# 行政院國家科學委員會專題研究計畫　成果報告

## 子計畫三：汽車縱向防撞雷達技術研發

計畫類別：整合型計畫
計畫編號：NSC92-2213-E-009-011-
執行期間：92 年 08 月 01 日至 93 年 07 月 31 日
執行單位：國立交通大學電信工程學系

計畫主持人：鍾世忠

計畫參與人員：鍾卓如、陳南君、施俊仰、蕭智軒、何丹雄、李明洲、廖伸憶、林俊甫、陳揚裕、王雅瑩、陳信全、鄭怡力、陳凱得

報告類型：完整報告

處理方式：本計畫可公開查詢

中　華　民　國 93 年 10 月 28 日

**中文摘要（關鍵詞：**縱向防撞雷達、毫米波電路）

汽車防撞雷達（Collision Avoidance Radar , CAR）為全智慧型運輸系統核心組件之一，其目的在輔助人類感測能力的不足，利用先進的通訊與控制科技，偵測車輛週遭的動態狀況，以適時通知駕駛人採取必要措施。在各種防撞雷達中，縱向防撞雷達(longitudinal collision avoidance radar)在功能需求及技術水準上，均遠較其必他雷達為高，不只要能偵測物體的存在，其方位角、距離、速度、加速度等也須得知，方能在各種路況及車輛環境中應變，防止撞擊情況發生。為達到這些目的，其前端架構必須利用毫米波技術（訊號頻率在 30GHz 以上）實現，才可兼具高精確度、高可靠度及低成本的要求。

本計畫設計完成一組毫米波縱向防撞雷達。雷達訊號的頻率定為 38GHz，採 FMCW(Frequency-Modulation Continuous Wave) 方式調變，以同時測距及測速。雷達主體包括毫米波天線、毫米波收發電路及、FMCW 控制電路及 DSP 數位信號處理等部分。

**Abstract (Key words:** Longitudinal collision avoidance radar, folded reflectarray, narrow beam, millimeter-wave circuits)

Among the various components of the advanced vehicle control and safety system in ITS, the collision avoidance radar (CAR) plays the key function, which utilizes the advanced communication and control technology to sense the environment so as to warn the driver of the potential hazard in his/her path. The CAR is generally grouped into three kinds, that is, the longitudinal CAR, the lateral CAR, and the backward CAR, in which the longitudinal CAR is a long-distance forward-looking radar and serves the most important role for preventing damage collision. This is because that this radar does not only sense the existence of the potential obstacles, but also detect the obstacles' relative directions, distances, and velocities. To achieve these requirements, the millimeter-wave (MMW) technology is the most promising technology to implement the longitudinal CAR due to both high reliability and high position resolution.

This project develops a MMW longitudinal collision-avoidance radar. The radar operates at 38 GHz and adopts the frequency-modulation continuous wave (FMCW) for both distance and velocity detection. Three major parts are included in the radar, i.e., the MMW antennas, the millimeter-wave transceiver circuits, the FMCW circuits, and the DSP signal processing unit.

INTRODUCTION

Collision avoidance radar (CAR) plays an important function in advanced vehicle control and safety system in the future Intelligent Transport System (ITS). There are many ways to satisfy the vehicle control and safety system, the radar sensor has the best immunity to bad weather condition such as snow, rain, and mist. In a radar system, a radio signal is transmitted outward from a radar sensor. The radio wave then propagates through the surrounding media and is reflected back to the sensor by objects in the path. The distances and the relative speeds of the objects can then be determined from these radar echoes. Many different types of radars exist varying from the very basis to multi-million-dollar systems. The beauty of radar is that it allows an extension of senses. Vision only works when the environment is lit and clear of smoke, clouds, snow etc. Radar allows one to see or detect objects in the dark or behind clouds or objects that are tens and even hundreds of miles away. In the automotive applications, many radar designs use the FMCW (frequency-modulated-continuous-wave) technology. The front-end configuration of the radar sensor presented in this study is suitable for the use of the FMCW technology and fills a niche in the vehicle radar sector. In this report, a DSP (digital-signal-process) radar signal processor and an analyzing algorithm for the FMCW radar echo is represented.

