Fractional-N PLL-Based Frequency Sweep Generator For FMCW Radar

Austin Harney, Analog Devices Inc.,
Rudolf Wihl, Analog Devices Inc.,
Analog Devices in ADAS

- **Analog Signal Processing**
  Leading Edge Performance, low cost, wide range of automotive qualified standard components
  ADC, DAC, MUX, Switches, LNA, VGA/PGA, PLL, Sensors, Video Encoder/Decoder

- **Digital Signal Processing**
  Blackfin and Sharc covering all ADAS application areas, automotive qualified and optimizes for performance/price/power-consumption

- **ASSP**
  Application Specific Standard Products, for further system integration and cost optimization.
  e.g. Integrated RADAR AFE (AD8283);
  e.g. Integrated Ramp/Chirp Timing (ADF4158)

- **New System Architecture / IP**
  Enable unique ways to address and solve technical challenges or realize new applications concepts and areas.
  e.g. Lidar/Radar Baseband Modulation/Correlation Approach;
  e.g. Optical Position Sensor

- **ADAS**
  - Adaptive Cruise Control
  - Blind Spot Detection
  - Lane Change Assist
  - Pre-Crash Sensing
  - Parking Assist
  - Pedestrian Detection
  - Lane Departure Warning
  - Lane Keeping
  - Birds-eye view
  - Sensor Fusion
  - NaVision
  - NightVision

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2

**Analog Devices**
ADAS – Multiple Systems / Continued Evolution

- Over-take detection
- Blind Spot Detection
- Lane Change Assist
- Parking Assist
- Lane Departure Warning
- Adaptive Cruise Control
- Collision Mitigation
- Pedestrian Detection
- Night Vision
- Self-Parking
Automotive Lidar Status

◆ Reasons Why Lidar Is In Decline
  ● Sensitive to environmental conditions (rain, spray, fog, snow, dirt)
  ● Mounting position
  ● Cost for Laser Diode and APD, especially for electronic scanning systems

◆ Advantage of Lidar vs. Radar
  ● wide field of view, up to 360° for mechanical scanning system
  ● excellent angular and distance resolution
When was RADAR invented?
Radar: A 105 year-old "Baby" Patent-Paper from 1905

Method to notify the observer about remote metallic object, by using radio waves
Radar Frequency Bands: Limitations + Applications

- **24 GHz ISM**
  - Frequency: 24.00 - 24.25 GHz
  - Low target separation
  - Excellent target separation
  - Low transmit power
  - Obsolete in Europe 2013
  - Proposed to replace 24 GHz UWB
  - Possibility for worldwide standard

- **24 GHz UWB**
  - Frequency: 21.625 - 26.625 GHz
  - Good target separation
  - Very low transmit power
  - Obsolete in Europe 2013
  - Proposed to replace 24 GHz UWB
  - Possibility for worldwide standard

- **26 GHz UWB**
  - Frequency: 24.25 - 29.0 GHz
  - Proposed to replace 24 GHz UWB
  - Possibility for worldwide standard

- **77 GHz**
  - Frequency: 77.0 - 81.0 GHz
  - Medium target separation
  - High transmit power
  - Low integration level
  - High cost, yield
  - Usually used as die, packing issue

- **79 GHz**
  - Frequency: 77.0 - 81.0 GHz
  - Very good target separation
  - Low transmit power
  - Easy to package in plastic
  - High integration level
  - Reasonable cost
  - Large antenna 3x of 77GHz

