Forward-Looking Automotive Radar Using a W-band Single-Chip Transceiver

Kwo Wei Chang, Huei Wang, *Member, IEEE*, Greg Shreve, *Member, IEEE*, James G. Harrison, *Member, IEEE*, M. Core, A. Paxton, M. Yu, C. Harry Chen, and G. Samuel Dow

***Abstract*—A prototype W-band all-weather automotive radar based on a single-chip 0.1-μm AlGaAs/InGaAs/GaAs HEMT transceiver has been developed. This radar has the features of simple architecture and small size, with adequate performance. Owing to the maturity of HEMT MMIC technology, this radar is potentially low cost to implement in personal vehicles. The prototype radar used for autonomous intelligent cruise control in a passenger car is presented in this paper. The MMIC development, together with the radar system design, is also addressed.**

I. Introduction

OVER the past few years, automotive sensors/radars have become an important and interesting area for microwave and millimeter-wave (MMW) applications. They not only have the huge market potential of the automotive industry but also will play an important safety role in future intelligent vehicle highway systems (IVHS). The forward collision warning (FCW) and autonomous intelligent cruise control (AICC) radars are forward looking automotive radars (FLAR's) that require a sensor range of about 100 m. The FCW radar will detect potential forward collision situations and provide a warning to the driver, while the AICC will operate in an autonomous control loop to maintain a continuous safe following distance.

Many different sensor/radar technologies for automotive applications have been reported [1]–[5]. The three most commonly used technologies are MMW, microwave, and laser-based sensor systems. While all these systems have adequate range and range resolution, the laser-based system has the disadvantage of limited field of view and poor close-range resolution as well as possible eye safety concerns. Most of all, its performance is affected by weather conditions. The disadvantages of microwave radar are congested frequency bands and large antenna size. Basically, there are two dominant factors, in addition to the performance requirement for all-weather conditions, that drive the technology for automotive radars: cost and hardware size. Low cost is the key factor for consumers to accept the radar as a safety and affordable component of their vehicles. The size constraint is essential for easy integration of the radar on the vehicle without major impact on the vehicle design and performance. These problems can be overcome by MMW radars.

The reported MMW radars use either hybrid or multiple monolithic microwave and millimeter-wave integrated circuit (MMIC) chip approaches [4]–[5]. Compared with hybrid circuits, MMIC's are more attractive for automotive radar applications because of their higher reliability, greater compactness, and lower fabrication and integration costs for mass production. Among MMW radar technologies, the W-band radar has a clear technical merit over other frequency bands since it has a larger RF bandwidth and better range resolution, and smaller hardware size. Owing to the recent advanced 0.1-μm pseudomorphic (PM) high electron mobility transistor (HEMT) MMIC technology [6], the key W-band monolithic circuit elements have been successfully developed over the past few years [7]–[10]. These components have been further integrated into a W-band single-chip transceiver used as the front-end of a FMCW radar [11]. Moreover, this 0.1-μm PM HEMT process development has been transferred to production [12] and high fabrication yield of high-level W-band MMIC's have been demonstrated [13]–[16]. This ensures that the MMIC's can supply future automotive electronics in volume.

This paper reports a FLAR prototype developed for AICC applications. The proof-of-concept unit consists of two antennas, one RF front-end which uses a W-band transceiver MMIC, one IF receiver, and one digital signal processor (DSP). The prototype radar utilizes a frequency modulation continuous wave (FMCW) and homodyne radar scheme because of its simple architectures, and thus it has the potential for low cost mass production. On the other hand, other radar architectures, e.g., the super-heterodyne scheme with a low phase noise LO source [17], can provide better performance. However, this approach requires separate HBT (heterojunction bipolar transistor) and HEMT MMIC chips for the W-band RF transceiver unit under current technologies and thus may cause higher cost. The homodyne FMCW radar prototype unit has been extensively field tested and demonstrated all core technologies required for MMW automotive radars. The MMIC development is presented in section II. Section III discusses the design approach of this prototype. The radar test results are described in Section IV followed by a brief summary.

II. MMIC Development

The HEMT has demonstrated high gain, low noise, adequate power transmitting capability in MMW frequency

