This appendix describes the design, development and testing of 2.4GHz (ISM band) Doppler or Continuous Wave RADAR, which is used to measure the speed of the target. The basic idea is taken from the MIT Coffee Can Radar and the system is designed using various RF components like VCO, LNA, Splitter, Mixer and antennas. Instead of using Coffee Can as antenna, microstrip patch antennas operating at 2.4GHz are employed here. A personal computer is used for estimating the doppler frequency shift. Real time measurements are taken on the public road inside the university campus and the results are discussed.

A.1. Introduction

The radar is a target detection system that uses RF signals to determine the range, altitude, direction and speed of the target. It can be used to detect the targets like aircraft, ships, spacecraft, guided missiles, motor
vehicles, weather formations, terrain, etc. The radar antenna transmits pulses of radio waves or continuous microwaves and detects the reflected energy from any object in its path. Reflected signal can be picked up by the same antenna or separate receiver antenna which can be placed near to transmitting antenna or at a different location (bistatic). Pulsed Radar was the first technology developed during World War II, following which different types of radar technologies have been developed for different applications. Some of the common radar technologies are

1. Pulsed Radar [1]
2. Continuous Wave Radar [2]
3. Frequency Modulated Continuous wave Radar [3]

High tech radar systems with digital signal processing are capable of extracting target information containing high noise levels. The modern Radar technology has many applications like [7] the following

**A.1.1. Civilian Applications**

- Airport surveillance
- Marine Navigation
- Weather RADAR (Storm avoidance, wind shear warning, weather mapping)
- Altimetry (Aircraft or spacecraft)
A.1.2. Military Applications

- Air and Marine navigation
- Detection and tracking of Aircraft, Missiles, Spacecraft, etc.
- Missile Guidance
- Fire control for missile and artillery
- Weapon fuses (Guided weapon systems require a proximity fuse to trigger the explosive Warhead)
- Ground Penetrating Radar

A.1.3. Scientific Applications

- Astronomy
- Mapping and Imaging
- Precision distance measurement
- Remote sensing of natural resources

Different applications in the radar use different frequency spectrums which depend on the range resolution and size of the target. Presence of water and other atmospheric conditions causes considerable attenuation to some frequencies. Different frequency bands used in the radar technology and their applications are listed in Table. 1.
### Table 1: Radar Bands, Frequencies, Wavelengths and their Applications

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency</th>
<th>Wavelength</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF</td>
<td>3 to 30 MHz</td>
<td>10 m to 100 m</td>
<td>Coastal radar systems, over-the-horizon (OTH) radars; 'high frequency'</td>
</tr>
<tr>
<td>P</td>
<td>30 to 300 MHz</td>
<td>1 m to 10 m</td>
<td>'P' for 'previous', applied retrospectively to early radar systems</td>
</tr>
<tr>
<td>UHF</td>
<td>300 to 1000 MHz</td>
<td>0.3 m to 1 m</td>
<td>Very long range (e.g. ballistic missile early warning), ground penetrating, foliage penetrating; 'ultrahigh frequency'</td>
</tr>
<tr>
<td>L</td>
<td>1 to 2 GHz</td>
<td>15 cm to 30 cm</td>
<td>Long-range air traffic control and surveillance; 'L' for 'long'</td>
</tr>
<tr>
<td>S</td>
<td>2 to 4 GHz</td>
<td>7.5 cm to 15 cm</td>
<td>Terminal air traffic control, long-range weather, marine radar; 'S' for 'short'</td>
</tr>
<tr>
<td>C</td>
<td>4 to 8 GHz</td>
<td>3.75 cm to 7.5 cm</td>
<td>Satellite transponders; a compromise (hence 'C') between X and S bands; weather radar</td>
</tr>
<tr>
<td>X</td>
<td>8 to 12 GHz</td>
<td>2.5 cm to 3.75 cm</td>
<td>Missile guidance, marine radar, weather, medium-resolution mapping and ground surveillance; in the USA the narrow range 10.525 GHz ± 25 MHz is used for airport radar. Named X band because the frequency was kept secret during World War 2.</td>
</tr>
<tr>
<td>Ku</td>
<td>12 to 18 GHz</td>
<td>1.67 cm to 2.5 cm</td>
<td>High-resolution mapping, satellite altimetry; frequency just under K band (hence 'u')</td>
</tr>
<tr>
<td>K</td>
<td>18 to 27 GHz</td>
<td>1.11 cm to 1.67 cm</td>
<td>K band is used by meteorologists for detecting clouds and by police for detecting speeding motorists. K band radar guns operate at 24.150 ± 0.100 GHz. Automotive radar uses 24.26 GHz.</td>
</tr>
<tr>
<td>Ka</td>
<td>27 to 40 GHz</td>
<td>0.75 cm to 1.11 cm</td>
<td>Mapping, short range, airport surveillance; frequency just above K band (hence 'a'); photo radar, used to trigger cameras that take pictures of license plates of cars running red lights, operates at 34.300 ± 0.100 GHz</td>
</tr>
<tr>
<td>mm</td>
<td>40 to 300 GHz</td>
<td>1 mm to 7.5 mm</td>
<td>Millimeter band, subdivided as below. The letter designators appear to be random, and the frequency ranges dependent on waveguide size. Multiple letters are assigned to these bands by different groups.</td>
</tr>
<tr>
<td>Q</td>
<td>40 to 60 GHz</td>
<td>5 mm to 7.5 mm</td>
<td>Used for military communications</td>
</tr>
<tr>
<td>V</td>
<td>50 to 75 GHz</td>
<td>4 mm to 6 mm</td>
<td>Very strongly absorbed by the atmosphere</td>
</tr>
<tr>
<td>W</td>
<td>75 to 110 GHz</td>
<td>2.7 mm to 4 mm</td>
<td>76 GHz LRR and 79 GHz SRR automotive radar, high-resolution meteorological observation and imaging</td>
</tr>
</tbody>
</table>
A.2. RADAR Range Equation

