

Evaluation of a Frequency Modulated Continuous Wave Doppler Radar for Proximity Sensing

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ABSTRACT

This paper presents the implementations and evaluation of a low cost 2.45 GHz Frequency Modulated Continuous Wave (FMCW) Doppler radar system for proximity sensing applications. The radar platform supports Doppler Time Intensity (DTI), Range Time Intensity (RTI) and the Synthetic Aperture Radar (SAR) imaging modes. MATLAB is used for the post processing including data acquisitions, signal processing and visualizations. The radar is intended to be used partially for the moving-object detection system that is currently still under development for our homegrown automated driver assistant system (ADAS). The approach is superior compared to other sensing technique such as infrared and ultrasonic which easily interfered by environment factors such as dust and acoustic distractions. Experimental results show that the proposed radar system can reliably detect motion with object speed between 0.15m/s (0.5 km/h) and 8.82 m/s (30 km/h). The system can estimate distance accurately and generate two-dimensional SAR images for object presence of less than 10 meter. The study demonstrates the potential of a compact FMCW radar system as practical and economical alternatives to conventional high-cost radar platforms for educational and experimental applications.

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1. INTRODUCTION

Previously, radar was synonymous with military and avionics applications for detections of distance moving objects far away and beyond human capability. However today, radar can be found even in daily applications such as for determining object presence, motion speed and approximating object distances in modern automotive system. In such an application, it is used mainly as part of safety and early warning systems. Radar is used because it is more reliable compared to other sensing approach such as infrared and ultrasonic. Traditional proximity sensors like infrared and ultrasonic are cheap and easy to use but require good lighting. They are susceptible to surroundings conditions such as the presence of dust, smoke and acoustic interference. One of its most typical drawbacks is its limitations to only sense a binary presence without direct velocity information. Radar-based sensing on the other hands provides a powerful, non-contact

means which is relatively immune to these environmental factors and is also able to provide direct velocity measurement of the target due to the Doppler effect [1] – [4].

Frequency Modulated Continuous Wave (FMCW) Doppler radar is especially attractive for short-range proximity sensing because it has the ability to simultaneously obtain range and velocity information from a low-power transmission [5]. FMCW systems eliminate the need for high power devices which is ideal for low cost and compact implementations.

Although Doppler radar theory has been mature for a considerable time, little has been discussed on the performance of a full, robust and inexpensive radar design. In this paper, a simple and cheap Doppler radar system for proximity sensing is explained and aim for measuring speed and approximate distance.

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In this work, a 2.45 GHz FMCW Doppler radar is designed and characterized, consisting of a transmitter and a receiver system supported with MATLAB based signal processing platform. An experimental testing has been performed to investigate its capability of distinguishing between moving and stationary targets and to estimate the range of the targets in practical outdoor environments under realistic conditions.

2. THE FMCW DOPPLER RADAR CONCEPT

Doppler radar exploits the Doppler effect, whereby the frequency of a wave reflected from a moving target is shifted in proportion to the target's relative radial velocity [6]-[11]. For a monostatic radar operating at wavelength λ , the Doppler frequency shift f_D produced by a target moving at radial velocity v is given by

$$f_D = 2v/\lambda \quad (1)$$

so that target velocity can be recovered directly from the measured Doppler shift once the operating wavelength is known [12].

FMCW radar extends this principle by linearly sweeping the transmitted frequency over a bandwidth B during a chirp period T . The instantaneous frequency difference between the transmitted and received signals (the beat frequency, f_b) is proportional to target range R according to

$$R = cf_b T / (2B) \quad (2)$$

where c is the speed of light [11]. Mixing the transmitted and received signals produces a beat signal containing both range and Doppler information, which can be extracted through spectral analysis such as the Fast Fourier Transform. MATLAB is used to extract and post process this information and translate into meaningful illustrations for ease reference by the users.

