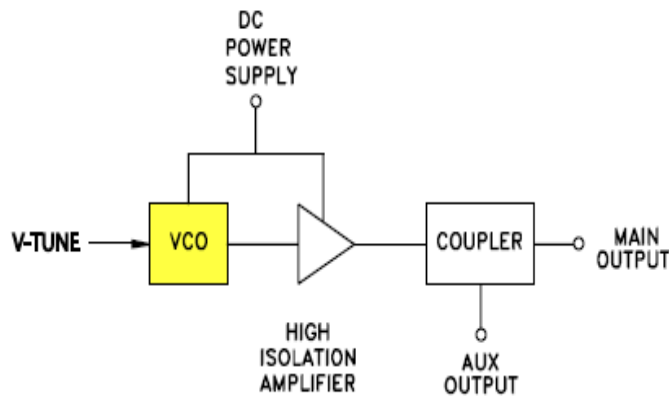
Features

- Wide bandwidth
- Linear tuning
- Excellent harmonic suppression, -25 dBc typ.
- Rugged shielded case



Electrical Specifications

FREQUENCY (MHz)		POWER OUTPUT (dBm) Typ.		TUNING VOLTAGE (V)		PHASE NOISE (dBc/Hz) SSB at offset frequencies: Typ.			PULLING (MHz) pk-pk (open/short)	PUSHING (MHz/V)	TUNING SENSITIVITY (MHz/V)	HARMONICS (dBc)		3 dB MODULATION BANDWIDTH (MHz)	DC OPERATING POWER	
Min.	Max.	Main	Aux.	Min.	Max.	10 kHz	100 kHz	1 MHz	Typ.	Typ.	Typ.	Typ.	Max.	Typ.	V _{cc} (volts)	Current (mA) Max.
685	1025	+8	-13	1	16	-92	-112	-136	0.051	1.00	30	-25	-18	0.1	12	140



3. RF Power Amplifier

Since the output power from the VCO does not achieve the desired output power level for RADAR, so we have to add a power amplifier with a suitable gain to increase the VCO output power up to the desired value.

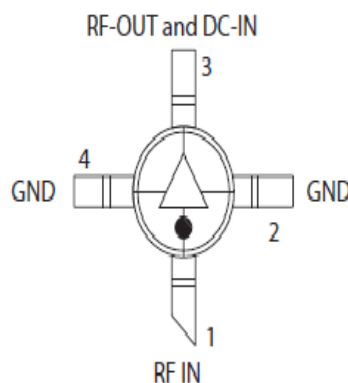
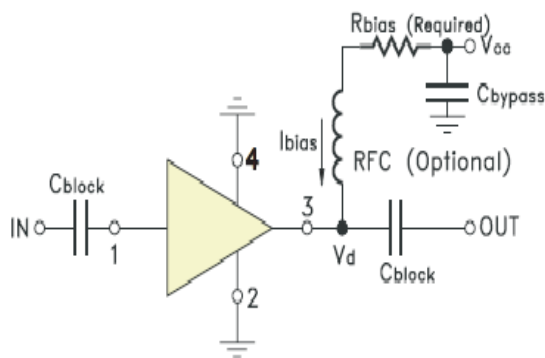
The selected Power Amplifier was ERA-4SM+. ERA-4SM+ is a wideband amplifier offering high dynamic range. ERA-4SM+ uses Darlington configuration and is fabricated using InGaP HBT technology.

Features

- DC-4 GHz
- Single Voltage Supply
- Internally Matched to 50 Ohms
- Low Performance Variation Over Temperature
- Transient Protected



Recommended Application Circuit



Electrical Specifications

Parameter	Condition (GHz)	Min.	Typ.	Max.	Units
Frequency Range*		DC		4	GHz
Gain	0.1	13.7	14.4	15	dB
	1.0		14.2		
	2.0	12.5	13.0	13.6	
	3.0		12.0		
	4.0	10.8	11.3	12.2	
Magnitude of Gain Variation versus Temperature (values are negative)	0.1		.003	.006	dB/°C
	1.0		.0025	.006	
	2.0		.0031	.006	
	3.0		.0042	.008	
	4.0		.0051	.01	
Input Return Loss	0.1		35		dB
	2.0		30		
	3.0		21		
	4.0		21		
Output Return Loss	0.1		35		dB
	2.0		21		
	3.0		21		
	4.0		16		
Reverse Isolation	2.0	18	23		dB
Output Power @ 1 dB compression	0.1		17.5		dBm
	1.0	15	17.3		
	2.0		16.1		
	3.0		14		
	4.0		11.7		
Saturated Output Power (at 3dB compression)	0.1		17.8		dBm
Output IP3	2.0		16.5		dBm
	0.1		32	36.1	
	1.0		31	35	
	2.0		27	30.4	
Noise Figure	0.1		4	5	dB
	1.0		4.2	5.2	
	2.0		4.2	5.2	
	4.0		4.5	5.5	
Group Delay	2.0		80		psec
Recommended Device Operating Current			65		mA
Device Operating Voltage		4.3	4.6	4.9	V
Device Voltage Variation vs. Temperature at 65mA			-2.9		mV/°C
Device Voltage Variation vs. Current at 25°C			10.4		mV/mA
Thermal Resistance, junction-to-case ⁽¹⁾			196		°C/W

*Guaranteed specification DC-4 GHz. Low frequency cut off determined by external coupling capacitors.

4. Power Splitter

As shown in block diagram, the power splitter splits the RF Power from RF amplifier output and feeds the Transmit antenna and Mixer LO port. The selected Power Splitter was ZFSC-2-4+ from Mini circuits with following Specifications:

Features

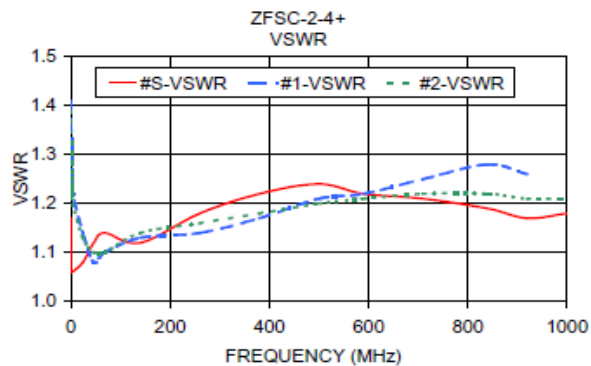
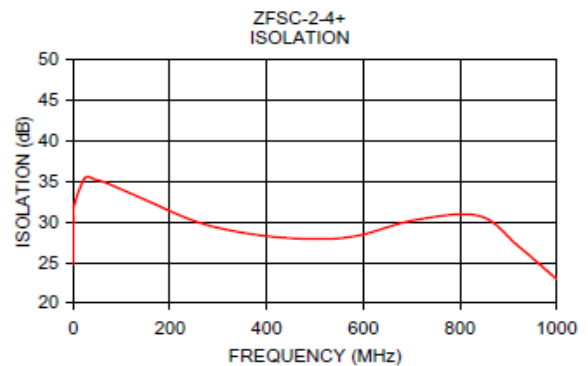
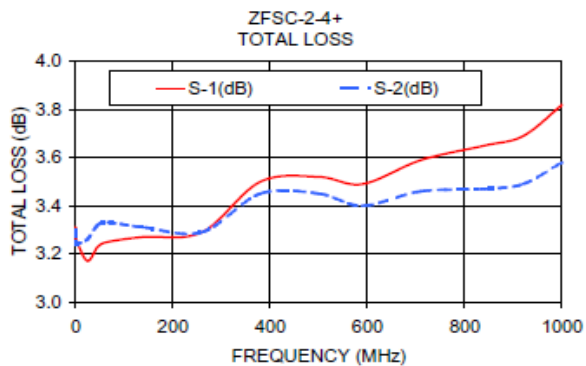
- wideband, 0.2 to 1000 MHz
- low insertion loss, 0.5 dB typ.
- good isolation, 25 dB typ.
- excellent amplitude unbalance, 0.1 dB typ.
- excellent phase unbalance, 0.5 deg. typ