The radar range equation expresses the factors affecting the radar performance, which gives radar characteristics in terms of received power. Radar technologies are used to find the target properties like range, speed, direction, etc. Signal strength at the receiver section in the radar is usually of the order of nano watts compared to the transmitted power of several Watts. The reflected power in the radar system depends on many factors like free space path losses, radar cross section of the target ($\sigma_{\text{target}}$), fading and other environmental parameters. The general radar system is described in Fig.A.1, which transmits a pulse of energy through the transmit antenna of gain $G_t$. Depending on the wavelength ($\lambda$) of the transmitted signal and distance between the transmitter and receiver ($R$), the amplitude of the signal is reduced due to the free space propagation loss. At the target a part of this power is reflected back towards the radar. The ratio of the backscattered power to the incident power is the Radar Cross Section (RCS) ($\sigma_{\text{target}}$) of the target. The signal is then received by the receiver antenna with gain $G_r$ and detected by the receiver. The power level $P_r$ is the power received in the radar receiver [1]-[3].

$$P_r = \frac{P_t G_t G_r \sigma_{\text{target}} \lambda^2}{(4\pi)^3 R^4} \quad \text{(A.1)}$$

where $P_t$ is the transmitted power from the radar transmitter. Block diagram with power at each section in the radar system is described in Fig.A.2.
A.3. Radar Cross Section (RCS)

RCS or echo area ($\sigma$ or $\sigma_{\text{target}}$) of a target is defined as the area intercepting that amount of power, which when scattered isotopically, produces at the receiver a density equal to that scattered by the actual target [8]. In equation form
\[ \lim_{R \to \alpha} \left[ \frac{\sigma W_i}{4\pi R^2} \right] = W_s \]  \hspace{1cm} (A.2)

or

\[ \sigma = \lim_{R \to \alpha} \left[ 4\pi R^2 \frac{W_s}{W_i} \right] \]  \hspace{1cm} (A.3)

where

\[ W_i = \text{incident power density (W/m}^2\text{)} \]
\[ W_s = \text{scattered power density (W/m}^2\text{)} \]

**A.4. Range**

The distance between the target and radar can be calculated by finding total round trip time taken by the RF signal to travel between the radar and the target. In the case of Pulsed Radar, consider a pulse of energy being sent at a given instant in time. It travels towards the target at a speed of light (‘c’ meters/sec). After hitting the target it gets reflected back at the same speed. After \( T_R \) seconds, radar receiver receives the reflected signal, then the distance or range \( R \) (in meter) to the target is given by

\[ R = \frac{cT_R}{2} \]  \hspace{1cm} (A.4)

In the case of FMCW radar, the transmitter sends a band of frequency which is controlled by a sweep generator. Therefore receiver section also receives the same frequency band after a short time delay of \( \Delta t \) (as shown in Fig.A.3), which represents the range between radar and target. Therefore distance \( R \) for continuous type radar can be calculated as

\[ R = \frac{c\Delta f}{4\times\Delta f \times f_m} \]  \hspace{1cm} (A.5)
where \( \Delta f \) is the instantaneous difference in frequency (Hz) of the transmitter at the times the signal is transmitted and received, \( \Delta F \) is the RF modulation bandwidth (Hz) and \( f_m \) is the RF modulation rate.

