A CMOS 79GHz PMCW Radar SoC

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Abstract

- High-performance, small form factor millimeter-wave radar systems are key enablers for the new smart society. Application for automotive driver assistance and even autonomous cars is obvious, but also many other systems like vital signs monitoring, gesture recognition, self-guided drones, etc are envisioned.

- The research presented in this talk investigates the use of nanoscale CMOS technology for 79GHz radar systems, which will be a key enabler to open up this market for cost-effective high-volume production, and allows integration of large digital processing in the same System-on-Chip. A new concept of phase-modulated radar detection is also introduced that blends perfectly with the integration capabilities of CMOS.
Why mmWave radars?
mmWave Sensors are Extremely Robust

- snow & rain
- fog
- smoke
- dust
- lighting
- noise & vibration
- dirt
- heat
mmWave Sensors are Fully Sealed and Invisibly Mounted

perfect aesthetics
discreet monitoring
privacy
Radar evolution

yesterday

fixed mobile

automotive today

79 GHz radar SoC module

tomorrow

140 GHz antenna-on-chip systems?
Radar resolution (smaller is better)

- Speed: improves with higher carrier
- Range: improves with wider bandwidth
- Angle: improves with larger antenna

 Frequencies:
- 24 GHz
- 77 GHz
- 79 GHz
- 140 GHz
10+ radars per car

- High-resolution, 360 degree radar coverage

Short Range Radar (SRR) up to 30m

Medium Range Radar (MRR) up to 80m

Long Range Radar (LRR) up to 250m
79 GHz PMCW Radar System
New Paradigm: mmWave CMOS Radar-on-Chip

high **resolution** – low **power** – low **cost** – small **size**

leveraging **standard foundry technology**
## High Level Comparison: PMCW vs FMCW

<table>
<thead>
<tr>
<th>Feature</th>
<th>PMCW</th>
<th>FMCW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambiguity function, sidelobes</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Sensitivity to phase noise, flicker noise</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>ADC resolution</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>ADC speed / IF bandwidth</td>
<td></td>
<td>+++</td>
</tr>
<tr>
<td>PSD</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Sensitivity to interference</td>
<td>+/-</td>
<td></td>
</tr>
<tr>
<td>TX orthogonality for MIMO</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Communications capability</td>
<td>++</td>
<td></td>
</tr>
<tr>
<td>Industrial acceptance</td>
<td></td>
<td>+++</td>
</tr>
<tr>
<td>easier market entry / limited IP and patents</td>
<td>++</td>
<td></td>
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</tbody>
</table>
PMCW Radar Operating Principle

Target at
\[ D = \frac{4 \times T_{\text{chip}} \times C}{2} \]

\( C \) = speed of light in air
\( G \) = Path Loss

TX

RX

Distance D

Target

2 Gbps

\( T_{\text{chip}} \)

\( m \) \( T_{\text{chip}} \)

79 GHz LO

\( m \) Correlations (multiplication and integration)

\( G \) \( m \)
... and TX-to-RX Spillover

Target at

\[ D = \left( \frac{4 \cdot T_{\text{chip}} \cdot C}{2} \right) \]

\( C = \) speed of light in air
\( G = \) Path Loss

Spillover produces a large response for 0 delay.
PMCW Radar System

Radar IC

- FFT N
- Accumulate M
- Integrate Lc
- Correlation/pulse compression
- Code length Lc
- Rate Rc
- Range Bins
- Lc parallel branches (range gates)
- D⁻¹
- D⁻¹

Correlations with delayed version of the PN sequence → Determine the delay T → the position R

Accumulations → improve SNR

FFTs → determine the frequency shift of every range bin → the speed of the object found on that range bin (Doppler)
Also improves SNR

\[ T = \frac{2R}{c} \]
System design, Implementation and Verification

Validation & demonstration

Module & antennas

IC design

System design
System design

Matlab chain

**Tx waveform generator & DAC**
- detection
- DoA
- beamformers

**Tx analog baseband**
- correlators
- integrators

**Tx analog RF incl. mixers**
- array modeling
- array analysis
- array design
- element modeling
- beamformers

**Rx Doppler bank DoA estimation classification**
- analog: Matlab models
- digital: mixed models?

**Rx range correlator & accumulator & ADC**

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**PLL**

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**Tx antenna array & packaging**
- coordinate systems (location and motion)
- propagation
- clutter models
- target models
- jammer