Electrical Specifications

FREQ. RANGE (MHz)	ISOLATION (dB)						INSERTION LOSS (dB) ABOVE 3.0 dB						PHASE UNBALANCE (Degrees)			AMPLITUDE UNBALANCE (dB)		
	L		M		U		L		M		U		L	M	U	L	M	U
	Typ.	Min.	Typ.	Min.	Typ.	Min.	Typ.	Max.	Typ.	Max.	Typ.	Max.	Max.	Max.	Max.	Max.	Max.	Max.
0.2-1000	20	15	25	20	23	18	0.2	0.8	0.5	1.0	0.9	1.2	2	4	4	0.15	0.15	0.30

L = low range [f_L to $10 f_L$] M = mid range [$10 f_L$ to $f_U/2$] U = upper range [$f_U/2$ to f_U]

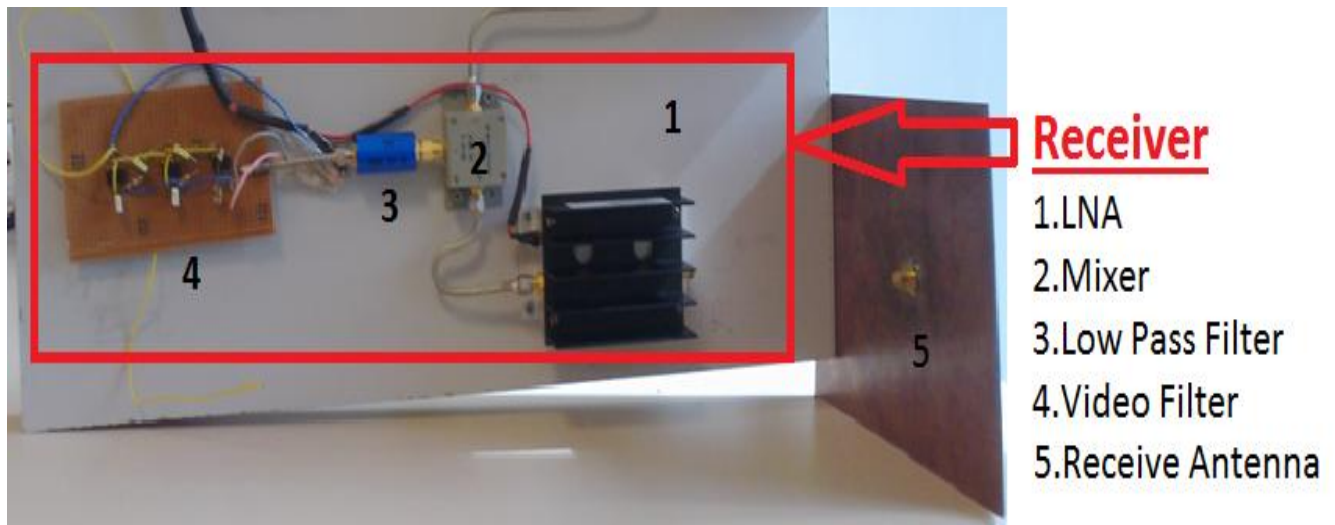


electrical schematic



RADAR Receiver

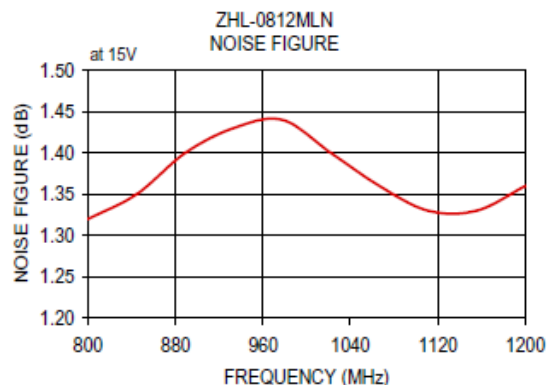
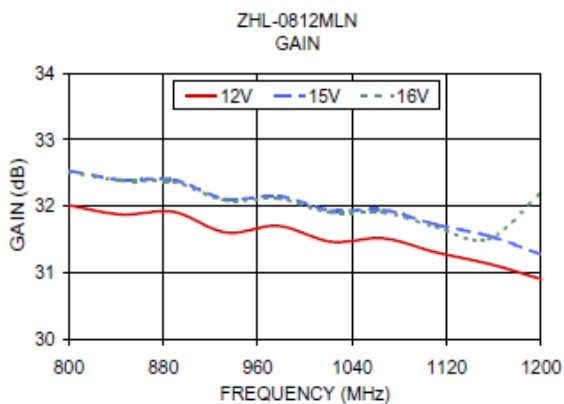
Receiving RF front-end of Doppler Radar consists of Antenna, LNA (Low Noise Amplifier), Mixer, Low pass Filter and Video Filter. The receiver structure is highlighted with 'red-box' in Fig. below.



Completed Doppler Radar Set. Red box shows the receiver structure.

1. Low Noise Amplifier (ZHL-0812MLN)

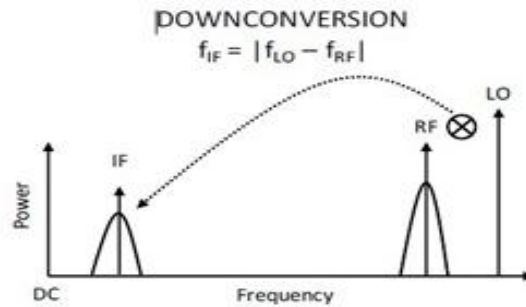
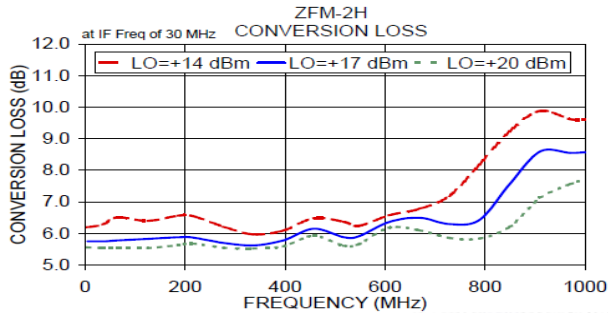
After receiving the low-level signal by the antenna, it has to be amplified to process the signal with the rest of circuit. LNA is fed with 15V and as seen from Fig.2, gain at 1GHz is found as 32dB with a low noise figure level which is 1.4dB and a good return loss.