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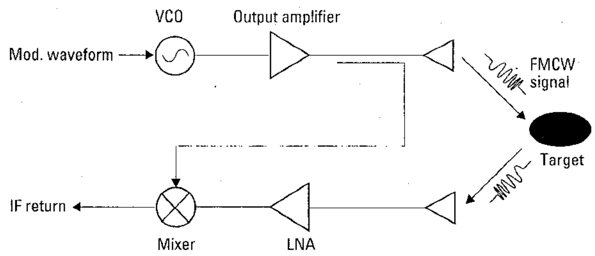
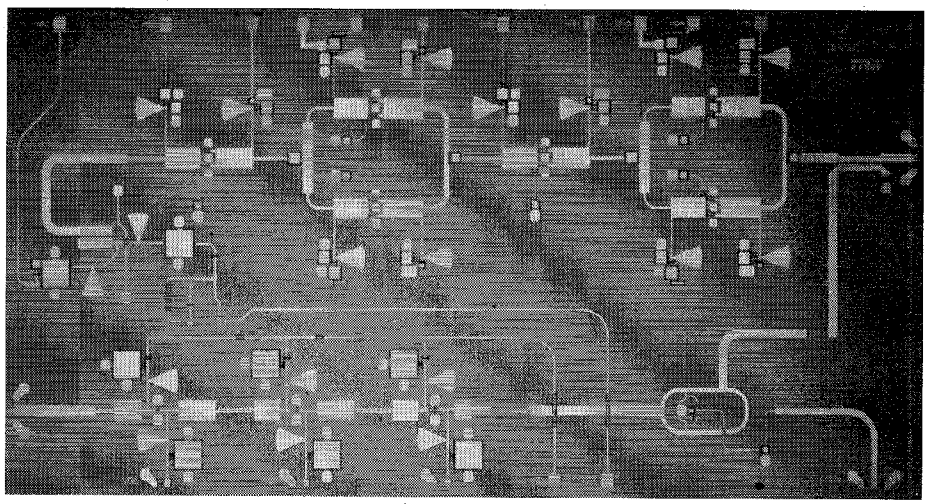


(a)



(b)

Fig. 1. (a) The block diagram and (b) the photograph of the W-band single-chip transceiver chip.

components. The recent advancement of HEMT technology makes it possible to achieve a high level of integration for MMW monolithic IC's, allowing the single-chip W-band transceiver for FMCW, homodyne radar applications to be developed using 0.1-μm T-gate AlGaAs/InGaAs/GaAs PM HEMT technology [6].

The block diagram of the single-chip FMCW transceiver is shown in Fig. 1(a). The transmit and receive channels use separate antennas for better isolation. An FMCW signal is generated from the VCO and fed to the transmit amplifiers. A portion of the transmit power is coupled back to the receiving channel and used as an LO source for the mixer.

The VCO is a common gate design which uses gate bias voltage to adjust the oscillation frequency, and the output power is coupled out of the drain terminal through the microstrip edge-coupled lines. The transmit amplifier consists of two identical two-stage amplifiers which are capable of delivering more than 10 mW of output power at 90–94 GHz. To ensure circuit stability at the out-of-band frequencies, a lossy series resonator was used at the gate of each HEMT device. The dc biases can be provided on both sides of the circuit for ease of system integration.

The receiver has a three-stage LNA at the front and is followed by a single-balanced diode mixer. The LNA is designed for low noise figure based on the reactive matching technique while the mixer is designed using a 180° rat-race hybrid and a pair of 16-μm diodes. In addition, the three gate bias lines for the LNA are connected together to simplify the test fixture design. The diodes are fabricated using the gate-to-channel junction of a HEMT device and thus are fully

