Advancement of PMCW Radar and Its Board-Level Prototyping

Michael Brown
Department of Electrical and Computer Engineering
Texas Tech University
Lubbock, TX, 79409, USA
michael.c.brown@ttu.edu

Changzhi Li
Department of Electrical and Computer Engineering
Texas Tech University
Lubbock, TX, 79409, USA
changzhi.li@ttu.edu

***Abstract*—This paper reviews recent advancements in phase-modulated continuous-wave (PMCW) radar design and implementation, along with the design and prototyping of PMCW radars on the board level for rapid testing and iteration. In the last five years, a plethora of PMCW radar simulation research has been conducted, which modern IC and board-level microwave component design has caught up to. Benchtop systems and embedded system-on-chip PMCW radars have been realized, allowing for progress toward high-accuracy radars that incorporate advanced digital signal processing techniques. With access to faster semiconductor technologies, embedded chip solutions, and improved printed circuit board (PCB) techniques, PMCW radars can be realized on a portable board-level system. This paper reviews the concepts surrounding PMCW radars, as well as recent simulation efforts and radar system realizations through PCB designs and integrated system-on-chips.**

***Keywords*—Automotive radar, noncontact measurement, orthogonal waveform encoding, PCB technology, phase modulated continuous wave (PMCW) radar, radar interference mitigation, system prototyping.**

I. INTRODUCTION

With recent improvements in on-chip development and CMOS design, as well as printed circuit board (PCB) technology, millimeter-wave radars are now able to implement digital methods that have been theorized and incorporated into communications systems. Modern millimeter-wave radar systems, driven mainly by the automotive industry's push toward autonomous driving, have begun to incorporate these digital concepts to tackle the growing spectrally cluttered working environment. Until recently, the application of theorized techniques for monitoring and imaging targets by measuring their distance, angle, and velocity using radars has been limited by the processing speed, cost, and modulation speed of digital components.

In modern radar, the main beneficiary of improved digital components and integration methods is phase-modulated continuous-wave (PMCW) radars. A simplified block diagram of a basic PMCW radar is shown in Fig. 1. For these systems, which focus on the time-domain signal response of a target, the modulation and sampling speeds of components plays a large role in the performance of these radars. New radar designs must compete for application and frequency spectrum space with the well-studied and prevalent frequency-modulated continuous-wave (FMCW) radar architecture. FMCW radars have held the advantage with methods to increase the bandwidth of the signal,

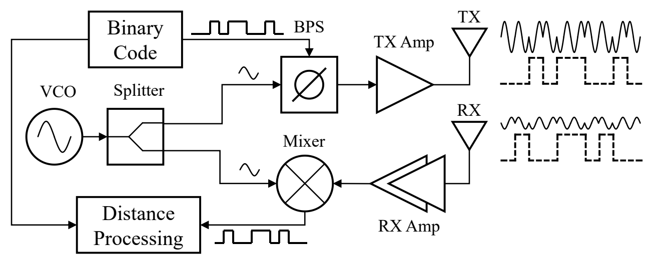

Fig. 1. Simplified PMCW block diagram.

which is directly correlated to the range resolution of the system. Now, as clock speeds of components have increased and become more stable, the available sampling and processing speeds have widened the potential for PMCW radars. By increasing clock speeds, PMCW radars directly increase their operational bandwidth and improve their range resolution. Now that signal modulation and receiver sampling rates, as well as their component costs, have caught up with FMCW components, PMCW radars are starting to become a competitive alternative.

As applications of radar systems continue to grow, so does the frequency spectrum clutter in which they operate. The conventional FMCW radar will intermittently occupy its entire frequency band [1], which leads to rippling interference patterns shown in Fig. 2a [2]. To address this issue, various techniques have been investigated to improve mutual operation and reduce the impact of generated interference [3]. A more attractive solution to the growing condensed signal environment is to use PMCW radars, which look to reduce system-system interference by operating with a modulated single-frequency carrier. Whereas FMCW radars will intermittently occupy their operating bandwidth, PMCW radars instead spread out the modulated carrier. By taking pages from communication systems, PMCW radars can use pseudorandom encoding to isolate from one another, as shown in Fig. 2b. This results in a broad noise floor increase, but one in which the target can still be easily extracted provided the interfering radars use different encoding schemes [2]. To achieve a low interference level, the encoding schemes can be different code lengths, autocorrelation code families, or bit rates.

