USC Viterbi
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# Monolithic UWB Transceivers for Accurate Localization, Sensing, and Imaging

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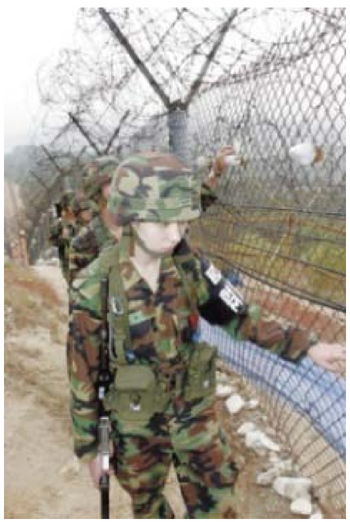
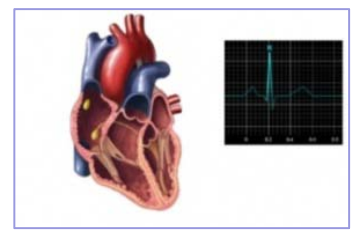
# Outline

- Why Ultra-Wideband?
- UWB Radar Transceivers
- Introduction to Antenna Arrays
- Narrowband Antenna Arrays
- Ultra Wideband Timed Arrays
- Multi-Beam Architectures
- Case Studies: Integrated Timed Arrays in Silicon
- Human Feature Detection using UWB
- Conclusion: Looking Forward

# Why Ultra-Wideband?





# UWB for Localization, Sensing, and Imaging

- **UWB radar offers depth resolution that is inversely proportional to bandwidth.**
- **UWB arrays offer angular resolution that is inversely proportional to bandwidth and to the total array size.**
- **Attenuation of UWB waveforms at lower frequencies (< 5GHz) through most materials is smaller compared with mm-wave, THz, and optical frequencies.**
- **Impulse-based UWB signals are more resilient to multi-path effects.**
- **Technology scaling favors generation and detection of UWB signals.**

# Sensing for an Intelligent Ambient

**Low-cost high-performance sensing devices embedded in the environment to *increase our awareness*, *improve the quality of life*, and *create an intelligent and responsive ambient*.**

**Sensing, in this context, is an ultimate form of communication, where signals carry the information about the environment, and location and conditions of people and objects.**

**It is conceivable that the society moves from "conventional" communication-centric to sensor-centric in the next decade.**

**Low-cost sensors are already embedded in our lives:**

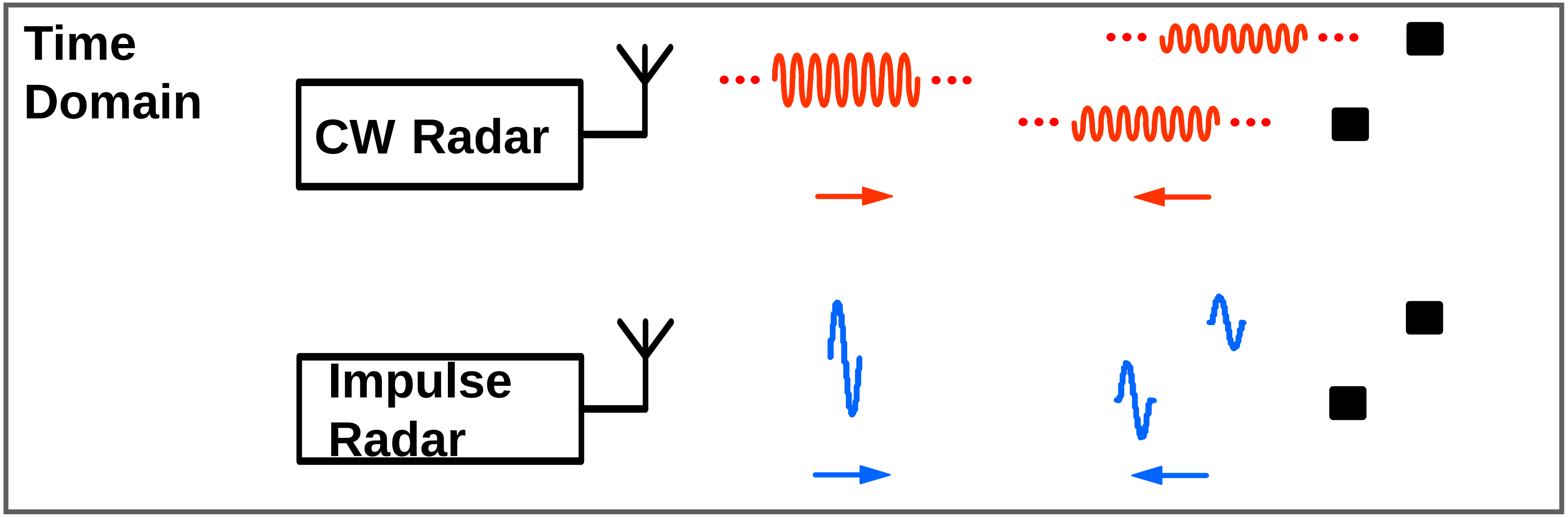
**iPhone, iPad, Wii, cars, several healthcare monitoring devices, …**

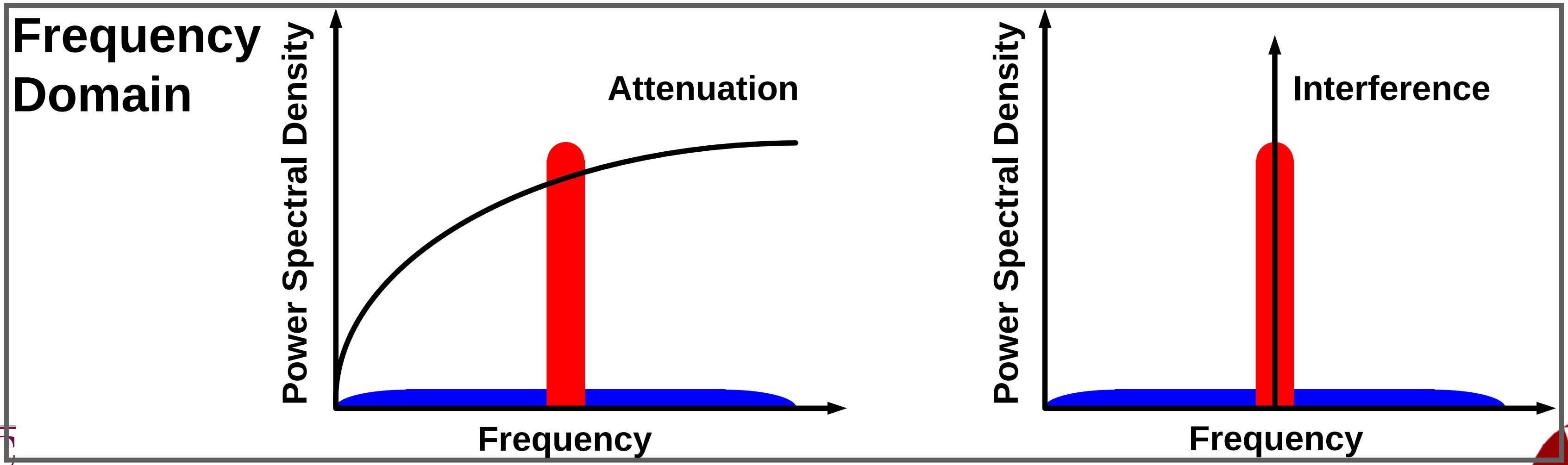
# Ultra-Wideband Sensing

- **Localization of objects and pedestrians in all weather conditions (Intelligent Transportation)**
  - **Park assist, stop-and-go, blind-spot detection, collision voidance, etc.**
- **UWB sensors for remote health monitoring (Intelligent Healthcare)**
  - **Wireless monitoring of human gait and cardiopulmonary information.**
- **Object identification in indoor environments (Intelligent Ambient)**
  - **Wireless localization and tracking of objects in indoor environments for industrial applications, responsive gaming, etc.**
- **Localizing and tracking for security and defense**

# UWB Radar Transceivers

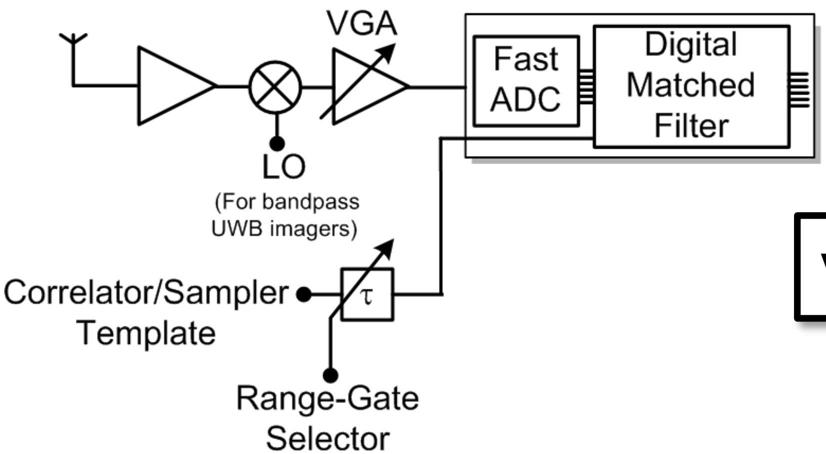
# Continuous Wave vs. Impulse Radar



# Analog vs. Digital Signal Processing

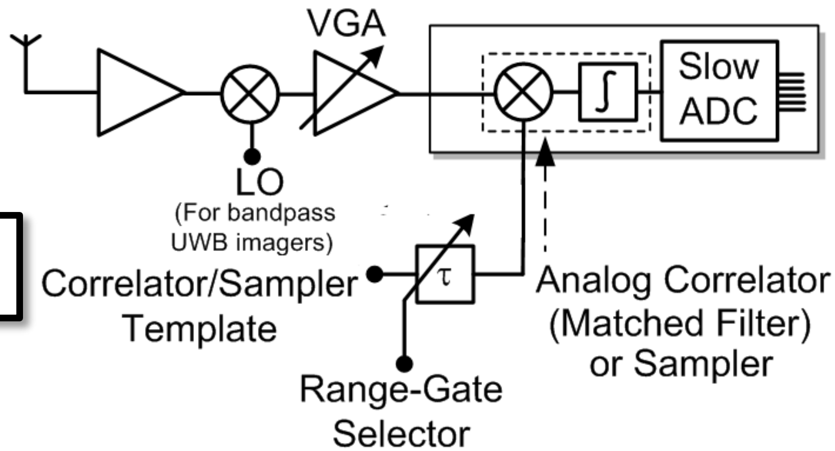
## All-Digital Approach




- Requires Nyquist ADC operating at 2xBW.
- Requires high-speed DSP for correlation, accumulation of mutiple pulses.

vs.

## Analog Pre-processing




- Analog correlator operates at signal BW.
- Subsequent ADC must only operate at the pulse-repetition rate.
- Accumulation of multiple pulses also possible in the analog domain → ADC speed requirement is further reduced!

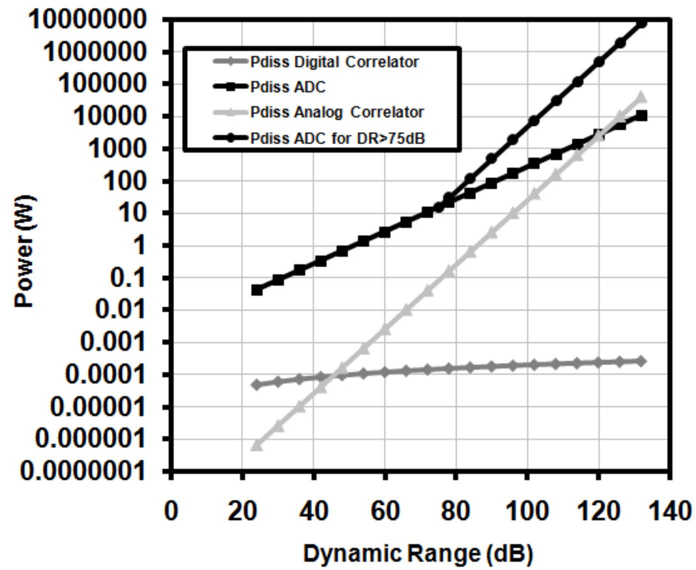
Analog pre-processing reduces the requirements on the subsequent ADC.

# Comparison for 22-29GHz Vehicular Radar

Comparison for vehicular radar
(BW=3GHz, DR=30dB, Duty Cycle=0.4%)

| Component | Analog Baseband | Digital Baseband |
|---|---|---|
| 6GSa/s ADC | N/A | 83.5mW |
| 3GHz Dig. Corr. | N/A | 60µW |
| Analog Corr. | 2.6µW | N/A |
| 12MSa/s ADC | 0.17mW | N/A |
| Total | 0.173mW vs. | 83.56mW |

## Power Diss. Comparison*




*6GSa/s ADC with $FOM_{ADC}$=2.3TSa/J, $T_{pulse}$=333ps, $\gamma$=3, $V_{od}$=0.175V, $V_{dd}$=1.2V (analog corr.), Code length=1, $f_{CLK}$=3GHz, L=80nm, $FOM_{corr}=3\times10^7$ (digital corr.)

In the future, other application-specific, analog/mixed-signal pre-processing techniques are possible to ease ADC requirements.

- Compressive sensing?

H. Hashemi and H Krishnaswamy, "Challenges and opportunities in ultra wideband antenna array transceivers for imaging", at the *IEEE International Conference on Ultra Wideband,* September 2009.

# Introduction to Antenna Arrays

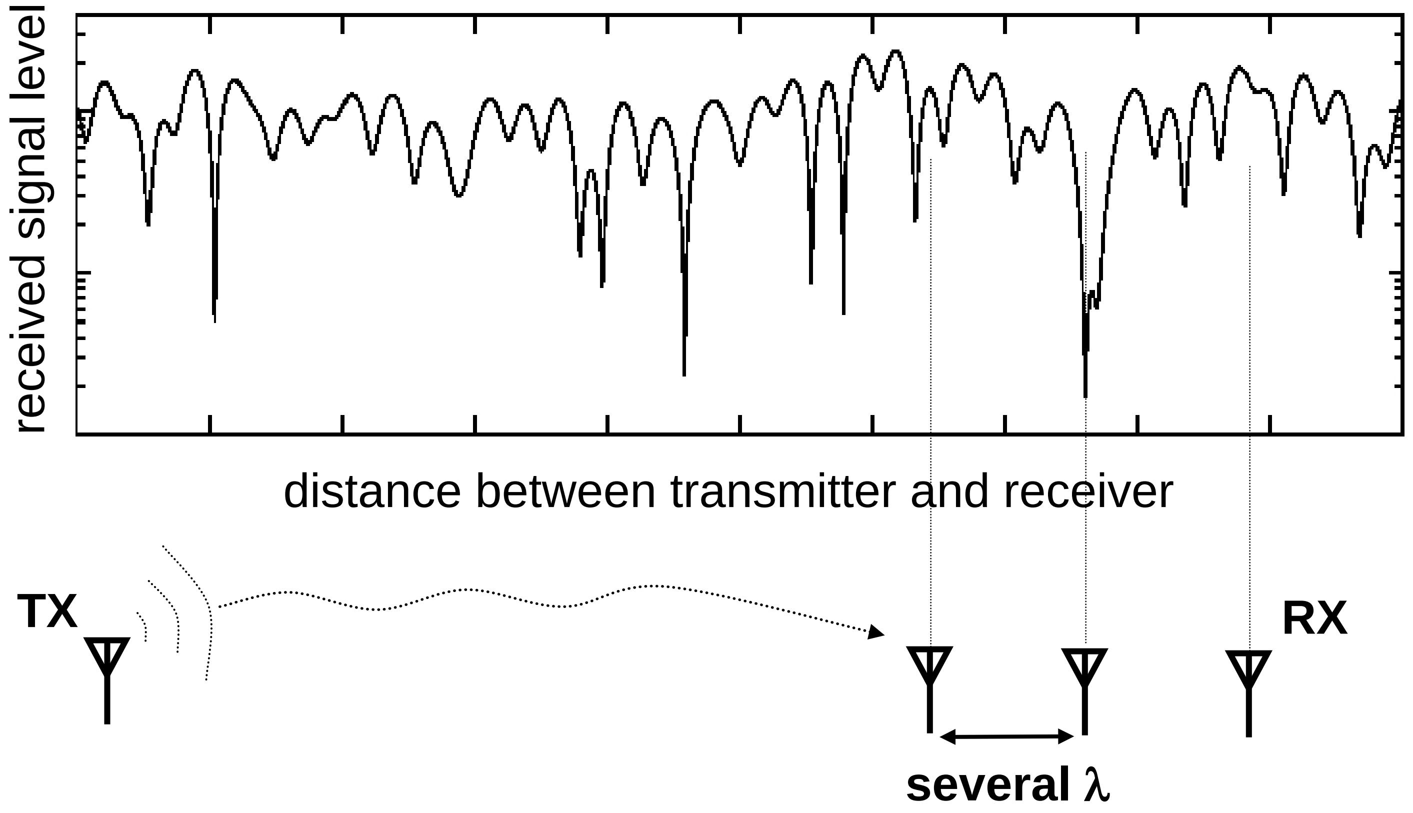
# Shannon's Capacity Formula

$$C = BW \cdot \log_2(1 + SNR)$$

- $C$ → channel capacity [bits/sec]
- $BW$ → bandwidth
- $\log_2$ → representing information in bits
- $SNR$ → signal-to-noise ratio (noise = noise + interference)

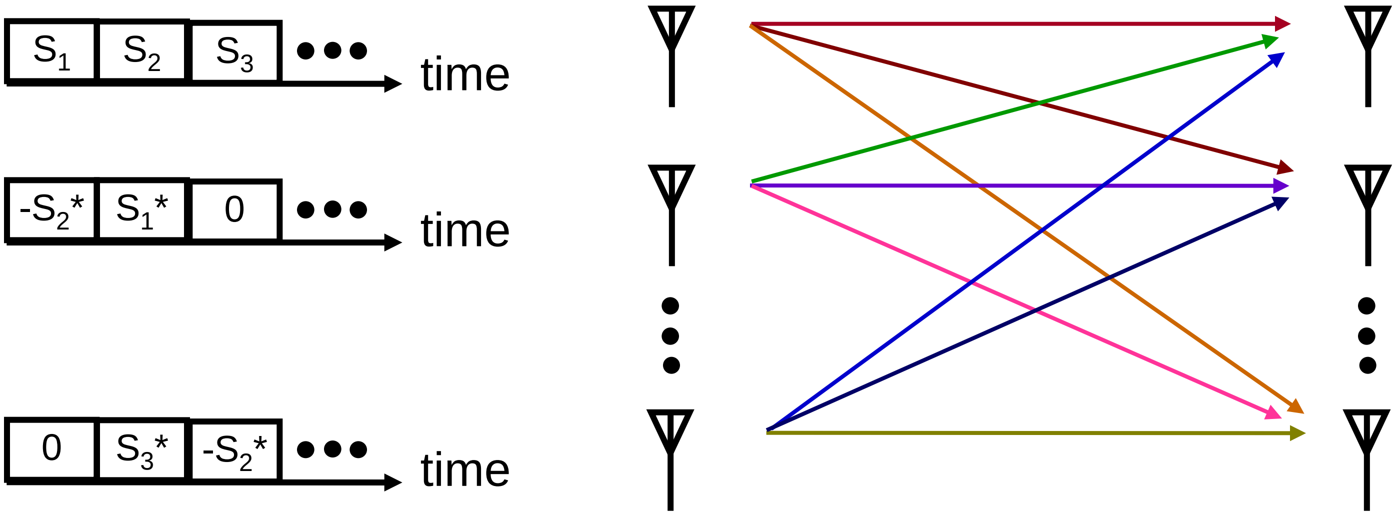
Multi-path fading and interference are major limiting factors in today's wireless networks (reduce SNR).

# Fading Channels & Spatial Diversity



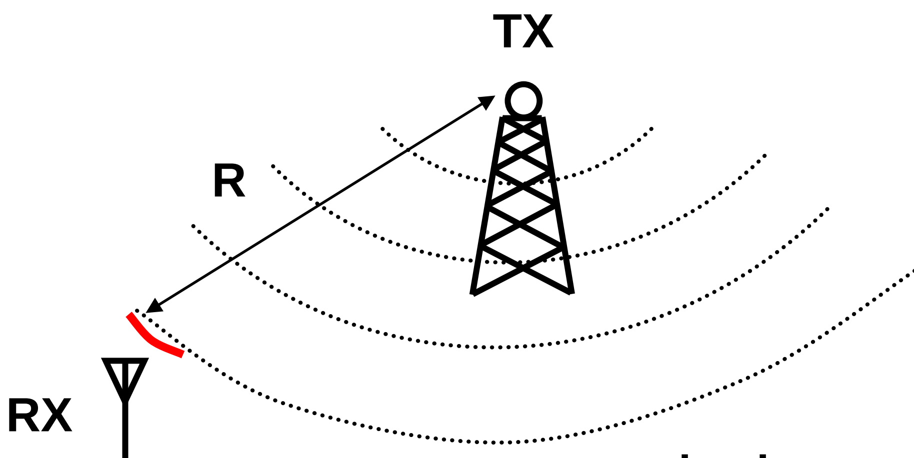

Spaced antennas create independent communication channels in a fading environment.

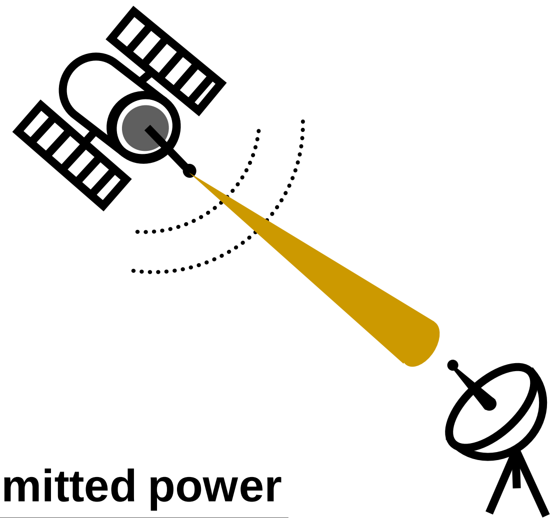
# MIMO Diversity Systems




- Multi-Input Multi-Output (MIMO) diversity systems require statistically independent communication channels (highly scattering environment) to improve the SNR.
- MIMO diversity systems usually require complex processing (linear delay-and-sum processing is not necessarily sufficient).
- Antenna spacing depends on the scatterers in the environment and can vary from sub-$\lambda$ to multiple-$\lambda$.

# Omni-Directional vs. Directional Comm.



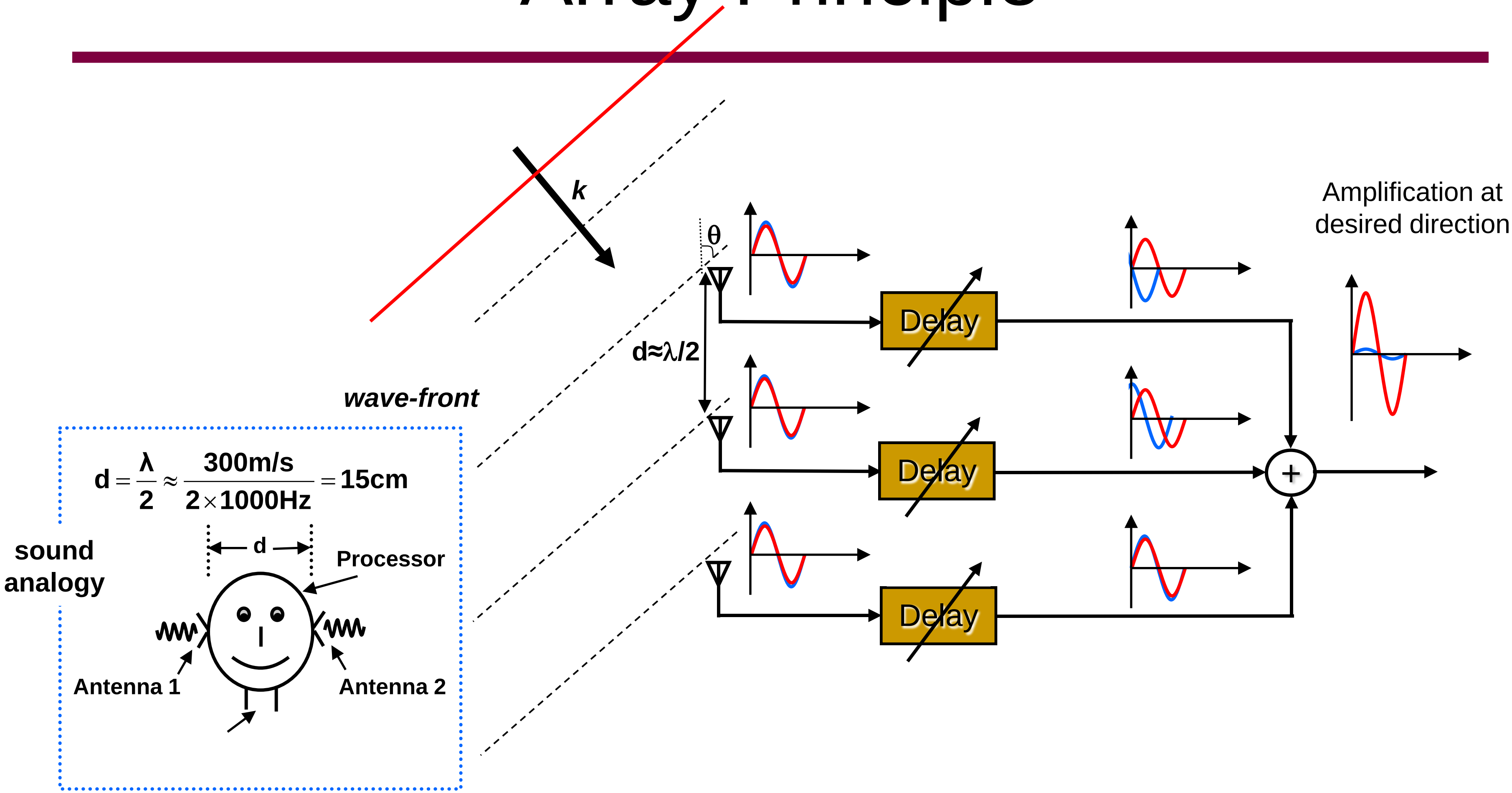



$$\text{received power} \propto \frac{\text{transmitted power}}{R^n}$$

**( Line of Sight Communication : n=2 )**

| Omni-Directional Communication | Directional Communication |
|---|---|
| • Wastes TX power<br>• Creates unwanted interference<br>• Suitable for broadcast | • Focuses energy at desired direction<br>• Suitable for fixed point-to-point comm.<br>• Not suitable for dynamic & mobile cases |

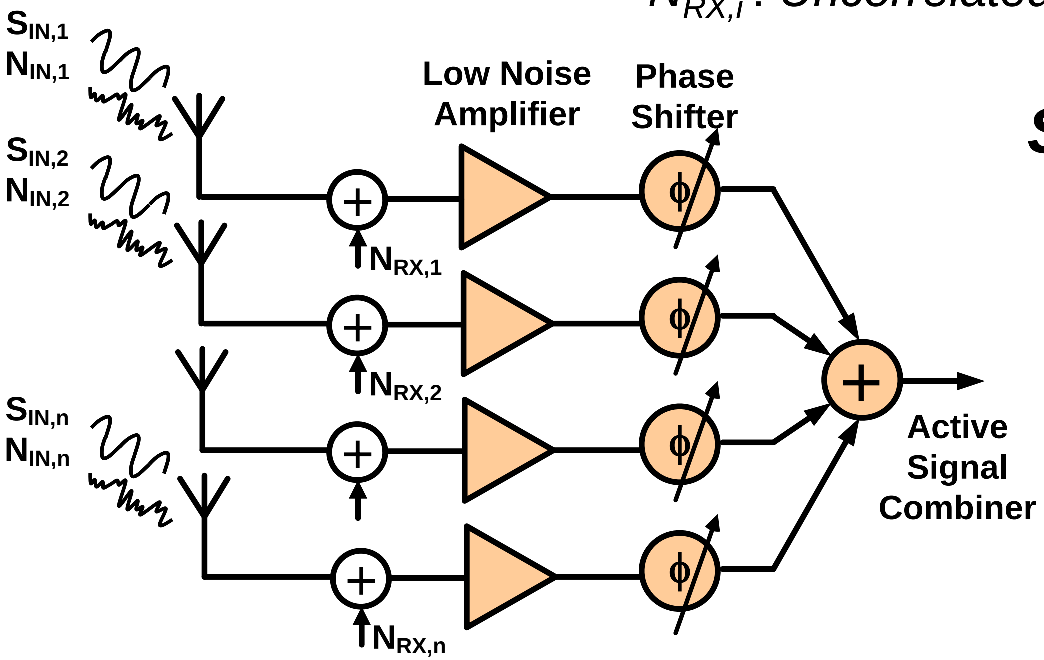
# Array Principle




Compensate for air propagation delay in order to amplify the signal from desired directions.
In narrowband, signals from undesired directions can be rejected.