**Situation is Not Static!**
New Techniques extending 24GHz to LRR and 77GHz to MRR/SRR

* e.i.r.p. equivalent isotropic radiated power
<table>
<thead>
<tr>
<th>Type</th>
<th>Range</th>
<th>Target Resolution</th>
<th>System/ Antenna Size</th>
<th>MMIC cost</th>
<th>Outlook</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Short &lt;80m</td>
<td>Medium &lt;150m</td>
<td>Long &lt;300m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24GHz ISM</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
<td>low</td>
<td>Low (integration possible; plastic pkg compatible)</td>
</tr>
<tr>
<td>24GHz UWB</td>
<td>✓</td>
<td></td>
<td>good</td>
<td>medium</td>
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<td>77GHz</td>
<td></td>
<td>✓</td>
<td>medium</td>
<td>Low (1/3 the size)</td>
<td>High (exotic materials; hard to integrate)</td>
</tr>
<tr>
<td>79GHz</td>
<td>✓</td>
<td>✓</td>
<td>Very good</td>
<td>Low (1/3 the size)</td>
<td>High (ditto)</td>
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- 24GHz ISM: Short range of 80m, medium range of 150m, long range of 300m. Target resolution is low. System/antenna size is medium. MMIC cost is low. Outlook is helping adoption in BSD and other near-range. SMS and others attempting LRR.
- 24GHz UWB: Short range of 80m, medium range of 150m, long range of 300m. Target resolution is good. System/antenna size is medium. MMIC cost is low. Outlook is obsolete in Europe after 2013.
- 26GHz UWB: Short range of 80m, medium range of 150m, long range of 300m. Target resolution is good. System/antenna size is medium. MMIC cost is low. Outlook is not yet approved.
- 77GHz: Short range of 80m, medium range of 150m, long range of 300m. Target resolution is medium. System/antenna size is low (1/3 the size). MMIC cost is high. Outlook is can cover SRR to LRR and is smallest form-factor; long-term, cost improvements to make more competitive.
- 79GHz: Short range of 80m, medium range of 150m, long range of 300m. Target resolution is very good. System/antenna size is low (1/3 the size). MMIC cost is high. Outlook is high (ditto).
# Possible Combinations using system synergy

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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>77GHz 79GHz</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>High (exotic materials; hard to integrate)</td>
</tr>
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**Outlook**

**24/26GHz**
- System cost will be further reduced
- LRR Performance and range will be improved but stays behind 77/79GHz
- Still dominate SRR applications, because of cost.

**77/79GHz**
- It will take several years to solve technical challenges.
- Integration level will improve and cost comes down, but stays above 24GHz
- The better LRR performance will solidify the position in ACC especially on high end cars
Radar Architectures in Automotive

<table>
<thead>
<tr>
<th>Automotive Radar</th>
<th>FMCW</th>
<th>Pulse Doppler Radar</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSR-Low Speed Ramp</td>
<td>HSR-High Speed Ramp</td>
<td>Pulse Train</td>
</tr>
<tr>
<td>~ 3ms</td>
<td>&lt; 150 us</td>
<td>~ 1ns</td>
</tr>
<tr>
<td>Doppler Frequency is usually determined through variable slopes and/or FSK modulation.</td>
<td>Increasing slope + bandwidth makes Doppler Frequency negligibly, Velocity is measured by distance over time.</td>
<td>Velocity and distance are measured instantaneously.</td>
</tr>
<tr>
<td>Can work with limited bandwidth like 24GHz narrowband but is scalable to higher bandwidth too</td>
<td>Requires higher bandwidth, typically used in 24/26GHz UWB or 79GHz</td>
<td></td>
</tr>
</tbody>
</table>
FMCW-RADAR

FREQUENCY MODULATED CONTINUES WAVE RADAR
FMCW Principle (simplified without Doppler)

FMCW Radar

Distance: D

(1) \( t_d = 2 \cdot D / c \rightarrow 1 \text{us at 150m} \)

(2) \( D = c \cdot t_s \cdot f_b / (f_s \cdot 2) \)

(3) \( \text{BW} = f_s \cdot t_{d_{\text{max}}} / t_s \)

(4) \( \text{BW} = f_s \cdot 2 \cdot D_{\text{max}} / (c \cdot t_s) \)

Example:

\( f_s = 200 \text{MHz} \)
\( t_s = 2 \text{ms} \)
\( t_{d_{\text{max}}} = 150 \text{m} \)

\( \rightarrow \) Bandwidth BW=100KHz

f_t: Transmit Frequency
f_r: Receive Frequency
D: Distance
t_d: Time of flight for D
f_b: Beat Frequency
f_s: Sweep Frequency
t_s: Sweep Time
C: Light Speed Constant
## Baseband Example

Why using different ramp profiles?

