Ultra Wide Band 24GHz Automotive Radar Front-End

Ian Gresham, Alan Jenkins, Robert Egri, Channabasappa Eswarappa, Frank Kolak, Ratana Wohlert, Jacqueline Bennett, J-P Lanteri

M/A-COM Corporate Research and Development, Lowell, MA 01853, USA

Abstract — **The recent approval granted by the FCC for the use of Ultra Wide Band (UWB) signals for vehicular radar applications has provided a gateway for production of these sensors as early as in 2004. However, the rules governing the allowable spectral occupancy create significant constraints on the sensors operation. The implications for waveform design and the consequent limitation on system architecture, including antenna design and receiver architecture are discussed. Other practical considerations such as available semiconductor technology with low-cost plastic packaging are reviewed. This is developed into a methodology for developing a single board sensor with integrated antenna. Results are presented for a specification compliant antenna, and a low-cost plastic package for 24GHz ICs. Finally, the required IC architecture for a Transceiver is presented, along with measured results of a single-chip homodyne I/Q down-conversion receiver fabricated in SiGe.**

I. INTRODUCTION

The demand for proximity sensors – be they radar, infrared, video, or ultra-sonic – from automotive customers and manufacturers is increasing. These sensors are intended to fulfill many functions and applications from simple parking aids, to blind-spot detection, and ultimately pre-crash detection, as illustrated in Figure 1. While originally portrayed as being driver-aids, the end goal is to improve road safety, and reduce the number of fatal accidents, through surrounding the car with a 360° radar map that monitors, detects, and automatically evaluates potentially dangerous situations [1].

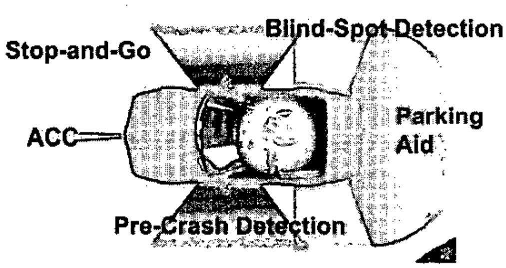

Fig. 1. A 360° radar map around the car will enable several functions for both driver aid, and safety applications.

The precise requirements for each of the applications – detection range, update rate, range resolution – are variable depending upon the manufacturer and the level of networking between sensors. The long-term vision of automotive manufacturers sees complete interaction between radar sensors – with for example, overlap between the longer range Autonomous Cruise Control (ACC) and the Stop-and-Go functions – with additional support from other monitors that are aware of driver attentiveness, road conditions, et cetera. The ability of radar sensors to provide this versatility of function is therefore perceived as critical, as they offer the level of range resolution and immunity to weather unavailable with other technological solutions [2].

II. FCC UWB RULING AND IMPLICATIONS

FCC UWB Ruling, FCC 02-48, Section 15.515
Sensor Operating only when engine running, upon specific activation
Bandwidth contained between 22 - 29 GHz, Center Frequency greater than 24.075 GHz
Minimum Signal BW 20% or 500 MHz
Radiated Emission 22 to 29 GHz limited to −41.3 dBm EIRP, 1 MHz BW, 1 ms average
Radiated Emission Peak 0 dBm EIRP in 50 MHz around highest emission frequency
Emissions 23.6 to 24 GHz 30° above horizon - 25 dB below spec limit by 2005 - 30 dB below spec limit by 2010 - 35 dB below spec limit by 2014

Table 1. Summary of the key elements of the FCC ruling governing UWB radars for vehicular applications [3].

Although ACC radars are available today, their intended operation is very different from that required of short-range sensors, and requires a minimum range of between 20m-30m, and a range resolution of around 2m. Distance resolution of approximately 7.5cm requires, simplistically,

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a waveform that occupies 4GHz of spectrum, and has precluded the use of UWB sensors to date due to regulatory constraints. After several years of preparation and consultation with the industry and the public, the FCC issued an UWB ruling in February 2002 that opens the door for UWB communications and automotive radar. Due to numerous inputs, comments and objections, especially from remote sensing and astronomy users of the 24 GHz band, the ruling is complex and limits emission levels in several ways. The principal points of the ruling are summarized in Table 1. The most stringent of these restrictions is the level of spectral emissions in the 23.6GHz-24GHz band which is used for astronomical study.