# SNR Enhancement in Active Phased Arrays

*$N_{IN,i}$: Uncorrelated noise received by each antenna*
*$N_{RX,i}$: Uncorrelated noise of each receive path*




$$SNR_{OUT} = n \frac{S_{IN}}{N_{IN}+N_{RX}}$$

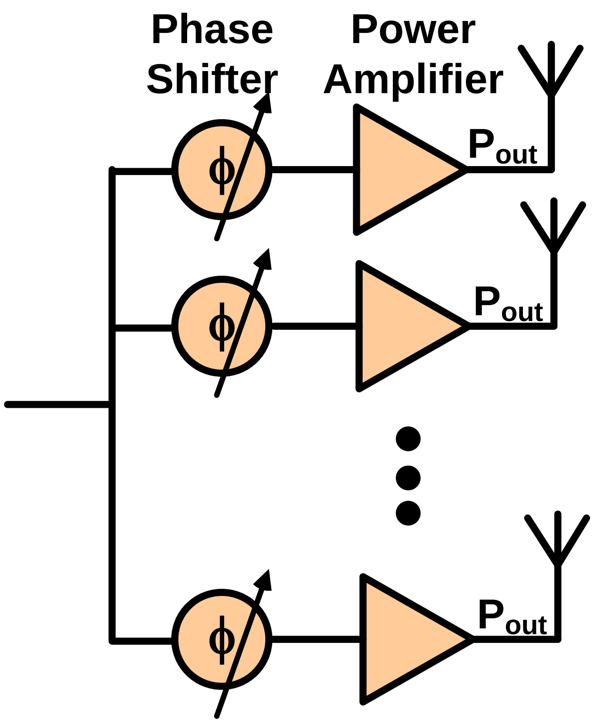
**Example: 60GHz Link**

**$BW_{channel}$ = 1.76GHz**
**$SNR_{in}$ = 6dB**
**$NF_{1\text{-}path}$ = 8dB**
**n = 8**

**Sensitivity = $SNR_{out}$ + 10log(kT.BW) + NF = (6+ 9) + (-174+92.4) + 8 = -58.5dBm**

For fixed antenna size, the SNR always improves in an array due to uncorrelated noise in parallel independent receivers.

# Relaxed Output Power in Phased Arrays




$E_{rad} = E_{out} \times n$

$P_{rad} = P_{out} \times n^2$

**Example: 60GHz Link**

$BW_{max} = 1.76GHz$
$G_{antenna} = 0dB$
$n = 8$

$P_{rad} = P_{out} + \underline{20\log(8)} = P_{out} + \underline{16dB}$

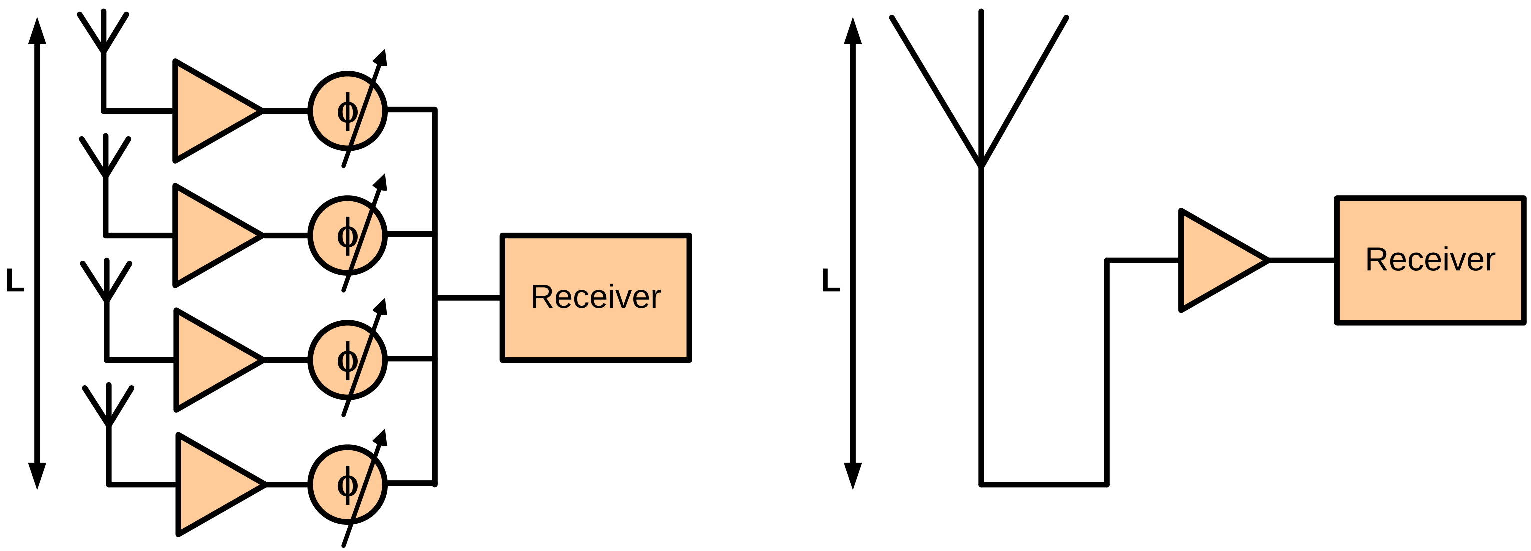
- Power amplifiers with less output power requirement are more efficient and reliable
- It is better to design *n* PAs with *1/n²* output power requirement and spatially combine power.

# An Important Quiz! ☺

Which one of these systems is better (in terms of beam pattern, SNR, and other considerations)? Answer the same question for the TX.

Note: assume electronic and mechanical beam steering are both OK!

Hint: first, think about the similarities and differences between a large antenna and an antenna array of the same size; then, …



# New Age of Antenna Arrays

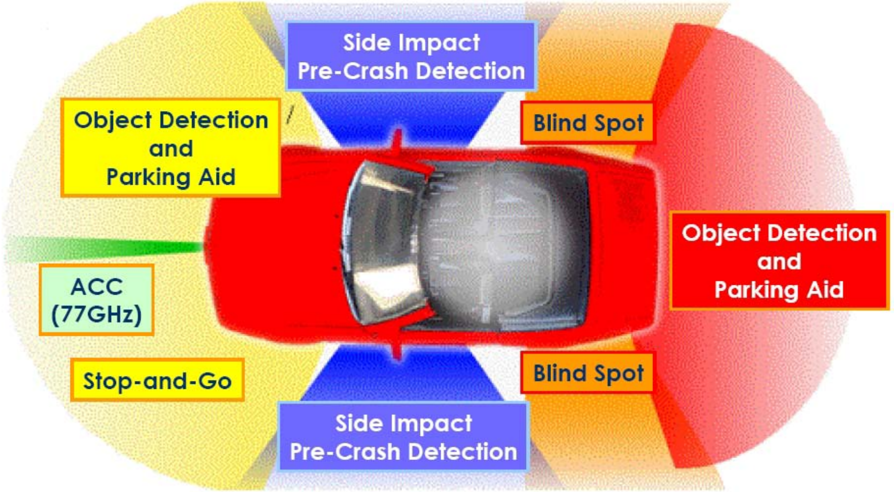
| | Conventional (> 50 years) | Emerging (~ 5 years) |
|---|---|---|
| Applications | Military radar | Wireless communication<br>Automotive radar<br>Imaging/Sensing |
| Typical Range | Long (> 1km) | Short (< 100m) |
| Array Size | Large (1000 – 10000) | Small (4 – 64) |
| Why Array? | - Focused, high-power beam<br>- Multiple simultaneous beams | - SNR improvement in RX<br>- Relaxed PA requirement<br>- Link reliability |
| Driver | Performance | Cost (Size)<br>Power consumption |
| Realization | Module based | Single chip |
| Technology | III-V | Silicon |

# New Age of Phased Array Radars

**Patriot Radar (~5000 elements)**

**Phased Array TRack to Intercept Of Target**

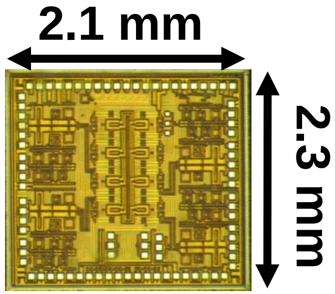
**Cost = Several Millions of $**




**Single-chip CMOS Radar for Automotives (4-8 elements)**

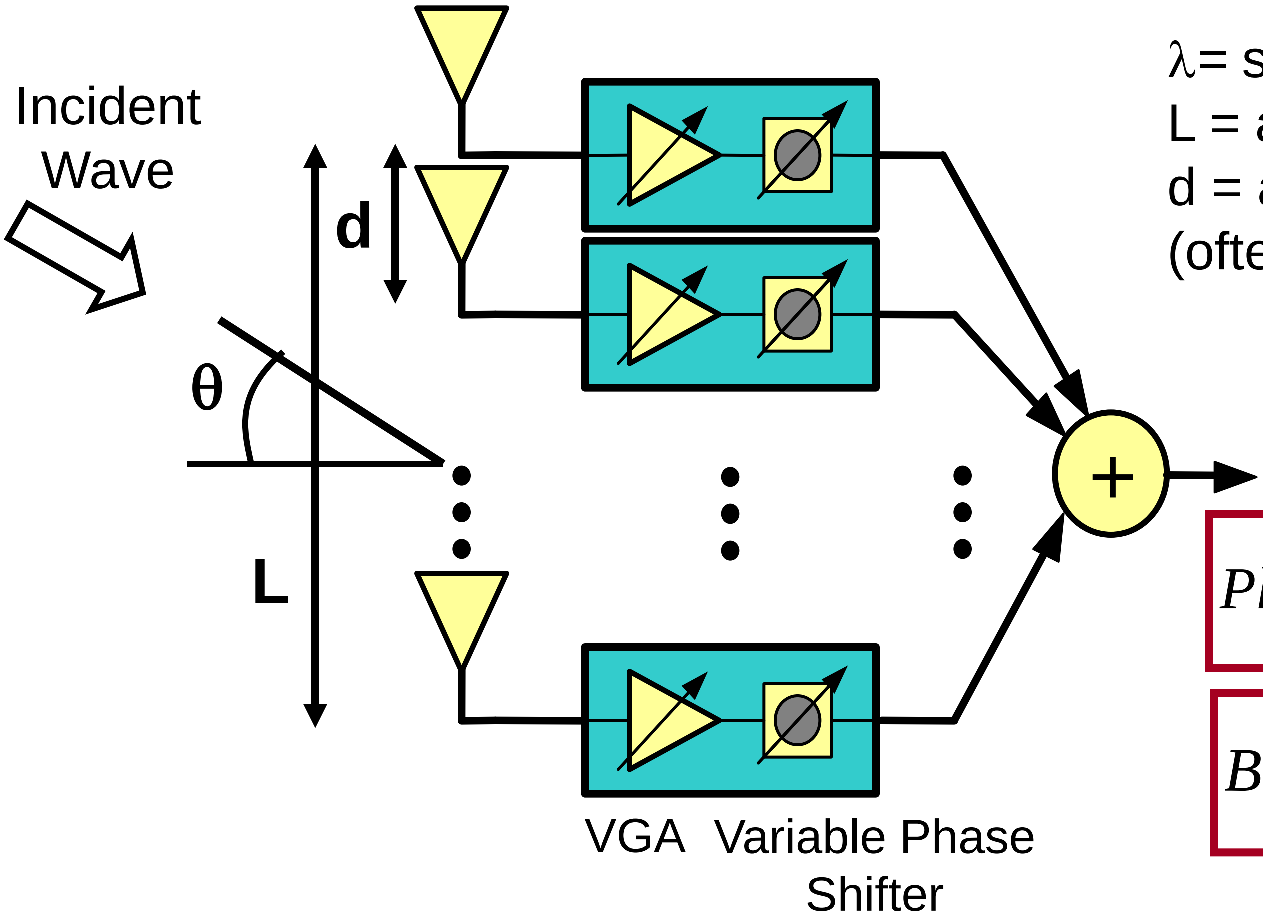
**Sensor cost < $50 (in production)**

**CMOS cost < $5 (in production)**



# Narrowband Antenna Arrays

# Narrowband Phased Array



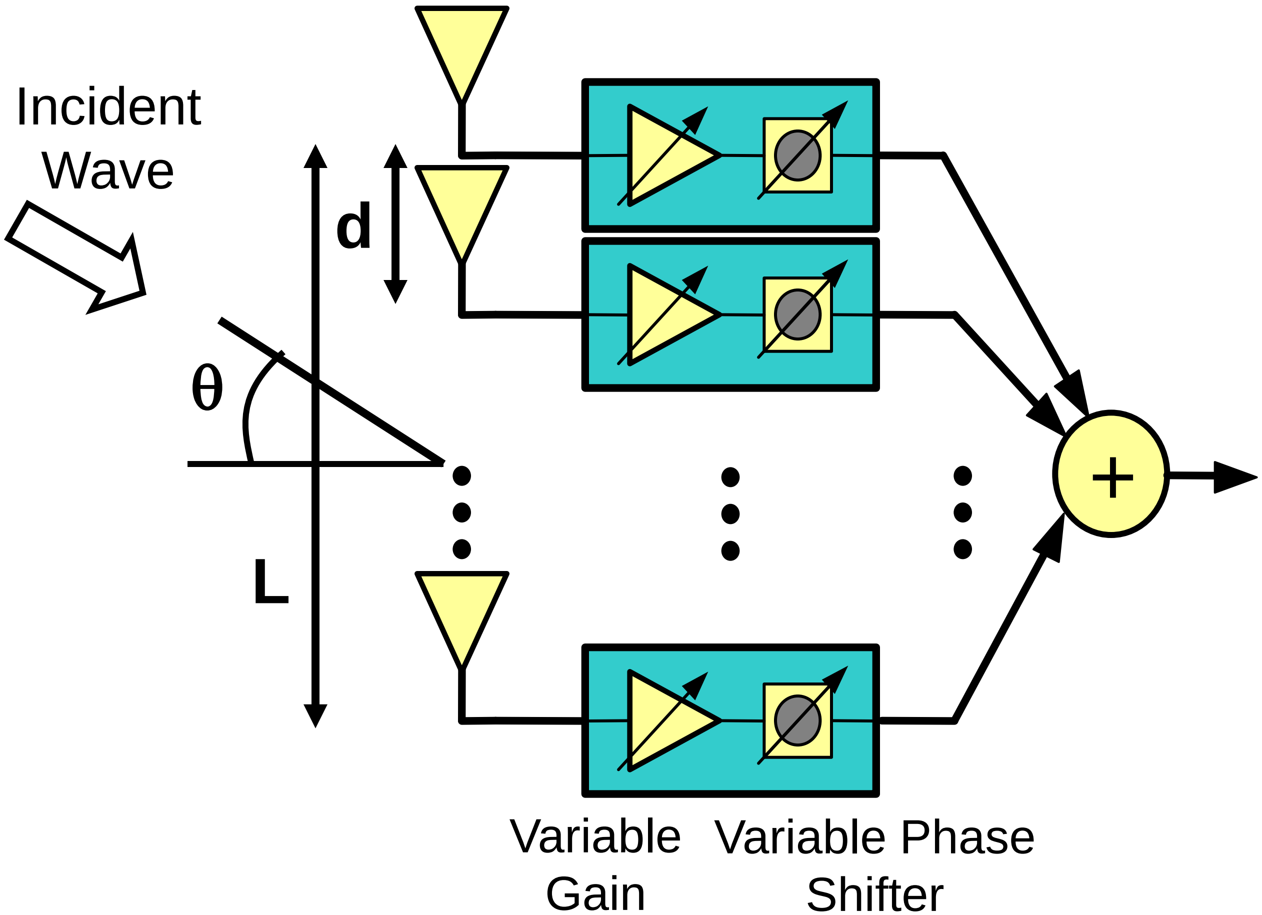

λ= signal wavelength
L = array size
d = antenna spacing
(often λ/2 in phased arrays)

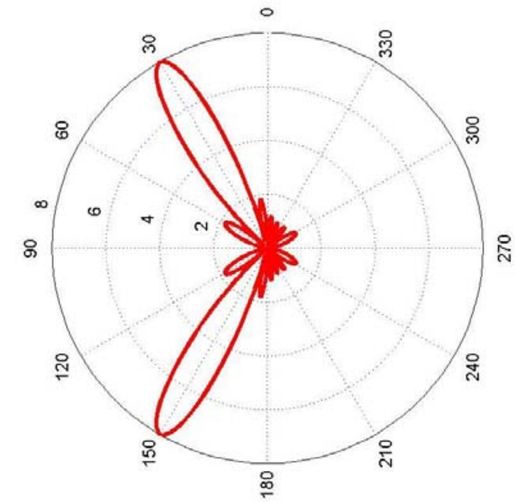
$$\text{Phase Shift} = \frac{2\pi d \sin\theta}{\lambda}$$

$$\text{Beam Width } \alpha \ \frac{\lambda}{L}$$

- Phase shifter approximates time delay in narrowband array.
- Beam-width is inversely proportional to total array size (always).

# Narrowband Array Patterns




$$Beam\ Width\ \alpha\ \frac{\lambda}{L}$$

By controlling the phase and amplitude of each path, the location of multiple peaks and nulls in the beam pattern can be controlled.

# Approximating Time Delay with Phase Shift

**d**: antenna spacing, **L**: array size, **n**: number of elements

$\lambda$: carrier wavelength, $\mathbf{f_C}$: carrier frequency, $\mathbf{T_S}$: symbol period, **c**: speed of light

- Maximum propagation delay in the array (between the first and the last elements): $\boldsymbol{\tau_{max}} = L/c$
- If $\tau_{max} \ll T_s$ then, time delay can be approximated with phase shift.
- For high-BW signals (fast symbol rate), phase shifted signals from multiple antenna elements won't be aligned in time (Inter-Symbol Interference type distortion).
- OFDM is more resilient to the above ISI effect.
  - Each sub-carrier is like a narrowband tone. Using a constant phase-shifter means a different EM beam is formed for each sub-carrier (due to their frequency difference)! Technically, this is not ISI.

# When phase-shifters can be used?

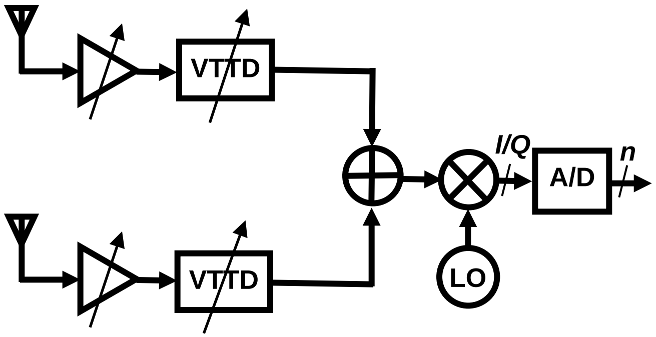
- Useful expression for an *n*-element phased arrays with λ/2 spacing

$$\begin{cases} T_s \approx \dfrac{1}{BW} \\ L = (n-1)\dfrac{\lambda}{2} \end{cases} \Rightarrow \frac{\tau_{max}}{T_s} \approx \frac{\dfrac{(n-1)\frac{\lambda}{2}}{c}}{\dfrac{1}{BW}} = \left(\frac{n-1}{2}\right)\left(\frac{BW}{f_c}\right)$$

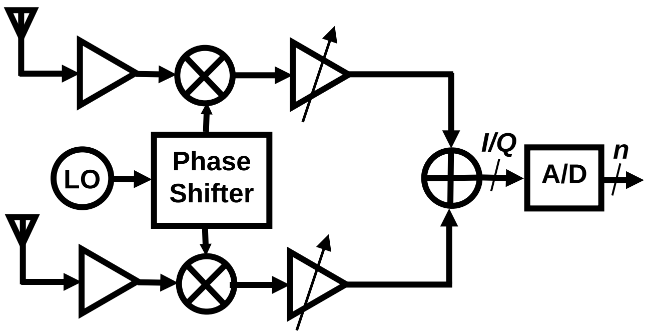
- Example 1: 60GHz wireless link, $BW_{channel}$=1.76GHz, 8-element phased array with λ/2 spacing
  - $T_s$ ~ 1/BW = 568ps
  - $\tau_{max}$ = L/c = (7λ/2)/c = 58ps << $T_s$
  - Variable phase shifters can be used instead of variable time delay elements.

