A 4-Channel 24-27 GHz UWB Phased Array Transmitter in 0.13μm CMOS for Vehicular Radar

Harish Krishnaswamy and Hossein Hashemi

University of Southern California, Los Angeles, CA

Sep 19th, 2007 Custom Integrated Circuits Conference
Outline

• Overview of Vehicular Radar
• Overview of Phased Arrays
• VPRO-PLL UWB Phased Array
• Implementation and Measurements
• Conclusion
The Vehicular Radar Application

Frequency bands allocated by FCC:

- **22-29 GHz**: Minimum BW > 500MHz or 20%
  Range = 0.3m – 20m

- **77 GHz**: Range = 20m - 150m
Correlation-based receivers are used for maximum SNR.
The Linear FM Chirp Waveform

\[ \text{sin} \left( 2\pi f_c t + \frac{1}{2} \mu t^2 \right), \quad |t| < T/2 \]

0 \quad \text{otherwise}
The Linear FM Chirp Waveform

\[ \sin (2\pi f_c t + 1/2\mu t^2), \ |t| < T/2 \]

\[ 0 \quad \text{otherwise} \]

\[ f_c = 25.5 \text{ GHz}, \ \mu T = 7 \text{ GHz}, \ T = 1\text{ns} \]

Frequency (GHz)

Normalized Fourier Transform (dB)

Time (ns)

Signal (V)

Normalized Fourier Transform (dB)
The Linear FM Chirp Waveform

-1.5
-1
-0.5
0
0.5
1
1.5

Time (ns)

Signal (V)

Normalized Autocorrelation (V)

sin \((2\pi f_c t + 1/2\mu t^2)\), |t| < T/2

0
otherwise

-1.5
-1
-0.5
0
0.5
1

Time (ns)

A larger BW leads to better range resolution.

\(f_c = 25.5 \text{ GHz}, \mu T = 7 \text{ GHz}, T = 1\text{ns}\)

as \(\mu T \uparrow\)
The Need for Phased Arrays

- Interference from reflections off the road can lead to false alarms.
- Mechanical steering of directional antennas is undesirable.
Outline

• Overview of Vehicular Radar
• **Overview of Phased Arrays**
• VPRO-PLL UWB Phased Array
• Implementation and Measurements
• Conclusion
Principle of Phased Arrays

Controlling the time delay between the N channels “steers” the EM beam electronically.

Phased Array Transmitter Benefits

• Minimization of spatial interference
• $20 \log(N)$ improvement in TX EIRP
Principle of Phased Arrays

Controlling the time delay between the N channels “steers” the EM beam electronically.

\[ \theta_{tr} = \cos^{-1}\left(\frac{\omega \Delta \tau}{\pi}\right) \]

Phased Array Transmitter Benefits

- Minimization of spatial interference
- \(20\log(N)\) improvement in TX EIRP
Timed Arrays vs. Phased Arrays
In narrowband systems, the variable delay blocks can be replaced with phase shifters.
For 22-29GHz UWB waveforms, phased arrays are sufficient.
Outline

- Overview of Vehicular Radar
- Overview of Phased Arrays
- VPRO-PLL UWB Phased Array
- Implementation and Measurements
- Conclusion
Variable-Phase Ring Oscillator*

Tunable boundary phase shifter allows for controllable phase progression for beam steering.

Variable-Phase Ring Oscillator*

Tunable boundary phase shifter allows for controllable phase progression for beam steering.

Inter-element Phase Shift Limitation

Achievable phase shift is limited by loop gain restrictions.

Tuned Load Characteristics
(L=200pH, C=195fF, Q=15)

Achievable phase shift

Loop gain limit

25.5GHz VPRO

-100
-80
-60
-40
-20
0
20
40
60
80
100

Phase Shift (deg.)

Frequency (GHz)

Impedance (Ohms)
A half-rate VPRO followed by a frequency doubler doubles the achievable phase shift.

Full coverage is achieved through programmable, 1-bit, sign inversion in the PAs.
VPRO in an Analog PLL

- PLL stabilizes the frequency over phase shifts.
- PM/FM modulation is also accomplished through PLL.
- Divider-less, analog PLL allows for high-speed modulation.
Outline

• Overview of Vehicular Radar
• Overview of Phased Arrays
• VPRO-PLL UWB Phased Array Architecture
• Implementation and Measurements
• Conclusion
Implemented in a 0.13μm CMOS process.
Wideband VPRO Design

Varactors are used for frequency control.