**Rx antenna array & packaging**
- antennas and packaging: Matlab models (imec param. import?)

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**Targets & propagation**
- targets and propagation: Matlab models

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imec
PMCW Radar-on-Chip: SISO Block Diagram

- **antennas**
- **RF**
- **PRN code**
- **ADCs**
- **ADC**
- **PRN code**
- **Integrate \(L_c\) pulses**
- **Accumulate \(M\) pulses**
- **Lc parallel paths**
- **Lc parallel**
- **N-point DFT**
- **CFAR detection**
- **DoA estimation**
- **Tracking**

**Variables and Corresponding Functions**

- \(T_c\) → Range resolution
- \(L_c\) → Ambiguous range
- \(M\) → Ambiguous speed
- \(N\) → Speed resolution

**High-speed digital front-end**

**Reconfigurable digital baseband**
MIMO Block Diagram

High-speed digital front-end

Reconfigurable digital baseband

Peak extraction
- DoA estimation
- Tracking

MIMO array synthesis

N-point DFT

Nrx*Ntx virtual MIMO antennas

Beam-forming

ADCs

antennas analog front-end

Integrate Lc pulses

Accumulate M pulses

Integrate Lc pulses

Accumulate M pulses
IC – Module - Platform

Integrated circuit containing the core functionality

Carrier containing antennas and mounted ICs, similar form factor to product

Carrier containing module, components and connectors, complemented with computation component (PC, FPGA or similar) for demonstration
PHADAR 2x2 SoC

- Integrated mmWave PLL, TRX, ADCs, digital front end
A 5th Subharmonic, Inverter-Based Injection Locked Oscillator
  - Avoid frequency distribution at 79GHz across the IC

Frequency multiplication
  - Harmonic based multipliers
    - Wide functional range, but less damping at $\omega_0/N$
  - Injection locked oscillators
    - Oscillator must be locked

3X or 5X?
  - 3X locks easier, but PLL @26.333 GHz
  - 5X is only 15.8GHz PLL and frequency distribution
    - Needs lots of 5th order distortion generation
    - Inverters!
Inverter Based ILO for 79GHz

- A > 1V for $i_{out} = 0.82\,mA$, while VDD in 28nm is 0.9V
- Also reliability is worse

<table>
<thead>
<tr>
<th>Input</th>
<th>$i_{out}$ (mA)</th>
<th>$\Theta$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_0$</td>
<td>0.31</td>
<td>148.6</td>
</tr>
<tr>
<td>$\omega_0,3\omega_0$</td>
<td>0.58</td>
<td>148.7</td>
</tr>
<tr>
<td>$\omega_0,3\omega_0,5\omega_0$</td>
<td>0.82</td>
<td>143.8</td>
</tr>
<tr>
<td>Up to $15\omega_0$</td>
<td>0.91</td>
<td>145.1</td>
</tr>
</tbody>
</table>
Implementation

- **Inverter chain**
  - $W_p/W_N$ ratio is adjusted to have 50-50 duty cycle.
  - $L_{mos}=35\text{nm}$
  - 12um, 9um, 16um, 13.5um

- **Oscillator core**
  - $V_{DC2}$ used to enhance self resonance
  - $Q_{\text{var}}=8.5\sim20$
  - $Q_{\text{ind}}=15$
  - $V_{\text{DC}}$
  - $M1:M2=5:1$
Measurements

8GHz Free-running Tuning Range

Locked Phase Noise

10GHz Locking Tange

Oscillation Frequency (GHz)

79 ± 2GHz

Varactor bits

Input Power (dBm)

VDC2=0.55 V
VDC2=0 V

SMR40@15.8GHz
ILO@79GHz

14dB±1dB
PLL and LO Distribution

TX

In-Phase ILOs

PPF for quadrature phase shifters

Poly-phase filters generate quadrature

RX QILOs

Combiner

LP F

Div/8

25MHz

To Dig/ADC

PFD/C

P

Div/N

(79)