<table>
<thead>
<tr>
<th>Distance</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Speed Ramp 200MHz@2ms</td>
<td>33KHz</td>
<td>66KHz</td>
<td>100KHz</td>
<td>133KHz</td>
<td>166KHz</td>
</tr>
<tr>
<td>High Speed Ramp 200MHz@20us</td>
<td>3.3MHz</td>
<td>6.6MHz</td>
<td>10MHz</td>
<td>13.3MHz</td>
<td>16.6MHz</td>
</tr>
</tbody>
</table>

![Graph showing echo amplitude vs target range with different ramp profiles.](image)
FMCW with Doppler Shift

\[ f_{b1} = f_b - f_D \]
\[ f_{b2} = f_b + f_D \]

\[ \rightarrow f_b = \frac{(f_{b1} + f_{b2})}{2} \]
\[ \rightarrow f_D = \frac{(f_{b2} - f_{b1})}{2} \]

Doppler shift is eliminated/determined by triangular ramp with identical slope rate up and down
Doppler Shift to Baseband Frequency

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Carrier Frequencies</th>
<th>24GHz</th>
<th>76GHz</th>
<th>Doppler Frequency (KHz)</th>
<th>200MHz@2ms</th>
<th>3.3MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.04</td>
<td>0.01</td>
<td></td>
<td>0.04</td>
<td>0.8%</td>
<td>0.15%</td>
</tr>
<tr>
<td>10</td>
<td>0.44</td>
<td>0.14</td>
<td></td>
<td>0.44</td>
<td>0.4%</td>
<td>0.14%</td>
</tr>
<tr>
<td>50</td>
<td>2.22</td>
<td>7.04</td>
<td></td>
<td>2.22</td>
<td>2.2%</td>
<td>1.4%</td>
</tr>
<tr>
<td>100</td>
<td>4.44</td>
<td>14.1</td>
<td></td>
<td>4.44</td>
<td>4.4%</td>
<td>2.8%</td>
</tr>
<tr>
<td>180</td>
<td>8.00</td>
<td></td>
<td>25.3</td>
<td></td>
<td>8.0%</td>
<td>5.0%</td>
</tr>
</tbody>
</table>

This does not mean that the High Speed Ramp approach is better than the Low Speed Ramp approach, there are pros & cons for both systems.
Dynamic Range Requirements

Radar Equation

\[
\frac{P_r}{P_t} = \frac{G^2 \cdot \lambda^2 \cdot \sigma_s}{(4\pi)^3 \cdot R^4}
\]

- \(G\) = Antenna Gain (assumes \(G_t = G_r\); i.e. same antenna used for Tx and Rx; ex. 31 dB)
- \(P_t\) and \(P_r\) = Transmit and receive power
- \(\lambda\) = wavelength of carrier frequency (ex. 76 GHz => 3.95mm)
- \(\sigma_s\) = Radar Cross Section (ex. 2m\(^2\) for motorcycle)
- \(R\) = range (ex. maximum 150m; time of flight = \(2R/c = 1\mu s\))

Dynamic Range

\[
DR = 10 \cdot \log\left(\frac{P_{R_2}}{P_{R_1}}\right) = 10 \cdot \log\left(\frac{R_1^4}{R_2^4}\right) = 40 \cdot \log\left(\frac{R_1}{R_2}\right)
\]

<table>
<thead>
<tr>
<th>Range</th>
<th>Short</th>
<th>Short - Medium</th>
<th>Short - Long</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 (m)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>R2 (m)</td>
<td>50</td>
<td>150</td>
<td>300</td>
</tr>
<tr>
<td>DR (^1)</td>
<td>68dB</td>
<td>87dB</td>
<td>100dB</td>
</tr>
</tbody>
</table>

\(^1\) + fixed gain depended MMIC RF Level
+ certain resolution to detect and classify object
- attenuation of high pass filter at the input
FMCW RADAR
Signal Chain Representation