Switched VNCAPs are used to obtain phase shifts.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>M₁</td>
<td>25x3.2 μ/0.12 μ</td>
</tr>
<tr>
<td>M₂</td>
<td>25x2 μ/0.12 μ</td>
</tr>
<tr>
<td>M₃</td>
<td>30x6 μ/0.28 μ</td>
</tr>
<tr>
<td>M₄</td>
<td>25x4 μ/0.12 μ</td>
</tr>
<tr>
<td>M₅</td>
<td>25x2 μ/0.12 μ</td>
</tr>
<tr>
<td>M₆</td>
<td>25x3 μ/0.5 μ</td>
</tr>
</tbody>
</table>
• The buffer’s frequency control is also tuned along with the control voltage.
• UWB performance is achieved using a narrowband tuned design.
Performance with Frequency Tuning

- Control Voltage of the VPRO is linearly ramped in simulation with time to generate a linear chirp.
- When the buffer is also tuned, distortion is minimized.
Performance with Frequency Tuning

• Control Voltage of the VPRO is linearly ramped in simulation with time to generate a linear chirp.
• When the buffer is also tuned, distortion is minimized.
The frequency-doubler is implemented as a squarer using pseudo-differential, Gilbert-style, doubly-balanced mixers.
Two differential pairs with inverted inputs and controllable current sources are used to achieve 180° sign inversion.

Matching circuits are implemented using spiral inductors.
The PA achieves a saturated output power > 12.1 dBm at 26GHz at drain efficiency > 13%.

Wideband large signal performance is observed from 24 to 27GHz.
12GHz Reference VCO

\( V_{dd} (1.5 \text{ V}) \)

4.6 to 9.8mA

30x5μm

173 ohms

25x6.8μm

10x4μm/0.36μ

362 pH

-95 to -102 dBc/Hz at 600kHz

pMOS negative-\( g_m \) cell and tail resistors are used to mitigate 1/f-noise.
Divide-by-128 Digital PLL

- Standard tri-state PFD and charge pump are used.
- Standard master-slave FF with inverted output feedback divider design.
Array Pattern Measurement Setup

Variable delay elements mimic wave propagation in space.
Narrowband spatial selectivity is verified.

Patterns at 24.75GHz with 2 elements enabled

Peak at -42°
Null at 13°

Narrowband 2-element Array Patterns

Narrowband spatial selectivity is verified.
Narrowband 4-element Array Patterns

On-Chip mismatches and measurement inaccuracies mainly manifest themselves in side-lobe levels and peak-null ratios.

Narrowband 4-element Array Patterns

On-Chip mismatches and measurement inaccuracies mainly manifest themselves in side-lobe levels and peak-null ratios.

• Wideband output is generated by direct modulation of VPRO control voltage.
• UWB spatial selectivity is verified.
UWB Array Patterns

- Wideband output is generated by direct modulation of VPRO control voltage.
- UWB spatial selectivity is verified.
## Performance Summary

### Technology

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>0.13 μm CMOS</td>
</tr>
<tr>
<td>Total Power Consumption (incl. 4 PAs)</td>
<td>744 mA (1.5V)</td>
</tr>
<tr>
<td>Chip Area</td>
<td>1.8 x 2.7 mm²</td>
</tr>
</tbody>
</table>

### Transmitter Performance

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. PA Output Power @ 26GHz</td>
<td>&gt;12.1 dBm</td>
</tr>
<tr>
<td>Max. 4-element EIRP @ 26GHz</td>
<td>&gt;24.1 dBm</td>
</tr>
<tr>
<td>Peak PA Drain Efficiency</td>
<td>&gt;13 %</td>
</tr>
<tr>
<td>Power Consumption (per PA)</td>
<td>86.5 mA (1.5V)</td>
</tr>
</tbody>
</table>

### Array Performance

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam-steering resolution</td>
<td>3 bits</td>
</tr>
</tbody>
</table>

### 12GHz Ref. Path Performance

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Synthesizer Loop BW</td>
<td>10 MHz</td>
</tr>
<tr>
<td>VCO Free-running Phase Noise @ 1M</td>
<td>-110 dBc/Hz</td>
</tr>
</tbody>
</table>
Conclusion

• An UWB VPRO-PLL phased array transceiver architecture is demonstrated that achieves full phased array functionality while eliminating key building blocks such as mixers, phase-shifters and power splitters.

• A Waveform-Adaptive UWB design paradigm is introduced that simplifies the design of the building blocks.

• Future work includes the extension of the architecture to support more general UWB waveforms, including amplitude modulation.