## 1. SYSTEM CONSIDERATION AND ARCHITECTURE OF THE FMCW RADAR

In order to design a radar system that is suitable for ACC applications, the radar requirements are confirmed first. Table I gives a list of the system requirements for the longitudinal collision avoidance radar system. The detection range is from 2 to 100 meters with a azimuth angle below 5 degrees. The azimuth angle should not be larger than 5 degrees to prevent the unwanted warning of objects on the other lanes. Among various frequency band used for radar applications, the frequency in 38 GHz has numerous available devices ready for use and an acceptable wavelength to design high gain and narrow beam antenna. Thus, the frequency band of 38 GHz is in an advantageous position to achieve low cost longitudinal collision avoidance radar. The operating bandwidth of 150 MHz is determined by the FMCW principle to achieve a distance resolution of 2 meters. The receiver sensitivity of -100 dBm is a sensible value to recent receivers. The output power of 12 dBm and antenna gain of 20 dBi are good to fulfill the range requirement of 100 meters, this specs still has a power margin of 10 dB for non-ideal weather conditions.

Fig. 1. shows the system block diaram of the FMCW radar system. In this system, FMCW waveform is generated using a VCO (voltage-controlled oscillator) at about 4 GHz. The output of the VCO is then tripled to 12 GHz through a frequency tripler. A FLL (frequency-lock-loop) is composed of a 12 GHz frequency discriminator, comparator, and a loop filter to generate a linear FMCW ramp. In this architecture, frequency variation is transformed into voltage by the frequency discriminator. The output voltage of the discriminator is then compared to the modulating signal. An error correcting signal is generated by the comparator to make the VCO output linear. This architecture holds the benefits of high linearity, fast response time, and low cost.

## 2. DESIGN AND MEASUREMENT OF THE TRANSCEIVER

The designed radar system is proposed to be small and cost effective, to achieve these requirements, the design process is broken into modules. The modules are designed individually using commercially available microwave design software (MWOffice and ADS) and then integrated together to form a front-end transceiver. Before assembly, each component is examined by the measurement and optimized to ensure proper operation.

The 38 GHz FMCW radar front-end sub-system presented here is a forward-looking, radar based, detection system for CW application. This system can be extended by changing the modulating signal in the baseband for FMCW applications. The 38GHz transceiver for FMCW radar was integrated with micro-strip line VCO and discriminator to form a frequency locked loop, which provide clean source and high linear sweeping frequency. The transceiver is divided into two modules, the microwave module and the millimeter-wave module. In the microwave module, Fig. 2 gives the photo of the VCO. The output of the VCO is from 4.2 to 4.3 GHz with a phase noise of -115 dB/Hz. A new frequency discriminator circuit has also been proposed here, which consists of three individual Wilkinson power dividers and two temperature compensated power detectors, with the isolation resistors in two of the power dividers being removed. Fig. 4 gives the experimental result of the fabricated discriminator. It has a linear voltage output from -80mV to 100mV@ 12.5~12.9GHz. The frequency multiplier is a schottky diode design, this design need no bias and will not oscillate due to unstable bias voltage. Fig. 5 and Fig. 6 shows the photos of the finished FLL and gain stage circuits. The measured output power of the microwave module is 12 dBm from 12.6 to 12.9 GHz with phase noise of -98 dBm/Hz. The millimeter-wave module contains a frequency tripler, a BPF (band-pass-filter), an amplifier, and a rat-race mixer. The frequency used to multiple the output of the microwave module to the 38 GHz band. The BPF is designed to have highly rejection ratio to filter out the unwanted harmonics. The amplifier is a commercial available medium power MMIC used to supply enough power. The millimeter-wave module is fabricated on the RT5880 5-mil substract for proper operation performance. Fig. 7 shows the photo of the completed module. The measured output power and conversion loss of the integrated transceiver are presented in Fig. 8 and Fig. 9, respectively. It is seen from Fig. 5 that the output power is around 10.6 dBm from 38.1GHz to 38.4GHz. Also from Fig. 6, it is observed that, for the receiver performance, the conversion loss is about 7 dB. This implies that, without a low-noise amplifier (LNA), the noise figure is 7 dB. The performance is well agreement with the gain budget.