Transmit Channel Signal Generation

Chirp-Ramp Generator

VCO

Ref. OSC

Antenna

DSP

Receive Channel Signal Processing

ADC

AF

PGA

LNA

ADC

AF

PGA

LNA

ADC

AF

PGA

LNA

ADC

AF

PGA

LNA

MMICs

PA

ADI Supported Functions
FMCW RADAR
Signal Chain Representation

ADI Supported Functions

Transmit Ramp Generation

Receive Channel Signal Processing
Integrated Radar AFE

MMICs

Ref. OSC

VCO

PA

Temperature Sensor

Blackfin/Shar

DSP

ADC

MUX

AF

PGA

LNA

Antenna

ADF4158

High Resolution PLL

ADC 18

ADF4158 Blackfin/Shar Integrated Radar AFE

ADI Supported Functions

MMICs
FMCW Radar Ramp Generation

- FMCW Radar are used in a wide range of automotive applications and the system performance has been improved significantly over the last years.
  - Larger dynamic range, <0.5 to 300m
  - Wider Field of View
  - Better velocity, distance and angular resolution
  - Reliable target detection, separation and tracking
  - Faster response time

- Ramp generation is one of the key elements in the signal chain to achieve this system level performance. Unique and proprietary modulations schemes and ramp-timings have been developed set new challenges on the FMCW ramp generation
Transmit Ramp Generation
Key Design Objectives:

- Wide range of ramp profiles are used in automotive radar, ranging from triangular (variable slopes), saw tooth, FSK modulation and variable timing.
  - flexibility
- Linearity, low phase noise, high resolution and temperature stability have direct impact on system performance
  - performance
- Low power to reduce self heating, keep fuel consumption low
  - low power consumption
- Complex ramp functions might require significant system/CPU overhead
  - self-contained ramp function
- And all above at reduced system cost
  - low cost
Ramp Generation Options

→ DAC

+ flexible ramp shape
+ very fast ramps possible
+ less spurs than PLL
- discriminator and look-up table needed
- usually higher system cost than PLL
- (additional MCU/DSP resources)
Ramp Generation Options

→ DDS and PLL

+ limited ramp speed
+ less spurs than PLL with FND
+ always linear, no correction for VCO needed
- higher cost
- higher power consumption
- additional DAC needed depending on ramp modulation scheme
Ramp Generation Options

PLL+DAC

Transmit Channel Signal Generation

D/A

PFD

LF

FND

VCO

*M

Ref. OSC

Phase Frequency Detector

Loop Filter

Fractional-N Divider

Higher Frequency Modulation

up conversion

CONTROL

+ any ramp speed generated.
- correction for VCO needed
- additional DAC needed depending on ramp modulation scheme
Ramp Generation Options

→ ADF4158

+ lower system cost
+ always linear, no correction for VCO needed
+ lower MCU/DSP interaction (especially ADF4158)
ADF4158: Direct Modulation/Waveform Generating 6GHz Fractional-N Frequency Synthesizer

**KEY SPECIFICATIONS**
- 500MHz – 6000MHz Range
- 25 bit divider modulus
- 32MHz PFD maximum frequency
- Normalised PN Floor = -207dBc/Hz
- FSK deviation up to 32MHz

**FEATURES**
- Sub-1Hz frequency resolution
- FSK and PSK modulation capability
- Generates highly linear sawtooth and triangular waveforms
- Cycle slip reduction for fast locktimes
- 24-LFCSP (4mm x 4mm)
FMCW Radar Using High Resolution ADF4158 Ramp Generator
Measurement Setup

ADF4158

128MHz

R2

R1

C2

C1

C3

VCO

SMA100 Signal Generator

E5052 with E5053 Signal Analyzer

10MHz
Basic Triangular ramp

Locked to 5790MHz
Jump 200 × 250kHz steps at 10us

200 × 250kHz
50MHz

200 × 10us
2ms
Triangular ramp with delay

Locked to 5790 MHz
Jump 100 x 100 kHz steps at 100us
0.5 ms Delay
Saw tooth ramp
Multiple slope ramps
Other ramp function

Parabolic ramp

Linear ramp + FSK
Conclusions

- Innovative architectures and components are being developed to enable improved cost/performance optimization in automotive radar systems.
- Precise ramp generation is critical in FMCW applications to achieve the desired target resolution.
- Advancements in PLL technology now enable affordable capabilities such as multi slope ramps or FSK modulation superimpose to the ramp.
- Lower-Cost, Higher Performance systems will evolve through optimized partitioning of high-volume standard products from Communications Applications coupled with specialized Automotive ASICs.
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