The main radar application space looking to be bolstered by PMCW systems is multiple-input multiple-output (MIMO) systems, which allow for improvements in target positioning and isolation through virtual transmitter-receiver arrays [4]. MIMO radars have various methods of distributing their signals to

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(a) (b)

Fig. 2. Radar-to-radar interference examples from [2]. (a) FMCW-to-FMCW uncorrelated interference scenario caused by residual coherence over slow-time samples. (b) PMCW-to-PMCW interference scenario for APAS(3868) and ZCZ(4096) code families.

generate these virtual arrays, such as time-division multiple access (TDMA), orthogonal frequency-division multiplexing (OFDM), and code-division multiple access (CDMA). TDMA suffers from having to cycle each transmitter individually, slowing the processing speed by the number of transmitting antennas, while OFDM sacrifices frequency bandwidth to achieve channel orthogonality. In contrast, at the cost of more complex processing, CDMA-based MIMO radars can utilize the full frequency bandwidth while preserving the orthogonality of the transmission channels by using binary encodings [5].

This paper covers an introduction to PMCW radar theory along with advancements in signal encoding, recovery, and interference mitigation techniques. It then discusses various PMCW chip-level implementations, and lastly how improvements in PCB technology have allowed for board and system-level radar realizations.

II. PMCW Radar Theory

With continuous wave radar systems, information about the target is acquired through the reflected radio signal. For moving targets, the reflected signal will induce a Doppler frequency shift on the carrier, which is recoverable through downconverting the received signal with the unmodulated carrier. By applying additional modulation to the carrier, information such as target position can be recovered. This is commonly done using FMCW radars and analyzing the frequency domain of the baseband signal. PMCW radars, however, modulate the phase with a known pseudorandom signal and look at the time domain response to correlate the recovered signal into range bins.

Keeping pace with FMCW radar systems has been a daunting challenge for PMCW radars. Much of the recent PMCW advancements have been focused on system-level simulations that aim to reduce the spectral impact of modulated waveforms through improved modulation methods [6], to work with fewer bits on the baseband analog-to-digital converter (ADC) [7], and analyzing Doppler shift tolerance of binary sequences [8]. The range resolution of PMCW radars is dependent on their modulation bit frequency F_c, similar to how FMCW radars' range resolution is dependent on the bandwidth of their frequency sweep B_F [9]. This can be simplified to

$$R_{Res} = \frac{c}{2 * F_c} = \frac{c}{2 * B_F} \tag{1}$$

where c is the speed of the electromagnetic wave. For FMCW radars, the bandwidth can be swept with a ramp signal on the voltage-controlled oscillator (VCO) or signal source, allowing for straightforward access to wide bandwidths. From (1), the range resolution is also tied to the carrier frequency of the radar, since as VCO frequencies increase their proportional operating bandwidths tend to remain the same. This allows for FMCW radars with a 6% operational bandwidth at the designated automotive radar band (77-81 GHz) to perform substantially better than at the previous ISM band (24 GHz to 24.25 GHz), in addition to being allowed to increase the maximum range through higher transmit power allowance [10].

PMCW radars, on the other hand, need to increase their phase modulation rate to achieve better range resolution. Additionally, a quadrature downconverter can be used to overcome nulls in the recovered phase response. In binary phase shift PMCW radars that use perfectly out-of-phase states such as 0° and 180°, the baseband signal can be simplified to

$$\begin{aligned} BB_I(t) &= \cos\left(\theta + \frac{4\pi x(t)}{\lambda} + M\left(t - \frac{4\pi d_0}{\lambda}\right)\right) \\ BB_Q(t) &= \sin\left(\theta + \frac{4\pi x(t)}{\lambda} + M\left(t - \frac{4\pi d_0}{\lambda}\right)\right) \end{aligned} \quad (2),$$

which are the quadrature *I/Q* signals defined in [11] that include the binary modulation sequence $M(t)$ and where θ is the phase modulation constant in the system. $4\pi x(t)/\lambda$ is the Doppler shift induced by the target, and $4\pi d_0/\lambda$ is the introduced phase delay from the time-of-flight from the radar to the target. From (2) the rate at which $M(t)$ changes, as in the modulation clock frequency, needs to be much high than the induced Doppler frequency shift from a target to recover the time-induced phase delay of the modulated signal. To achieve high-range resolution, a heavy load is placed on the baseband signal acquisition. This is because the sampling frequency of the data acquisition device needs to be either synchronous with the baseband signal frequency as in [5] or adhere to Nyquist sampling frequency requirements where $F_{samp} \geq F_c$. Development for digital processers and modulators that operate at comparable speeds with FMCW bandwidths is still ongoing but is within reach thanks to recent progress in high-speed field programmable gate arrays (FPGA) and oscilloscopes capable of multiple Gsa/s which can measure the baseband.