Low Noise Amplifier specifications: Gain & Noise Figure Graphs.

2. MIXER (ZFH-2H+)

After signal amplification, in order to detect the doppler frequency, we need to downconvert the signal to level of Hz. Since received signal at the RF port of mixer is at 1000MHz + fdoppler for Doppler mode and at 800-1000MHz + fdoppler for FMCW mode, and LO port of mixer is at either 1000MHz or between 800-1000MHz after power splitter, with respect to mode of operation, a signal with fdoppler frequency in IF port will be obtained so that down-conversion is completed excluding other harmonics created by the mixer (see the topology in Fig.3b). The mixer has a conversion loss of 6.3-8.6dB between 800-1000MHz with below 25dB L-R & L-I isolation and LO power of 17dBm as reported below.



F Mixer conversion loss (+17dBm graph is taken into account)

3. FILTER (SLP-50+)

Completing down-conversion process and obtaining doppler frequency allows us to clear the undesired signals in spectrum through low pass filter. The filter used in the design has a half power beamwidth (3dB loss) frequency of 55MHz in passband (see Fig.4). Stopband is determined as 70-90MHz with more than 20dB loss and 90-200MHz with more than 40dB loss. Return Loss performance is also good and VSWR is found as 1.7.



CASE STYLE: FF99

Insertion loss of Filter.

4. Video Amplifier

In our radar system, we need to use a video amplifier to be able to amplify and filter our IF signal. Video amplifier would be designed with above 30dB voltage gain and as band pass filter. An active 5-stage low-pass filter is designed and measured. In figure 1, first order passive high-pass filter is given. Transfer function is given in equation 1.

$$H(s) = \frac{V_o}{V_{in}} = \frac{sRC}{sRC + 1} \quad Eq(1)$$

$$s = j\omega + \sigma.$$

For pure sinusoidal signals $\sigma = 0$, therefore, $s = j\omega$. Cut-off frequency is $f_c = \frac{1}{2\pi RC}$ and it will cut the signals in frequencies below 1.5 kHz with 100nF capacitor and 100k resistor. We need to build active band pass filter, so we will add a gain stage. This step can be seen at figure 2.

For building an active high pass filter, an OP-AMP is used and as an OP-AMP, UA741 component is used for the design.

$$G = 1 + \frac{R_3}{R_2} \quad Eq(2)$$

The gain of this high pass filter can be found from equation 2 that is 46.4545 and in dB, 33.34dB voltage gain.

After this step, a low pass filter is needed for realizing band pass filter. The topology of the low pass filter can be seen at figure 3.

The topology shown in figure 3 is a second order low-pass filter. The transfer function of this topology can be seen in equation 5. Q factor and cut-off frequency calculations are given equation 3 and equation 4 in order.

$$Q = \frac{\sqrt{R_4 R_5 C_2 C_4}}{C_2 (R_4 + R_5)} \quad Eq(3)$$

$$f_c = \frac{1}{2\pi \sqrt{R_4 R_5 C_2 C_4}} \quad Eq(4)$$

From these equations, $Q = 0.635$ and $f_c = 15.847.5$ kHz.

$$H(s) = \frac{V_o}{V_{in}} = \frac{1}{1 + C_2 (R_4 + R_5) s + C_2 C_4 R_4 R_5 s^2} \quad Eq(5)$$

This step is doubled in our design to increase the order of the filter and obtain sharper filter.

Our last video amplifier can be seen at figure 4 and specifications can be seen in table 1.