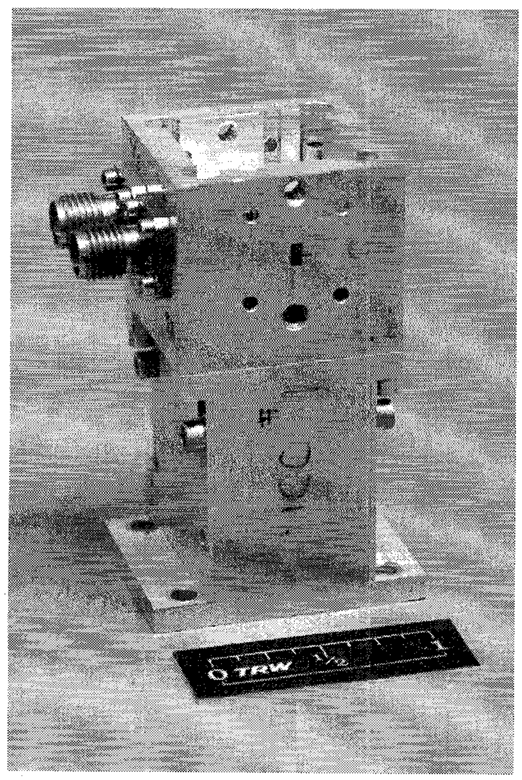
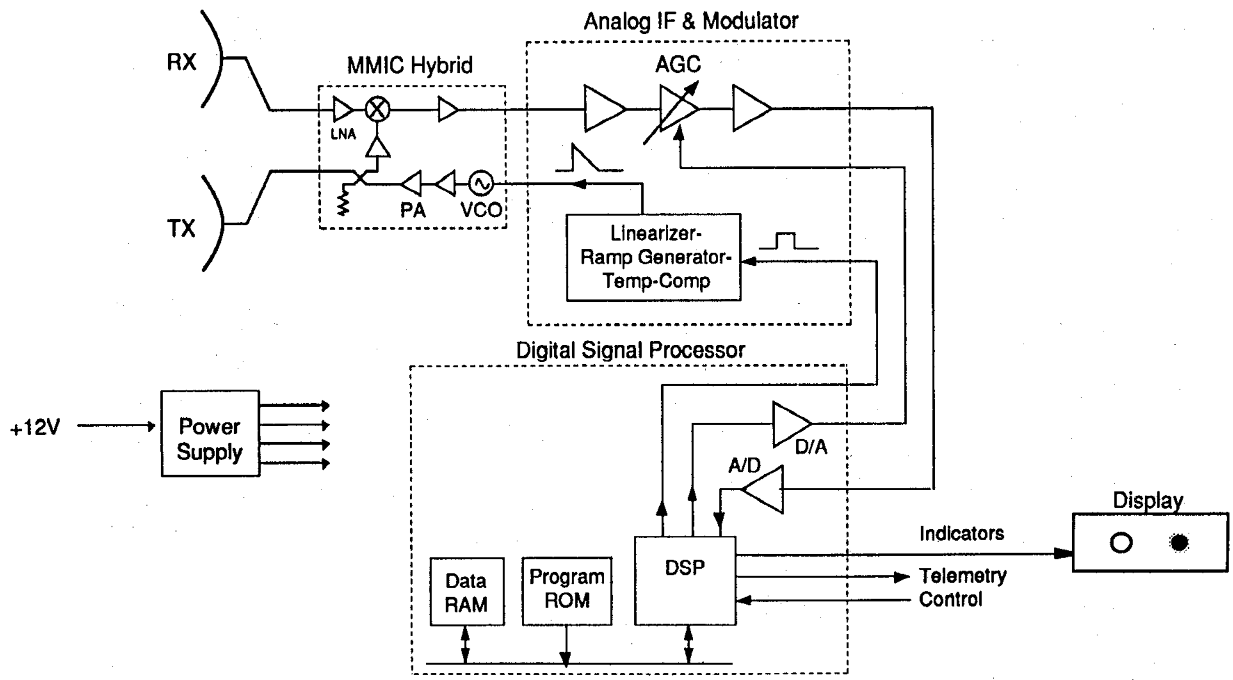


Fig. 2. The photograph of the single-chip transceiver housing.



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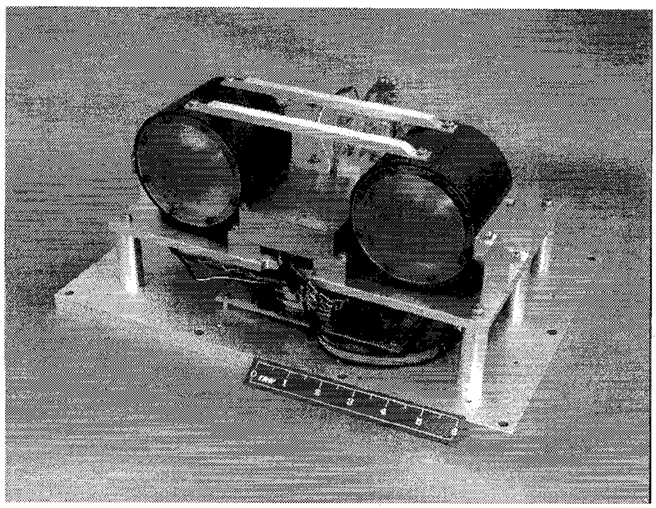


(b)

Fig. 3. The (a) function block diagram and (b) photograph of the FLAR unit.