Ibias, I Ibias, Q

2-stage PPF

2-stage PPF

Subsampling PLL

15.8 GHz distribution

SS-PD Gm

25MHz

PPF for quadrature phase shifters

15.8 GHz distribution

Integer-N PLL

RX QILO

VCO @ 15.8 GHz
Antenna Path Details

Sub-harmonic Injection Locked Oscillators multiply the PLL frequency by 5
TX architecture

- No LO quadrature
- Transmits @ Psat
- Low side-lobes

PRN Code: \( F_c = \frac{1}{T_c} = 2 \text{Gbps} \)

PRF: \( \frac{1}{(T_c \cdot L_c)} \)

BPSK frequency side-lobes at least -17dBc needed!
79GHz Phase-Modulator

Linear BB
X
Non-linear LO

PRN Code generator

79GHz LO

1 0 0 1 0 1 .. Lc

• Lower 79GHz swing
• More power efficient
TX Sidelobe Reduction by Harmonic Rejection

Most effective side-lobe rejection @ lowest cost
79GHz Modulator and PA: Schematic Detail
Receiver Implementation

Gilbert cell mixer 2dB Gain

2-stage LNA 18dB Gain

VGA stage ≈ 3 → 10.5 dB in 7 steps

ADC driver ≈-2dB gain
RX Spillover Cancellation

In steady state the mixer output is uncorrelated with the TX BB sequence: the spillover is cancelled!
Digital core generates the sequence and performs correlation and accumulation of the ADC samples.
IC Realization

- 28nm CMOS
- Die size 3 x 2.63mm
- Supply 0.9V/1.8V
- Flip chip assembly
IC Floorplan

- 28nm CMOS
- Die size 3 x 2.63mm
- Supply 0.9V/1.8V
- Flip chip assembly
IC Photograph

- 28nm CMOS
- Die size 3 x 2.63mm
- Supply 0.9V/1.8V
- Flip chip assembly
PLL Measurements

- 25 MHz reference
- 16GHz VCO
  - VCO only Phase Noise 
    -116 dBc/Hz @ 10 MHz
  - 2GHz VCO tuning range corresponding to 78 to 88 GHz at TX output
- 79GHz ILO
  - -107dBc/Hz @ 10 MHz

CP-PLL = Charge Pump PLL
SS-PLL = Sub-Sampling PLL
Measured at 79 GHz with R&S FS-Z90 and FSU and Agilent E5052 Signal Analyzer
Transmitter Measurements

- Pout > 10dBm
- 4 GHz BW

Measured with SAGE E band WR12 horn antenna, R&S FS-Z90 and FSU
Receiver Measurements

- NF $< 12\text{dB}$ @ 1 GHz
  - Including module input transition
- More than 30dB gain control in VGA
- BW $> 1\text{ GHz}$

Measured with NOISE COM 5112 and R&S FSU on a dedicated module with GSG pads instead of antennas.
Base Band Analog output before the ADC measured.
Indoor Antenna Module and Evaluation Board

- 2 dies on the back of the module
- Antennas on the front
- Panasonic MegTron6®
PMCW Demonstrator

Radar module (2 chips):
- 4 TX antennas in azimuth
- 4 RX antennas in elevation
- MIMO configuration results in 2x2 and 4x4 array
- Targets can be localized in both azimuth and elevation
Radar Measurements

3 targets in an anechoic environment at different distance, azimuth and elevation

RCS = 20dBs
RCS = 15dBsm
RCS = 10dBsm

Radar board with antenna facing the targets

Lc = 511 (m-Seq), M = 232
Range & Speed Measurements

Range profile at target speed

Doppler profile at target distance
MIMO 4x4 Measurements

Angle of Arrival:

- **RG = 24**,  
  - Azi. = -36.0,  
  - Ele. = 24.0

- **RG = 22**,  
  - Azi. = -33.0,  
  - Ele. = -1.0

- **RG = 13**,  
  - Azi. = 0.0,  
  - Ele. = -1.0
Conclusions

- CMOS Radar SoCs area key building block for next-generation (self-driving) cars
  - And smart homes, buildings, things, etc.
- PMCW radar system is a feasible alternative for current FMCW architectures
  - Major advantage for large-scale radar imagers
- IMEC PMCW radar SoCs prototypes show functionality
  - And are used by partner companies in various application experiments
- The future is still to come; we haven’t seen the last innovation in radars yet 😊
embracing a better life