## 3. DESIGN AND MEASUREMENT OF THE ANTENNA

A high gain and narrow beam antenna is a key point in the longitudinal CAR system. In this report, a folded microstrip reflectarray is proposed to form a high gain and narrow beam antenna in the 38 GHz band. Fig. 10 presents the photo of the finished folded microstrip reflectarray. The antenna structure contains three parts: main-reflector, sub-reflector, and a feed antenna. The main reflector includes hundreds of microstrip antennas used to produce twisted re-radiated fields and provide phase compensation for focusing. The sub-reflector parallel with the main-reflector is made of a substrate printed with high-density metal grid, which is transparent to one polarization but would reflect the other polarization. The feed antenna is a microstrip patch antenna located around the center the main reflector. The position of this feed antenna is movable so as steering the radiation beam of the antenna. Measured results showed good agreement with the calculated ones. Fig. 11 illustrates the frequency of the measured antenna gain, which shows a maximum gain of 35.4 dBi at 39 GHz. Fig. 12 depicts the measured antenna patterns for different feed positions d. It is seen that the antenna has the antenna gain of 25dBi, side-lobe-level of -15dB SLL, and 3-dB beamwidth of 4.6˚. As the feed position d changes from –4 mm to 4 mm, the beam scans over a range of 7.2˚.

## 4. **DIGITAL SIGNAL PROCESSING**

The object information such as distance and relative speed are carried on the radar echo. The radar echo signal is direct down converted to the IF (intermediate frequency) by the MMW module. In CW system, the IF signal represent the Doppler frequency shift of the object. In the FMCW system, the distance and speed (Doppler) information are mixed together and represented in the frequency and relative phase of the echo signal. Although direct analog process using counter or discriminator can easily get the information of object speed or distance, this method can not get accurate result with good resolution and the problem of multi-targets. DSP (digital signal process) has well accuracy and reliability which is a good solution to overcome these problems.

In CW system, the radar signal can be analyzed directly through FFT (fast-fourier-transform). The peak node in the frequency spectrum indicates the Doppler shift. The relative speed of the object and peak node follow the Doppler equation. Fig. 13 shows the integrated CW radar prototype for demonstration. A microwave module, a millimeter-wave module, two antennas, a IF signal processing unit, and a power supplier are integrated in this system. The CW radar system can detect the velocity a small vehicle in 150 meters with resolution of 0.25 km/hr within 0.1 seconds. According to the FMCW principle, the distance information is carried on the center frequency of the echo signal. Thus, perform FFT can identify the object distance. Fig. 14 shows a result of an experimental system test of the integrated radar system. In this test, a delay line of 4 meters is connected to the transmitting and receiving ports of the radar transceiver. Fig. 14 (a) shows the measured spectrum and (b) the simulated one. There is perfect match between the simulated and measured result. In FMCW system, the object distance and speed is hardly extracted from the frequency spectrum. Fig. 15 shows a simulation result of a target in 50 meters moving far away with relative speed of 10 km/hr. In this spectrum, the distance and Doppler information are mixed together making the disordered spectrum distribution. To overcome this problem, the 2D-FFT technique should be involved to solve this problem. The samples of the radar echo are rearranged to a 2D array, and perform FFT on the x- and y-axis in sequence. The result of the 2D spectrum shows the relative power in distance and speed domain. By searching of peak node, we can get the target information in the whole field of view. A full system simulation using the 2D technique was performed to verify the analyzing algorithm. The target distance, speed, scattering parameter, antenna pattern, and channel attenuation are taken into consideration. Fig. 16 illustrates the result of two targets (one car and one truck) in 10 and 20 meters with speed of 10 and 5 km/hr. There are two peak nodes in this result indicating the car and truck respectively. Fig. 17 illustrates the functional block of the FMCW analyzing algorithm. Fig. 19 gives a screen shot of the FMCW radar system test. In this test, the target to be detected is a person who walks in 5 meters with speed of 2.5 km/hr. In this screen shot, a light-spot shows in the monitor that indicates the detected object. The x- and y-axis of the chart in monitor represent the distance and speed respectively.