- Example 2: 26GHz automotive radar, BW=5GHz, 8-element phased array with λ/2 spacing
  - $T_s$ ~ 1/BW = 200ps
  - $\tau_{max}$ = L/c = (7λ/2)/c = 135ps
  - Variable time delay elements must be used (timed array), at least, after every few elements (sub array)

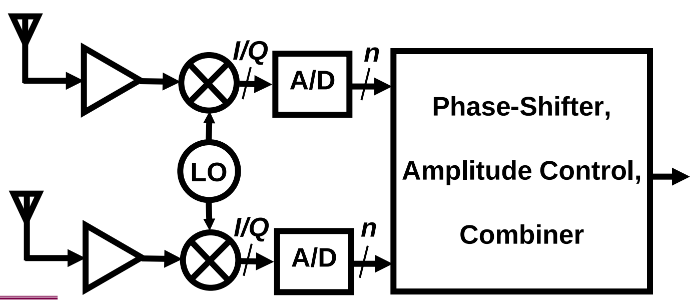
# Antenna Array Transceiver Architectures




- RF Variable True Time Delay (VTTD) is major challenge
- Variable phase-shifter instead of VTTD in narrowband
- More relaxed requirement for blocks after combiner (spatial cancellation of in-band interferers in narrowband)
- Lower power consumption due to fewer active blocks
- Suitable for narrowband and wideband arrays



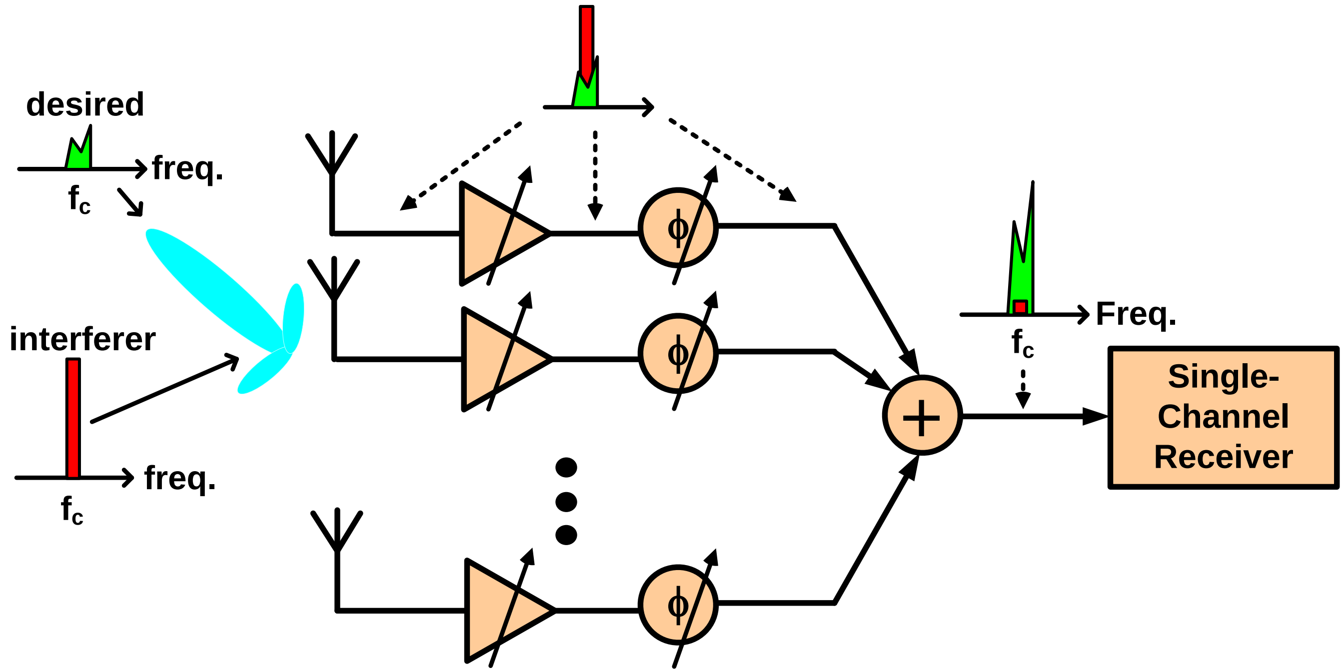

- Limited bandwidth (phase-shift rather than TTD)
- More relaxed requirement for LO phase-shifters
- Requires RF mixers with higher dynamic-range (before spatial cancellation of in-band interferers in narrowband)
- Variable gain can be placed at RF or IF/BB
- Low/moderate power consumption




- Phase-shifting and combining is trivial (at BB)
- The most flexible/adaptive architecture
- Suitable for phased arrays and MIMO
- All blocks & ADCs must have high dynamic-range
- Higher power consumption (only synth. is shared)
- Handling large amounts of digital data is required

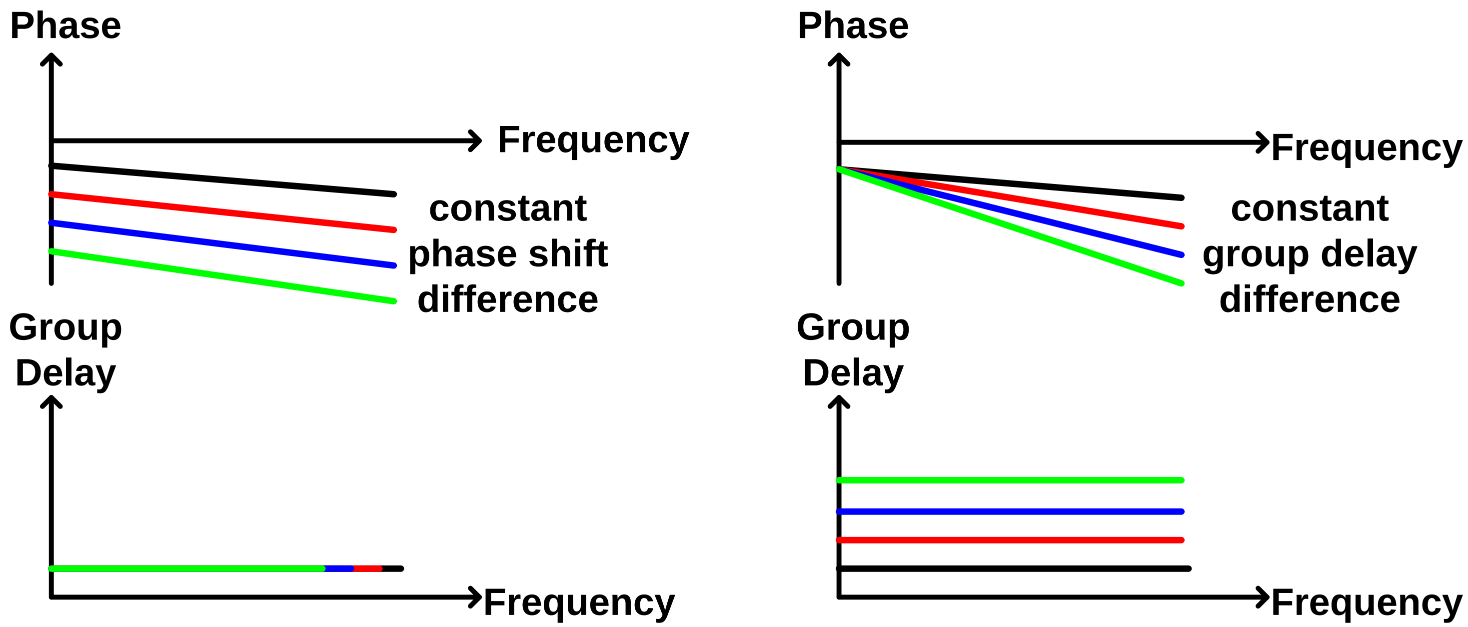
# Things to Remember (1)

- Only <u>in-band interferences</u> are cancelled in a phased-array.
- In-band interferences are only cancelled <u>after the signal combiner</u>. Hence, the dynamic range of the phase shifters and other preceding blocks is NOT relaxed.



# Things to Remember (2)

- Antenna arrays with <u>wide instantaneous bandwidth</u> require variable true time delay elements (constant group delay) across the bandwidth of interest.
- Wideband phase shifter ≠ True time delay element

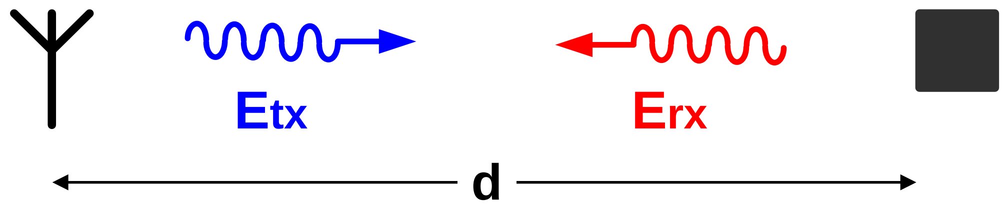


# Ultra Wideband Timed Arrays

# Ultra Wideband (UWB) for Radar & Imaging

## Radar

$$d = \frac{c \times \Delta t}{2}$$

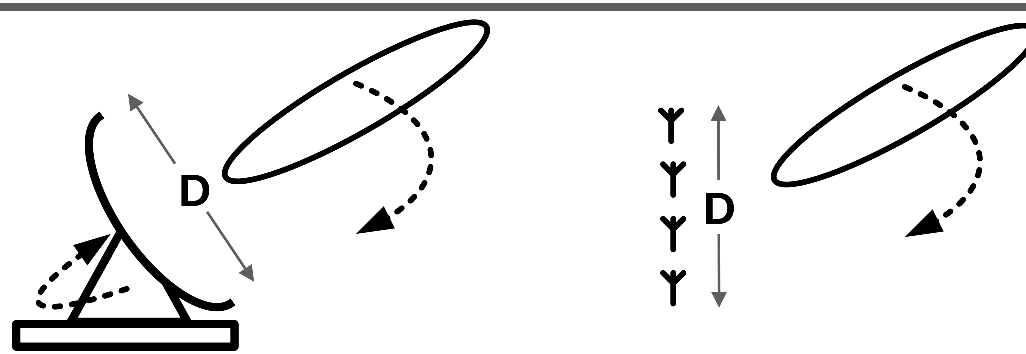



## UWB Radar
(depth resolution)

$$\text{Depth resolution} \;□\; \frac{1}{BW}$$

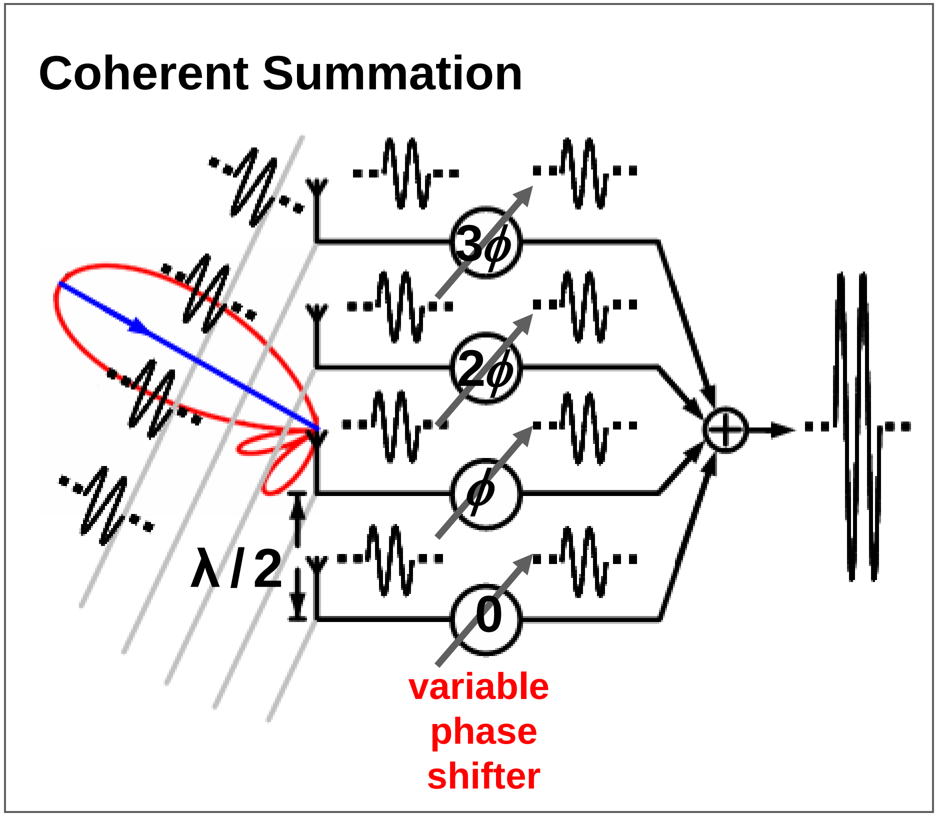

## UWB beam-former
(angular resolution)

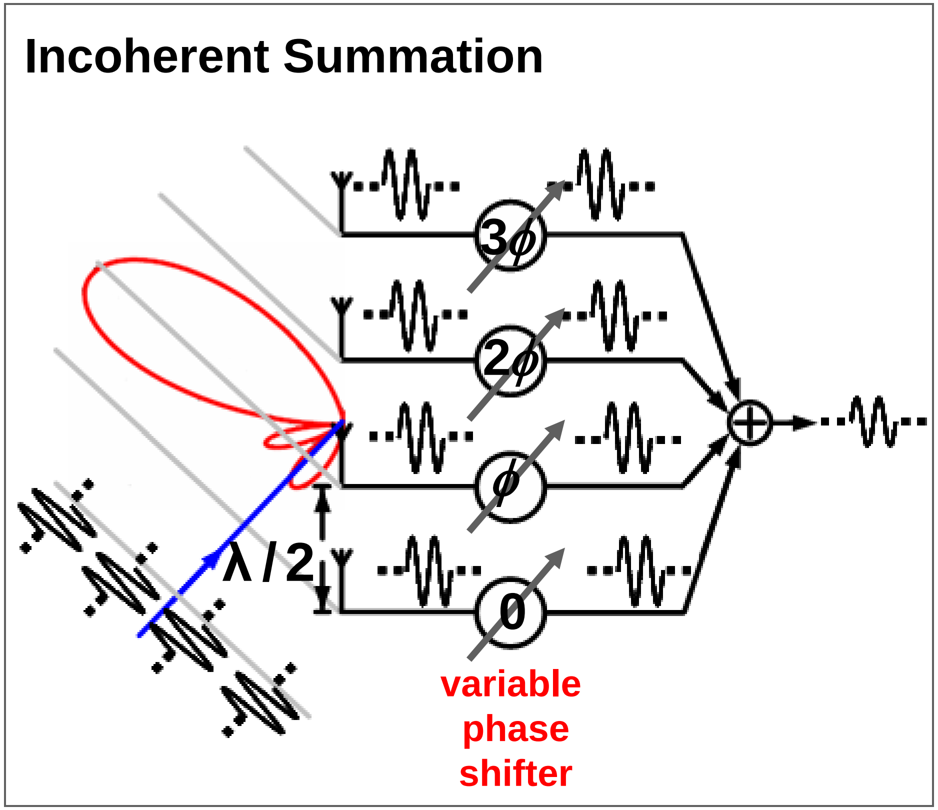
$$\text{Beam width} \;□\; \frac{1}{D}$$




Mechanical scanning    Electrical scanning

# Narrowband Phased Arrays

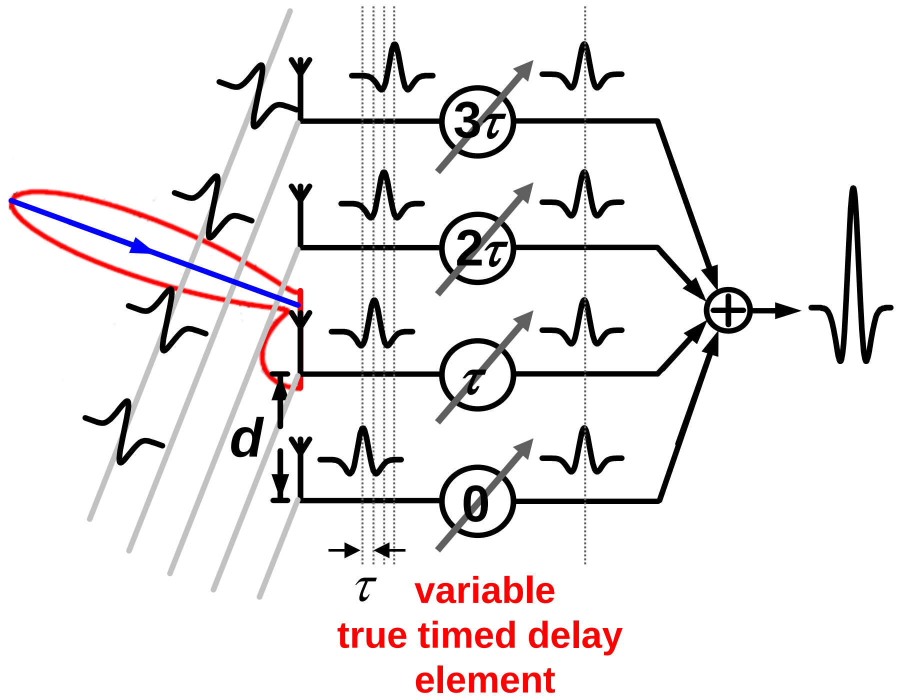


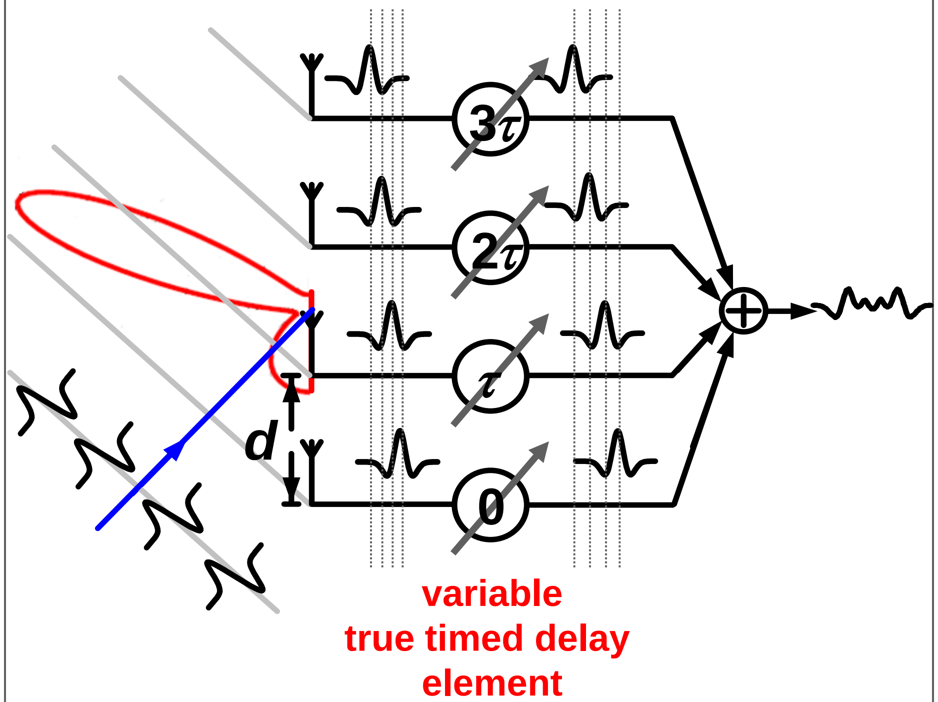

- Variable phase shifters are often used to approximate the time delay.
- The output waveform resembles the input waveform (~ sinusoid) for all incidence angles.

# Ultra Wideband (UWB) Timed Arrays

**Coherent Summation**

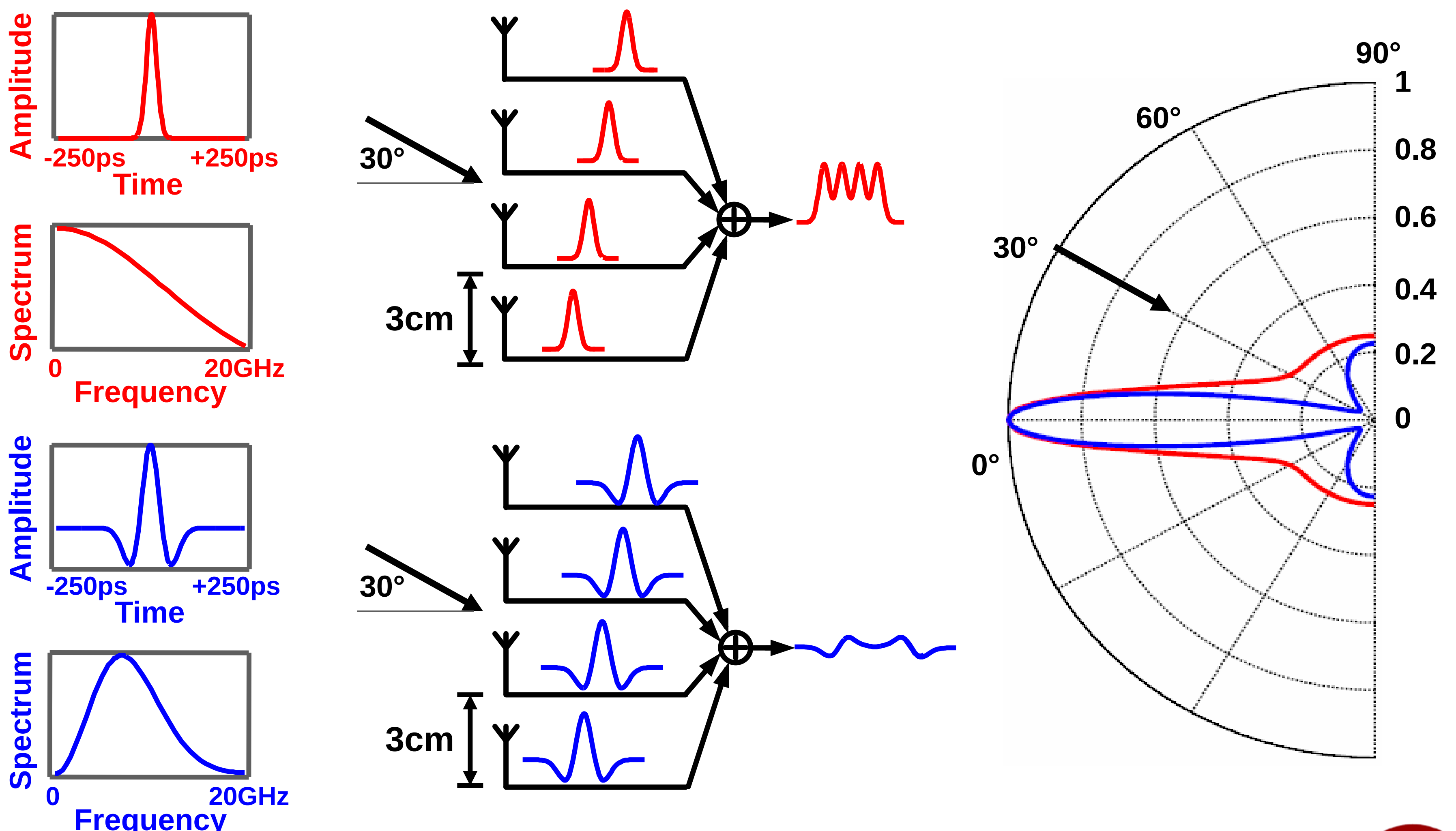



**Incoherent Summation**

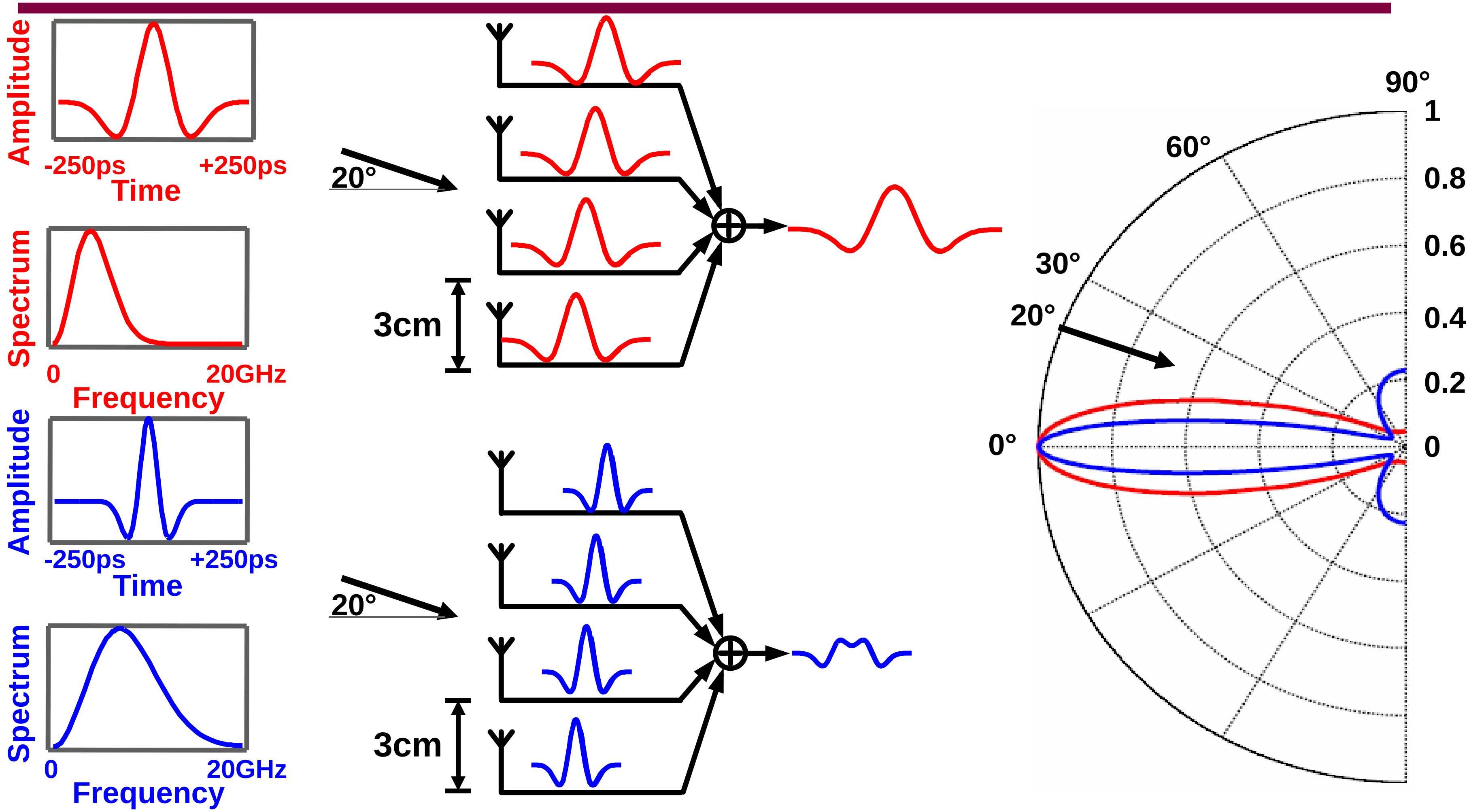



- Variable true time delay elements are needed in UWB timed arrays.
- Depending on the incidence angle, the combined output waveform may not be the same as the input waveform.

# Timed Array Patterns: Signal Waveform

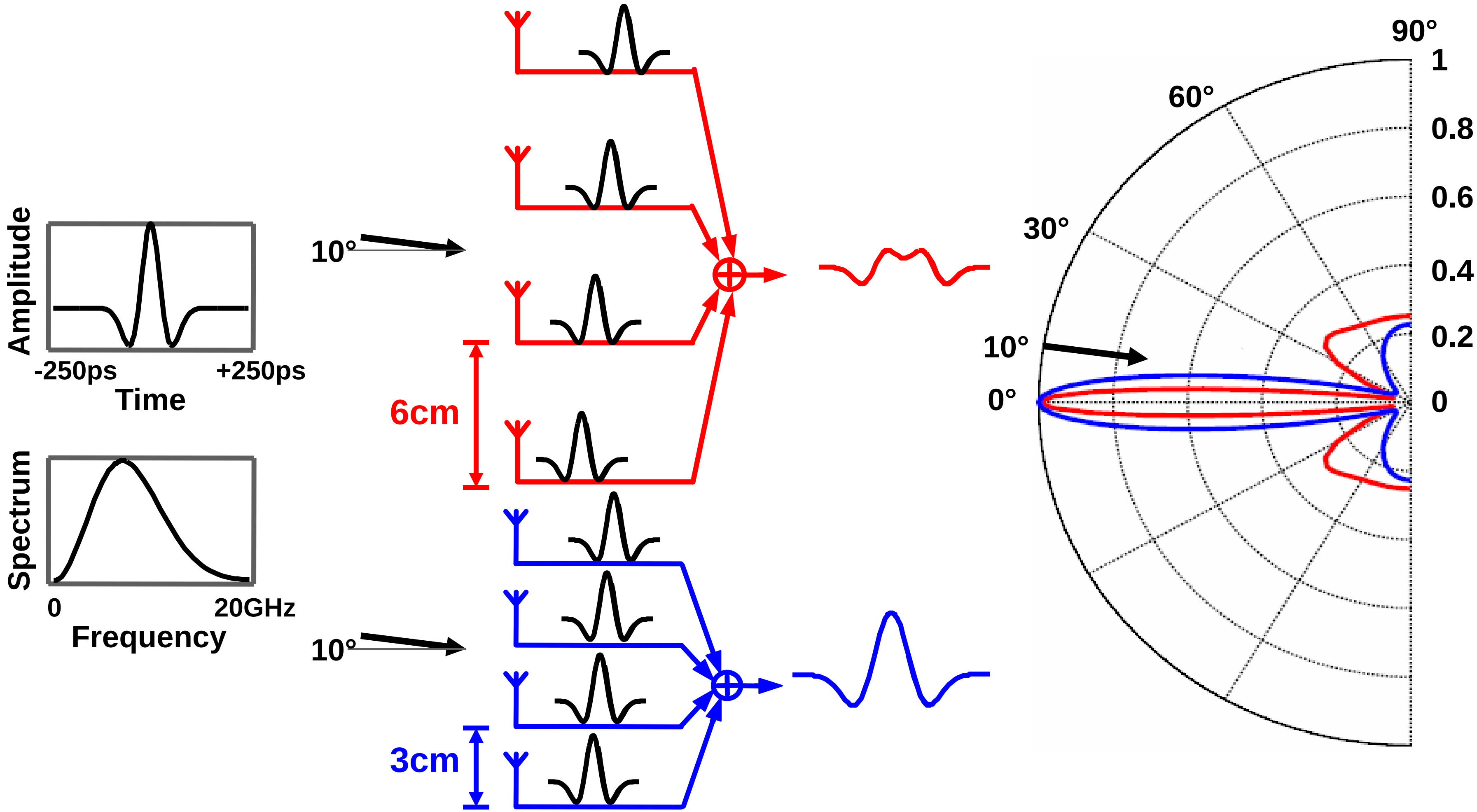


# Timed Array Patterns: Signal Bandwidth




Narrower beam-width for larger signal BW in UWB timed arrays.