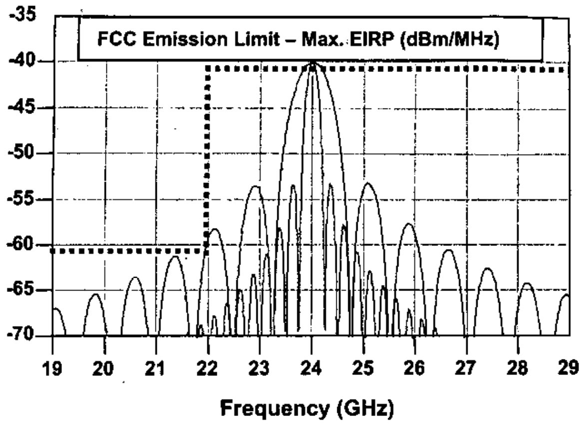

Fig. 2. Average Power Limitations of FCC UWB ruling with spectral power densities of varying pulse widths and p.r.i.

The functionality of the short-range sensor can be split into that of near-range (<5m) and mid- to far-range (15m-30m) applications. Near range functions require higher range resolution, and are still faced with a high-dynamic range of target Radar Cross Sections (RCS). These systems may often be realized with a PN-Coded or FMCW system architecture [4]. However, the difficulty of maintaining adequate isolation between the Tx and Rx antennae limits their dynamic range, and restricts operation to less than 10m. Longer range detection requires a pulsed architecture that, although it requires complex timing and delay circuitry, allows the isolation between the Tx and Rx to be increased thus enhancing the dynamic range [5]. Pulsed operation requires a complex trade-off between maximum and minimum pulse width (limited to 300pS < τ < 4nS by the FCC ruling) and the consequent range resolution, pulse-repetition interval (p.r.i) and spectral occupancy versus unambiguous detection, and average radiated power. This analysis is also a function of the antenna pattern (gain, beamwidth) and receiver architecture, and cannot be done in isolation of these considerations.

The average power limitations over 19-29 GHz are plotted in Figure 2. The FCC ruling limits the peak power to –17 dBm EIRP per 1 MHz of bandwidth, assuming constant power over 50 MHz. Combined with the –41.3 dBm limit, we can infer a pulsed operation, with a duty cycle of 1/269, around 0.4%, to take full advantage of the average power specifications. These specifications limit the detection range achievable with an UWB sensor and favor the use of the whole available 7 GHz band to increase the equivalent radiated power. Unfortunately a 7 GHz bandwidth would require a 300pS wide pulse, challenging with today's technology. Practical systems will use 1 to 4 GHz of bandwidth and not reach the maximum radiated emission possible over the band. Other system approaches need to be considered to extend the sensor range if required. The FCC ruling also limits emissions in the radio-astronomy band, 23.6 GHz to 24 GHz, by requiring significantly reduced power levels 30° above the horizontal, from –25 dB below the specification in 2005 to –35 dB in 2014. These stringent levels require novel antenna concepts to ensure very low sidelobe levels. The goal of these limitations is to protect remote earth sensing and radio-astronomy observations.

III. INTEGRATED SENSOR DESIGN

Clearly, a key enabler of this technology is the ability to produce very low-cost integrated mm-wave modules. Current sensors scheduled for production are built using conventional surface-mount, distributed circuits with discrete baseband processing and control circuitry. Aside from cost, repeatability, and yield issues of this approach, the wide instantaneous bandwidth of sub nS long pulses makes the design of distributed circuits problematic.

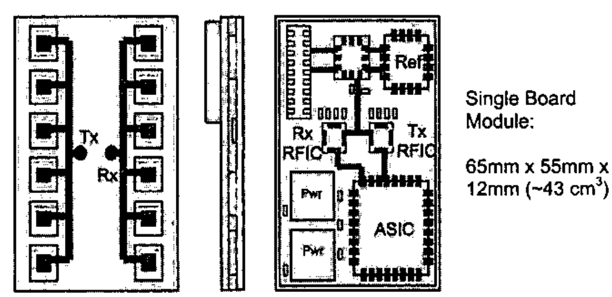

Fig. 3. Conceptual drawing of a single board mm-wave sensor with integrated Tx and Rx Antennae and Tx/Rx RFIC.