In this study, the radar is using S-band FMCW centred at 2.45 GHz. It is of the Industrial, Scientific and Medical (ISM) band popularly used for WiFi (home and office wireless networks and internet connectivity), wireless appliances products and industrial wireless sensor networks [7], [8]. This band was selected because it permits unlicensed operation and offers mature as well as easily available low-cost RF components. Most importantly, the frequency band yields a wavelength of approximately 12.5 cm which is a convenient balance between antenna size and Doppler sensitivity for typical object target.

This kind of Doppler and FMCW radar principles have been used in many applications, from radar-based indoor simultaneous localisation and mapping [13] to contactless vital-sign monitoring [14] and radar-camera sensor fusion for autonomous systems [15].

3. METHODOLOGY

3.1 System Overview

The radar system is divided into three main parts, the radio frequency (RF) part, antenna system and the MATLAB post processing scheme. The antenna system is using two

identical antenna which one of them will work with the radar transmitter section and the other will be connected to the receiver section. Conventionally, high directive antenna is the most suitable to be used for this purpose since it able to concentrate the radiated energy into narrower area, making the radar more sensitive to detect targeted objects with less interference from its surroundings.

The RF part is implemented using the discrete RF components, arranged as a FMCW Doppler transceiver, as shown in Fig. 1. The XR2206 monolithic function generator is used to serve as a modulator which drives a voltage-controlled oscillator (VCO) to generate a frequency-swept carrier in the range of 2.3 GHz to 2.5 GHz. The output RF power from this component is 6dBm. The VCO was from Mini Circuit (ZX93-2536C). The signal then passes through a fixed attenuator (ATT1) for power-level control (3 dB attenuations) before being boosted by a power amplifier (PA1). The amplifier is also from Mini Circuit, ZX60-272LN, which will provide a gain of around 14dB at 2.45GHz. The signal will then be divided by a two-way splitter (SPLTR1) with 3.5 dB attenuations, one output feeds the transmit antenna (Antenna TX), while the other serves as the local-oscillator reference for the receive mixer (MXR1). The developed prototype of the transceiver circuit is as shown in Fig.2, showing the RF circuit sections and the low frequency unit which supports the post-processing.

The antenna of this system is using the circular waveguide type as illustrated in Fig.3 and Fig.4, with gain of about 8.6dBi. The detail of the design and parameters are explained in Section 3.2 of this paper. Approximately, the total RF power transmitted out from the radar transmitter system is about 22 dBm EIRP. This constitutes to the transmitter part of the radar.

At the receiver part of the radar, the reflected signal from the target is captured by a separate receiver antenna (Antenna RX) which is identical with the transmitter antenna. It is then amplified by a low-noise amplifier (LNA1), and down-converted by the mixer to produce a low-frequency beat signal. This beat signal is then conditioned by a four-stage video amplifier chain (20 kHz bandwidth) using the quadruple operational amplifier of LM324, before being routed to a laptop sound card for digitization and MATLAB-based processing.

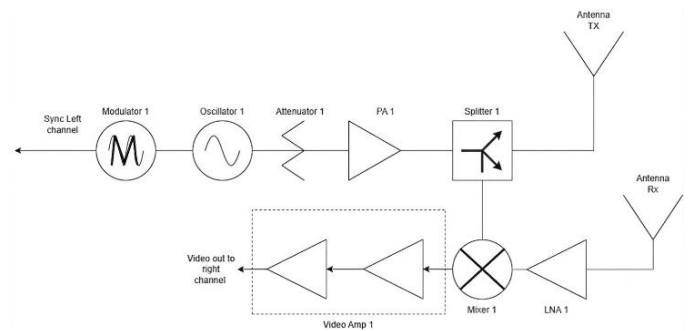


Fig. 1. System block diagram of the 2.4 GHz FMCW Doppler radar transceiver.