# Timed Array Patterns: Antenna Spacing



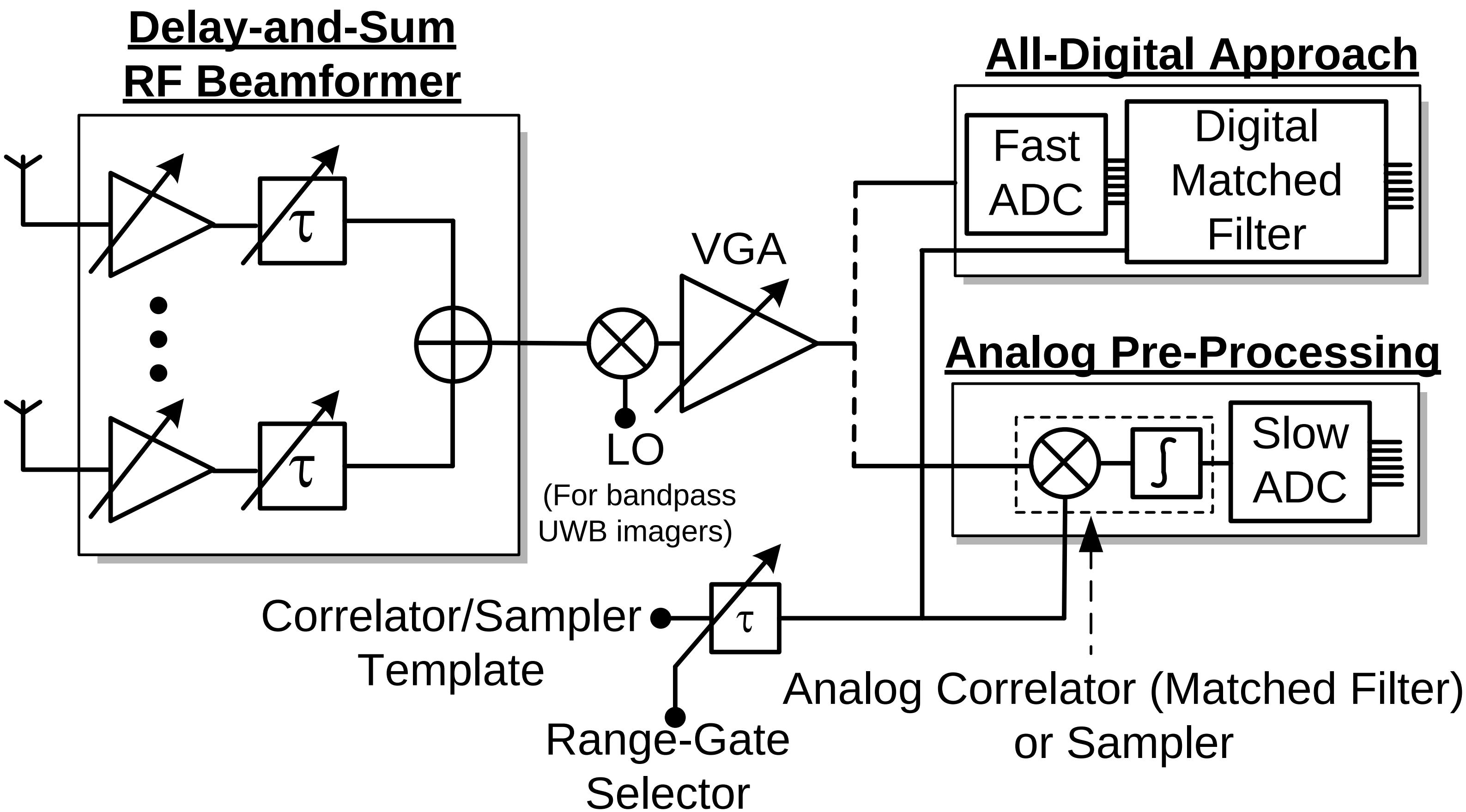

Narrower beam-width for larger arrays, given a fixed # of elements.

# UWB Timed Arrays VS NB Phased Arrays

| | *Timed Array* | *Phased Array* |
|---|---|---|
| **Signal Waveform** | discrete pulses | continuous sinusoid |
| **Bandwidth** | broadband | narrowband |
| **Implementation** | variable true time delay element | variable phase shifter |
| **Array Pattern** | signal waveform<br>signal bandwidth<br>antenna spacing<br>detection scheme<br>number of elements | antenna spacing $\approx \lambda/2$<br>number of elements |
| **Beam width** | $\propto cT/d$ | $\propto \lambda/d$ |

**c = velocity of light in free space**
**T = signal pulse width**
**d = antenna spacing**
**λ = wavelength**

# RF Beam-Forming in UWB Arrays




The major challenge is low-loss and compact implementation of UWB Variable True Time Delays (VTTD) in a silicon process.

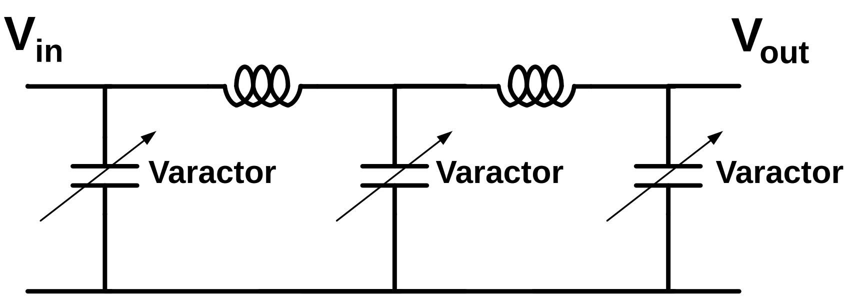
# Variable True Time Delay Realization

Vary Velocity

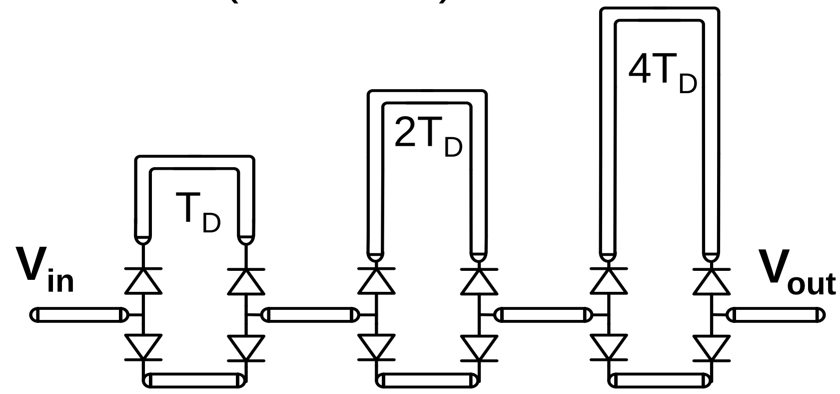
$$\text{Time Delay} = \frac{\text{Length}}{\text{Velocity}}$$

Vary Length

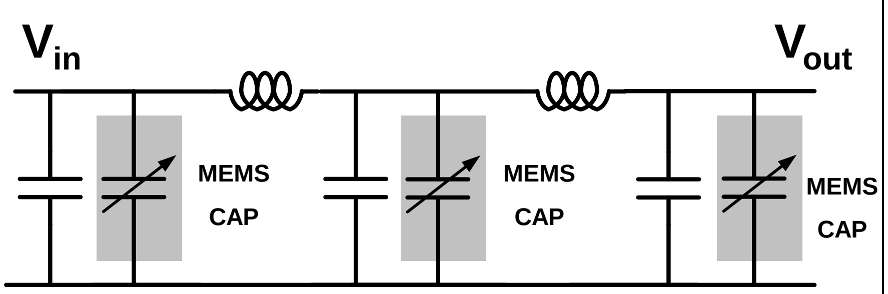
Varactor Tuned Lumped Element T-Line



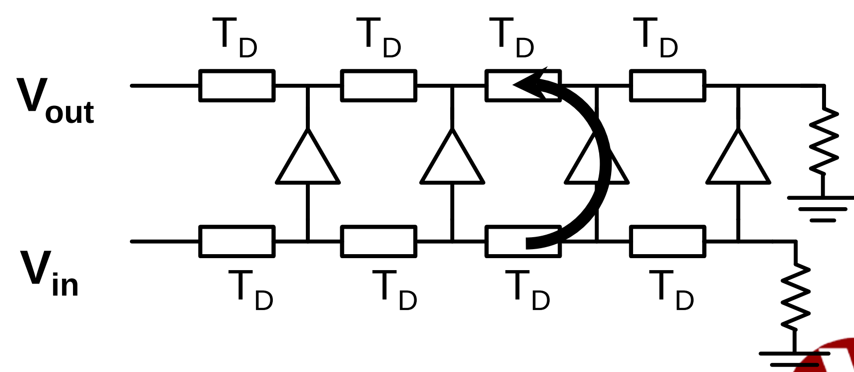

PIN Diode (or MEMS) Switched T-Lines




MEMS Tuned Lumped Element T-Line




Lumped Element Path Select Amplifiers

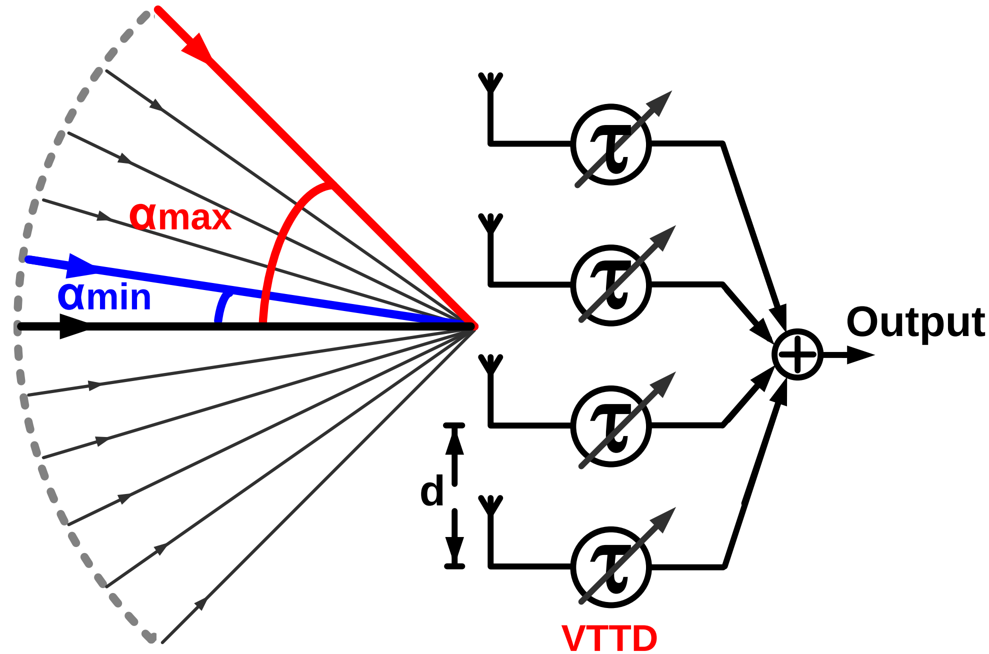


# Angular Resolution VS Delay Resolution

$$Td_{min} = \frac{d \times \sin \alpha_{min}}{c}$$

$$Td_{max} = (n-1) \times \frac{d \times \sin \alpha_{min}}{c}$$

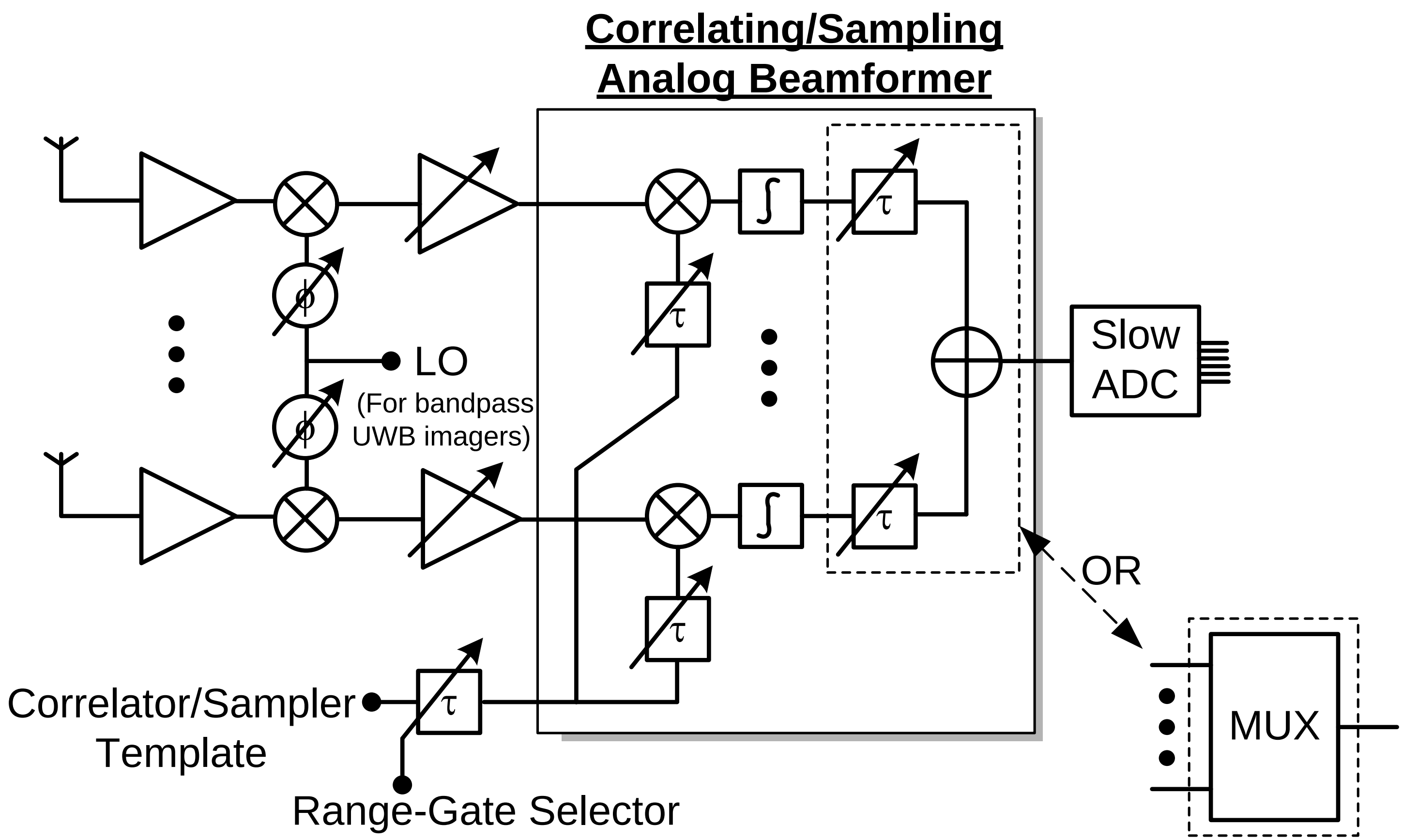
$\alpha_{min}$=minimum scanning angle
$\alpha_{max}$=maximum scanning angle
$Td_{min}$=minimum delay difference
$Td_{max}$=maximum delay difference
d=antenna spacing
c=velocity of light in free space
n=number of elements




**Example** 4-element array with 3cm antenna spacing
$\alpha_{min}$=9° → minimum delay difference is 15 psec.
$\alpha_{max}$=45° → maximum delay difference is 225 psec.

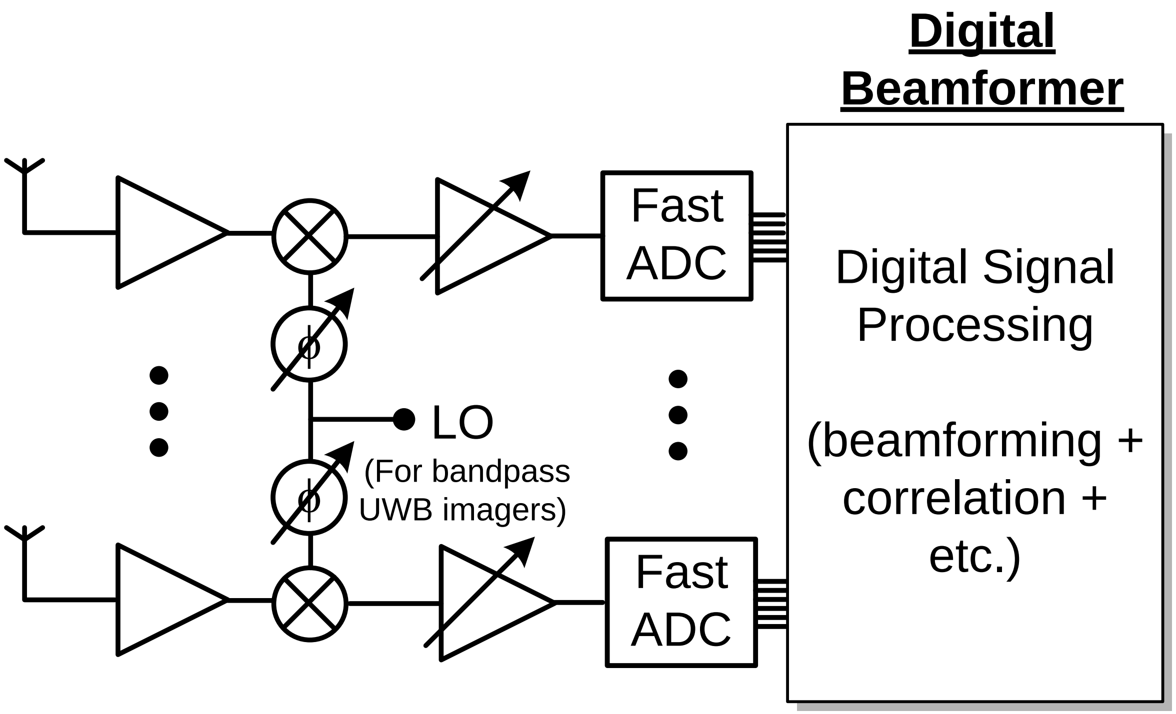
High angular resolution and wide scanning capability require VTTDs with a small delay resolution and a large overall delay.

# Correlating Beam-Forming in UWB Arrays




This architecture resembles the LO phase shifting architecture in narrowband phased arrays. It is simpler to delay the template or sampling signal that the incoming UWB signal using VTTD elements.

# Digital Beam-Forming in UWB Arrays



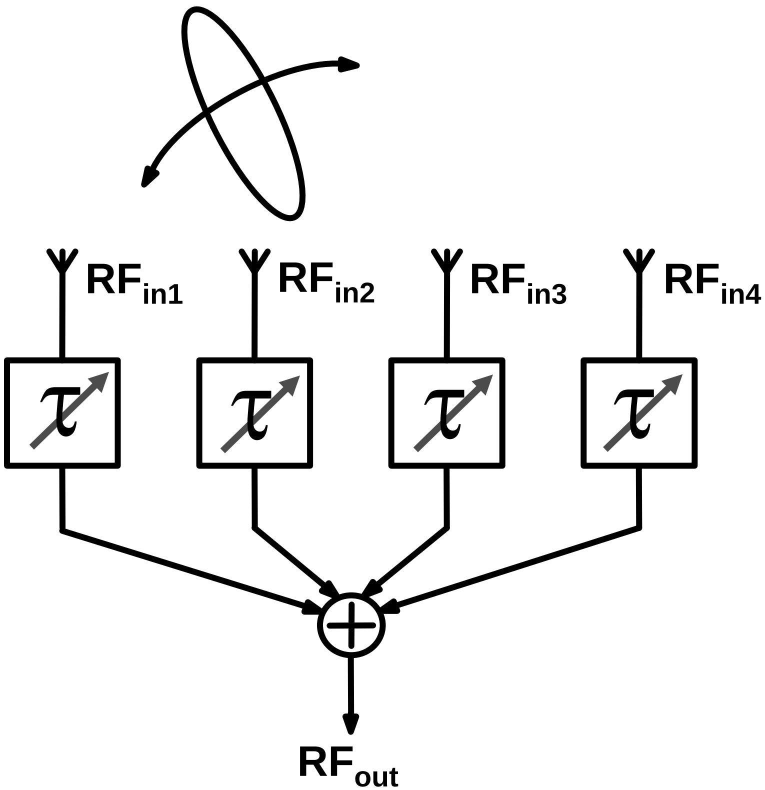

- Unless low-power high-speed ADCs become available, this architecture will not be practical for most commercial applications.

- Moreover, handing large volume of digital data in DSP is power hungry (although, it does improve with technology scaling).