Figure 3 shows a conceptual drawing of an approach to address this problem. Consisting of a single board with integrated Tx and Rx antennae on the reverse side, the base-band and microwave circuitry would be realized using essentially three separate integrated circuits – a single chip Tx IC, a single chip Rx IC, and an ASIC that produces control signals and performs pre-processing of received data for formatting and interfacing with the vehicles' CAN-bus. This modular approach extends the system-on-a-chip philosophy to the simultaneous design of the antennae, board, packaging, and IC to optimize performance. Clearly, any transition design between the IC and the module board for example, would also need to consider the IC driving circuitry, and in the case of the Tx output and the Rx input, the loading effect of the antenna. The top surface of the module would be potted with a typical molding compound to produce a sealed cover for the module. Following this philosophy, we have designed several of the required components.

A. RFIC Architecture

The architecture of the direct down conversion pulsed correlation radar is shown schematically in Fig. 4.

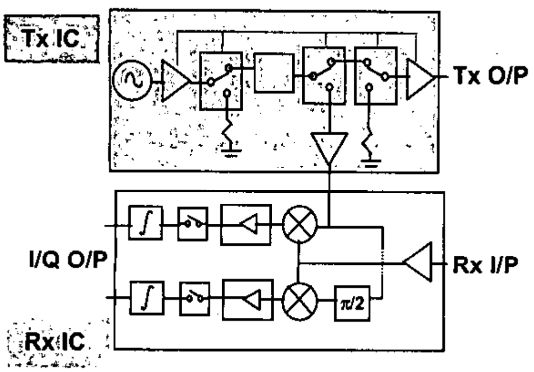

Fig. 4. Example of RF architecture for an RFIC solution for the pulsed radar sensor.

The large dynamic range required of the sensor to cover a range of 0.1m-30m, plus the myriad of potential RCS that the automotive operating environment presents suggests that the most natural segmentation of functionality is to break the Rx and Tx functions into separate ICs. This gives the designer the most control over isolation between the two functions, and allows the noise sensitive LNA to be mounted in a different location to the signal source and potentially noisy control signals. SiGe is the preferred semiconductor for this circuitry due to its low-cost potential, ability to integrate base-band functions, high circuit density, plus the relatively low signal power and high noise figure that can be accommodated in this particular function [6]. All of the circuit functions shown in Figure 4 – VCO, Switches, Amplifiers (LNA and Output PA), and Down-conversion multipliers – have been designed and demonstrated in SiGe at 24GHz, using the *Atmel SiGe2rf* process which is based on a 0.5μm emitter-width HBT with an intrinsic f_t > 80GHz. This commercially available 150mm bipolar process uses a standard substrate resistivity of 1000 Ω.cm.

Figure 5 shows a measurement of the single chip Rx IC that includes an LNA, power splitter, and I- and Q-channel down-conversion multipliers. The correlation architecture allows the Rx IC to use the same 24GHz source as that of the Tx IC by employing fast-switching techniques to steer the 24GHz signal. The plot shows the single-sideband Noise Figure and Conversion Gain of a –40dBm Rx signal at an IF of ±10MHz-1 GHz for a fixed LO signal of f_{LO} = 24GHz; P_{LO} = 0dBm.

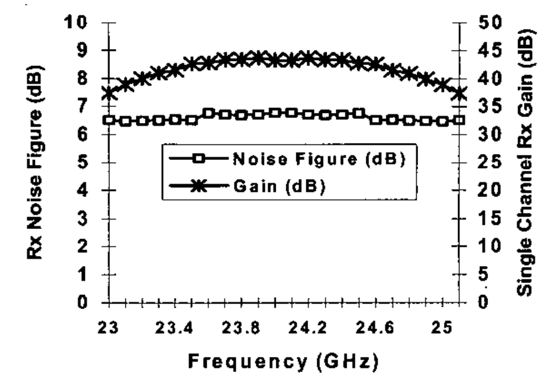

Fig. 5. Measured Single Channel Rx Gain and Noise Figure as a function of IF bandwidth (10MHz-1GHz) around 24GHz

A single channel receiver conversion gain of > 40dB with a Noise Figure of < 7dB across the 2GHz band was measured on-wafer. The measurement demonstrates the performance available from a single-chip SiGe receiver, and is commensurate with system-level requirements.