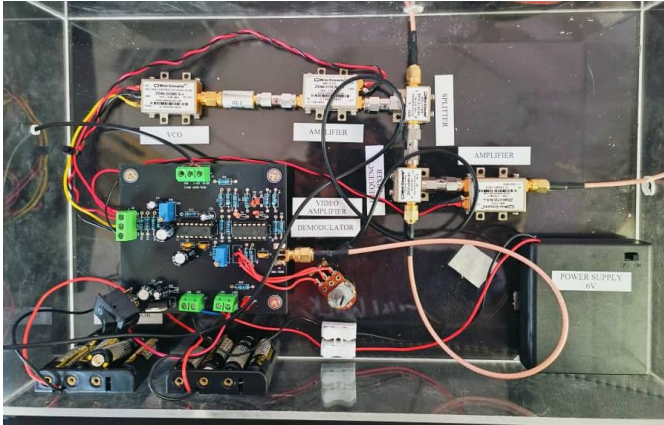


Fig. 2. Circuit connections showing the complete transceiver system.

3.2 Antenna Design

The antenna used in this study is a circular waveguide type antenna. The antenna was designed and simulated to operate at the 2.45 GHz ISM band. The antenna acts as a directional aperture radiator supporting the dominant TE_{11} mode. To ensure unimpeded propagation while restricting the excitation of higher-order modes, the inner diameter of the cylindrical cavity was optimized to 100 mm. At the operating frequency of 2.45 GHz, the fundamental propagation characteristics of the waveguide were analytically determined to establish the physical geometry of the antenna. The conditions required to preserve the TE_{11} mode and prevent signal attenuation are determined by these theoretical dimensions. Table 1 provides an overview of these computed parameters.

Table 1. Calculated Parameters for 100 mm diameter circular waveguide antenna at design frequency of 2.45GHz

Parameters	Value
Free-space Wavelength	122.45 mm
Cut-off Wavelength	170.60 mm
Guided Wavelength	175.86 mm
Cut-off frequency	1.758 GHz

The numerical analysis and geometric optimization of the antenna were performed using the Time Domain Solver in CST Studio Suite, utilizing a hexahedral mesh based on the Finite Integration Technique (FIT). To accurately model the electromagnetic boundary conditions, the waveguide walls and the inner monopole probe were assigned as Perfect Electric Conductor (PEC) materials. The feed mechanism was modelled as a standard 50Ω SMA bulkhead connector, with its internal dielectric core defined as loss-free PTFE (Teflon, $\epsilon_r = 2.1$). The structure was excited via a waveguide port assigned directly to the coaxial cross-section of the SMA connector (encompassing the inner probe, PTFE dielectric, and outer ground shield surfaces to guarantee proper TEM mode injection). Since the theoretical waveguide equations assume ideal boundary conditions and an infinitely thin wire, the physical thickness of the probe (1.27 mm) and the presence of the PTFE base introduce parasitic capacitance, which shifts the resonant frequency. To mitigate this and ensure optimal impedance matching at exactly 2.45 GHz, a parametric sweep was conducted on the monopole probe length. Table 2 lists the

physical dimensions and optimum geometry that match these geometric criteria.

Table 2. Optimum Antenna Design Parameter

Parameters	Value
Waveguide Diameter	100.00 mm
Height of Waveguide	131.90 mm
Iris Width	1.00 mm
Monopole Probe Length	30.61 mm
Monopole Wire Diameter	1.27 mm
Probe Distance to Back Wall	43.96 mm

The calculated parameters define the physical dimensions necessary to support the dominant TE_{11} mode and ensure efficient signal transmission. The resulting geometry and structural design of the circular waveguide antenna are illustrated in Fig. 3.

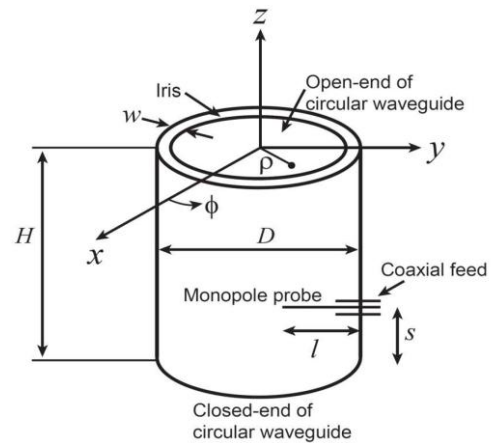


Fig. 3. Circular Waveguide Antenna Geometry [16]