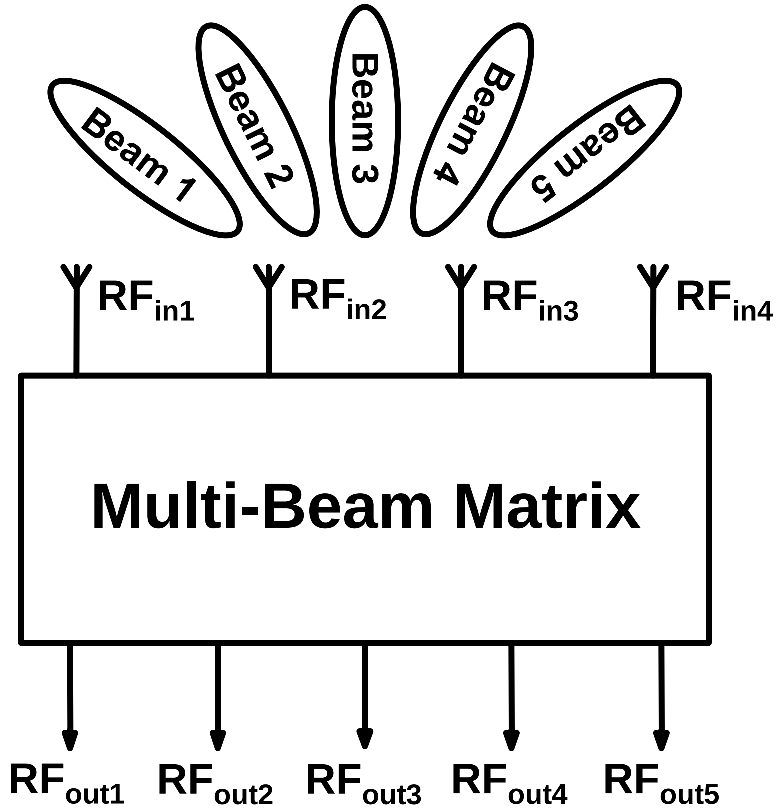
# Multi-Beam Architectures

# Scanning VS. Multi-Beam Starring Arrays

## Scanning Antenna Array

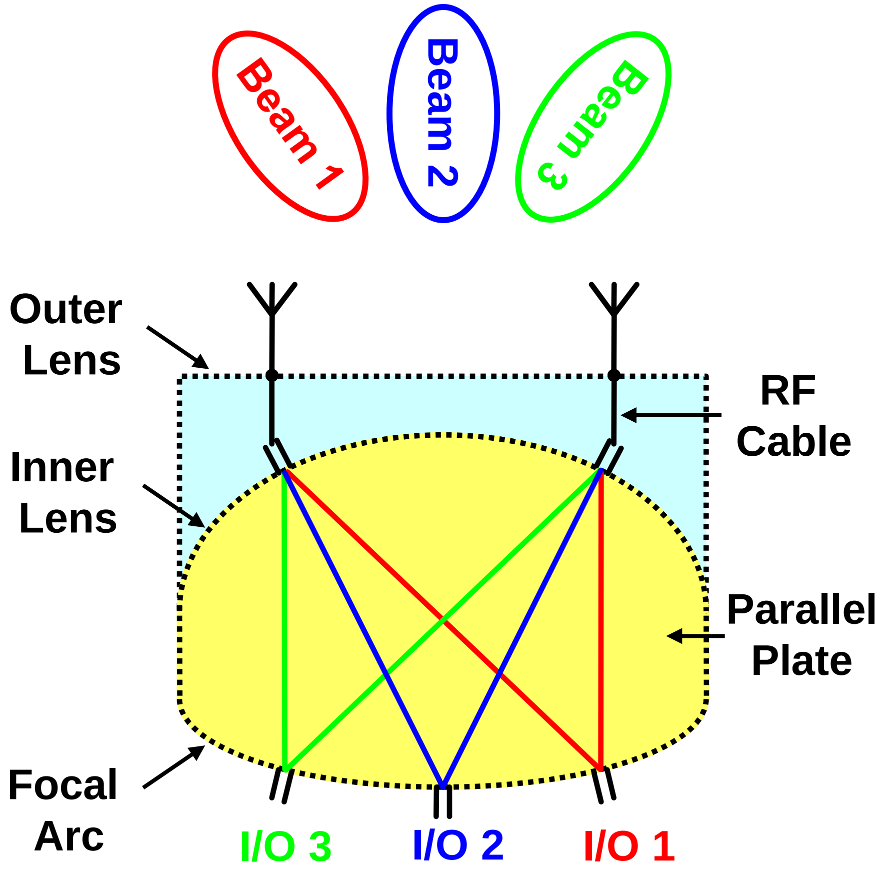



## Multi-Beam Staring Array

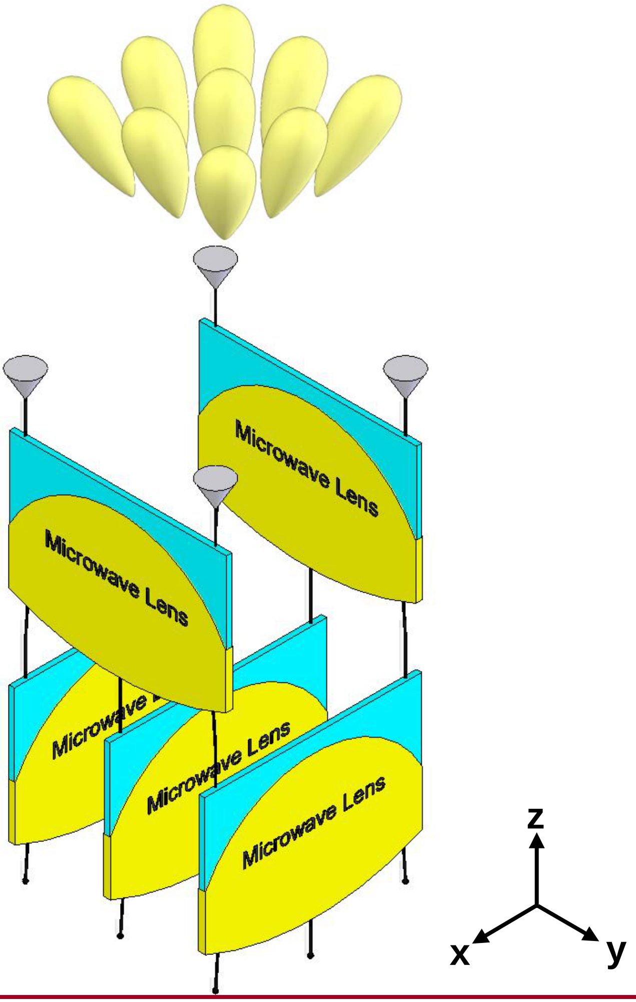


# Multi-Beam Antennas (Microwave Lens)

## 1D Array

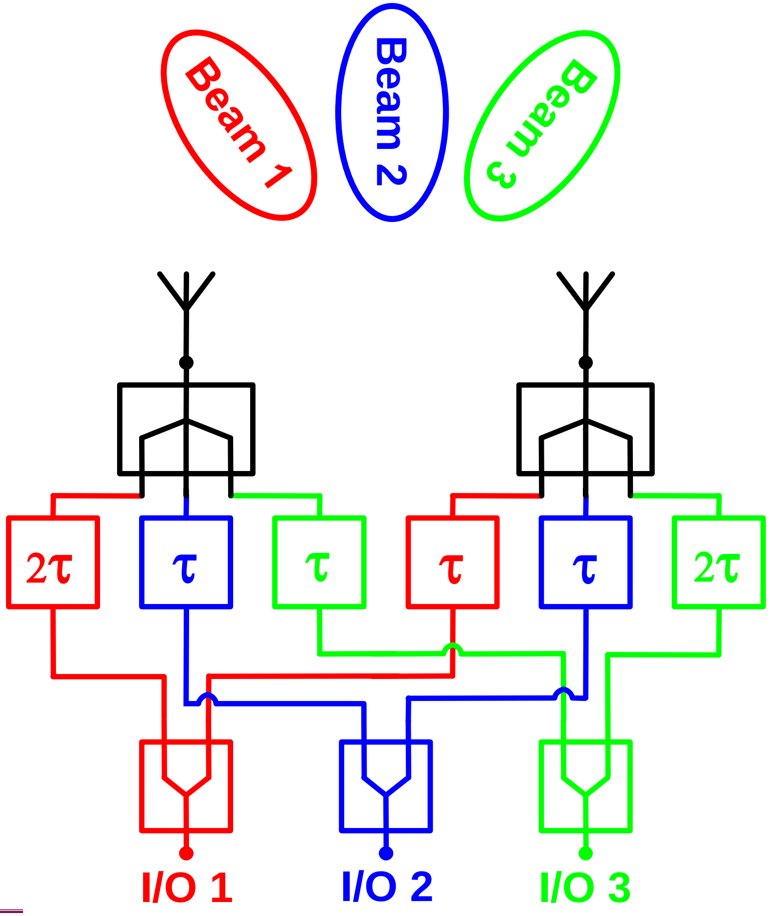



## 2D Array

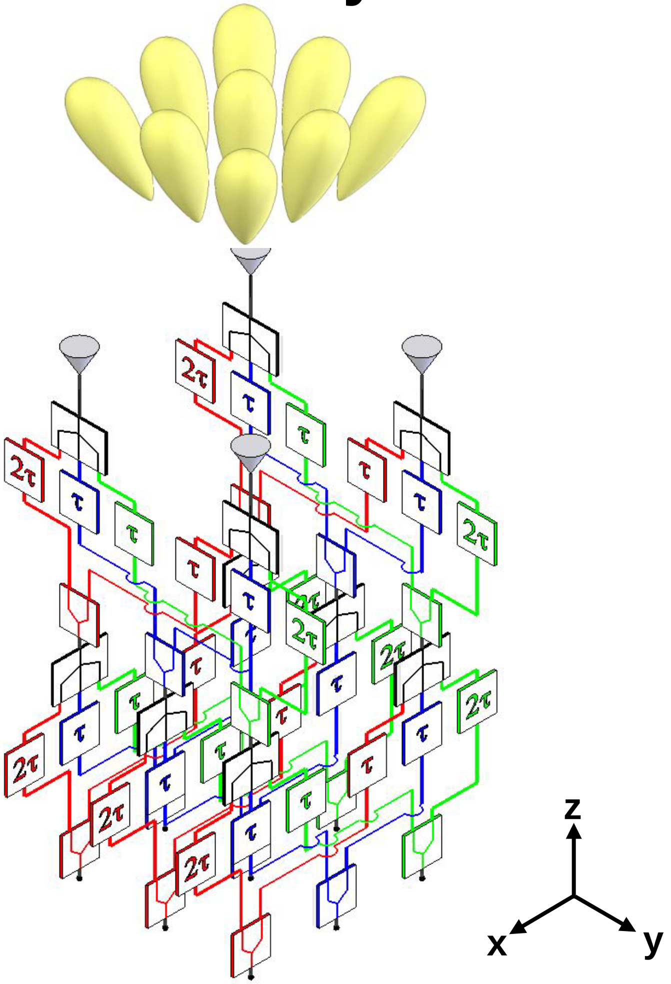


# Straight-Forward Multi-Beam Realization

## 1D Array

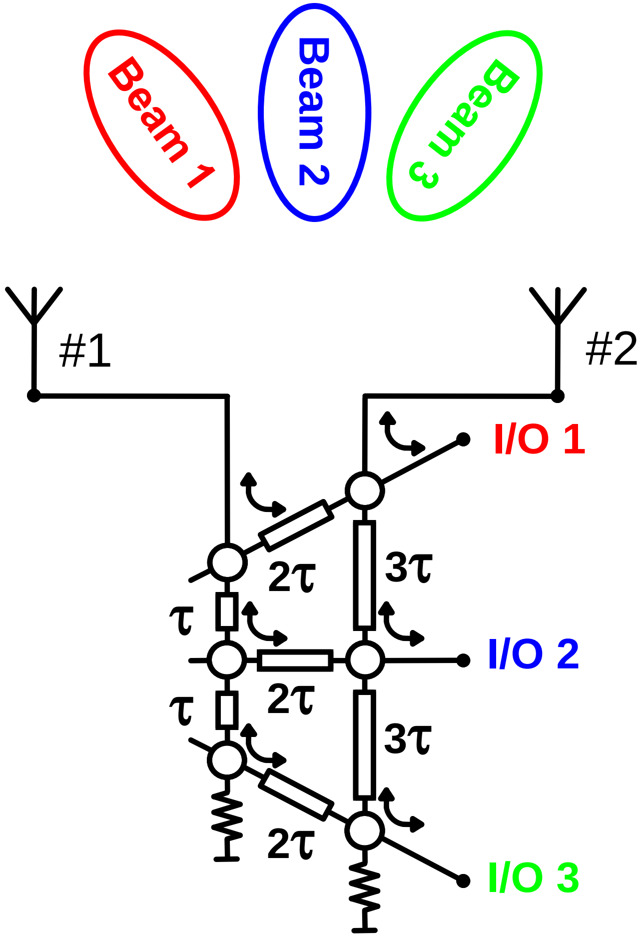



## 2D Array

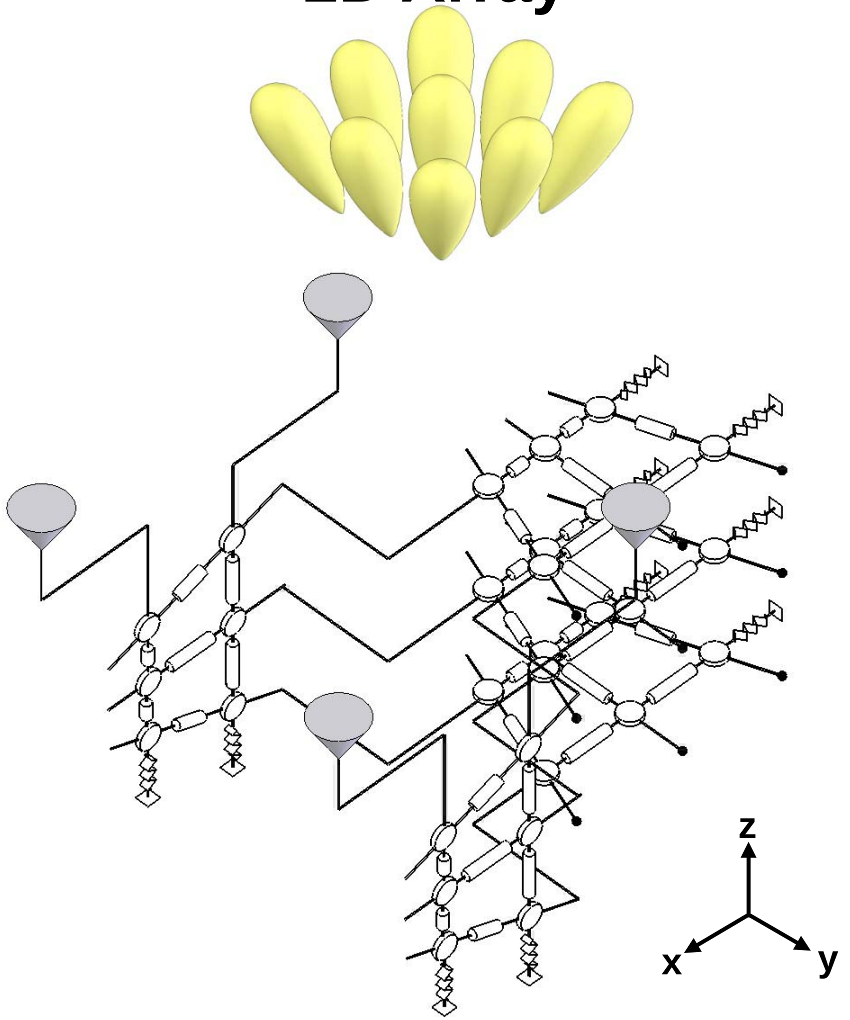


# Blass Multi-Beam Architecture

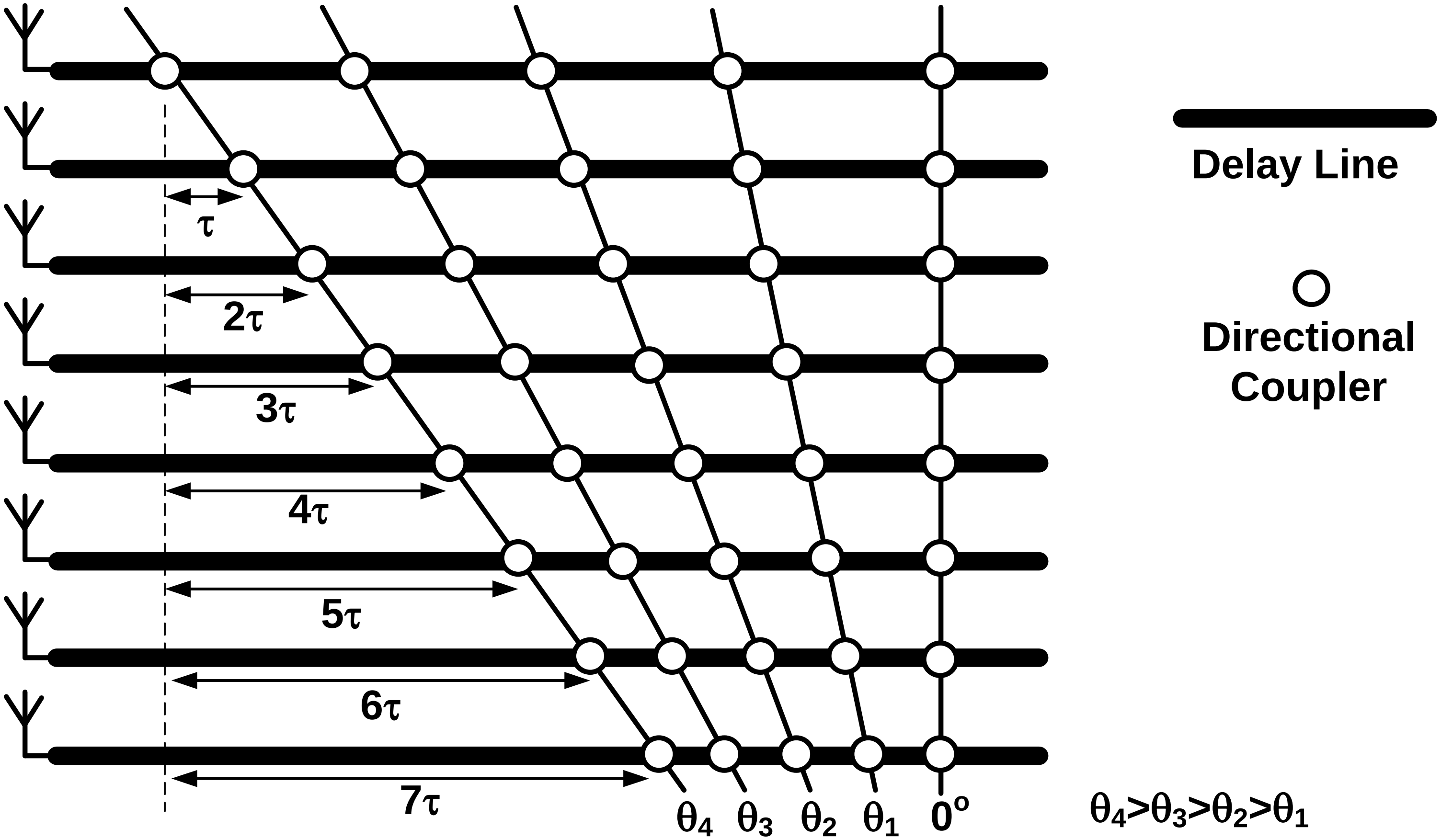
## 1D Array




## 2D Array

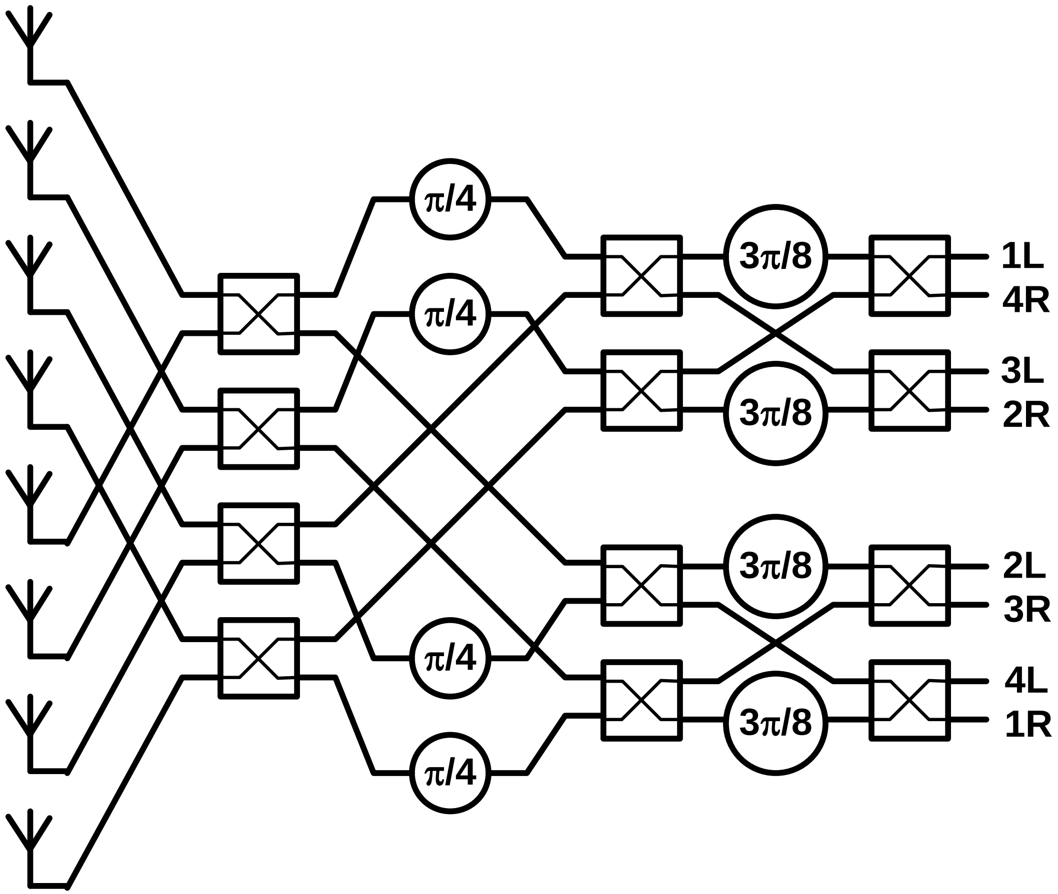


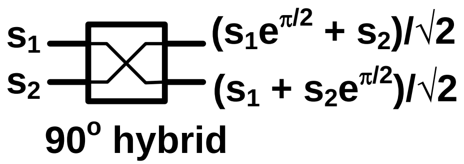
# Another View of Blass Matrix

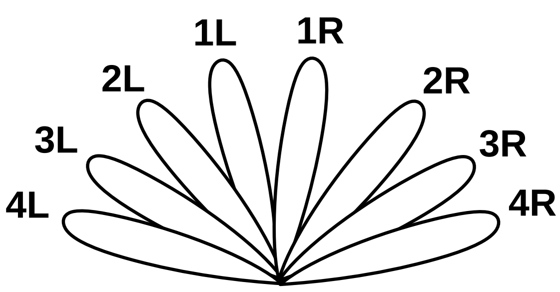



Blass matrix can be realized using TTD elements; hence, it can be used for wideband or narrowband arrays.

# Butler Multi-Beam Architecture



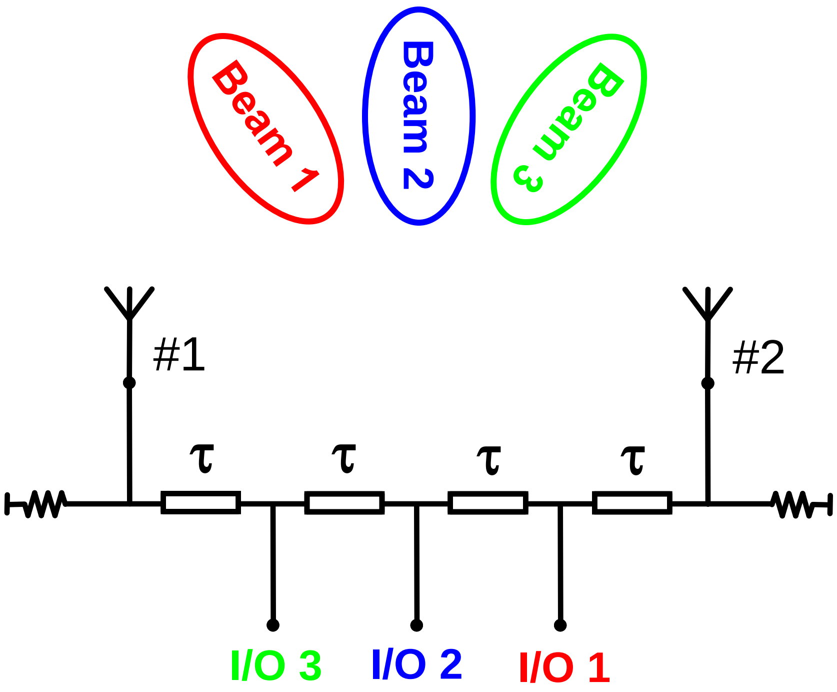



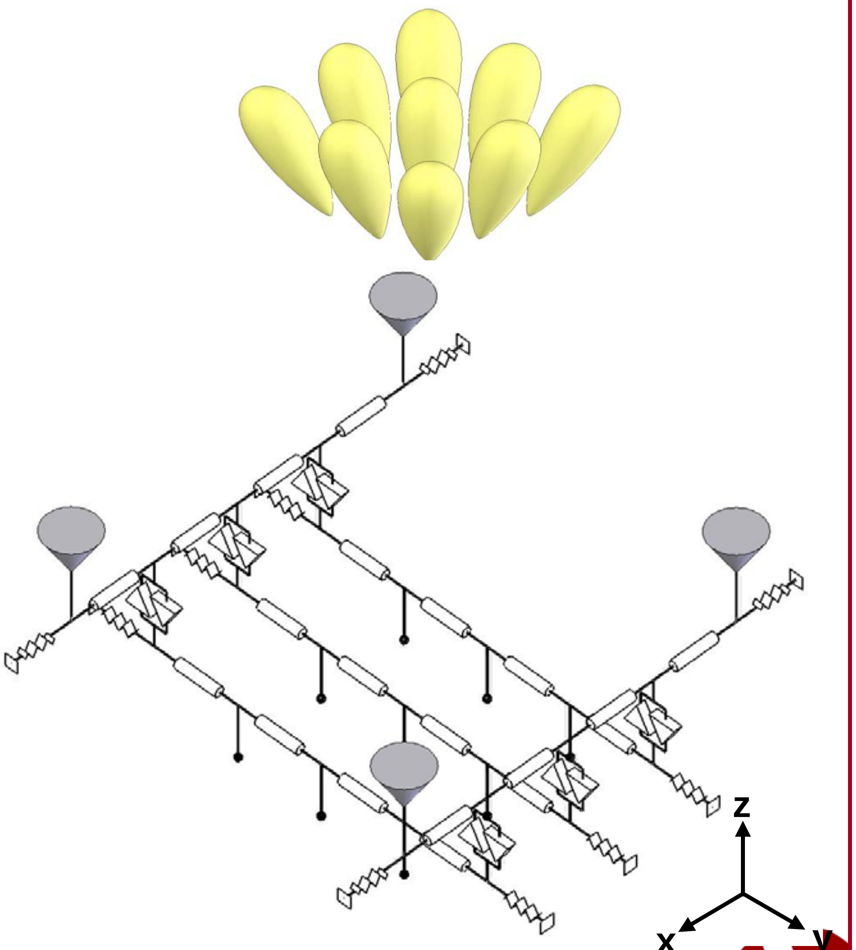

Butler matrix is only suitable for narrowband arrays.