	Lowest	Nominal	Highest
Filter Order		5	
Frequency	1.5kHz		15kHz
Gain			33dB

table 1: Specifications

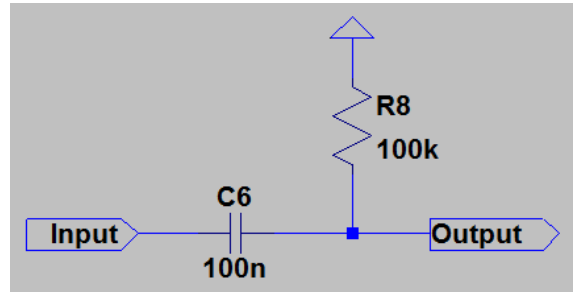


Figure 1: First Order Passive High-Pass Filter

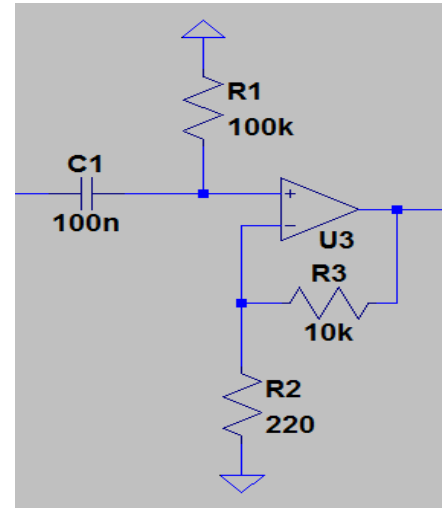


Figure 2: First Order Active High-Pass Filter

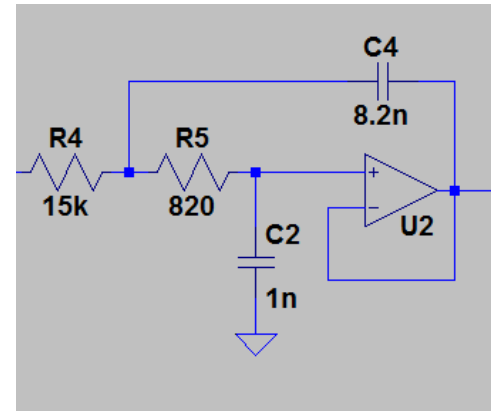


Figure 3: Unity-Gain Sallen-Key Low-Pass Filter

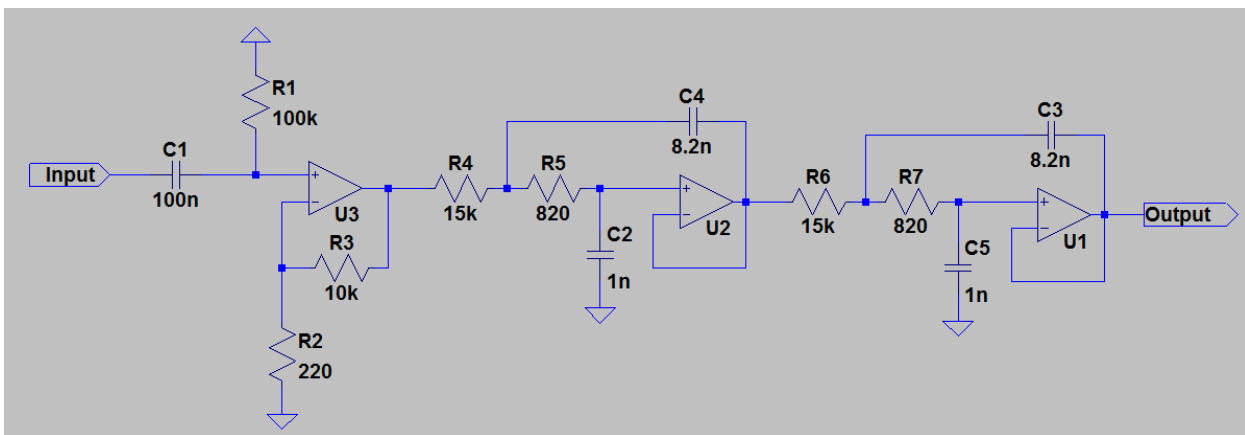
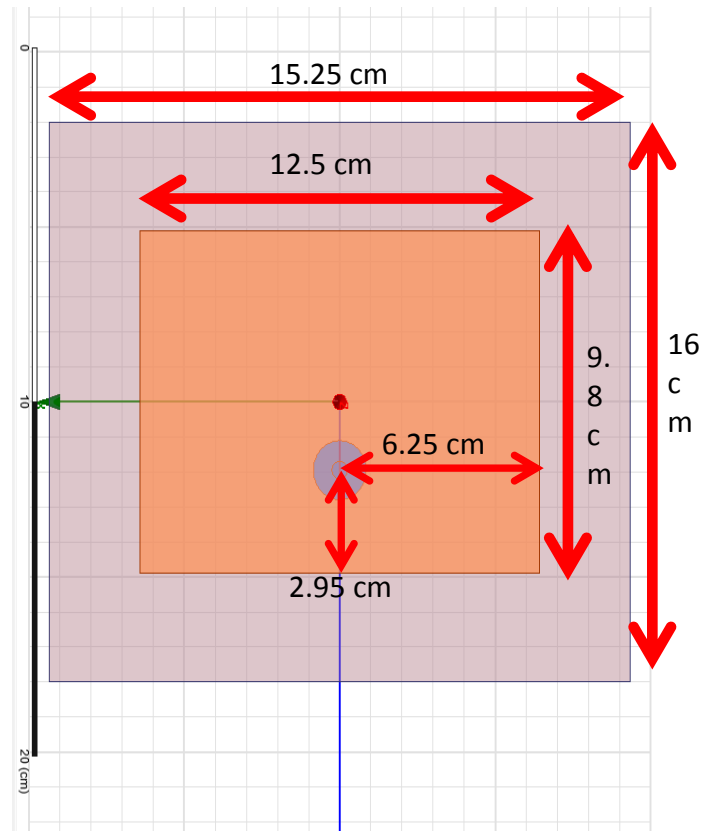


Figure 4: Video Amplifier-

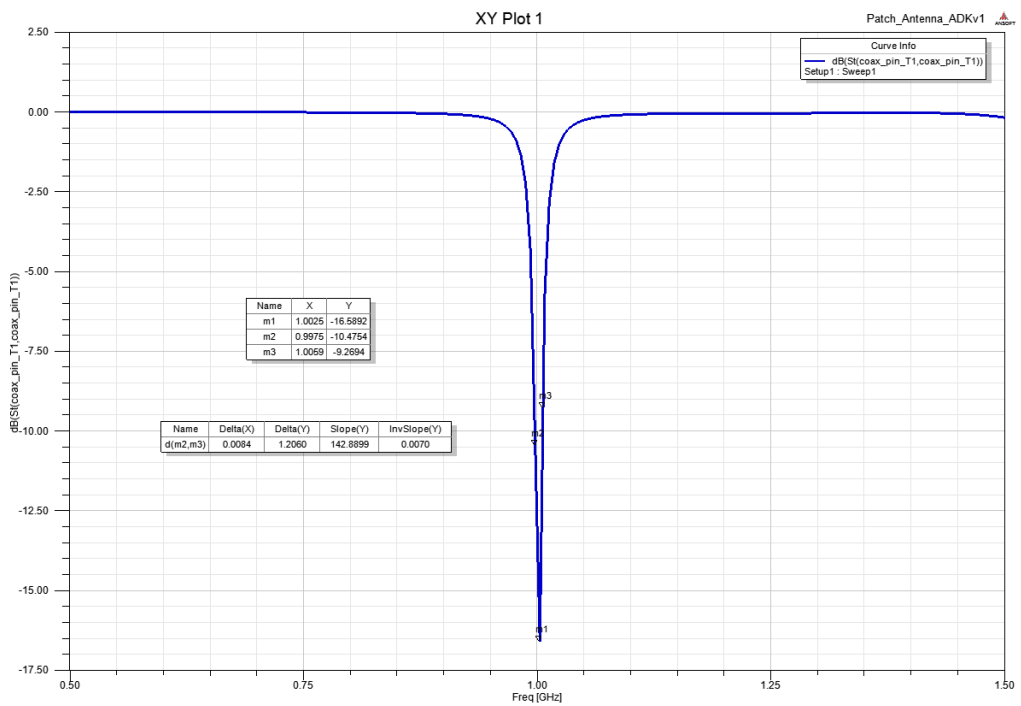
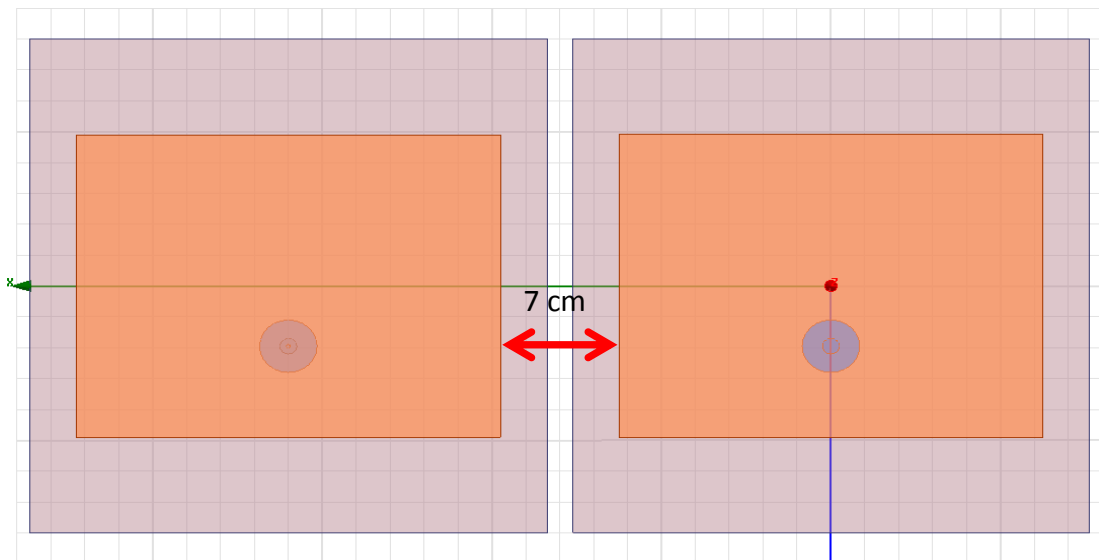
5. Transmit and Receive Antenna:

For transceiver part of the radar two same patch antenna designed. Dimensions, return loss, mutual coupling between antennas and realized gain of the designed antennas are shown in the figures.