## **5. CONCLUSION AND FUTURE WORKS**

A 38 GHz longitudinal collision avoidance radar prototyping system has been developed. The radar system contains a microwave module, a millimeter-wave module, a folded reflectorarray antenna, and DSP processor. The experimental result of the integrated radar transceiver shows good linearity and power flatness in the frequency band of 38.1 to 38.4 GHz. The antenna has gain of 25 dBi, side-lobe-level of -15 dB, and beamwidth of 4.6˚. The 38 GHz radar transceiver has been integrated and demonstrated in the CW mode. The integrated Doppler radar has distance resolution of 0.25 km/hr and detection range of 150 meters. A 2-dimensional DSP algorithm is proposed to analyze the radar signal in distance and velocity domain simultaneously.

Although the 38 GHz radar system shows good characteristics, the antenna size in this band is still too large to be assembled on a small vehicle. The operation frequency should be extended to the 77 GHz band, however in this frequency band component development and system fabrication and integration is a great challenge to the academic and industrial circles. In this system, the microwave and baseband module are developed in this work. The future works should be focused on the development of millimeter-wave devices and switch-beam high-gain antenna array.

## REFERENCES


[1] Leonhard Reindl, “Design, fabrication, and application of precise SAW delay lines used in an FMCW radar system,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 49, NO. 4, April 2001.

[2] P.Heide, “Commercial microwave sensor technology-An emerging business, ”*Microwave J.*, vol. 42, no. 5, pp. 348-352, May 1999.

[3] Errol Hayman, Youssef Kalatizadeh, Robert Pearson, Martin W Shelley, and Javier Vazquez "Novel reflector antenna design for ACC applications" *Antennas for Automotives, IEEE Colloquium on*, pp. 3/1-3/6, 2000.

[4] A. Nordbotten, "LMDS system and their application, " *IEEE communication Magazine*, vol. 38, Issue 6, pp. 150-154, June 2000.


| | | |
|---|---|---|
| 1 | Target detection range | 2m 100m |
| 2 | Range Resolution | ±2m |
| 3 | Relative Velocity | 0~100Km/Hr±2Km/Hr |
| 4 | Frequency | 38.15~38.3GHz |
| 5 | Antenna Azimuth FOV | < 5 deg |
| 6 | Antenna Elevation FOV | < 5 deg |
| 7 | Antenna Gain | >20dBi |
| 8 | Antenna Side-Lobe-Level | >15dBc |
| 9 | Occupied Bandwidth | 150 MHz |

| | | |
|---|---|---|
| 10 | Modulation signal | Triangle 20KHz |
| 11 | RF Output Power | 10dBm |
| 12 | Receiver Sensitivity | < -100dBm |

Table 1. System requirements of the longitudinal collision avoidance radar system.