TABLE I
MINI-SPECIFICATIONS OF THE FLAR PROTOTYPE

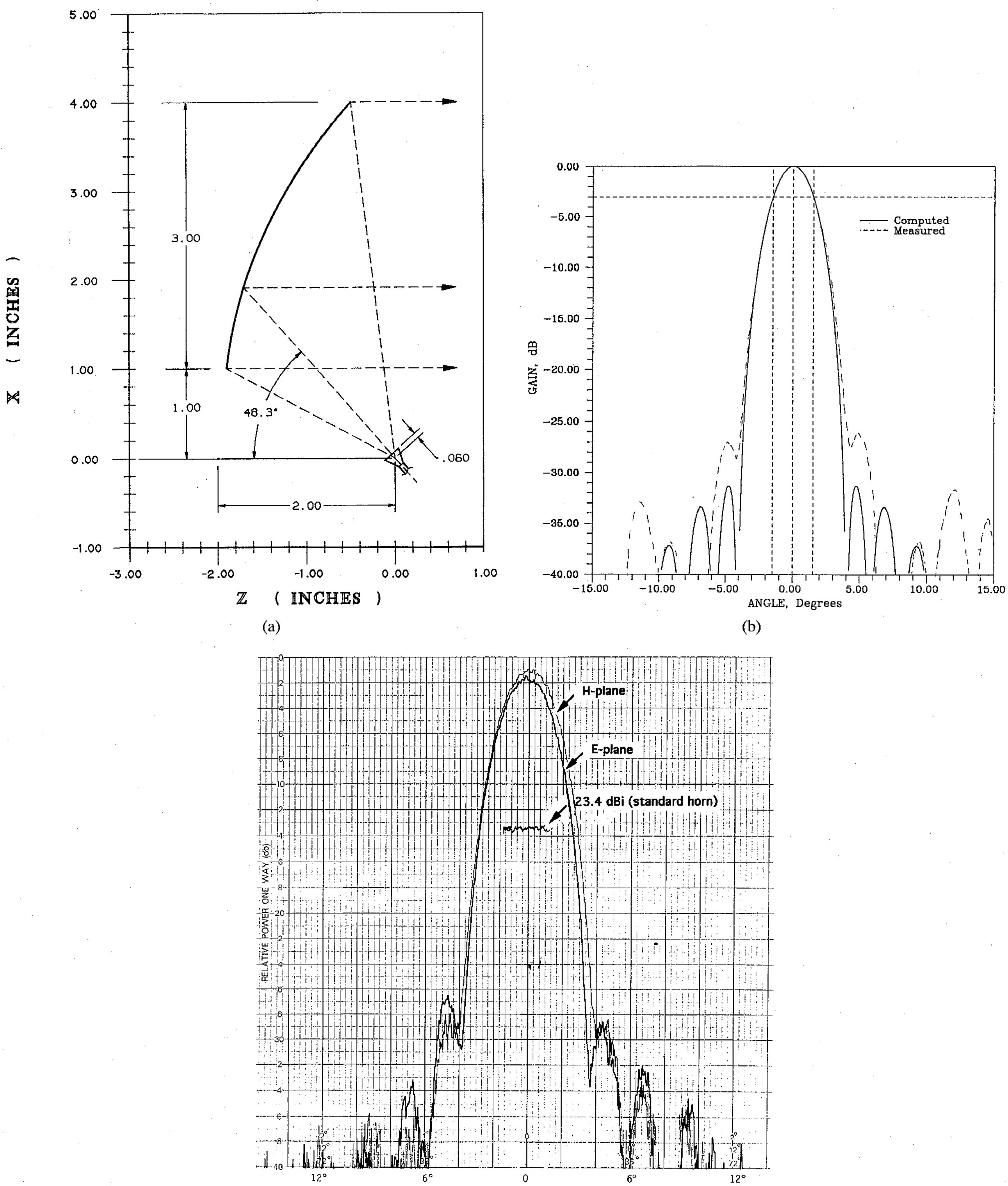
Parameters	Requirements
Range	2-100 meters
Range Resolution	0.5 meters
Range Rate Resolution	1.5 km/hr
Antenna Beamwidth	3 by 3 degrees, Linear
Antenna Sidelobes	< -30 dB
Modulation Type	FMCW
Modulation Bandwidth	350 MHz
Transmit Power	> 10 mW
S/N Ratio	10 dB
Display	Laptop Computer via RS232
DC Power Supply	12 volts

compatible with the fabrication process of the active devices. Fig. 1(b) is a photo of the transceiver chip. The chip size is 6.9×3.9 mm^2.

Fig. 2 shows the transceiver MMIC and voltage-regulated dc power supply all packaged in a housing. The top portion includes the MMIC and two finline transitions for interface of waveguide and transceiver chip. Two SMA connectors are for IF signal output and VCO tuning voltage input, respectively. Eight voltage regulators are assembled in the bottom housing. The complete unit requires a +5 V power supply with less than 250 mA total current.

III. RADAR SYSTEM DESIGN

Fig. 3(a) shows the block diagram of the prototype radar. While the requirements for RF front-end and IF receiver may be generic for different types of radars, the antenna and DSP requirements are different for different applications. Table I



(c)

Fig. 4. (a) The parabolic dish reflector geometry, (b) measured and calculated radiation patterns of the parabolic dish reflector, and (c) measured radiation patterns of the lens antenna.

presents the mini-specifications for the FLAR. The photograph of this prototype radar unit is shown in Fig. 3(b).