![FMCW radar waveform pattern](image)

Figure A.3 FMCW radar waveform pattern

A.5. Doppler Frequency

The doppler frequency is used to calculate the relative speed and direction of the target. The radar transmitter generates an RF pulse or continuous frequency \( f_0 \) and radiated by the antenna. Receiver antenna will pick up the reflected signal from the target. If the target is moving with a relative velocity \( V_r \) with respect to the radar, the received signal frequency will be shifted from the transmitted signal frequency \( f_0 \) by an amount \( \pm f_d \). The plus sign indicates target is moving towards the radar and the minus sign indicates the target is moving away from the radar. The shifted frequency \( f_d \) is called doppler frequency and it can be calculated as

\[
f_d = \frac{2V_r}{\lambda} = \frac{2V_r f_0}{c} \quad (A.6)
\]
where $\lambda$ is the wavelength of the transmitting frequency. Fig.A.4 shows the relation between doppler frequency shift and target speed. A radar system with measurement capability of 15 kHz can detect a target speed of 60m/s (216km/hr).

![Figure A.4 Relation between Doppler Frequency and target speed.](image)

**A.6. Doppler or Continuous Wave (CW) Radar**

Doppler or CW Radar is used to measure the relative speed of the target or vehicle based on the Doppler frequency shift and it cannot determine the distance or range of the target. The CW radar system may consist of single or two separate antennas for the transmission or reception of RF signal. In single antenna system duplexer is needed to isolate the reflected signal from the high power transmitted signal. Radar continuously transmits a single frequency with constant amplitude. The reflected signal has either exactly the same frequency for stationary target, or shifted by the amount of doppler frequency ($f_d$) due to the relative movement of the target. Fig.A.5
shows the transmitted and received frequency spectrum of doppler radar with different target conditions. From Fig.A.5 it is very easy to understand the doppler frequency variation for the target when it’s stationary, approaching and receding.

![Figure A.5 Transmitted and received signal frequency of CW Radar](image)

The CW radar devices are dedicated for processing doppler frequency shift in the reflected signal. Radar using two separate antennas is proposed in this chapter and block diagram of the radar is shown in Fig.A.6. A 2.4GHz signal generated by the RF source is amplified by the LNA, which is connected at the output of the attenuator. The attenuator is used to protect the LNA from the high input signal. A power splitter section is used in the transmitter section to couple a portion of transmitting energy to the receiver section through one output port and the other port is connected to the transmitter antenna. Transmitted signal ‘$E_t$’ from the radar can be expressed as

$$E_t = E_0 \cos \omega_0 t$$ (A.7)

where $E_0$ and $\omega_0$ are the amplitude and the angular frequency of the transmitted signal. Depending on the speed of the moving target, frequency and phase of the reflected signal will vary and it can be expressed as
\[ E_r = K_1 E_0 \cos[(\omega_0 \pm \omega_d) t + \phi] \]  
(A.8)

where,

- \( K_1 \) = constant calculated from the radar equation representing the reduction in power of the reflected signal
- \( \omega_d \) = doppler angular frequency shift
- \( \phi \) = a constant phase shift, which depends upon the range of initial detection (i.e., the distance between the radar and the target)

The receiver antenna picks up this weak reflected signal and it is fed to the LNA for amplification. The output of the LNA is connected to the mixer unit. Transmitted and received signals are combined at the mixer and it generates an IF (Intermediate Frequency) signal which consists of the sum and difference of the input signals. Therefore, the low IF signal at the output of the mixer is fed into the Video amplifier section. Video Amplifier section consists of an amplifier and active LPF filter with cutoff frequency of 15kHz. A video amplifier section amplifies and removes all the high frequency components at mixer output. The output of the video amplifier section is connected to the computer for further processing. A 16 bit ADC (Analog to Digital Converter) inside the mic jack of the computer with a sampling rate of 44.1kHz is used for digitizing the analog signal. Another purpose of the computer is to extract the doppler frequency and to estimate the speed of the target.
Most of the components inside the circuits have been explained in the earlier chapter. New additional components in the circuits such as 2.4GHz microstrip rectangular patch antenna and video amplifier are detailed in the following sections.

**A.6.1. 2.4 GHz Microstrip Patch Antenna**

Radar system requires two antennas working at 2.4GHz ISM band. The characteristics required for the antennas are, good isolation between transmitter and receiver antenna, directive radiation pattern, and good impedance match. A rectangular microstrip patch antenna with coaxial feed [8] is designed and fabricated in an FR4 substrate with dielectric constant 4.3, loss tangent 0.02 and substrate height 1.6mm. Fig.A.7 shows the rectangular microstrip patch antenna geometry with detailed dimensions. The antenna is simulated with the Ansys HFSS software and its simulated reflection...
coefficient is shown in Fig. A.8. The antenna shows very good impedance match for the desired 2.4GHz frequency. Isolation between the two antennas can be improved by placing them about 40-50cm apart. As shown in the 3D radiation pattern (Fig. A.9), maximum radiated power is towards the broadside direction of the antenna.