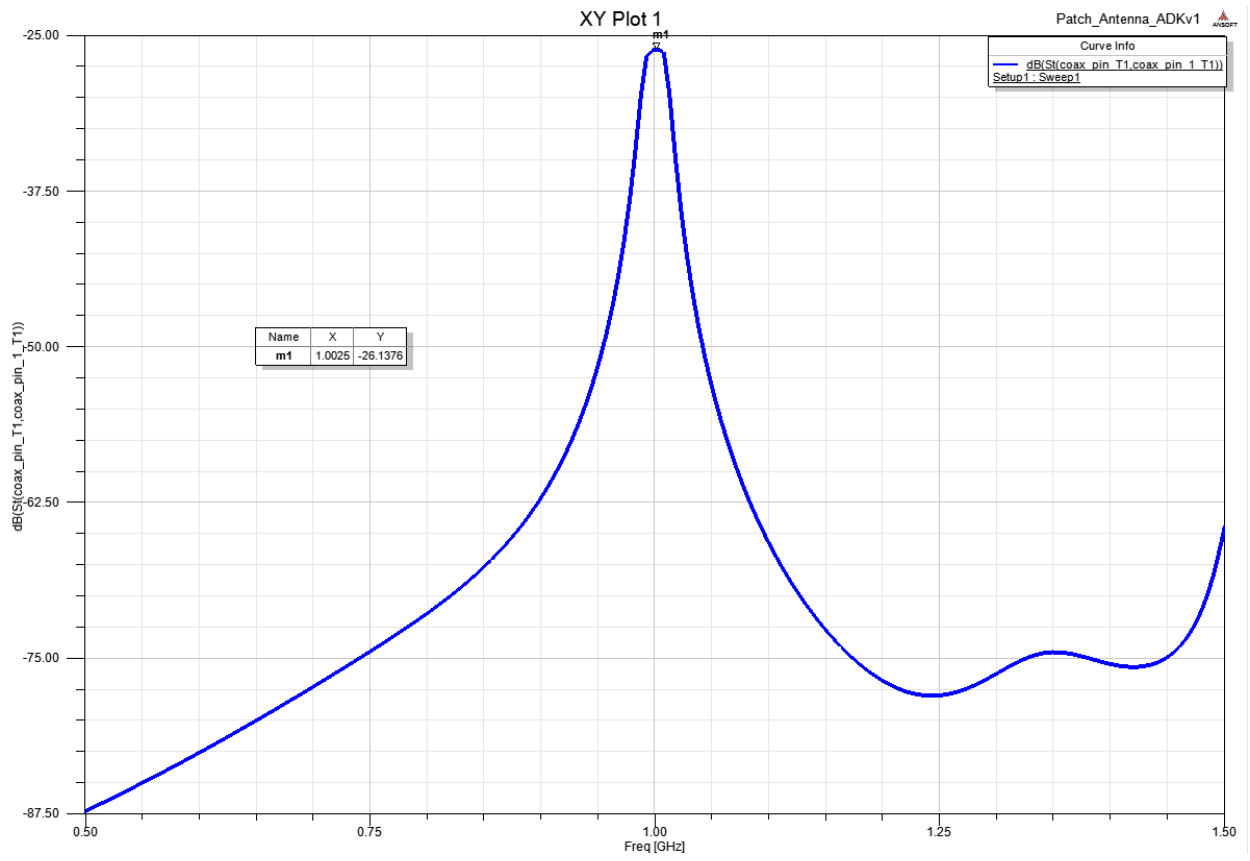
The antennas are manufactured on Rogers 5880 PCB board with thickness of 62 mil (1.57 mm) and $\epsilon_{ps} = 2.2$.