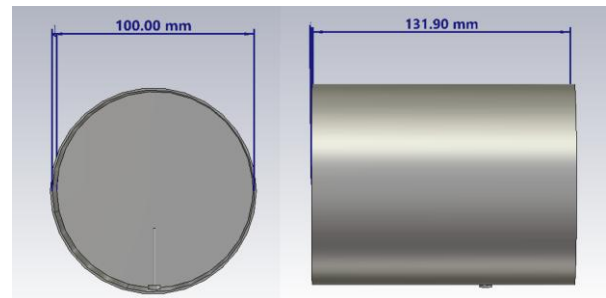


Fig. 4. Front and side views of the designed circular waveguide antenna model in CST

3.3 Complete Radar Assembly

The complete assembled radar sensor, comprising the modulator/demodulator circuits, RF component connections, antennas, and power supplies, is shown in Fig. 5. The compact layout allowed the sensor to be powered independently and positioned for outdoor line-of-sight target testing.

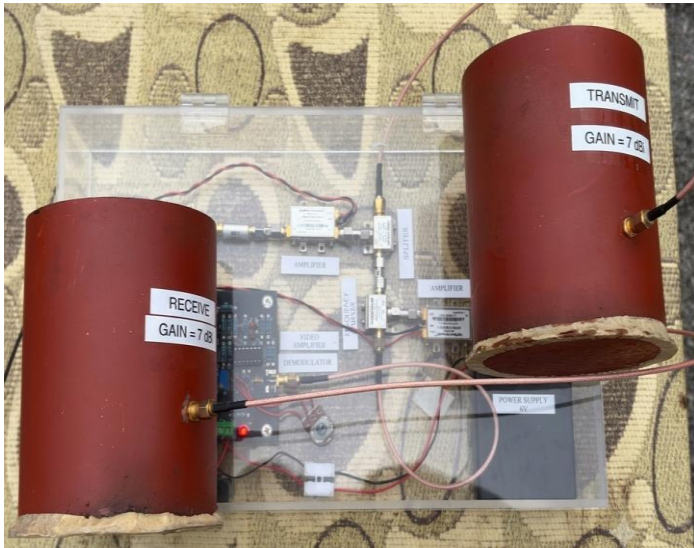


Fig. 5. The 2.45 GHz FMCW Doppler radar hardware showing the antenna system and the transceiver.

4. RESULT AND DISCUSSION

4.1 Antenna Characterization

The RF performance of the proposed circular waveguide antenna was evaluated by comparing the physical prototypes against the CST Studio Suite simulation model. The experimental return loss (S_{11}) measurements were conducted using a Vector Network Analyzer (VNA). Prior to measurement, a standard Short-Open-Load-Through (SOLT) calibration was performed at the coaxial test port to eliminate systematic errors and ensure measurement fidelity. The measured S-parameter data was extracted in ASCII format and post-processed alongside the CST simulation data to generate a comparative graphical analysis.

As shown in Fig. 6, the comparative reflection coefficient (S_{11}) analysis demonstrates a strong agreement between the simulated design and the fabricated transmitter (Tx) and receiver (Rx) antennas. All evaluated antennas exhibit a distinct, deep resonance specifically optimized for the target FMCW bandwidth. At the centre frequency of 2.45 GHz, both the measured and simulated S_{11} magnitudes drop well below the standard -10 dB threshold, indicating highly efficient power transfer and excellent impedance matching at the 50 Ω coaxial feed with minimal signal reflection.

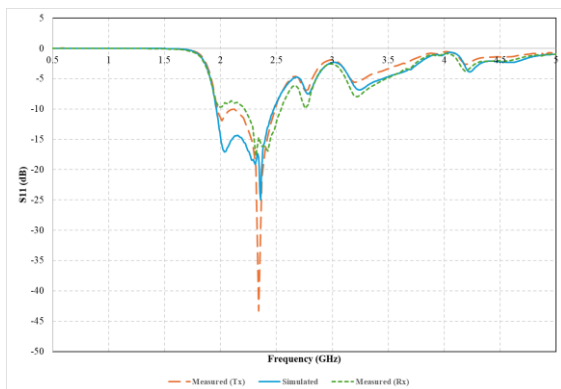


Fig. 6. Comparative reflection coefficient analysis of simulated and fabricated (Tx/Rx) antenna

In addition to impedance matching, the radiated power distribution of the antenna was evaluated to verify its directional characteristics. Fig. 7 and 8 present the simulated 2D far-field radiation patterns in the H -plane ($\Phi=0^\circ$) and E -plane ($\Phi=90^\circ$), respectively, at 2.45 GHz. The simulated results, producing a symmetrical main beam oriented longitudinally along the waveguide axis with a forward directivity of approximately 8.6 dBi.