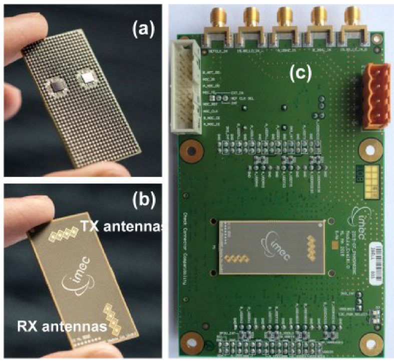

Fig. 3. 79 GHz SoC 4x4 MIMO PMCW Radar. (a) Antenna module die side. (b) Antenna side. (c) Evaluation board. From [5].

III. Hardware Advancements

To realize the large body of theoretical potential in PMCW radars, CMOS transmitters, receivers, phase modulators, and binary sequence generator chips have been developed for the 60, 79, and 140 GHz bands, where these wider available bands are less spectrally cluttered. These mainly target MIMO applications, such as automotive radar, but could be adapted for gesture recognition and vital sign monitoring [12].

In the D-Band (110-170 GHz), where radar technology is still emerging, key components for PMCW radars are starting to be designed and tested. In [13] a binary-phase-shift-keying (BPSK) modulator was integrated onto a 22-nm FDSOI CMOS package. Phase modulators are one of the critical components in a PMCW radar system, and this chip is capable of supporting a modulation frequency of 12.5 GHz at 140 GHz. This active modulator also meets low power demands, having a DC power consumption of 27 mW and an output P1dB of -7.2 dBm, well above similar state-of-the-art CMOS modulators and mixers. To enable D-Band PMCW and joint radar-communication systems with components such as [13], a 15-Gb/s pseudorandom binary sequence (PRBS) generator was developed on the same 22-nm FDSOI CMOS technology [14]. This chip can be used to generate efficient fast-time phase-modulated signals, and with the integrated slow-time encoder it can be expanded for use in orthogonal phase-modulated MIMO radars.

Looking to meet demands in the newly assigned W-band (75-110 GHz) automotive radar spectrum, a fully integrated 79 GHz MIMO PMCW radar 28-nm CMOS chip with two transmitters and receivers was developed in [5]. This chip includes a synchronous 2 Gsa/s seven-bit ADC, allowing it to process the receiver baseband as fast as it is modulated. The data rate for the chip is lowered to 80 Mb/s by accumulating multiple range correlations, which helps reduce strain on downstream processing systems. Additionally, the chips can be combined, as shown in Fig. 3 from [5], to make a 4x4 MIMO system. By utilizing an embedded FPGA, the modulation scheme is reconfigurable, allowing for a variety of pseudorandom encoding possibilities.

A Gaussian minimum-shift keying (GMSK) based MIMO radar system-on-chip in the 77-79 GHz band made on 28-nm CMOS technology is outlined in [15]. Unlike previously discussed systems, this radar uses four phase states rather than two binary ones to improve spectral efficiency. It also uses receiver multiplexing to allow for a second set of antennas, enabling azimuth and elevation target profiling. With 12 transmit and a pair of eight receive antennas, the radar offers a high angular resolution, up to 1° with 192 virtual channels. The chip also has built-in 2 Gsa/s ADCs, which are followed by a digital front-end and data control unit to handle the various radar data measurements.

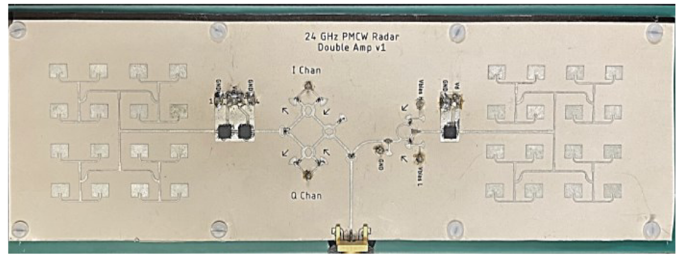

Fig. 4. A Rogers 3003-based PMCW RF front-end board level radar prototype mounted on FR4 baseband board.