A. Antenna

Two different types of antennas have been utilized to evaluate the prototype unit. The first one is a 3°-beam parabolic dish antenna as shown in Fig. 4(a). A 3-in. offset reflector with a 2-in. focal length is used for its high efficiency and blockage-free configuration. A rectangular feed horn illuminates the reflector with −12 dB edge taper to achieve better than −25 dB sidelobe level. The reflector was built by metalizing

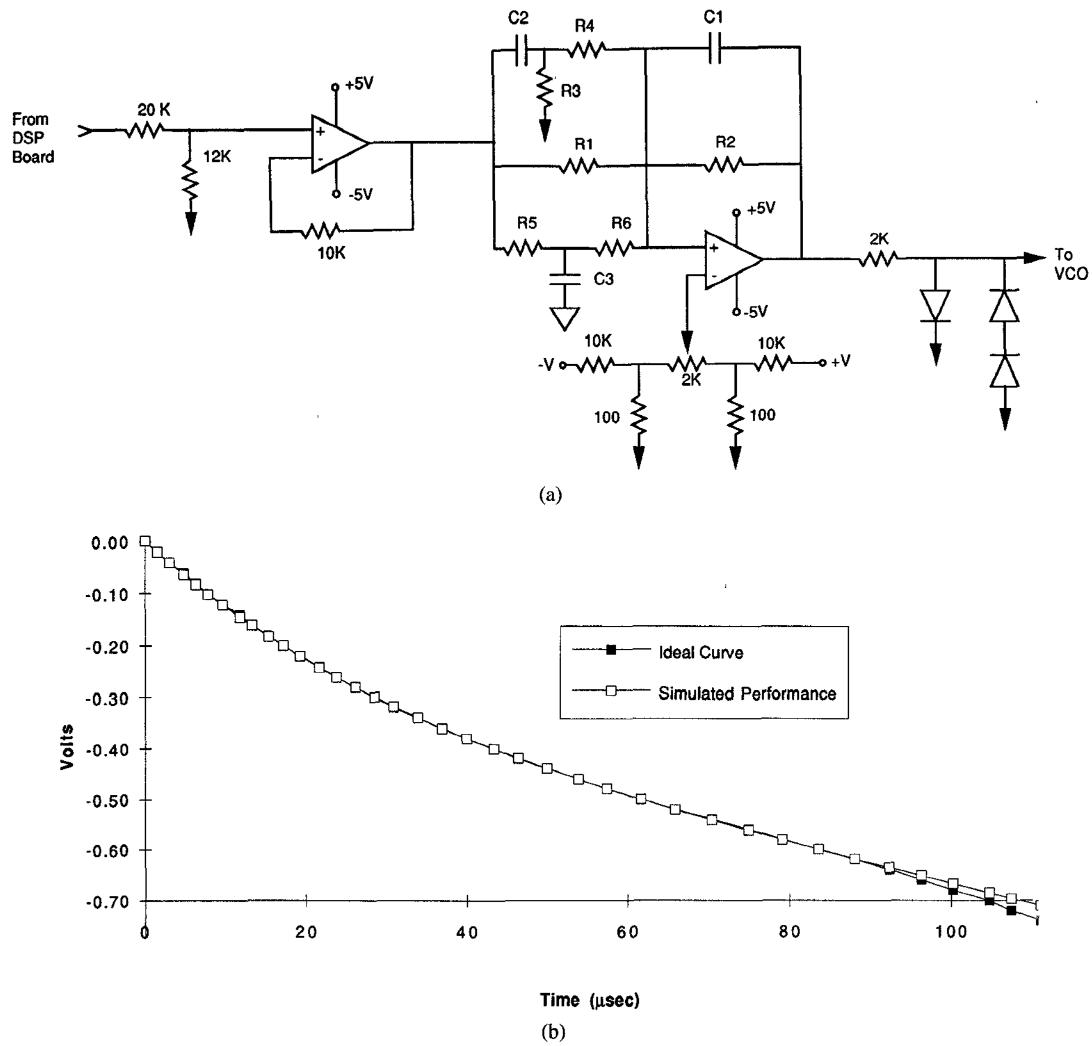


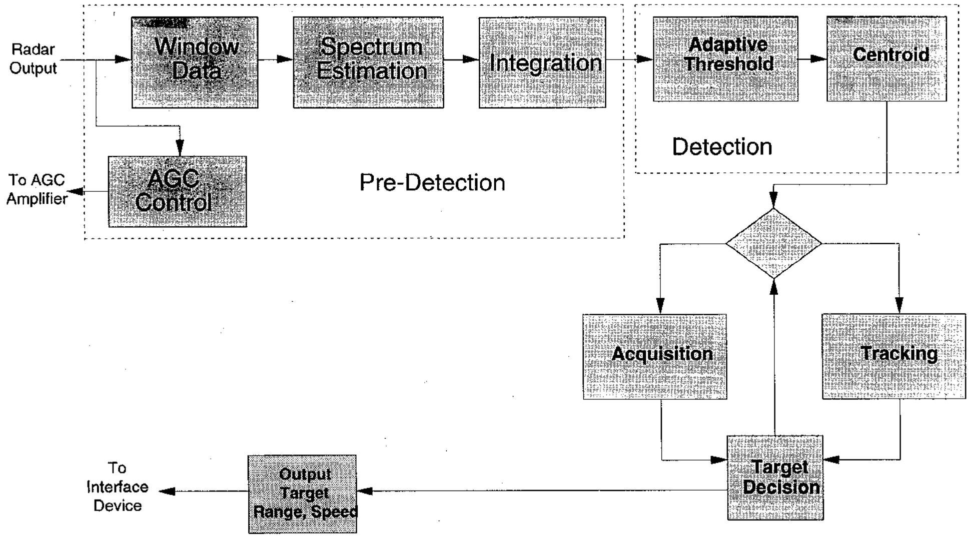
Fig. 5. (a) Circuit schematic diagram and (b) desired (ideal curve) and actual (simulated performance) curves for output voltage, of the linearizer.