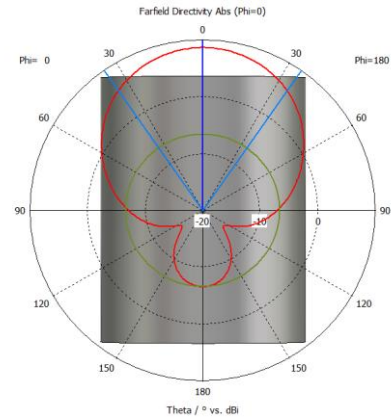


Fig. 7. H-plane radiation pattern of the circular waveguide antenna at 2.45 GHz

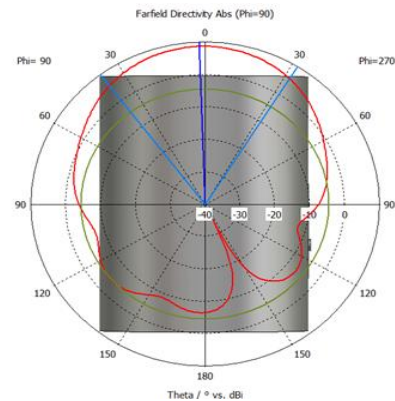


Fig. 8. E-plane radiation pattern of the circular waveguide antenna at 2.45 GHz

4.2 Radar System Validations

To verify the workability of the developed Doppler radar, an experimental study has been performed. The study was conducted at an isolated open space far away from any nearby building or office premises. Prior to run the testing, an RF ambient tests were performed to determine availability of signals that are using the same 2.45 GHz frequency. The presence of such a signals in the surroundings of the test area will have high tendency to interfere the radar's detections reading. However, the discussion of the ambient test technique was not detailed for simplicity of this paper.

In order to verify the range estimation capability of the developed FMCW Doppler radar system, a slowly moving car was directed towards the radar system and the separation distance was measured with a smartphone based augmented reality measuring application. In this example, the distance from the front of the vehicle (as it reaches the zebra crossing as in Fig.9) to the radar antenna was measured about 7.46 m.

This was the reference to determine the accuracy of the Range Time Intensity (RTI) analysis range estimation from the radar instrument.



Fig. 9. Range estimation measured using an applications in handphone.

4.3 Test Surrounding and Noise Mitigation

The experiment was carried out in an open outdoor space where there was a straight line of sight between the FMCW Doppler radar system and the target vehicle as illustrated in Fig. 8. The radar system was mounted on a stable platform 1 meter height from the ground. The selection of an open area with minimum surrounding obstacles was made to minimize the unwanted reflections and multipath effects. The target vehicle was positioned directly in front of the radar antennas in order to get the largest possible return signal strength and ensure consistency of measurement.

The experiment was conducted under low traffic conditions, with some restrictions on pedestrian and vehicle movements. Any metal objects were kept away from the radar system to prevent further scattering, and the radar electronics and laptop were set on a non-metallic table to minimise electromagnetic interference. These environmental factors helped to produce cleaner Doppler Time Intensity (DTI) and Range Time Intensity (RTI) results and improve signal to noise ratio (SNR).



Fig. 10. Outdoor experimental setup of the 2.45 GHz FMCW Doppler radar system used for range and velocity measurements.