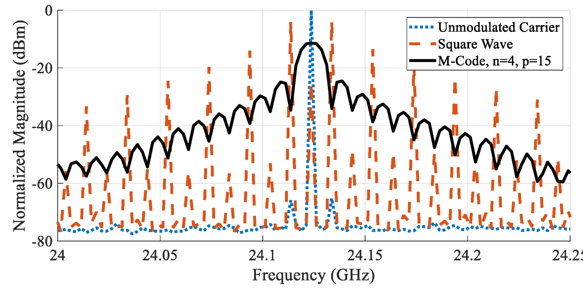

Fig. 5. K-band PMCW radar spectral output for an unmodulated carrier, a carrier modulated with a 10 MHz square wave, and a 10 MHz 15-bit m-code.

IV. Board level Prototyping

While CMOS technology is able to take PMCW concepts and integrate them into System-on-Chips (SoC), improvements in substrate and PCB technology have also been a boon to PMCW radar design. Substrates with lower loss tangents and dielectric constants open the door for compact planar components to be used in radar systems along with the ever-improving silicon components. The results of these improvements in PCB technology are more compact antennas, as well as more complex microwave structures that can have wider operational bandwidths, are less lossy, and can have a higher operating frequency. This allows for full radar systems to be implementable at the board level, such as [16] which also includes various test points and the ability to replace or adjust the antennas.

Board-level designs can also be adapted to provide component isolation test boards while building up to full system verification. For instance, the microwave structures in the K-band PMCW radar front-end that are implemented on a 10 mil (250 µm) Rogers 3003 substrate, shown in Fig. 4, can all be made on evaluation boards to allow for testing minor layout adjustments, impedance matching, and manufacturing tolerance. The output power spectrum of this PMCW radar, shown in Fig. 5, was measured when the phase was unmodulated, modulated with a 10 MHz square wave, and a 15-bit m-code sequence with

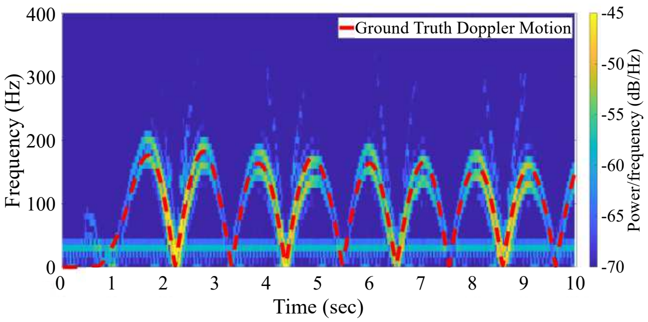

Fig. 6. K-band PMCW radar Doppler response of a target moving toward and away from the radar.

0.1 μsec symbol widths and a single point of circular autocorrelation. The spectrum shows the harmonics introduced every 10 MHz by the BPSK modulation, while the coded sequence spreads out the power across the spectrum. Fig. 6 shows the spectrogram response of the radar when the carrier phase is BPSK modulated at 10 MHz and measuring an oscillating target. The target induces an increasing Doppler frequency when moving toward or away from the radar, which decreases when slowing down in its motion arc.

One challenge with moving to higher frequencies faced at the board level is the need for thin substrates to reduce losses along with higher dielectric constants to accommodate line widths less than a quarter wavelength. Thin boards, such as 10 mil (250 μm) panels, also face physical integrity issues, but these can be alleviated by stacking or mounting additional board layers of thicker substrates to improve mechanical stability.

With the push to increase the range resolution of radars, wider bandwidth components are needed. CMOS chip development and testing, while successful, takes time compared to board-level designing. The improvements in substrate technology have allowed critical components, such as power splitters, hybrid couplers, and phase shifters to be realized using transmission line theory. These components can achieve high bandwidths through the implementation of additional stages, as in [17], while also being more open to iterations to improve system performance.

V. Conclusion

As demands for radar applications increase, along with the demands for operating space in the frequency spectrum, the requirements and designs of modern modulated radars will need to shift to accommodate noisier and more demanding working environments. Integrated systems and CMOS components, along with faster processing systems, have opened the door for PMCW radars to start to realize the potential of digital radars. Meanwhile, PCB technology is bolstering the testing and verification of phase modulation theories and simulations. As advancements in clock speeds, chip development, and PCB technology continue to improve radar systems, interference management will need to progress to keep up with the increasing demand for radar performance and implementation, such as in automated/assisted driving, vital sign detection, and gesture recognition systems.

Acknowledgment

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