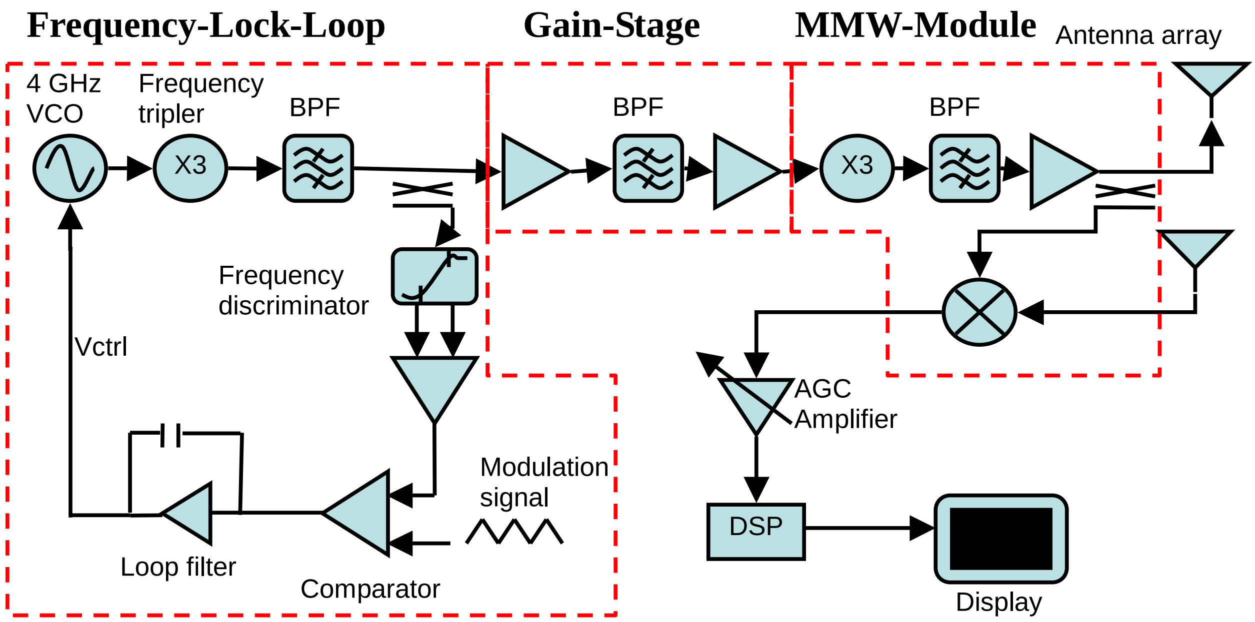



Fig. 1. Block diagram of the front end for FMCW forward-looking radar.

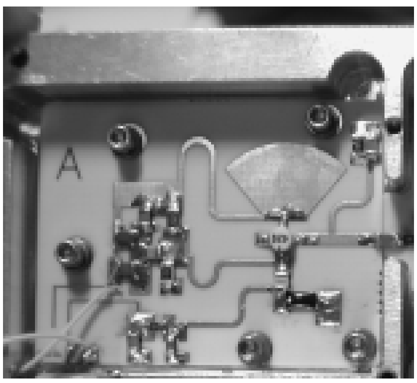


Fig. 2 Photo of the VCO. Output frequency is around 4.25 GHz.

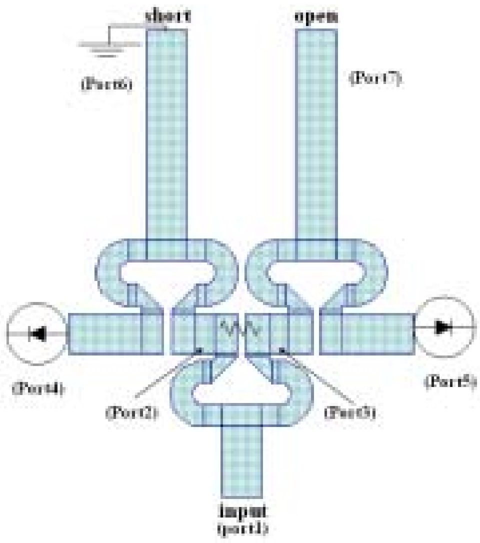



Fig. 3 The outline of the frequency discriminator.

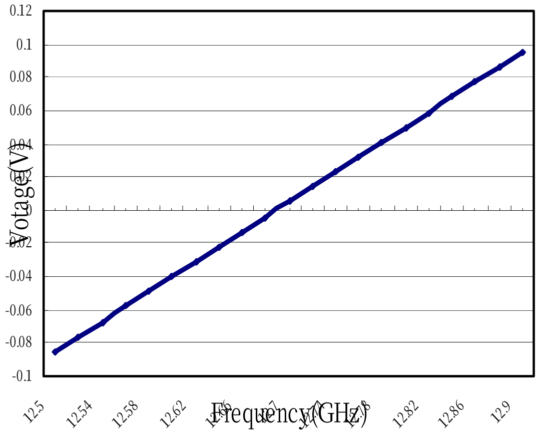



Fig. 4 Experimental result of the frequency discriminator.