# Chu Multi-Beam Architecture

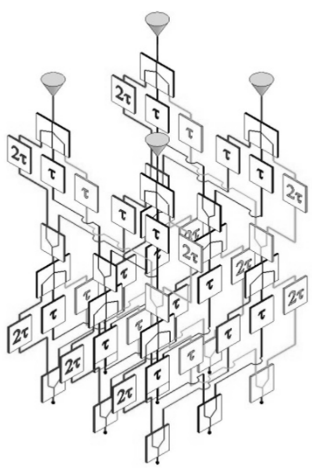
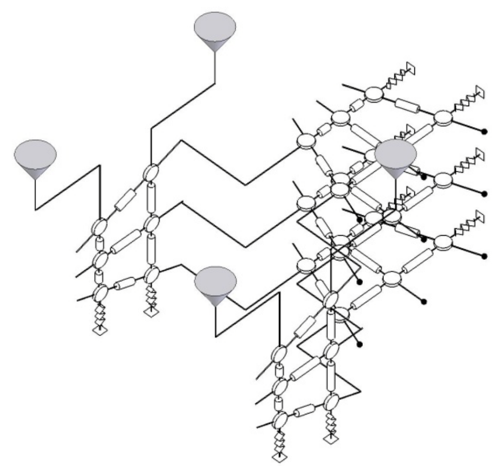
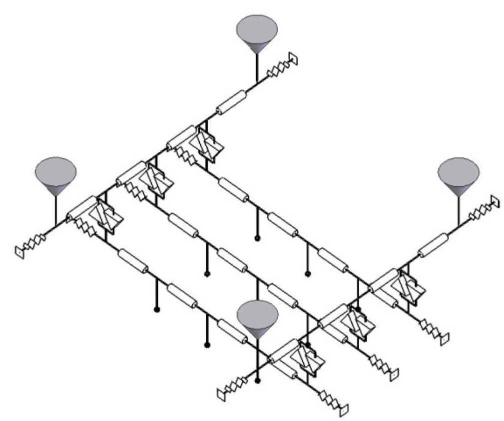
## 1D Array



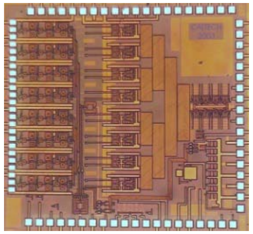

## 2D Array



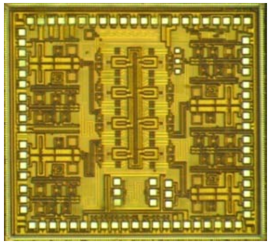
# Comparison of Multi-Beam Architectures

| | Straight-Forward Multi-beam Matrix | Blass Multi-beam Matrix | Chu Multi-beam Matrix |
|---|---|---|---|
| 2 inputs 3 outputs | $8\tau$ | $7\tau$ | $2\tau$ |
| 4 inputs 5 outputs | $56\tau$ | $70\tau$ | $27\tau$ |
| 2X2 inputs 3X3 outputs | $40\tau$ | $35\tau$ | $10\tau$ |
| 4X4 inputs 5X5 outputs | $504\tau$ | $630\tau$ | $243\tau$ |
| Complexity of 2D Array |  |  |  |

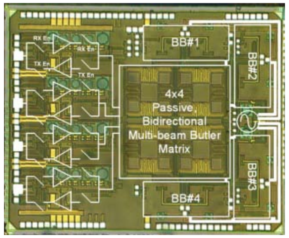
# Case Studies: Integrated Phased Arrays in Silicon



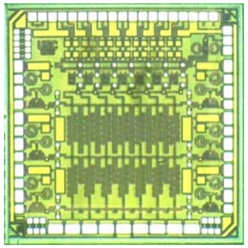
**24GHz 8-Elements RX**
**0.18μm SiGe**
**[2004]**



**24GHz 4-Elements RX+TX**
**0.13μm CMOS**
**[2007]**

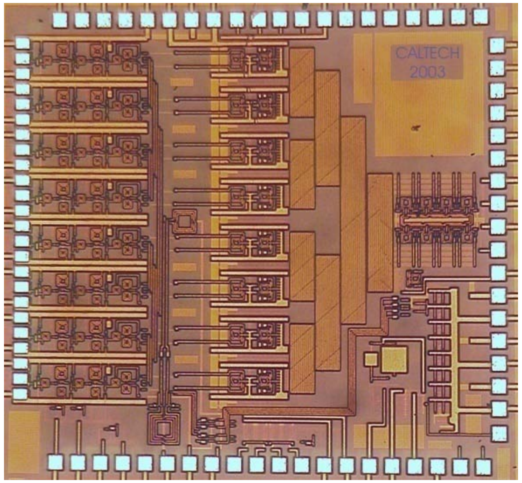



**24GHz 4-Channel**
**4-Beam**
**Spatio-Temporal Rake**
**RX+TX**
**90nm CMOS**
**[2010]**



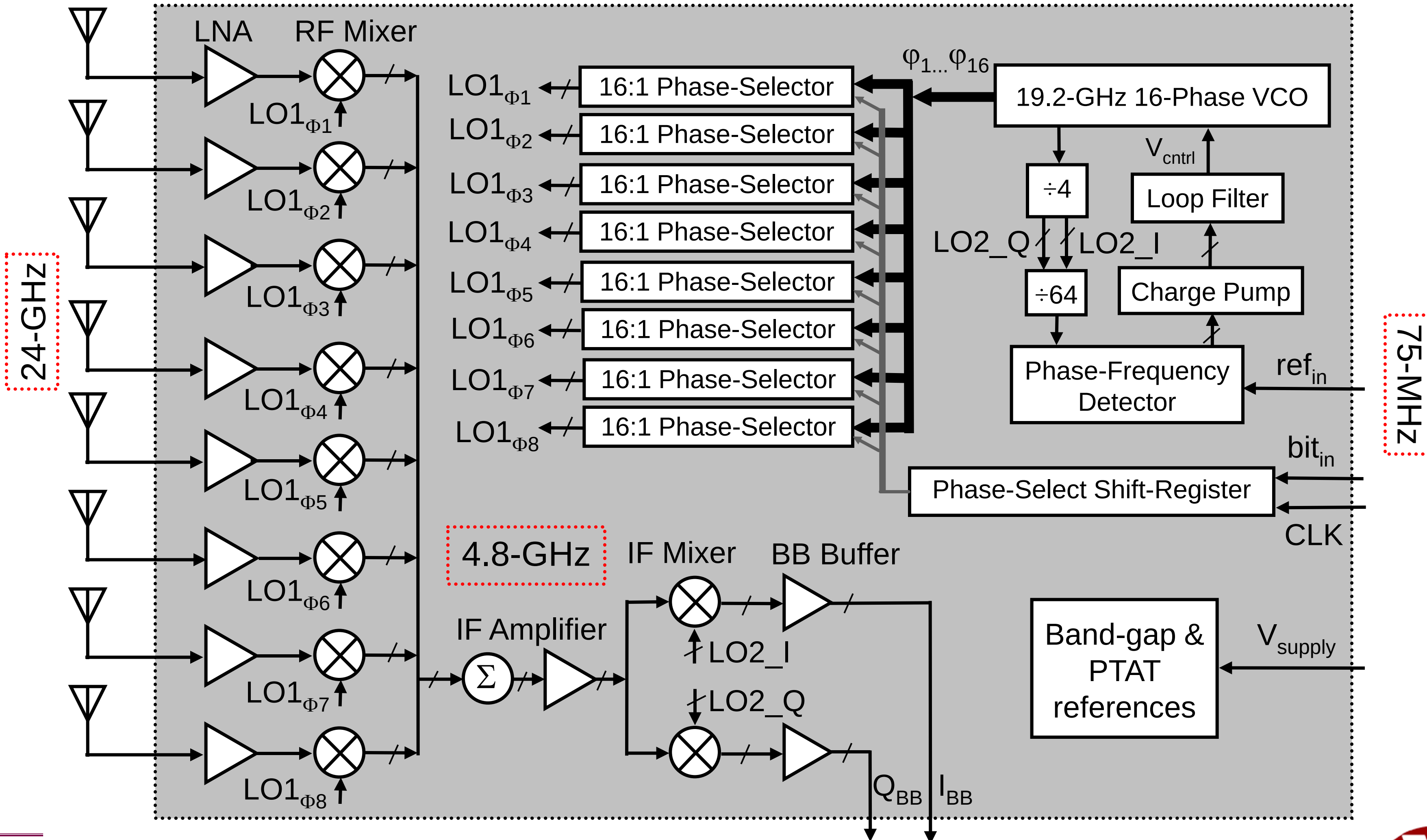
**35GHz 4-Channel**
**6-Beam**
**RX**
**0.13μm SiGe**
**[2010]**

# 24-GHz 8-Channel Monolithic Phased Array Receiver Chip in SiGe

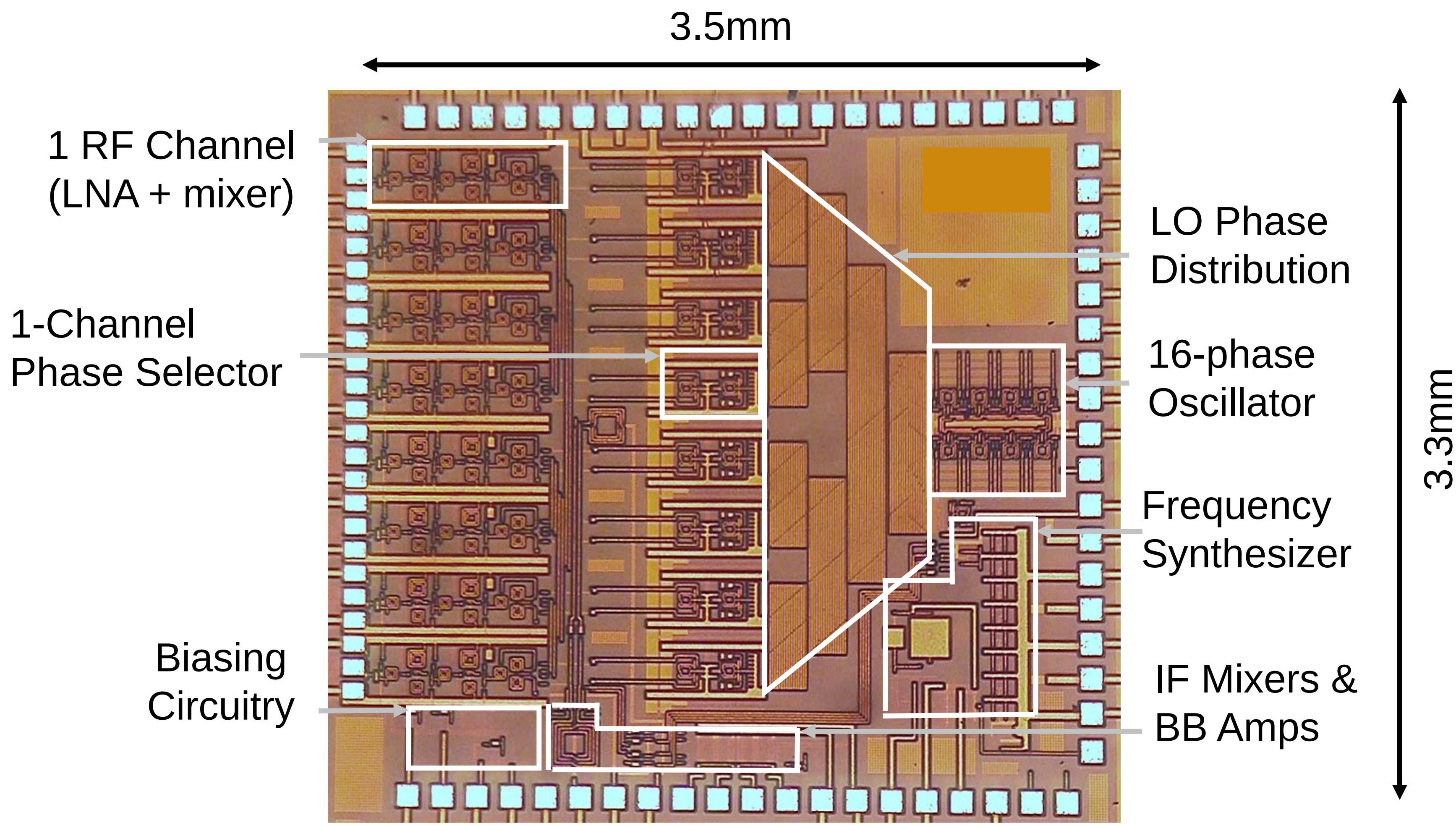



H. Hashemi, X. Guan, and A. Hajimiri, "A Fully Integrated 24-GHz 8-Path Phased-Array Receiver in Silicon," in *IEEE International Solid-State Circuits Conference* Digest of Technical Papers, San Francisco, CA, pp. 390-391, February 2004.

# Chip Architecture

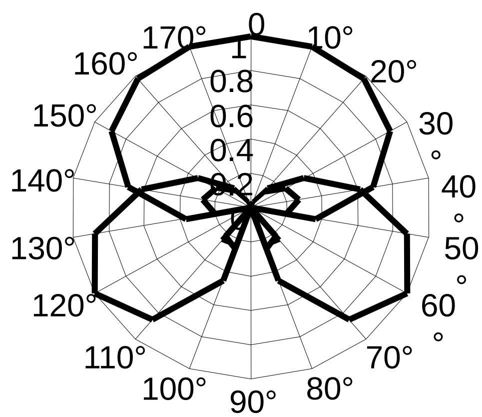


# Chip Microphotograph

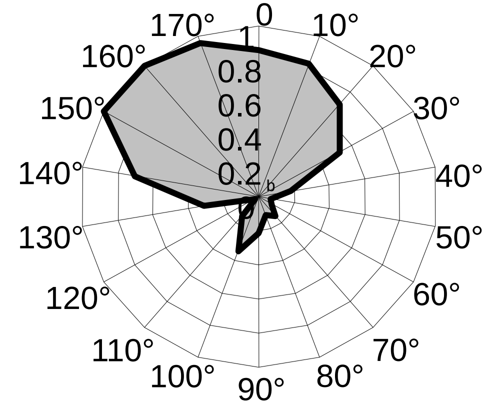


# 4-Channel Array Patterns w/o Antennas

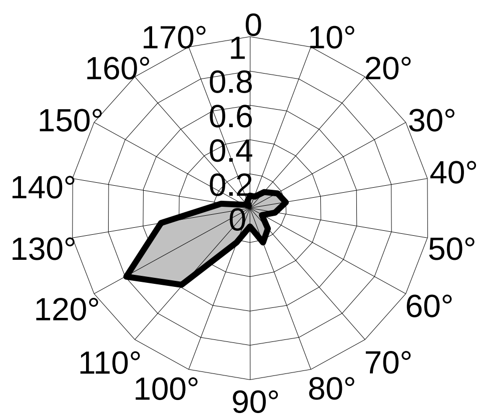
Theoretical



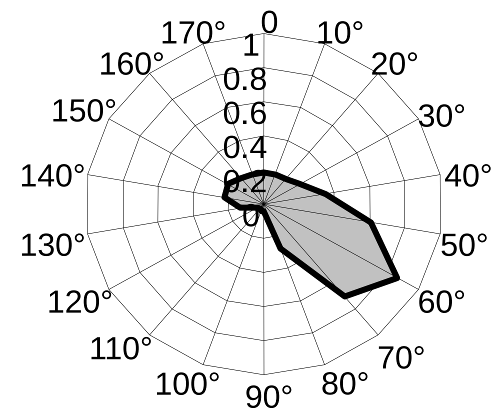

Measured




Measured




Measured



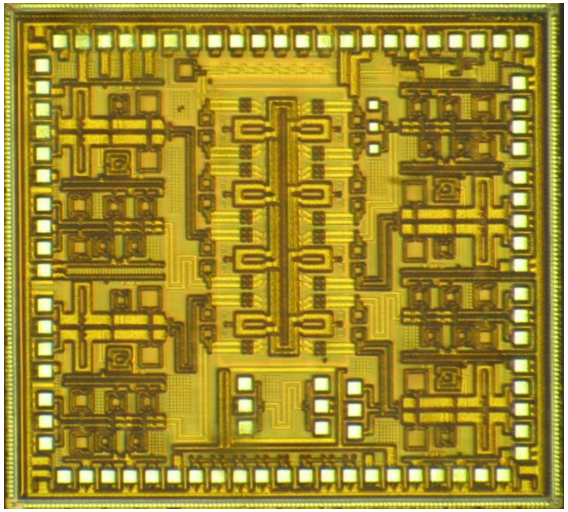
# Performance Summary

| | |
|---|---|
| ***Measured Performance per Element*** | |
| Peak Gain / Noise Figure | 43dB / 7.4dB |
| $IP_{-1dB}$ / IIP3 | -27dBm / -11.5dBm |
| On-chip image rejection | 35dB |
| ***Total Receiver Array Performance*** | |
| Total array gain / Resolution | 61dB / 4 bits |
| Beam-forming peak-to-null ratio | 20dB (4 elements) |
| Power dissipation | 287mA from 2.5V |
| ***Implementation*** | |
| Technology | 0.18μm SiGe BiCMOS (IBM7HP) |
| Die area | 3.3mm x 3.5mm |

The world's first silicon-based monolithic phased-array chip.

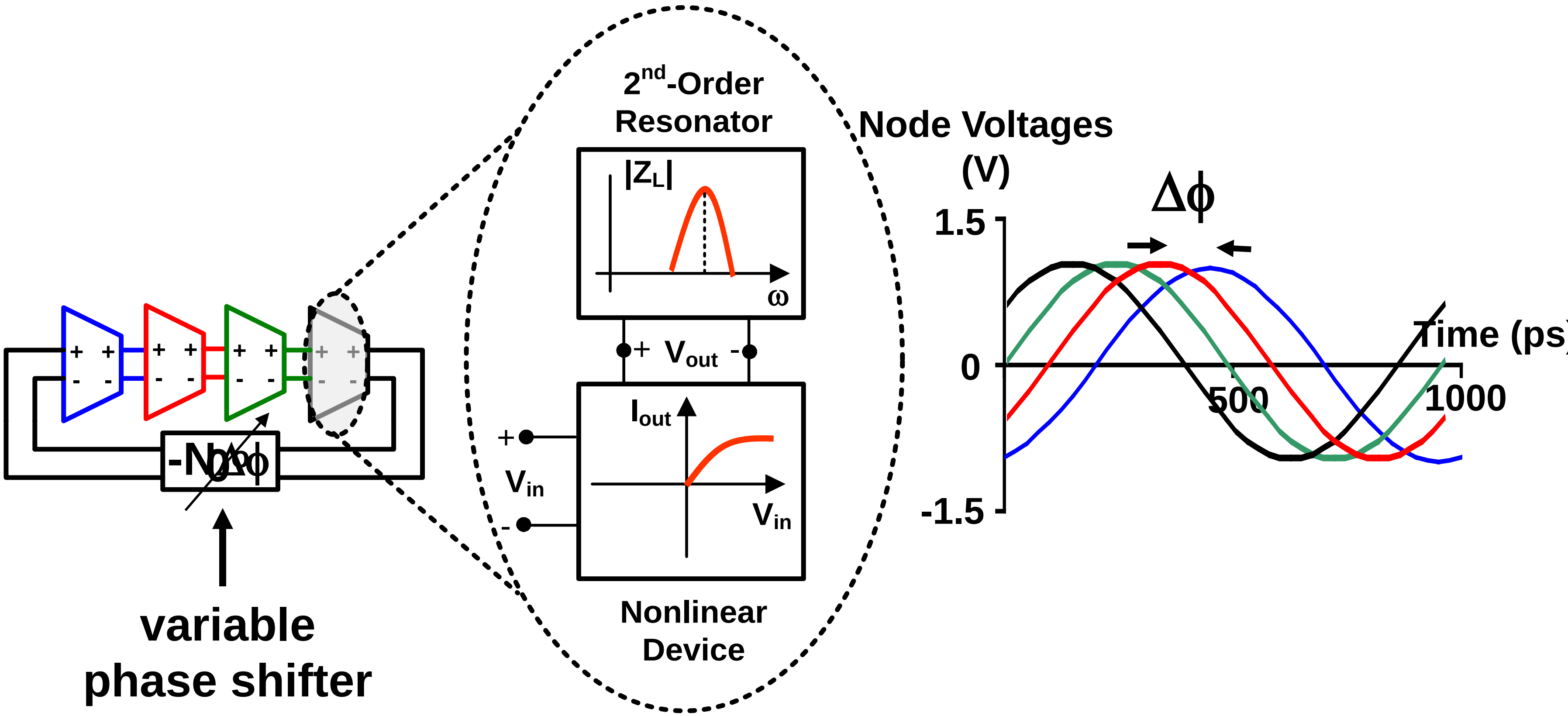
IEEE Journal of Solid-State Circuits Best Paper Award in 2004

# 24GHz 4-Channel Monolithic Phased Array Transceiver in 0.13μm CMOS



H. Krishnaswamy and H. Hashemi, "A Fully Integrated 24GHz 4-Channel Phased-Array Transceiver based on a Variable Phase Ring Oscillator and PLL Architecture" *IEEE International Solid-State Circuits Symposium* Digest of Technical Papers, pp.124-125, San Francisco, CA February 2007.

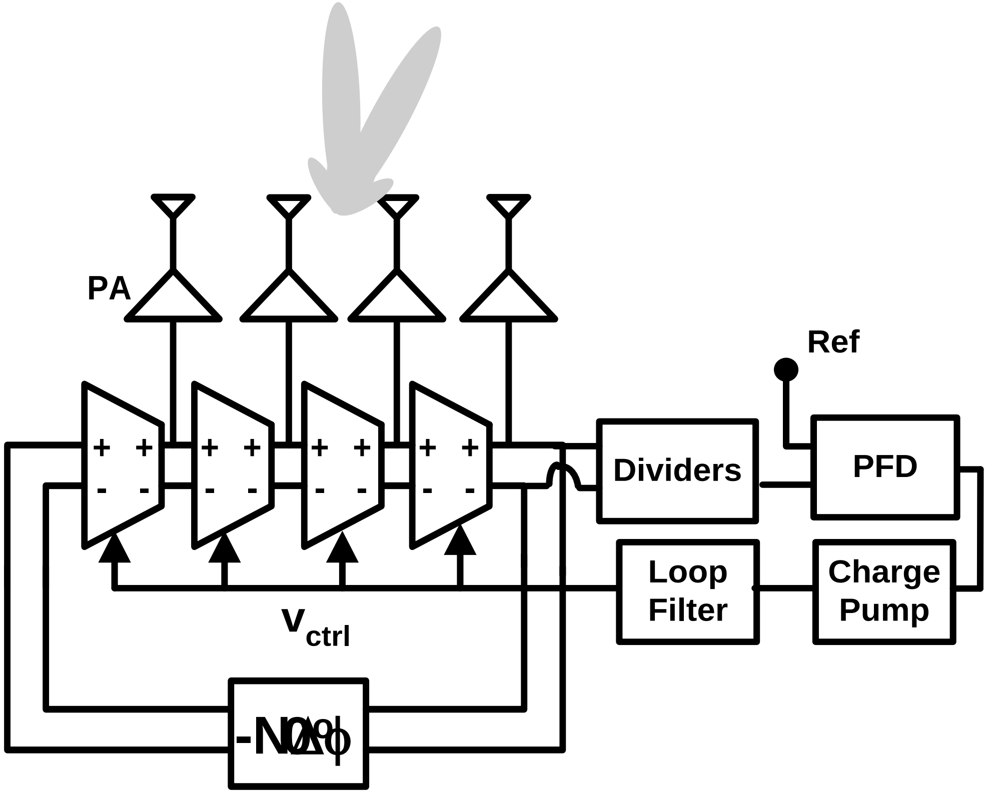
# Variable Phase Ring Oscillator (VPRO)

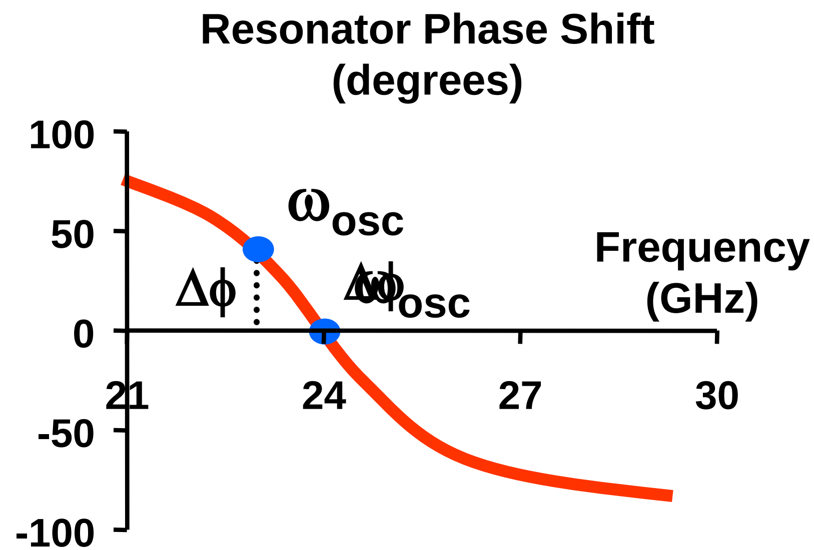



A single variable phase shifter provides the linear phase progression necessary for beam-forming.

Steady-state sinusoidal oscillation will persist in this 2N-order nonlinear system.

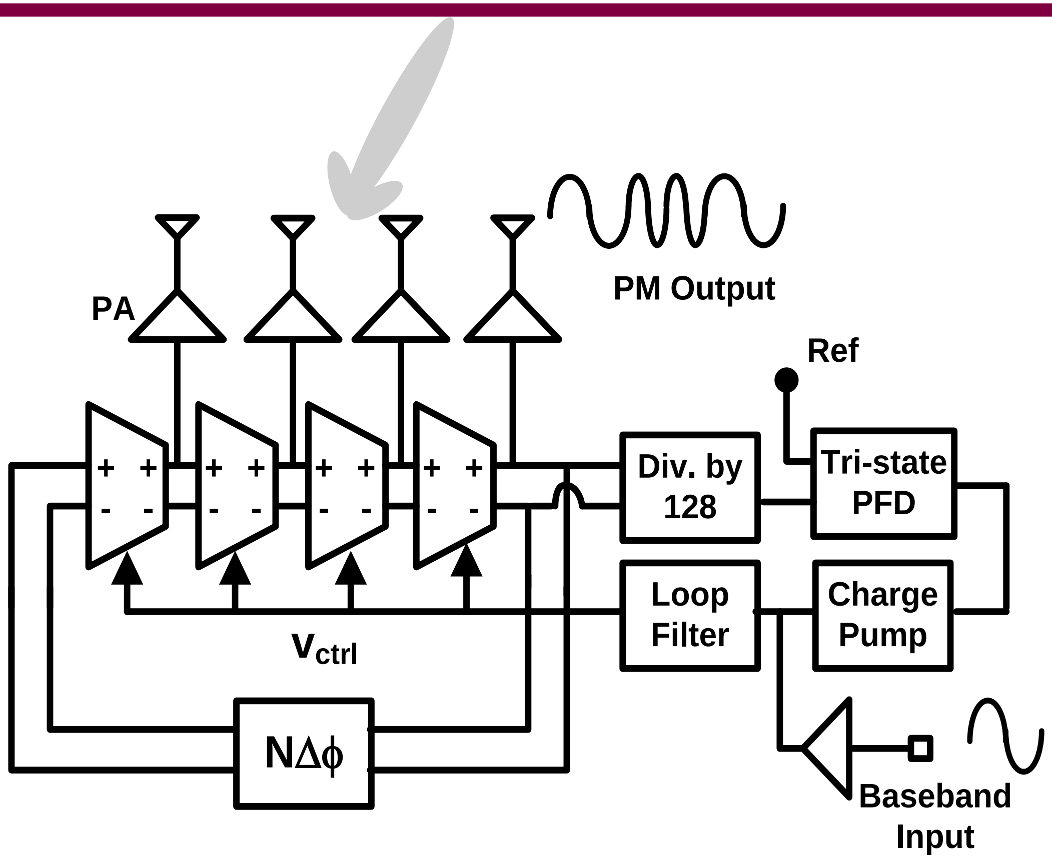
# Transmit Operation



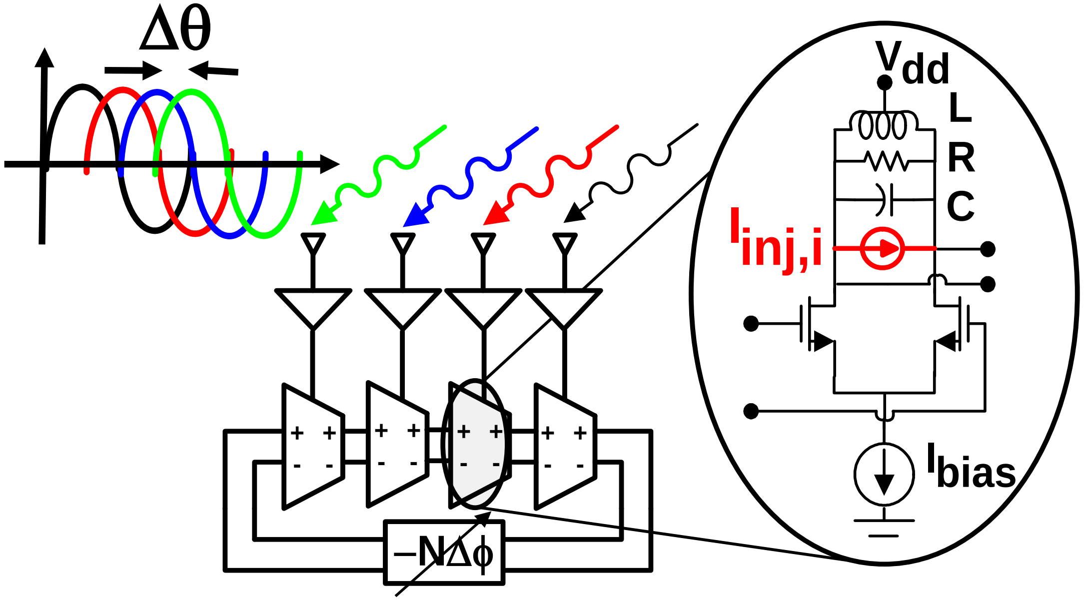

- VPRO generates a linear phase progression for steering.
- PLL ensures a constant frequency for all steering angles.