\[
\begin{align*}
\varepsilon_r &= 4.3, \\
tan\delta &= 0.02, \\
L &= 3.84, \\
W &= 2.98, \\
h &= 0.16 \text{ (all dimensions are in cm)}
\end{align*}
\]

**Figure A.7** Geometry of the rectangular patch antenna with coaxial feeding, where \( \varepsilon_r = 4.3, \) \( \tan\delta = 0.02, \) \( L = 3.84, \) \( W = 2.98 \) and \( h = 0.16 \) (all dimensions are in cm)

**Figure A.8** Simulated frequency response of the patch antenna
A.6.2. Video Amplifier Section

A large reflector in front of the antenna can generate a voltage of 50mV at the mixer output and this is insufficient for the ADC inside the computer. Thus an amplifier section is required to boost the backscattered signal. The signal from the mixer (IF) comprises of many frequency components, hence an antialiasing filter is also required before doing analog to digital conversion. Therefore video amplifier section proposed in the MIT Coffee Can Radar, comprises of three opamps, an amplifier and an LPF designed using LM 324 IC [10]. The first stage of the amplifier has a gain of about 50 and it can be varied using a 10K potentiometer in the feedback path. The second and the third stages are low pass filters (based on Sallen-Key architecture) [11] with cutoff frequency of the filter at 15 kHz. Circuit diagram designed is for video amplifier using ORCAD Capture software and its circuit model is shown in Fig.A.10.
The low frequency circuits consist of video amplifier section, power supply section and sweep generator (using XR 2209 IC) designed on a printer circuit board using Eagle PCB design software. PCB layout and fabricated circuit with electronic components are shown in Fig.A.11. The power regulator section shown in Fig.A.11 (b) is designed using 5V regulating IC (7805) for powering all the RF components and XR 2209 signal generator section. The sweep generator circuit is designed for the development of chipless RFID reader and FMCW radar. The circuit board is powered by 12V DC and it is used for powering video amplifier section and also used as in input voltage for 7805 regulating IC.
A.7. Result and Measurement

All the components and circuits are interconnected as per the block diagram given in Fig.A.6. A voltage controlled oscillator (ZX95-2536C+) from mini-circuit is used as the single frequency RF source with an output frequency of 2.4GHz by setting 1.8V at the V-tune pin. Fig.A.12 shows the full system assembly consists of two microstrip patch antennas, RF components, PCB circuit, battery pack and laptop computer. Field test of the Doppler radar was carried out along the University campus road and photograph taken during the measurement is shown in the Fig.A.13. During the measurement, reflected signal is stored as ‘wav’ file and latter processed in Matlab software.
Figure A.12 2.4GHz ISM band CW radar based on MIT Coffee Can Radar

Figure A.13 Filed measurement of CW radar in public road
Appendix

Measured doppler signal using CW radar is depicted in Fig.A.14 and the speed of vehicles calculated are plotted in Fig.A.15. Total measurement is taken for a time of 25 seconds and during that time four vehicles were passed through the road. The speed of each vehicle can be understood from the measured data. It is 29 km/hr (8m/s) for first 3 vehicles and about 36km/hr (10m/s) for last one. The strength of the doppler signal is dependent on the size of the target and it is clear from the Fig.A.14. It is also noted that when the target is leaving the radiation zone of the radar antenna, doppler frequency is reduced drastically and hence corresponding variation in speed occurs. Fig.A.15 shows the measured vehicle speed at different instants and confirms that almost all of the vehicles passing through the University campus are travelling below 40Km/hr speed.

![Figure A.14 Measured doppler signal](image)
Figure A.15 Measured speed of the vehicles using Doppler Radar

Figure A.16 Measured speed of the vehicles using Doppler Radar
A.8. Conclusion

This Appendix briefly describes different radars, applications, radar characteristics like radar range equation, range calculation, doppler, etc. The design and development of a Doppler Radar working at 2.4GHz ISM band is described. Two microstrip patch antennas are designed and fabricated for the transmission and reception of the radar signal. The real time measurements are taken along the University campus road and its calculated speeds are presented.

A.9. Future Works

The PCB and RF circuit designed for the proposed radar can be extended for the development of FMCW (Frequency Modulated Continuous Wave) Radar and SAR (Synthetic Aperture Radar). The FMCW radar can be used for the estimation of both speed and range of the target. Instead of using a constant frequency in the doppler radar, a band of frequencies is used in FMCW radar for the estimation of target range and speed. Wide band frequency can be produced by the combination of VCO and sweep generator circuit (XR2209 IC). The FMCW radar setup can be extended to SAR with an additional moving platform.

A.10. Reference


............(END)............