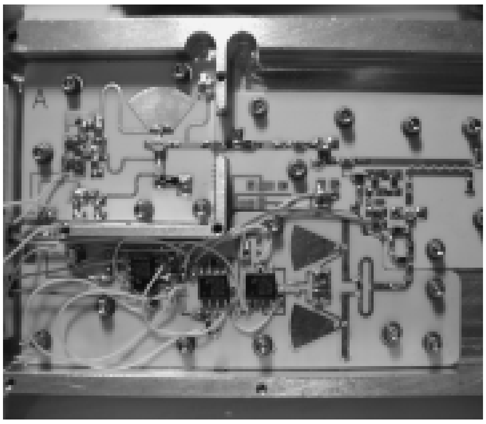


Fig. 5. Frequency locked loop of the 38GHz transceiver. Output frequency is around 12.75 GHz.

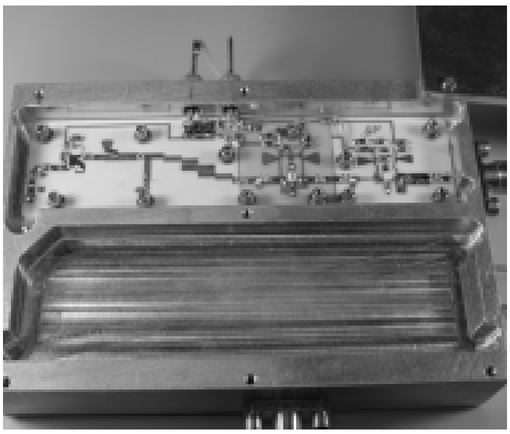


Fig. 6. Gain stage of the 38GHz transceiver. Output frequency is around 12.75GHz.

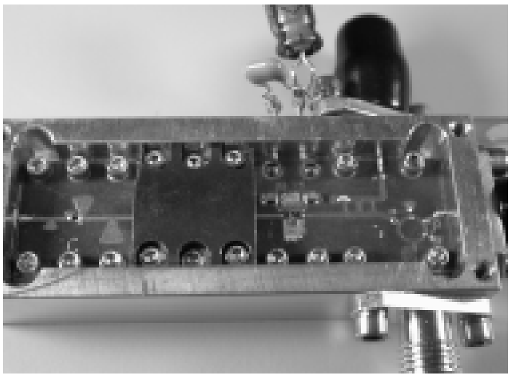


Fig. 7. MmWave module of the 38GHz Transceiver.

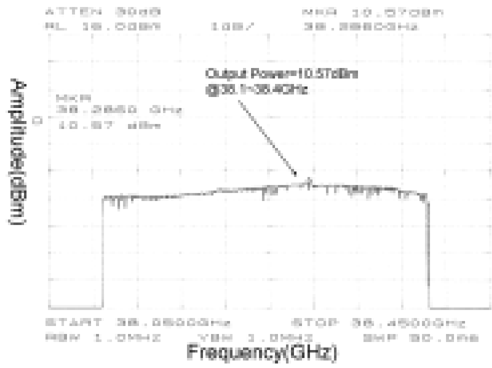



Fig. 8. Output power v.s. frequency for the transmitter.

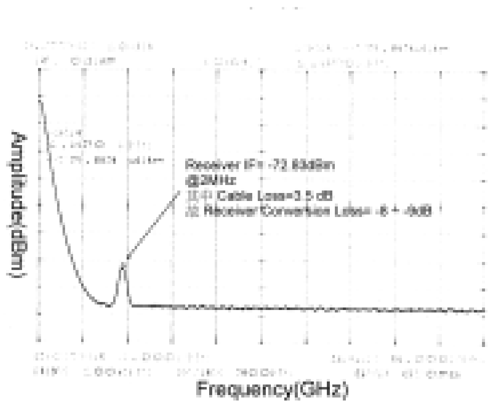



Fig. 9. Conversion loss for the receiver.