4.4 Velocity Measurement (DTI)

In the DTI plots, the x-axis represents detected velocity (m/s), the y-axis represents observation time (s). The colour intensity indicates the strength of the reflected signal. For the moving-target measurement (Fig. 11), the dominant detected velocity was approximately at around 8.82 m/s, (sustained as a continuous vertical high-intensity band throughout the observation window) indicating a relatively stable target speed. Moments later when the car is stopped, the strongest detected peak occurred at approximately 0.15 m/s (0.54 km/h). This near-zero residual velocity attributable to measurement noise and minor environmental clutter rather than genuine motion. Together, these results confirm that the system can reliably differentiate moving and stationary targets.

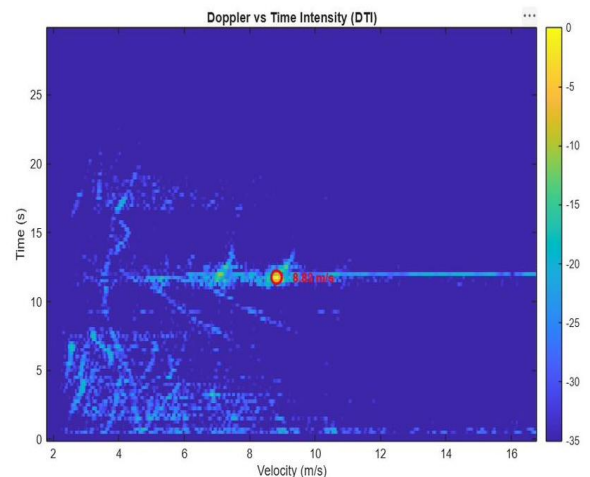


Fig. 11. DTI result for a moving target, showing a dominant velocity of approximately 8.82 m/s.

4.5 Range Measurement (RTI)

Range Time Intensity (RTI) analysis was performed to evaluate the system's ability to estimate target distance. As shown in Fig. 12, a consistent high-intensity reflection was detected at approximately 7.03 m from the radar system (very

close to the 7.46 m distance estimated using the augmented applications measurement approach), visible as a continuous vertical response across the observation period. This stable range estimations confirm that the system can reliably localize a target within its intended short- to medium-range sensing region using the beat-frequency-to-range relationship of Equation (2).

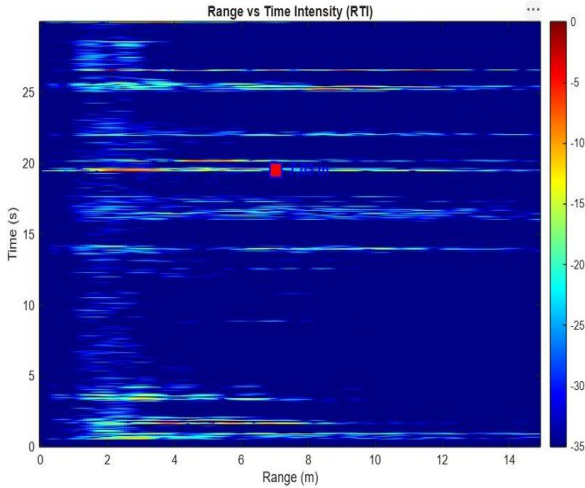


Fig. 12. RTI result showing a detected target range of approximately 7.03 m (red dot in the plot).

5. CONCLUSION

The design, implementation and testing of a low cost 2.45 GHz FMCW Doppler radar sensor for short range proximity sensing was presented. Discrete RF components were used to construct the hardware which worked in the 2.45 GHz ISM band range along with circular waveguide antennas to obtain stable signal generation, transmission, and down-conversion. The Doppler and beat-frequency information were successfully extracted from the recorded signals by processing the signals using the FFT algorithm in MATLAB, which enabled them to distinguish the moving target from a stationary one at a near-zero speed to estimate the range of the target. From experimental validations using a car as the target, distance and speed reading of the target agrees well with the reference measurements. The results obtained are consistent with the ability of a low-cost 2.45 GHz FMCW Doppler radar to reliably detect target presence, target motion and range for short to medium range proximity sensing. Sensing range and resolution is still limited by the modulation bandwidth and analog front-end noise. However, the developed system is good enough for educational purposes, to introduce and validate experimentally how a Doppler radar is functioning.

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