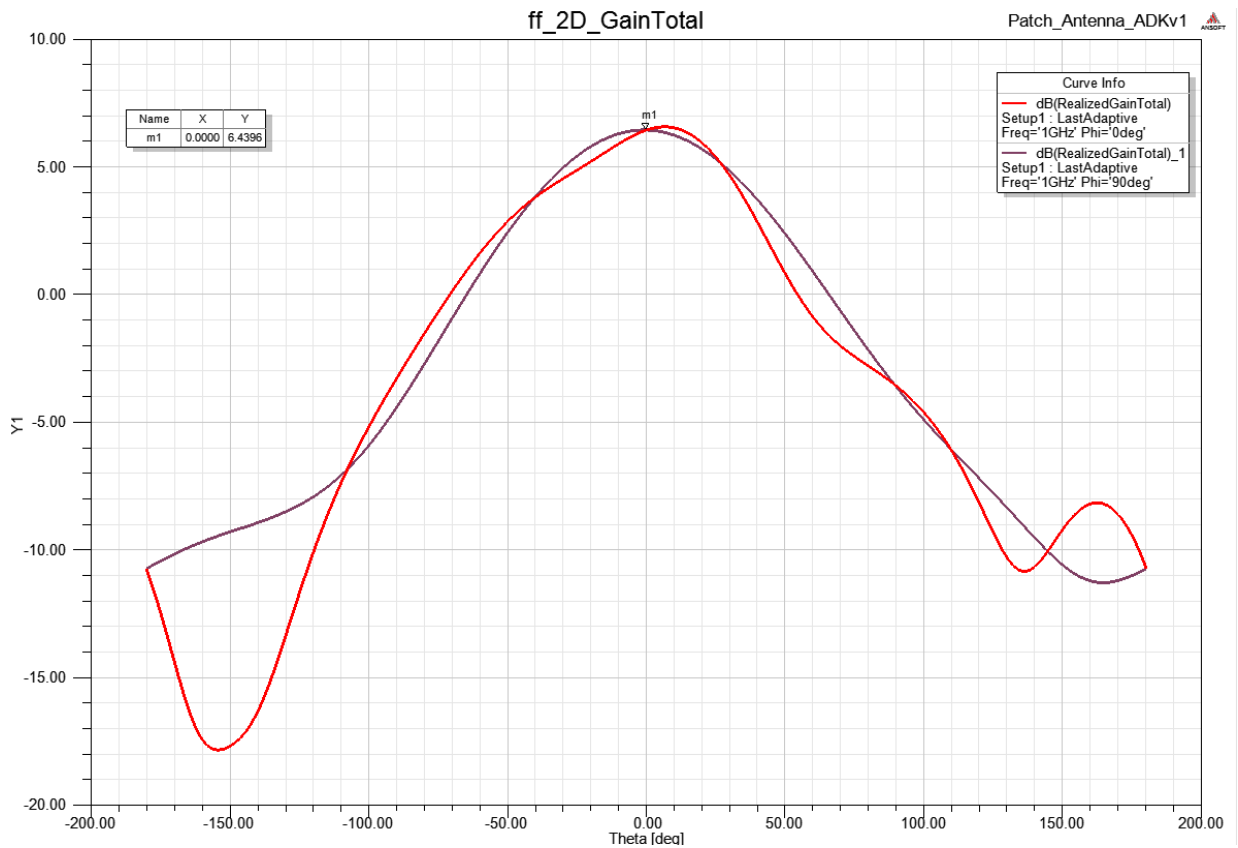
Patch antenna dimensions



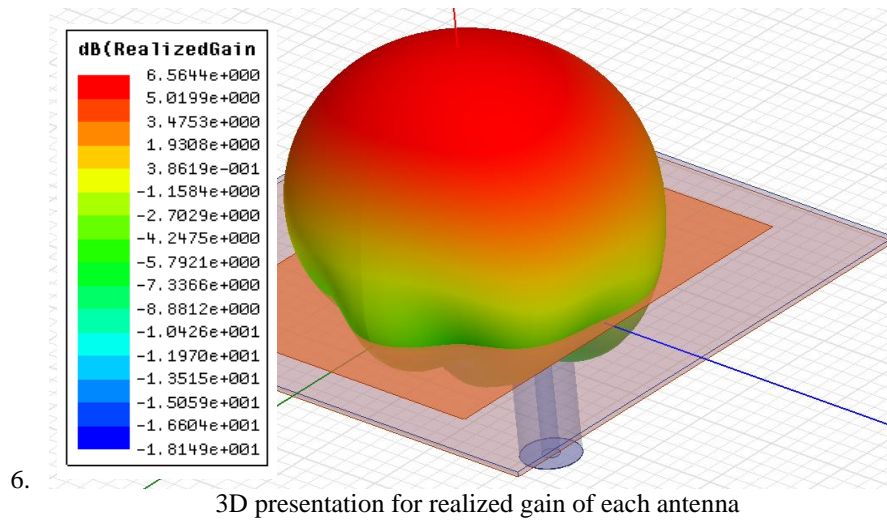
Return loss for each elements of the designed antenna



Mutual coupling (S21) between transceiver antennas with 7cm spacing



Realized gain for E and H-plane of each antenna

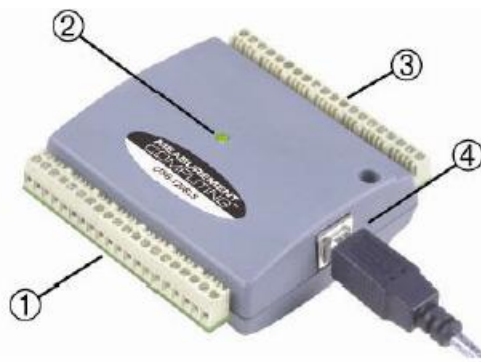


Designed patch antennas optimized for 1GHz are used for both transmitting and receiving modes as shown in Fig1.



7. Data Acquisition Card

To connect radar output to PC, we use measurement computing data acquisition device, USB-1208LS. USB-1208LS is 8 channels analog input. Based on the operating mode, continuous mode or burst mode, input signal can be sampled up to 8000Hz. Hence, according to the Nyquist criteria, we can detect IF signal up to 4000Hz. Below is the picture of USB-1208LS.



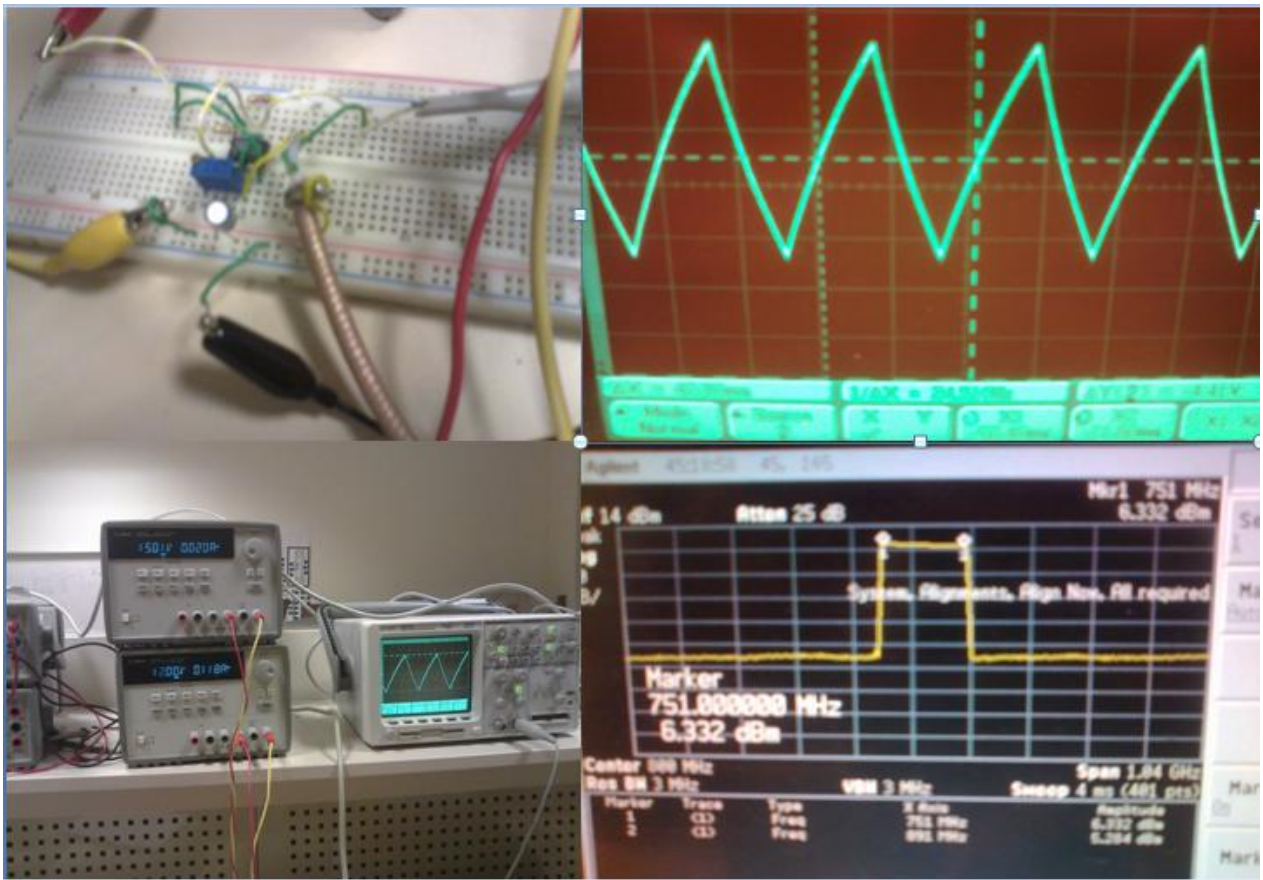
- | | | | |
|---|------------------------------|---|-----------------------------|
| 1 | Screw terminal pins 21 to 40 | 3 | Screw terminal pins 1 to 20 |
| 2 | LED | 4 | USB connector |