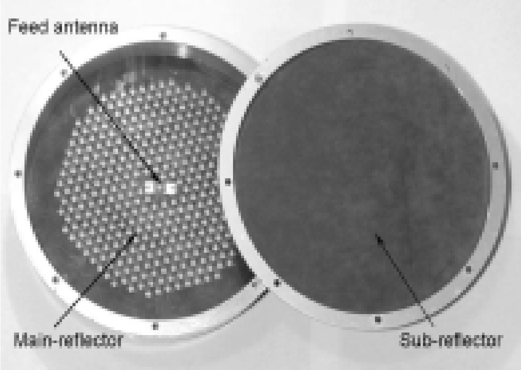



Fig. 10. Folded microstrip reflectarray antenna for the 38GHz radar sensor.

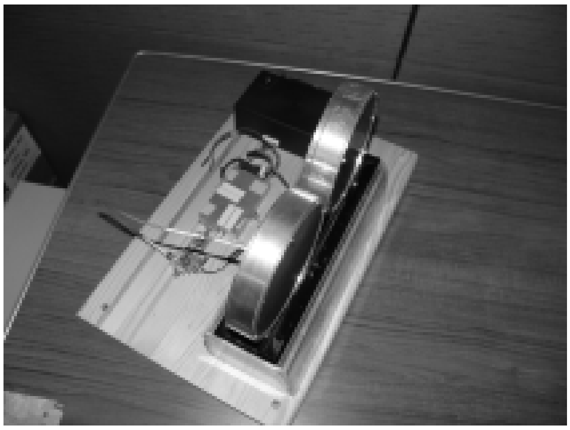


Fig. 13. A 38 GHz radar system prototype in CW mode.

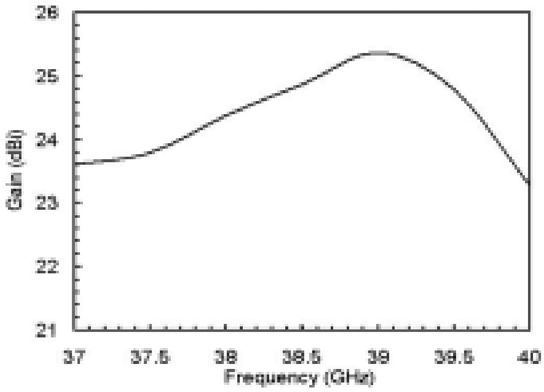



Fig. 11. Measured antenna gain, as a function of frequency, of the folded reflectarray antenna.

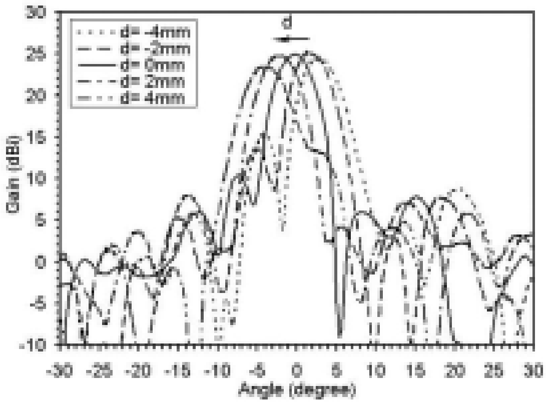
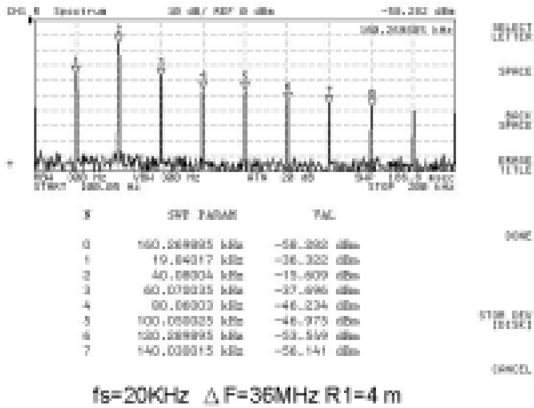
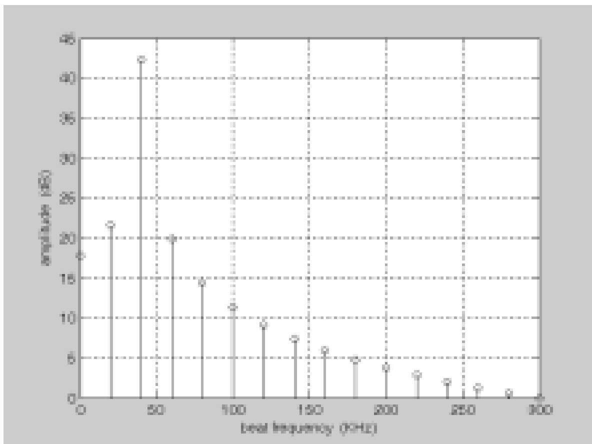