B. Plastic Packaging

Low-cost plastic packages are desirable due to their availability and price. They are a key element in the ability to produce truly low-cost mm-wave systems. Of particular interest are the series of MLF/MLP packages that have an open lead frame as the reverse side of the package thus offering a good, local RF ground. Traditionally, the long wire bonds and dielectric encapsulating material have proved problematic in employing these packages at high frequencies. However, the use of compensation circuitry can readily compensate for these discontinuities.

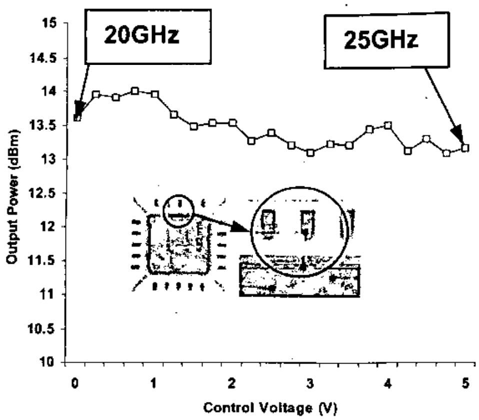

Fig. 6. Example of a plastic package VCO operating over 20-25GHz.

Fig. 6 shows a VCO MMIC mounted in a conventional MLF plastic package. The 18μm bond-wire for the output can be clearly seen in the X-ray image. Careful package and board interconnect design techniques maintain a flat output power characteristic (±0.5dB including device variations) over the 20-25GHz frequency range. The molding compound used is Shinetsu KMC218.

C. Antennae

The challenging specifications imposed by the FCC ruling on side-lobe generation in elevation are one of the principal considerations in antenna design. Typical azimuth coverage of a single sensor (one of the suite that surrounds the vehicle) is ±40°, with corresponding elevation coverage of approximately 12°-15°. Resulting antenna gain is between 11dBi and 14dBi depending upon the specific approach taken. The precise specification upon elevation side-lobe level is, therefore, a function of antenna gain and the particular waveform selected. The FCC specification only stipulates the emission level of the radiated power spectral density, and is therefore flexible. In our system, this translates to a maximum antenna side-lobe level in elevation of < -25dB relative to bore sight at θ>30°. Extensive EM-modeling was used to design a slot-radiated antenna that complies with this specification, and the excellent correlation between modeled and measured results is shown in Fig.7. Careful design was also employed to reduce the cross-talk between the adjacent Tx and Rx antennae to < -50dB, although this figure degrades when the sensor is mounted *in situ* behind the vehicles' fascia.

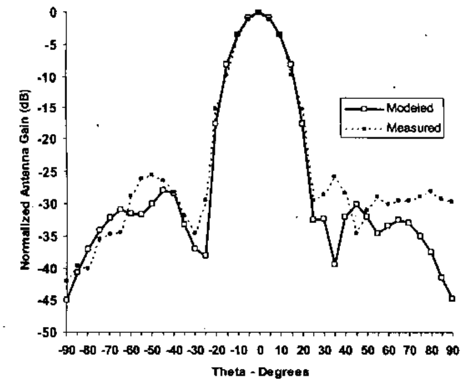

Fig. 7. Modeled versus measured result for a FCC specification compliant antenna showing elevation sidelobes.

IV. CONCLUSION

UWB automotive sensors require the utmost in performance while at the same time satisfying aggressive cost structures. In order to meet requirements, the design concept needs to embrace system design (to meet the application requirements), waveform design (to meet the regulatory requirements), novel circuit design to reach the cost/performance targets, and a packaging philosophy commensurate with all of the above. Key technology that addresses these issues for UWB automotive sensors has been developed and presented.

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