USB-1208LS external components

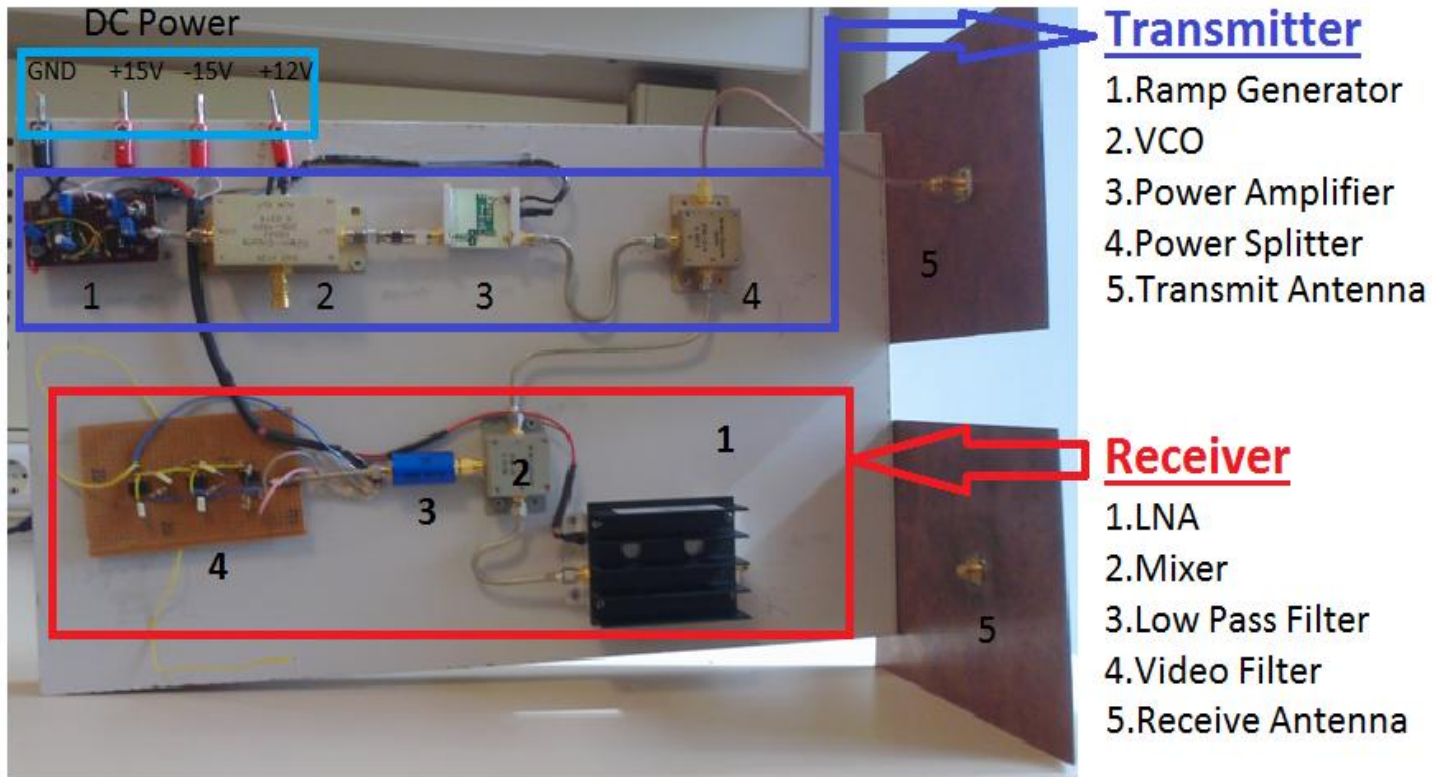
Test and Measurements

Testing and Measurement of Implemented Design was performed to evaluate its Performance. Each section was tested separately and after functionality testing of each section/ module, they were integrated to realize the hardware Implementation of complete module. Finally the complete system was tested to evaluate its Performance. For testing and measurements purposes during development stages and testing of Integrated System, following equipment was extensively used:

- Digital Storage Oscilloscope (DSO)
- Function Signal Generator
- Signal Generator
- Spectrum analyzer
- Dual Mode DC Power Supply



SMA Connectors were used for RF connections and SMA cables for RF Transmitter and Receiver connection with respective antennas and bananas Connector had been used for DC Power connections (+15 volts,-15 volts and +12 Volts).



DC Power Budget

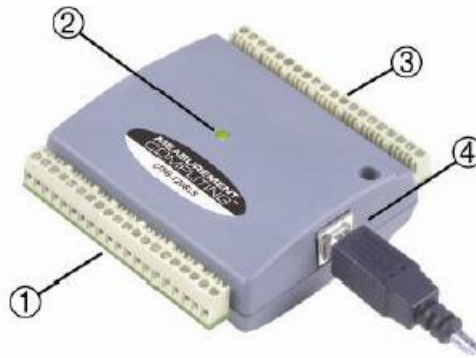
Module Name	Description	DC Voltage(volts)	DC Current(Amps)	DC Power(mW)	DC Power(mW)
Ramp Generator	555 as Ramp Generator	15	30	450	0,45
VCO	ZOS-1025	12	140	1680	1,68
Power Amplifier	ERA-4SM+	12	45	540	0,54
LNA	ZHL-0812MLN	15	300	4500	4,5
Audio Power Amplifier	741 Opamp	12	30	360	0,36
Total DC Power Requirements				7530	7,53

MATLAB Signal Processing:

In this part, we will go through signal processing detail of our radar system. Signal processing will give us velocity and range information. To connect radar output to PC, we use measurement computing data acquisition device, USB-1208LS.

USB-1208LS is 8 channels analog input. Based on the operating mode, continuous mode or burst mode,

input signal can be sampled up to 8000Hz. Hence, according to the Nyquist criteria, we can detect IF signal up to 4000Hz. Below is the picture of USB-1208LS.