the surface of a parabolic dish of 60-mil fiber glass using the vacuum deposit aluminum (VDA) process. The feed horn was electroformed. Fig. 4(b) shows the measured as well as the computed radiation patterns at 93 GHz. The antenna achieved 36.1 dBi gain, as compared to the predicted gain of 36.2 dBi. Another one is an off-the-shelf optical lens antenna as shown in Fig. 3(b). Fig. 4(c) shows that it has 35.4 dB gain and greater than 25 dB sidelobe rejection. In addition, it is easier to implement in the system and therefore was selected for the prototype.

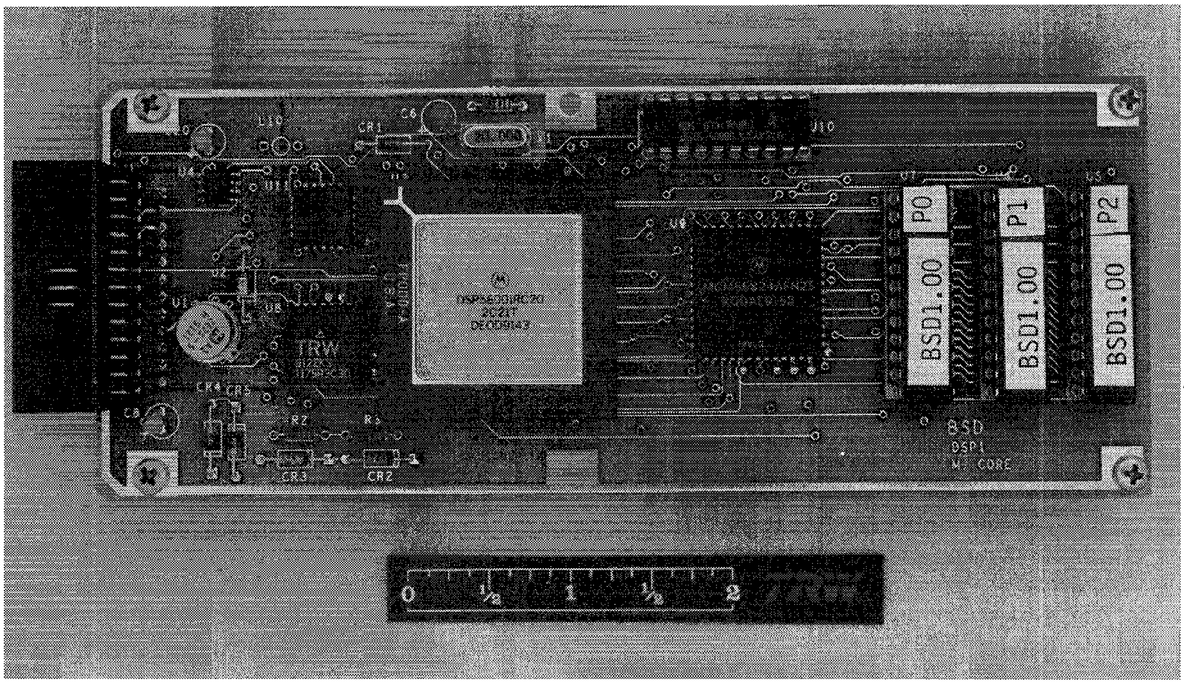
B. Linearizer, IF AGC, and DC Power Supply

In order to achieve the 0.5-m range resolution, the VCO requires a tuning range of more than 350 MHz; therefore, a linearizer is designed to compensate the VCO tuning curves. The linearizer circuit produces the voltage sweep waveform used to drive the VCO. The voltage sweep waveform is predistorted to produce a linear frequency ramp function at the VCO output. Fig. 5(a) shows the schematic diagram of the linearizer.