Fig. 12. Measured H-plane pattern of the folded reflectarray antenna.




(a)




(b)

Fig. 14. The measured (a) and simulated (b) result of the radar transceiver with a 4 meters delay line.

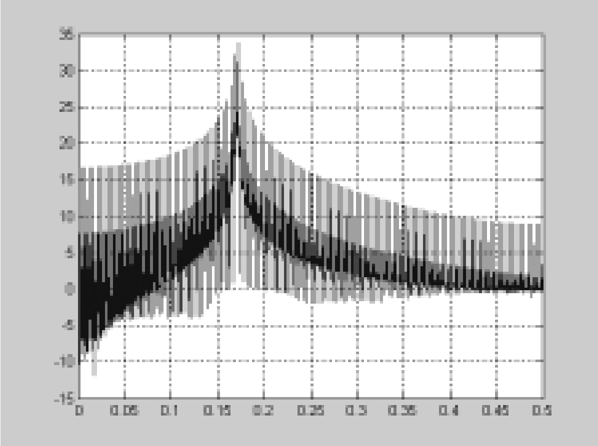



Fig. 15. The simulation result of the FMCW system. A object move far away with speed of 10 km/hr in 50 meters.

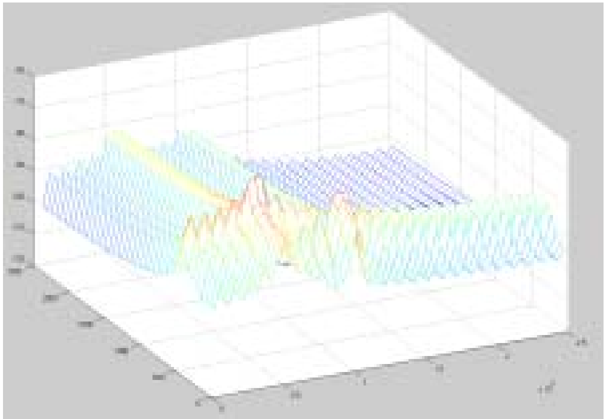


Fig. 16. The result of full system simulation using 2D algorithm. Two objects in 10 and 20 meters with speed of 10 and 5 mk/hr.

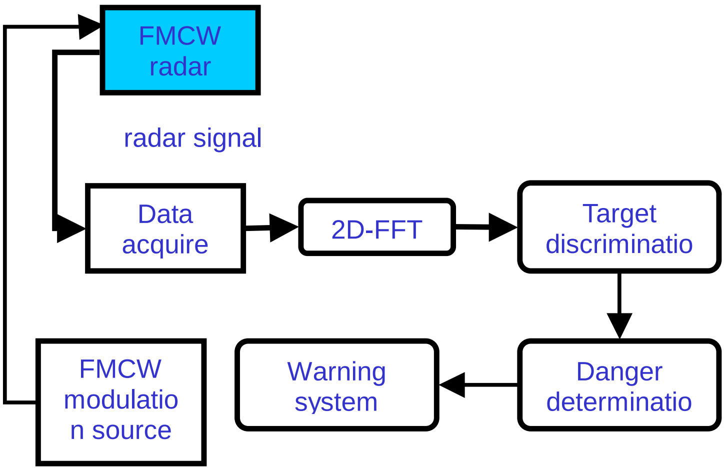



Fig. 17. Function block of the algorithm for FMCW radar.

Fig. 18. A screen shot of FMCW radar system test.