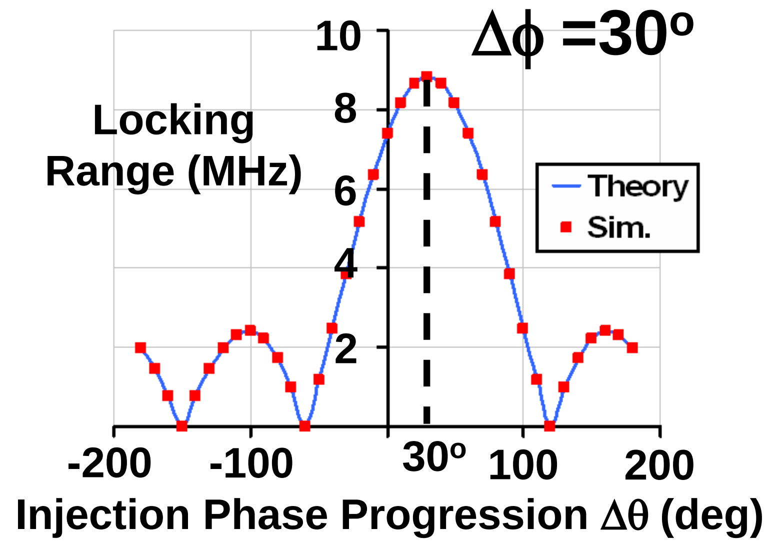
# Transmitter Architecture




- Mixers, power splitters, phase shifters are eliminated.
- Amplitude modulation can be done outside the loop.

# VPRO Injection Locking Properties



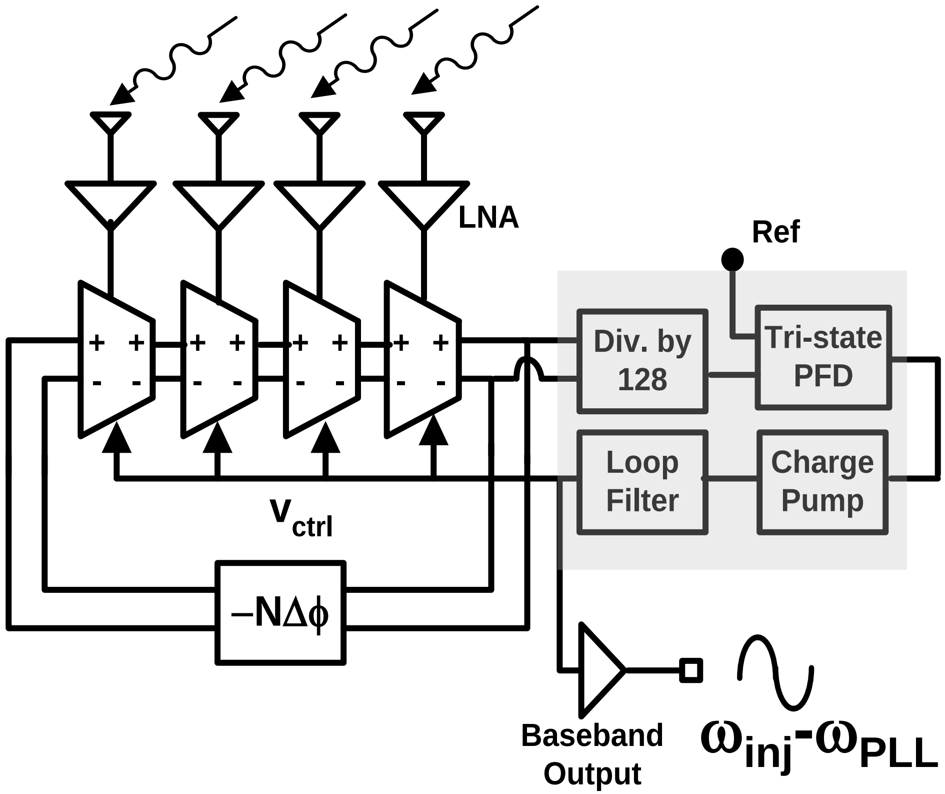



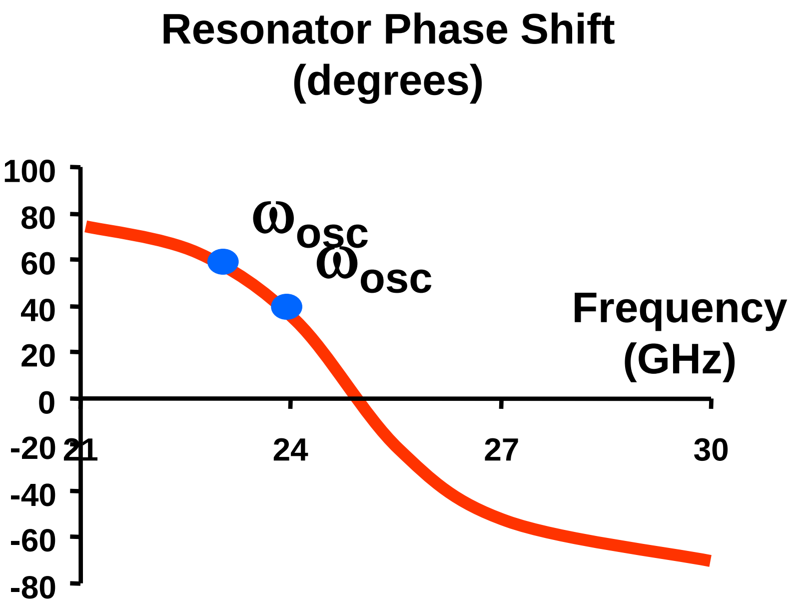

$$\frac{\Delta\omega_{lock}}{I_{inj}} = \frac{\omega_{osc}R(1+\tan^2\Delta\phi)}{A(2Q+\tan\Delta\phi)}\left|\frac{\sin\frac{N}{2}(\Delta\theta-\Delta\phi)}{N\sin\frac{(\Delta\theta-\Delta\phi)}{2}}\right|$$

**Phased Array Factor**

Injection locking range of a free-running VPRO shows phased array spatial selectivity.

# VPRO-PLL Response to Injection

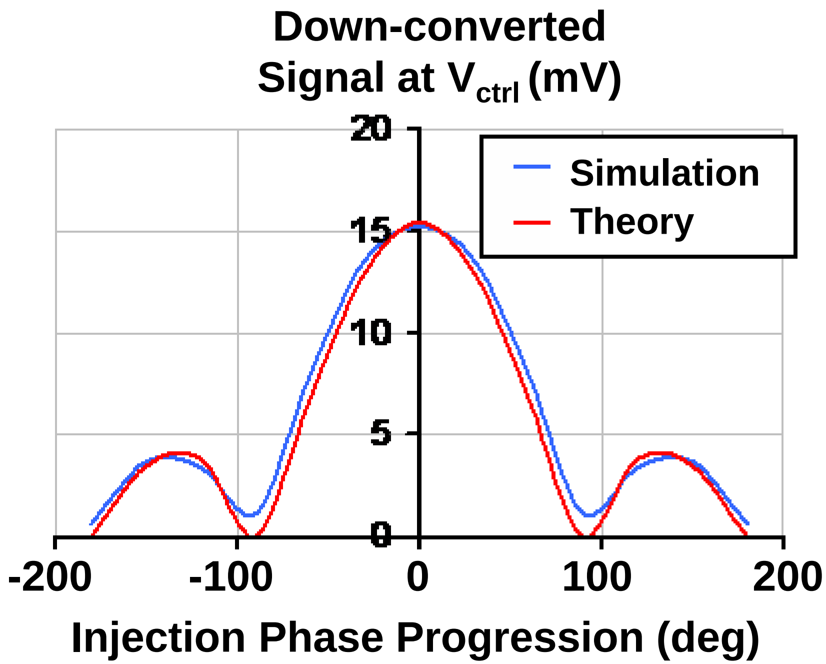


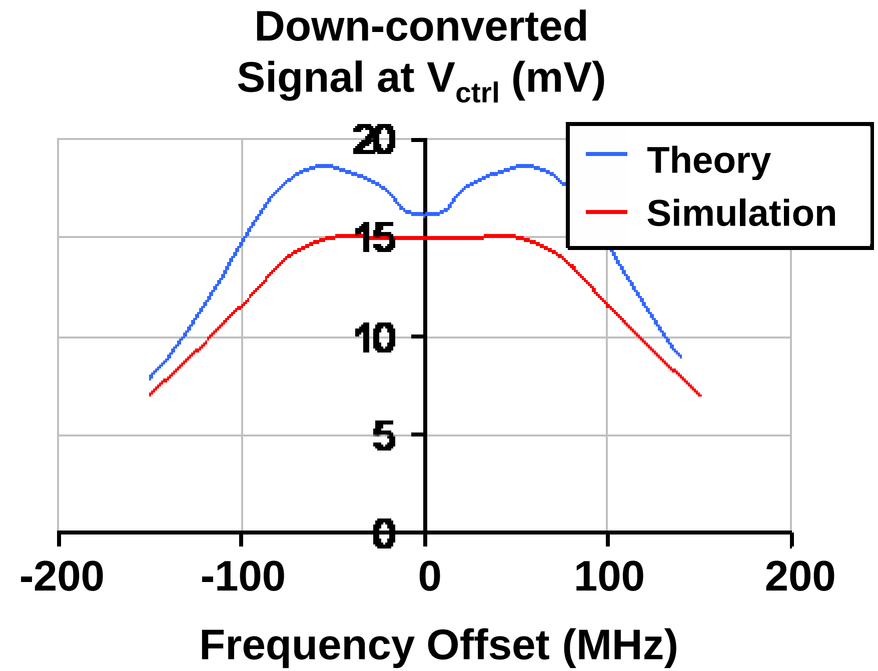

At $v_{ctrl}$, the PLL down-converts the injected signals.

# Receive Operation

## Spatial Selectivity

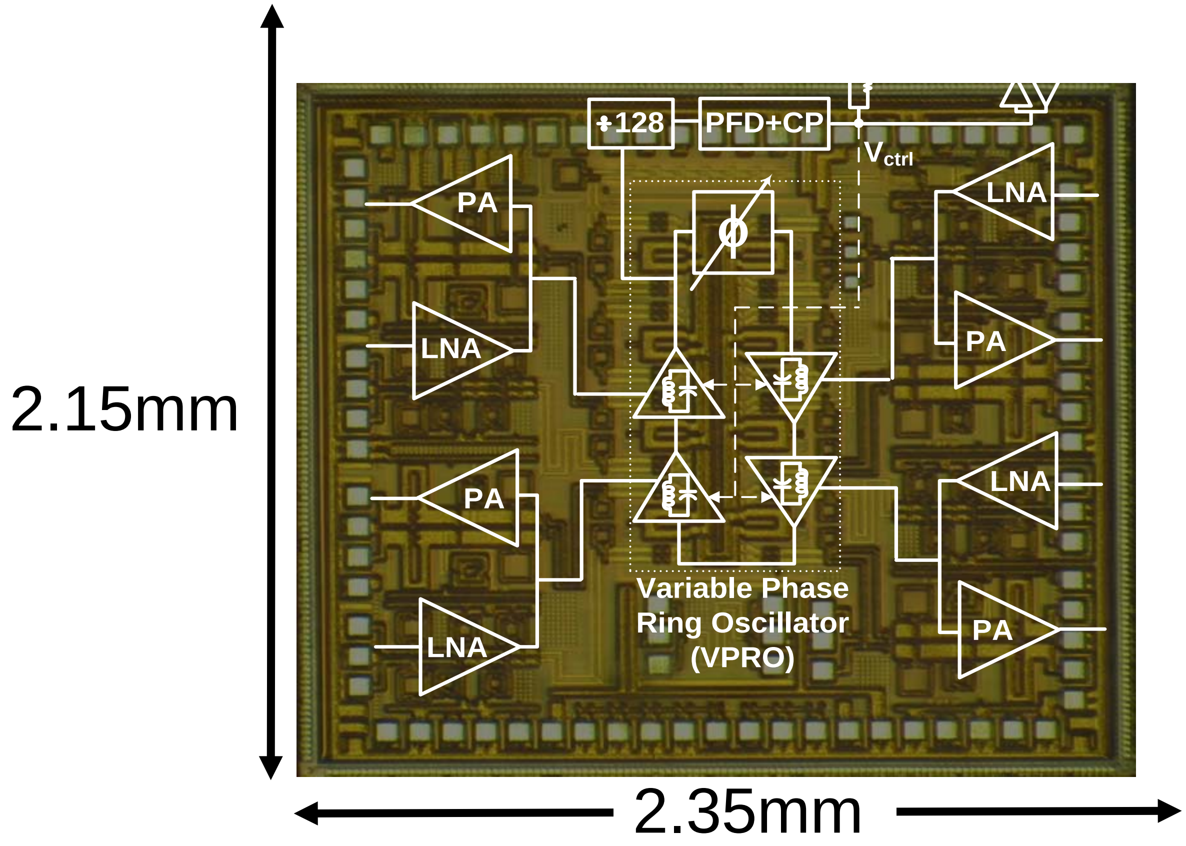



## Frequency Selectivity




$$\left|V_{ctrl}\right| = \frac{\Delta\omega_{lock}}{K_{vco}} \times \frac{K_d K_{VCO} F(s)}{sN_{div} + K_d K_{VCO} F(s)}$$

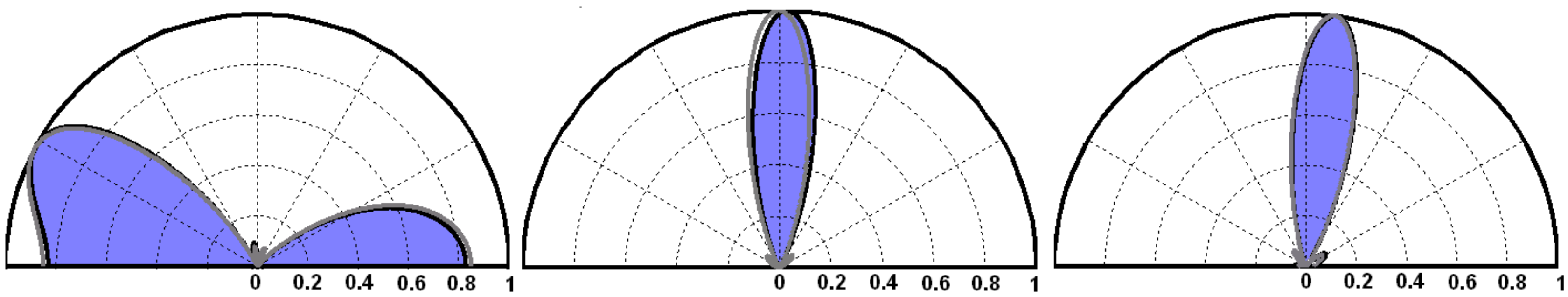
# Chip Architecture & Microphotograph




A compact low-power phased array chip based on a nonlinear transceiver architecture.

# Array Pattern Measurements in TX Mode

Measured patterns are based on amplitude and phase measurement of each channel for the probed chip.




___ Measurements ___ Theory (ideal array)

Close agreement between theory and uncalibrated measurements show the design robustness to process variations.

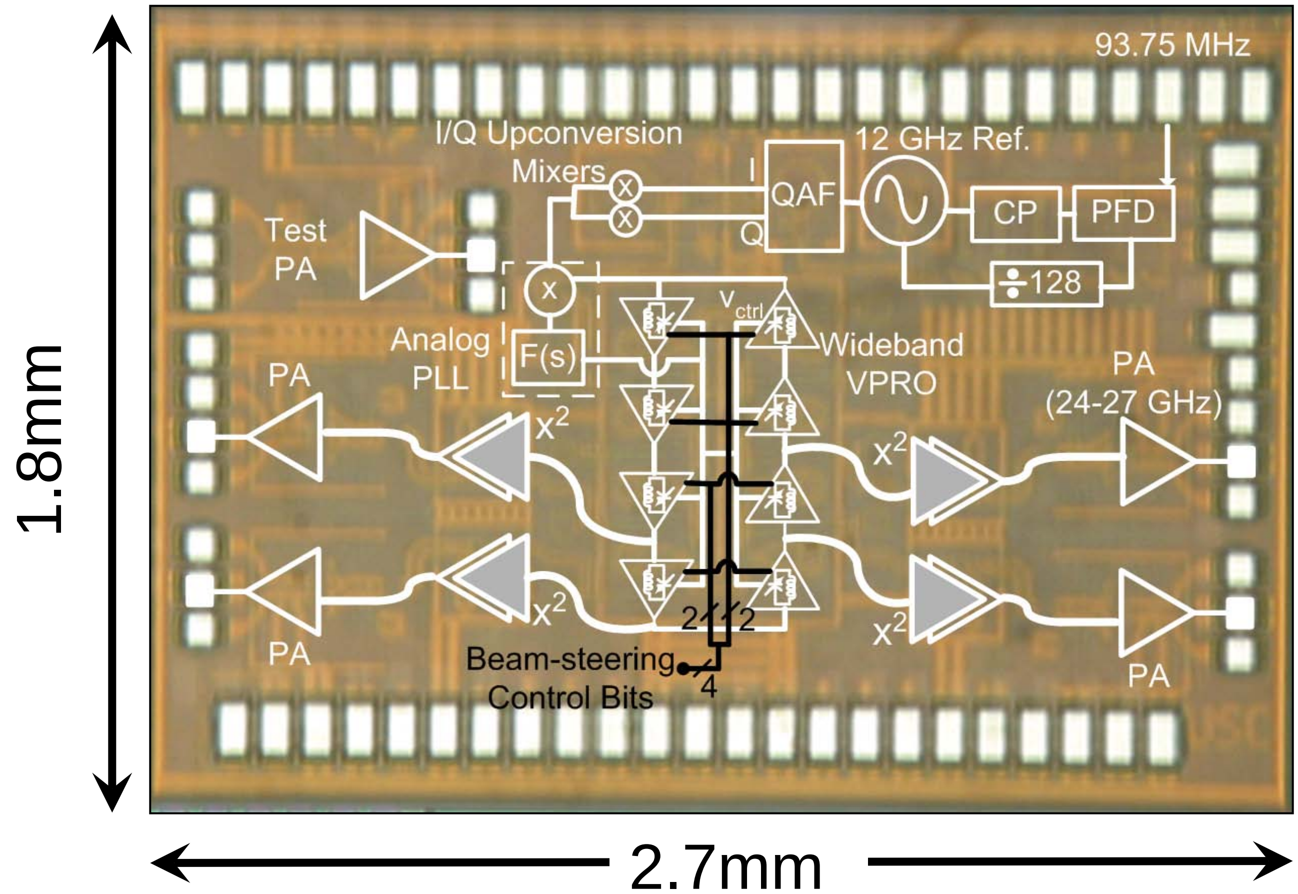
# Performance Summary

| | |
|---|---|
| ***Transmitter Performance*** | |
| Maximum output power per channel | > 12.9dBm |
| E-Channel EIRP | > 24.9dBm |
| Peak PA drain efficiency | > 19% |
| Power consumption | 0.98W |
| ***Receiver Performance*** | |
| Receiver gain per channel | 30dB |
| Total array gain | 42dB |
| Power dissipation | 0.52W |
| ***Implementation*** | |
| Technology | 0.13μm CMOS (IBM8RF) |
| Die area | 2.15mm x 2.35mm |

The world's first CMOS monolithic phased-array chip.

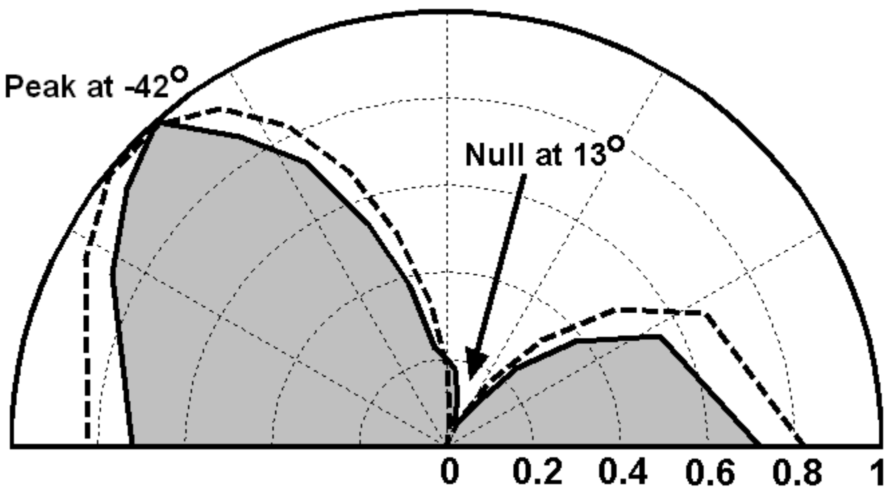
IEEE International Solid-State Circuits Conference Best Paper Award in 2007

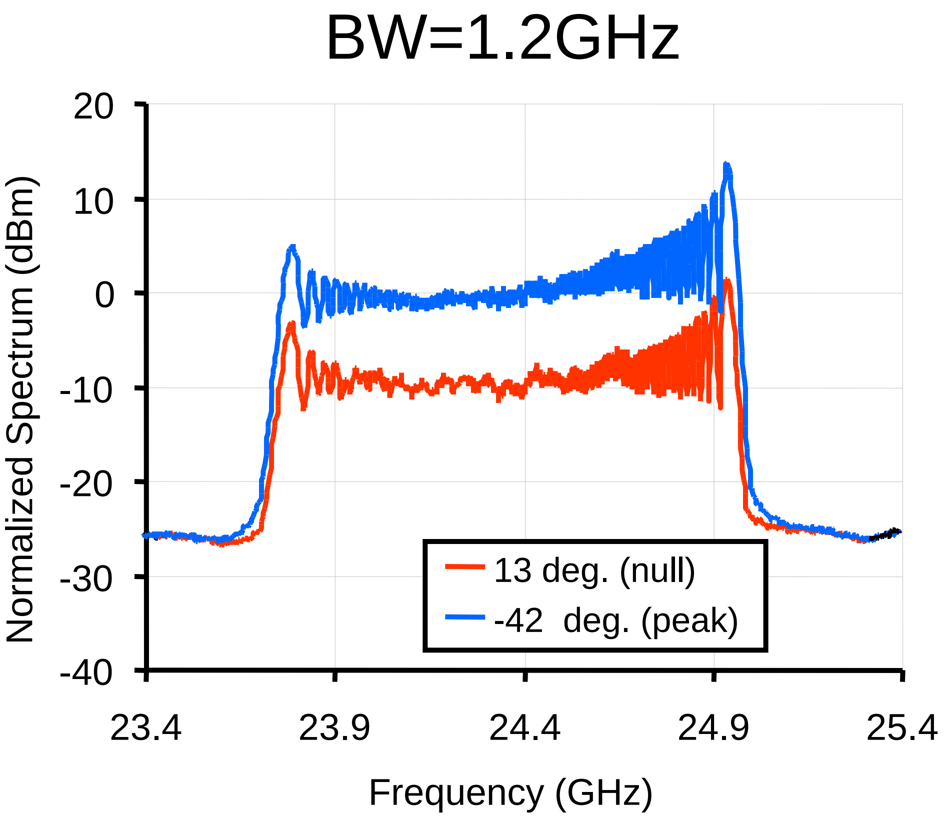
# 22-27GHz UWB CMOS Phased Array Tx




**H. Krishnaswamy and H. Hashemi, "A 4-Channel 24-27 GHz UWB phased array transmitter in 0.13µm CMOS for vehicular radar", in *Proceedings of the IEEE Custom Integrated Circuit Conference*, San Jose, CA, pp. 753-756, September 2007.**

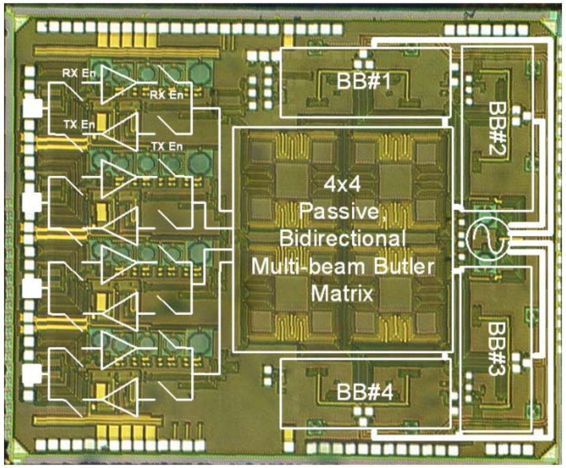
# Representative Measurement Results



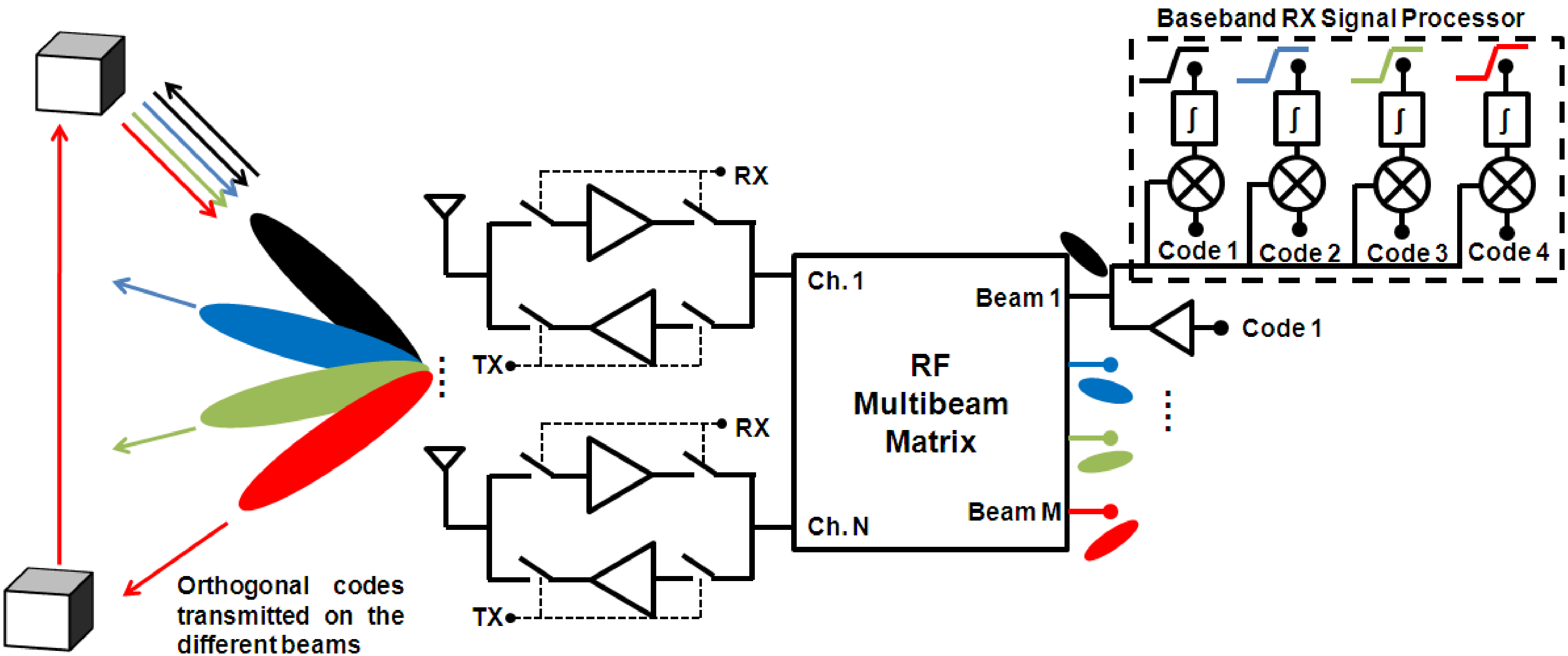

Measurement results for an UWB chirp waveform.