The input drive waveform is a voltage step with duration slightly longer than the desired output sweep and a low duty cycle. The first operational amplifier (op-amp) stage provides a high impedance load to the DSP board and a low impedance output to the linearizer. The linearizer is a modified integrator circuit. R1, C1 and the op-amp form an integrator which will produce a linear ramp of voltage versus time when V_{in} is nonzero. R2 was added to discharge C1 between sweeps; this is practical because of the low duty cycle. The input arm formed by R5, C3 and R6 provides a component of current that will accelerate the voltage ramp over time, increasing the ramp rate the most during the last half of the sweep. The input arm formed by C2, R3 and R4 provides a current component which is maximum at the beginning of the sweep and reduces over time so it has the most effect over the first half of the sweep. This approach provides freedom to set the ramp rate at the beginning, middle and end of the sweep. Both the amplitude and time constant of the current components were set to produce the desired waveform. Fig. 5(b) illustrates the desired (ideal curve) and actual (simulated performance) curves for the linearizer output voltage.



(a)



(b)

Fig. 6. (a) Functional block diagram and (b) photograph of the DSP board.

The IF receiver consists of two single-stage MMIC amplifiers and an analog variable attenuator. All of them are off-the-shelf components. Each amplifier has 24 dB gain and the attenuation ranges from 0–70 dB. The power supply board converts the +12 V battery voltage into ±5 and +10 V for RF front-end, IF receiver, and DSP board. Total power consumption is less than 2 W.

C. Digital Signal Processor

The digital signal processor converts the IF output to usable range and velocity values that can be fed to a cruise control or driver display. Depending on the application, the requirements on the signal processing can be quite severe, yet it must be accomplished at very low cost to be accepted by the automotive consumer.

Since FLAR is looking out along the road surface, there will be many cars in the field of view at close ranges. Also, large amounts of clutter will be observed in the form of road signs, guard rails, overpasses, cars parked along side the roadway, etc. These factors require sophisticated signal processing to ignore clutter and maintain track on the target of interest.

An intelligent cruise control requires high precision on the range and velocity measurements because they are part of

Fig. 7. Photograph showing that the prototype FLAR was mounted on a platform in front of the grill of the vehicle.

a closed-loop system servoing around zero relative velocity. A collision warning radar does not require high precision, but requires the capability to track high closing velocities and acquire new targets rapidly. It also requires a detection probability as close to one as possible and a false alarm probability as close to zero as possible.

Our application was for AICC. To meet the signal processing requirements within the cost constraints of the commercial automotive market, we chose to perform the signal processing digitally with a commercial programmable digital signal processor. Utilizing DSP rather than analog signal processing allows some very sophisticated algorithms to be used in a low cost system. In addition, the algorithms can be easily reprogrammed and are immune to factors such as temperature and aging.

The IF signal is digitized with an 8-bit analog to digital converter (ADC). An IF AGC is required before the ADC because the dynamic range of the radar signal is much greater than 8 bits. Once the signal is in digital form, some very sophisticated signal processing can be performed. Because this is an FMCW radar, the first step is to estimate the frequency spectrum of the IF output. This is done by windowing the time samples and then performing an FFT. The output of the FFT is the amplitude of the signal versus frequency. This is equivalent to amplitude versus range. Several of these range profiles can be integrated together to increase the signal-to-noise ratio against random noise. The next step is to distinguish targets from noise. This is determined using an adaptive thresholding algorithm known as constant false alarm rate (CFAR). The CFAR algorithm determines a threshold for each range cell that is based on the surrounding noise floor. If the amplitude of that range cell is above the threshold, then it is assumed to be a target. Because the total range of an automotive radar is small compared to the size of the targets, the target will cover several range cells. All adjacent cells with targets in them are assumed to represent one target and the centroid is computed to determine the range for that target.

The signal processing after this point is divided into two main functions: acquisition and tracking. Acquisition is deciding what is a valid target and deciding whether to begin tracking it. Tracking is following the target in the range space and reporting its range and velocity to the accuracy required by the application. Fig. 6(a) and (b) shows the functional block diagram and photograph of the DSP board, respectively.

IV. Radar Test Result

As shown in Fig. 7, the prototype FLAR was mounted on a platform in front of the grill of the vehicle. The platform can be slightly adjusted to align the antenna beam in a proper direction. Fig. 8(a) is the test result on a highway. It shows that the radar acquired a target at 35-m range and the range varied as the driver changed the vehicle speed to vary the distance between the target and driver. The radar tracked the target up to more than 100 m although the target range resolution decreased at longer distance, indicating that the VCO linearity needs to be further improved for better results. Fig. 8(b) and (c) illustrates the real time display showing the target range and velocity. It also features an audio signal to warn the driver of a potential obstacle. In a closed-loop test with the cruise control, this prototype FLAR automatically adjusted the vehicle speed to maintain a constant safe following distance from the lead vehicle.