- | | | | |
|---|------------------------------|---|-----------------------------|
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USB-1208LS external components

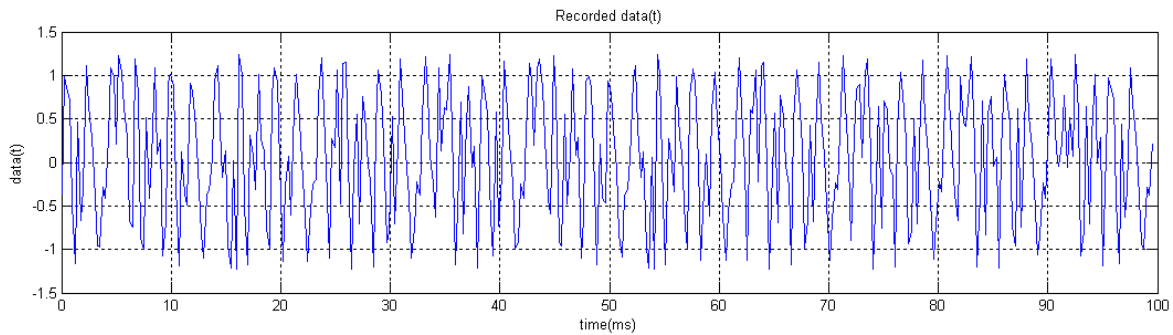
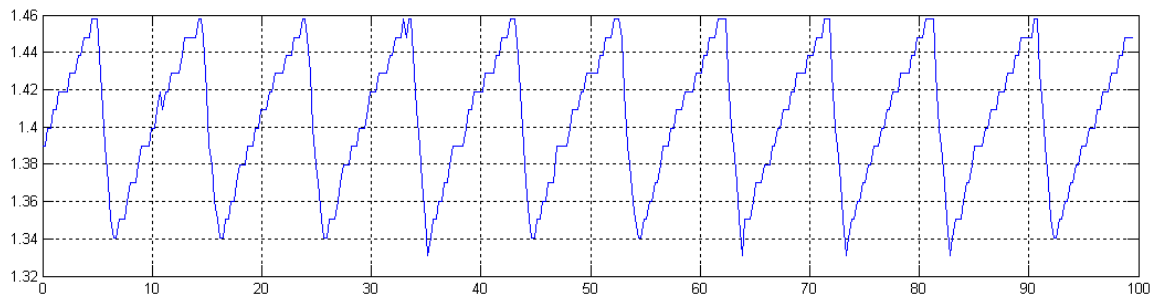
For detailed information you can go through datasheet.

MATLAB data acquisition Tool is used to record data from DAQ. In order to check whether your MATLAB have data acquisition Tool, you can type "ver" at work command.

To communicate with DAQ, this MATLAB code can be applied.

```
AI=analoginput('mcc',0)
addchannel(AI,0)      % add channel #num 0
Fs=8000;             % Sampling frequency
set(AI,'samplerate',Fs)
Duration=0.04;
set(AI,'samplespertrigger',Fs*Duration)
start(AI)
[data,time]=getdata(AI);
figure(1)
subplot(2,2,1)
plot(time,data)
title('Recorded data(t)')
xlabel('time(s)')
ylabel('data(t)')
grid
```

This code will get data from DAQ and plot acquired data. For example, you can see our ramp and IF signal sampled by DAQ.



Now, we have the signal of course distorted by noise. Transmitted message is frequency modulated:

$$s_t = \cos(2\pi f_c t + \int_0^t f_m d\tau)$$

and Received is transmitted, with delay and doppler shift:

$$t_d = 2BWR(t)/(cT) \quad f_d = 2vf_c/c$$

Transmitted signal is mixed with received signal and IF signal will contain both velocity and range information. To get frequency component of IF signal and hence get range and velocity information we need to get FFT from our signal. Below is the MATLAB code for FFT.

```
%Fourier transforms is to find the frequency components of a signal buried
%in a noisy time domain signal.
T = 1/Fs;           % Sample time
L = 1+(Duration/T); % Length of signal
t = (0:L-1)*T;     % Time vector
% Discrete FT is a periodic function since we sample signal so we will try
% to draw it in one period
NFFT = 2^nextpow2(L); % Next power of 2 from length of y
Y = fft(data,NFFT)/L;
f = Fs/2*linspace(0,1,NFFT/2+1);
```

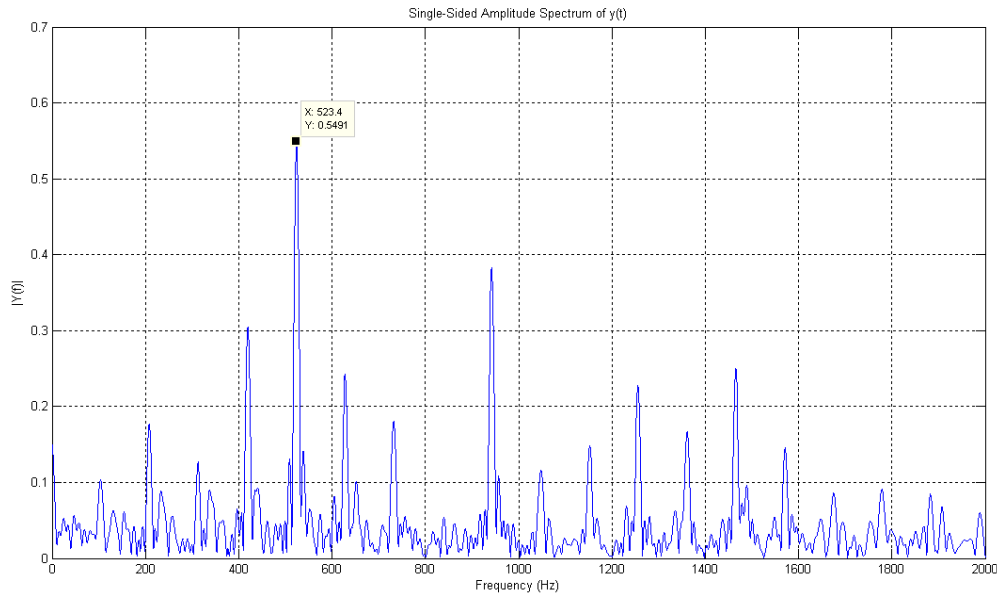
```
% Plot single-sided amplitude spectrum.
subplot(2,2,2)
plot(f,2*abs(Y(1:NFFT/2+1)))
title('Single-Sided Amplitude Spectrum of data(t)')
xlabel('Frequency (Hz)')
ylabel('|DATA(f)|')
grid
% get distance information
Tmod=50e-3;
c=3*1e8;
BW=200*1e6;
d=f*Tmod*c/(2*BW);
subplot(2,2,3)
plot(d,2*abs(Y(1:NFFT/2+1)))
```

```

title('Valid for Stationary object')
xlabel('Distance(m)')
ylabel('|DATA(f)|')
grid
% Get velocity information(valid based on doppler operation mode)
f0=1e9;
v=f*c/(2*f0);
subplot(2,2,4)
plot(v,2*abs(Y(1:NFFT/2+1)))
title('Valid in Doppler Mode')
xlabel('Velocity(m/s)')
ylabel('|DATA(f)|')
grid

```

One sample output of this code is like below.



Sample response

As you may noticed, our signal have component at some fixed frequency harmonics. Conducting the test for different scenrio confirm the previous observation. So, it seems that we have problem with one our components. This component have nonlinearity which result in response like this. Testing different component reveals that the problem arises from nonlinear effect of our mixer. Before solving this problem we can not get any reliable measurement.