V. Summary

We have presented a prototype W-band all-weather automotive radar based on a single-chip 0.1-μm AlGaAs/InGaAs/GaAs HEMT transceiver. The prototype radar used for autonomous intelligent cruise control in a passenger car is demonstrated. The computed range and velocity agree well with measurement data. The maturity of HEMT MMIC technology, as well as a simple radar architecture, enables the low cost and small size of the MMW component for this radar.

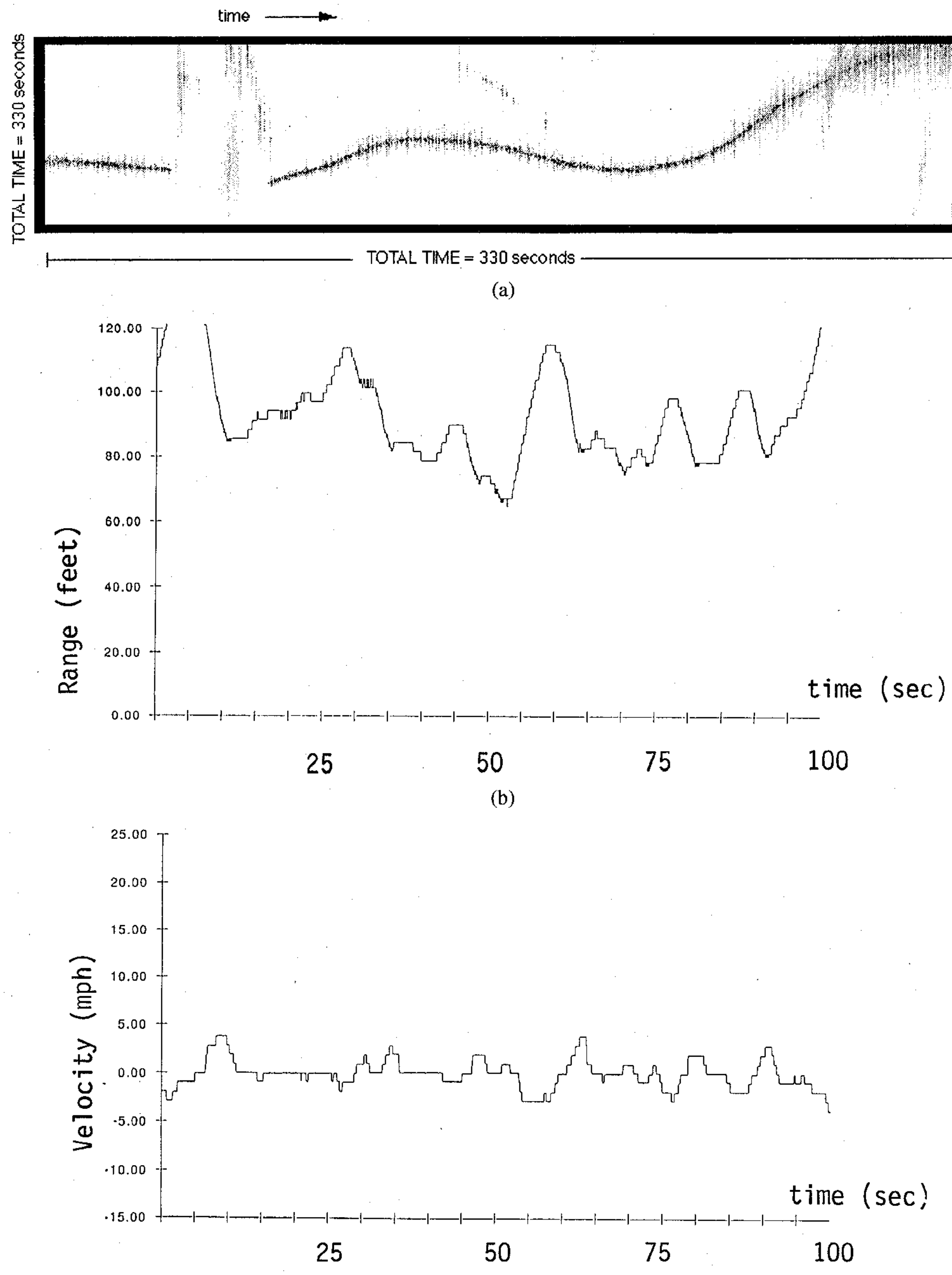


Fig. 8. Road test results of the FLAR. (a) Playback data of the test result on a highway. Real time (b) range, and (c) speed, display on a personal computer.

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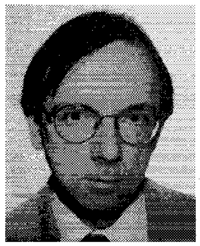

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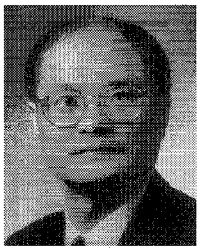

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