# 4-Channel 4-Beam 24-26GHz Spatio-Temporal RAKE radar in 90nm CMOS



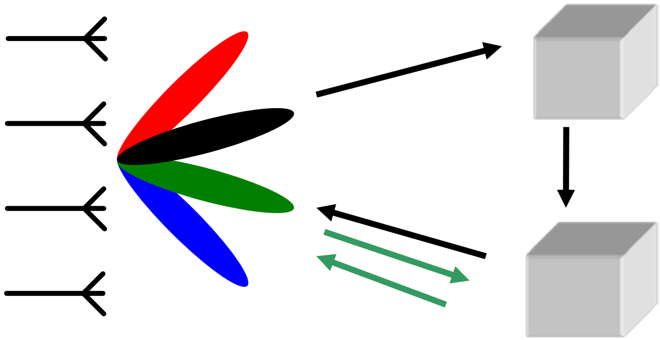

**H. Krishnaswamy and H. Hashemi, "A 4-channel, 4-beam, 24-26GHz, spatio-temporal RAKE radar transceiver in 90nm CMOS for vehicular radar applications," in *IEEE International Solid-State Circuits Conference* Digest of Technical Papers, San Francisco, CA, February 2010.**

# Multibeam Spatio-Temporal RAKE Radar

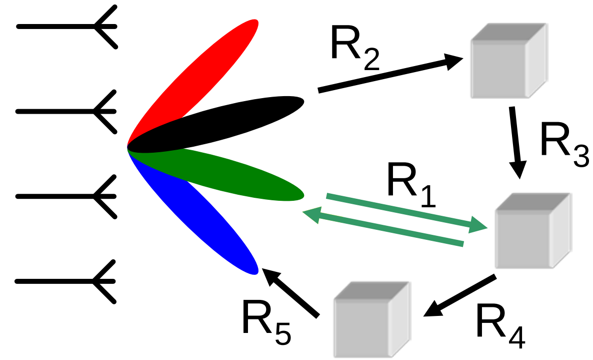



Exploit multibeam-based linear beamforming in conjunction with waveform diversity to gather more information about the scene.

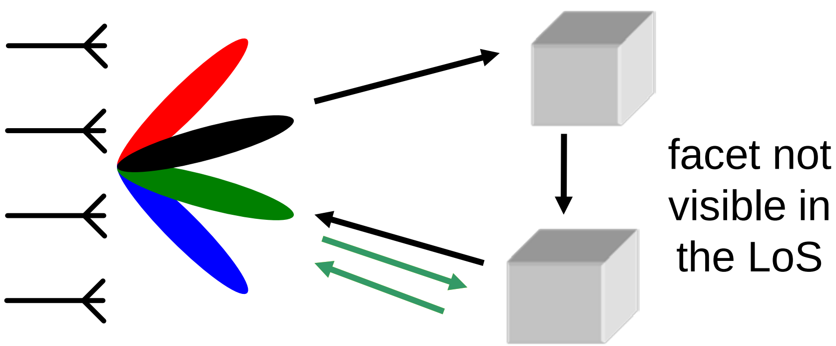
# Spatio-Temporal RAKE Radar Benefits



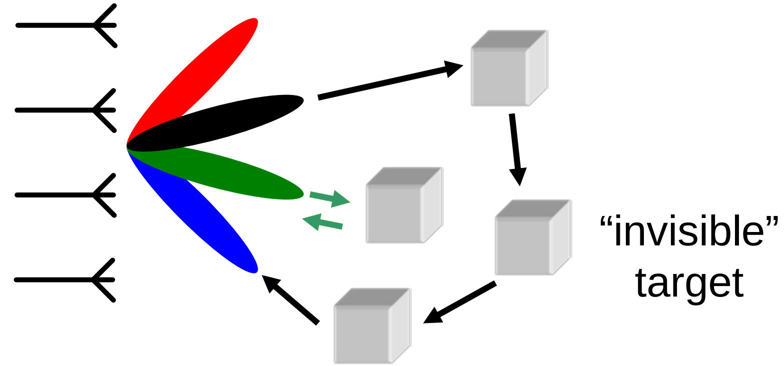
Separation of LoS from multipath reduces false alarms.




Ranging info. obtained from multipath enables more accurate localization.

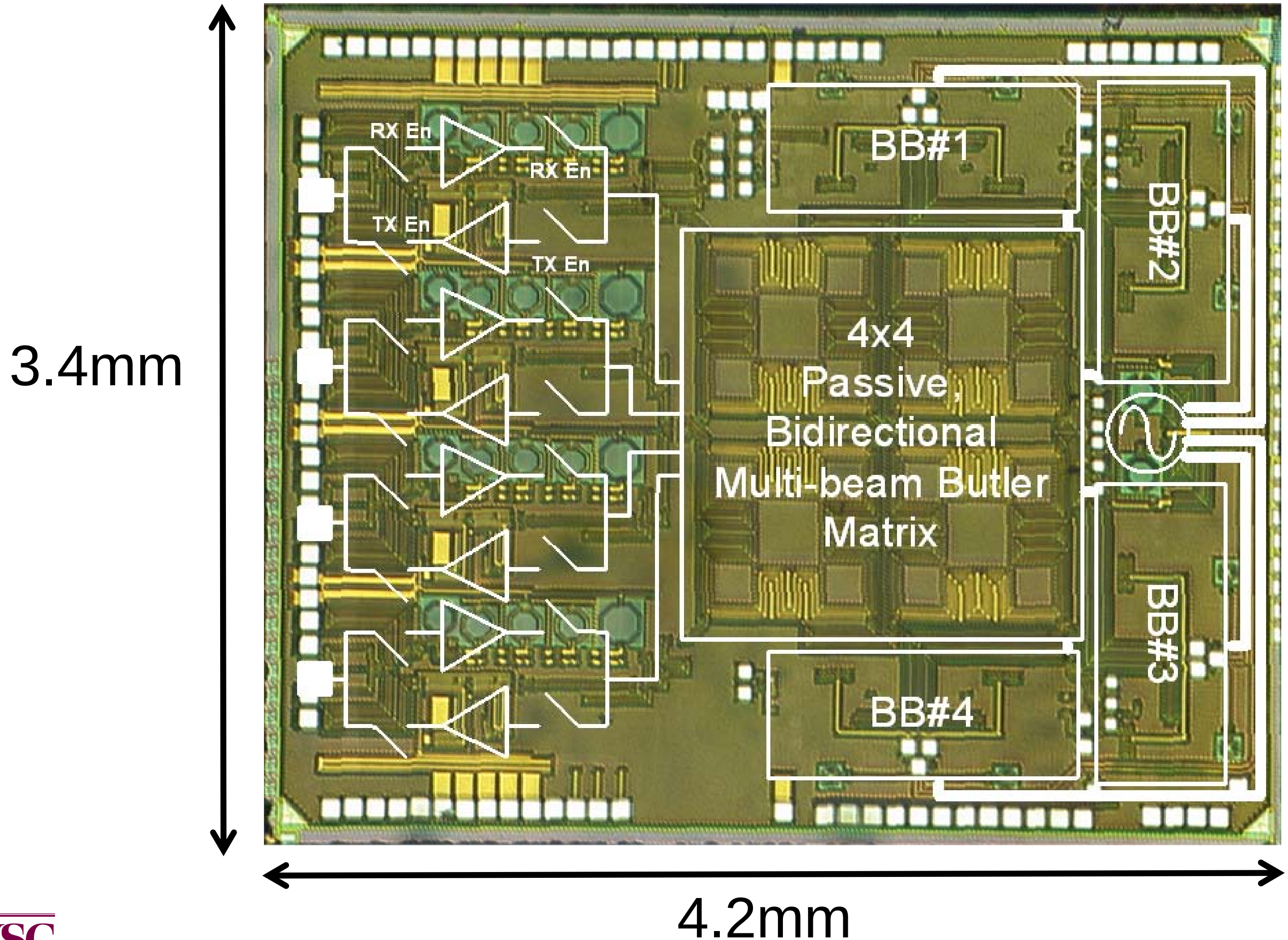



ST-RAKE radar enables imaging of facets not visible in the LoS.

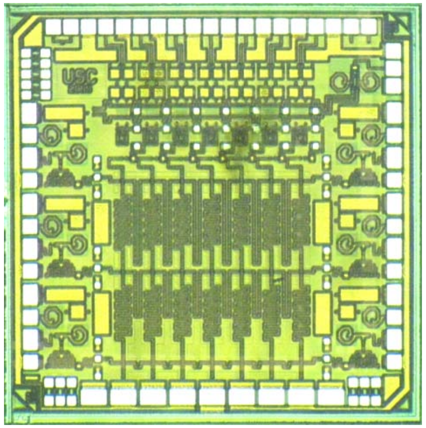



ST-RAKE radar enables detection of “invisible” targets.

# 4-Ch 4-Beam 24-26GHz in 90nm CMOS

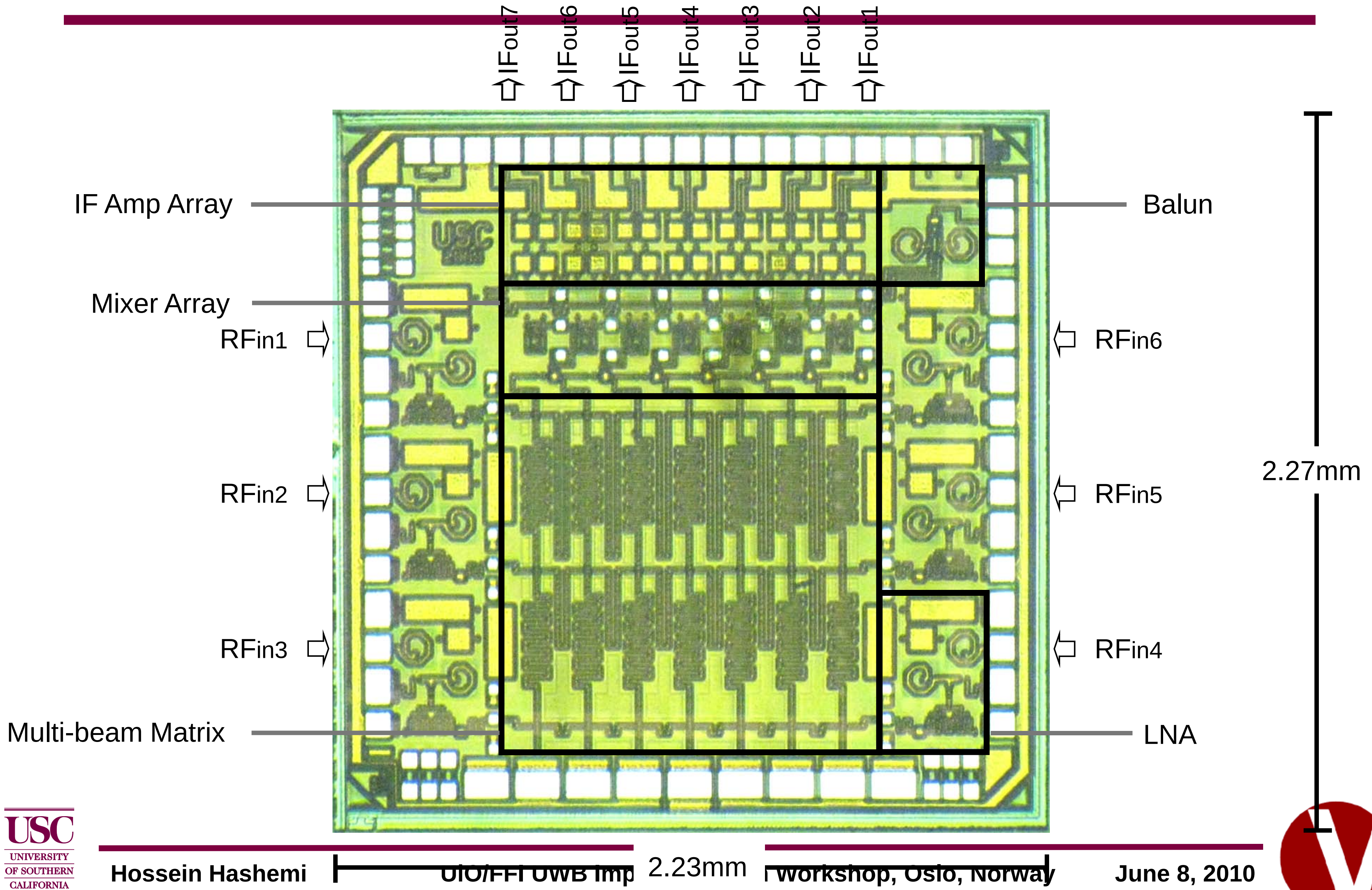


# 35GHz 4-Channel 6-Beam Monolithic Phased Array Receiver in 0.13μm SiGe

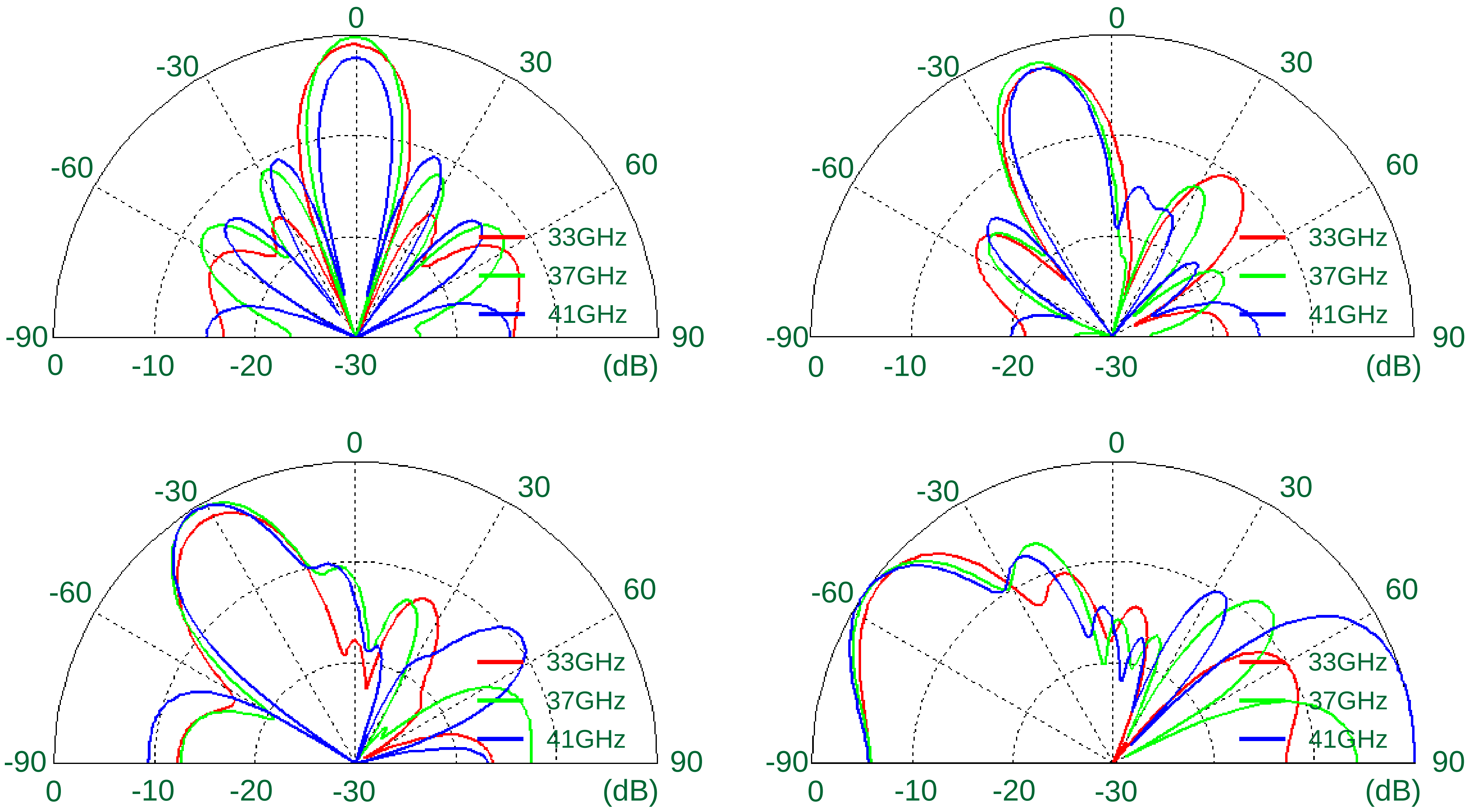


T. Chu and H. Hashemi, "A true-time-delay-based bandpass multi-beam array at mm-waves supporting instantaneously wide bandwidths," in *IEEE International Solid-State Circuits Conference* Digest of Technical Papers, San Francisco, CA, February 2010.

# 35-GHz Multi-Beam SiGe Chip



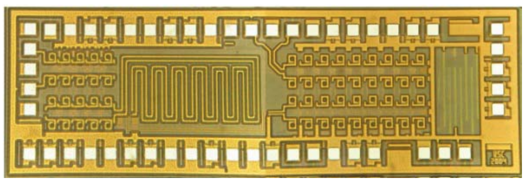
# Array Patterns



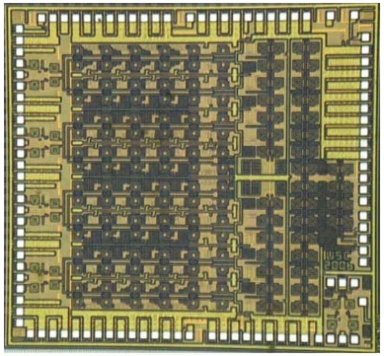
# Performance Summary

| | |
|---|---|
| **Reflection coefficient** | **< 10 dB** |
| **Power gain (per channel)** | **10 – 16 dB** |
| **Noise Figure (per channel)** | **< 4.9 dB** |
| **RF input channels** | **6** |
| **Total number of available beams** | **7 (simultaneously)** |
| **Array Gain (RF)** | **15.4 dB** |
| **Beam spatial resolution** | **18° (antenna separation = 4mm)** |
| **Maximum beam spatial angle** | **54° (antenna separation = 4mm)** |
| **Technology** | **0.13µm SiGe BiCMOS** |
| **Die Area** | **2.23mm x 2.27mm** |
| **Current consumption @2.5V** | **330mA** |

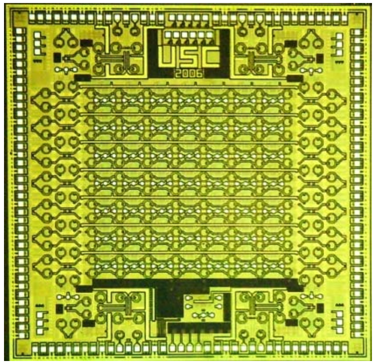
# Case Studies:
# Integrated Timed Arrays in Silicon



**1-15GHz 1-Element RX**
**VTTD: 0-64ps in 4ps**
**0.18μm SiGe**
**[2005]**

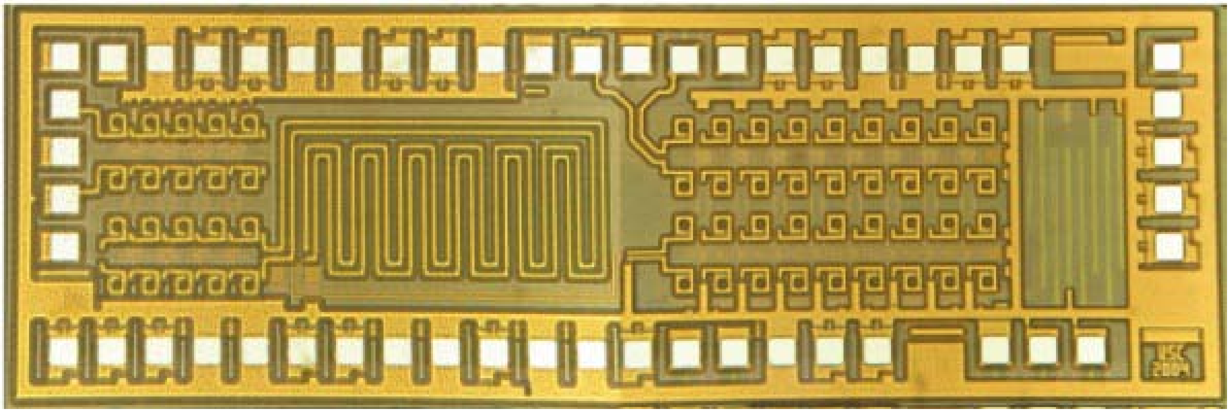


**1-15GHz 4-Element RX**
**TTD: 0-75ps in 15ps**
**0.13μm CMOS**
**[2007]**



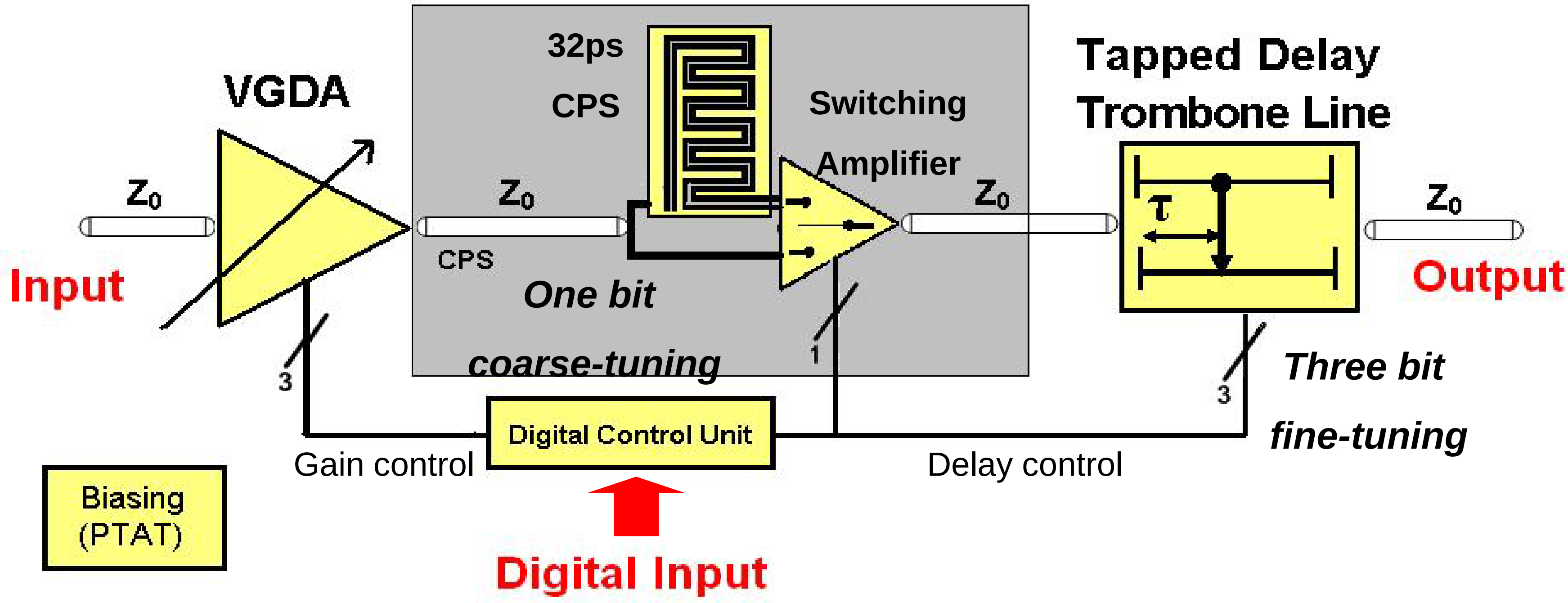
**1-15GHz 2x2 Multi-Beam RX**
**with 7x7 Outputs**
**0.13μm CMOS**
**[2008]**

# 1-15GHz 1-Channel Receiving Beam-former in 0.18μm SiGe



J. Roderick, H. Krishnaswamy, K. Newton, and H. Hashemi, “An UWB beamformer with 4ps true time delay resolution,” in *Proceedings of the IEEE 2005 Custom Integrated Circuit Design Conference*, San Jose, CA, pp. 805-808, September 2005.

# A Single-Element UWB Beam-Former

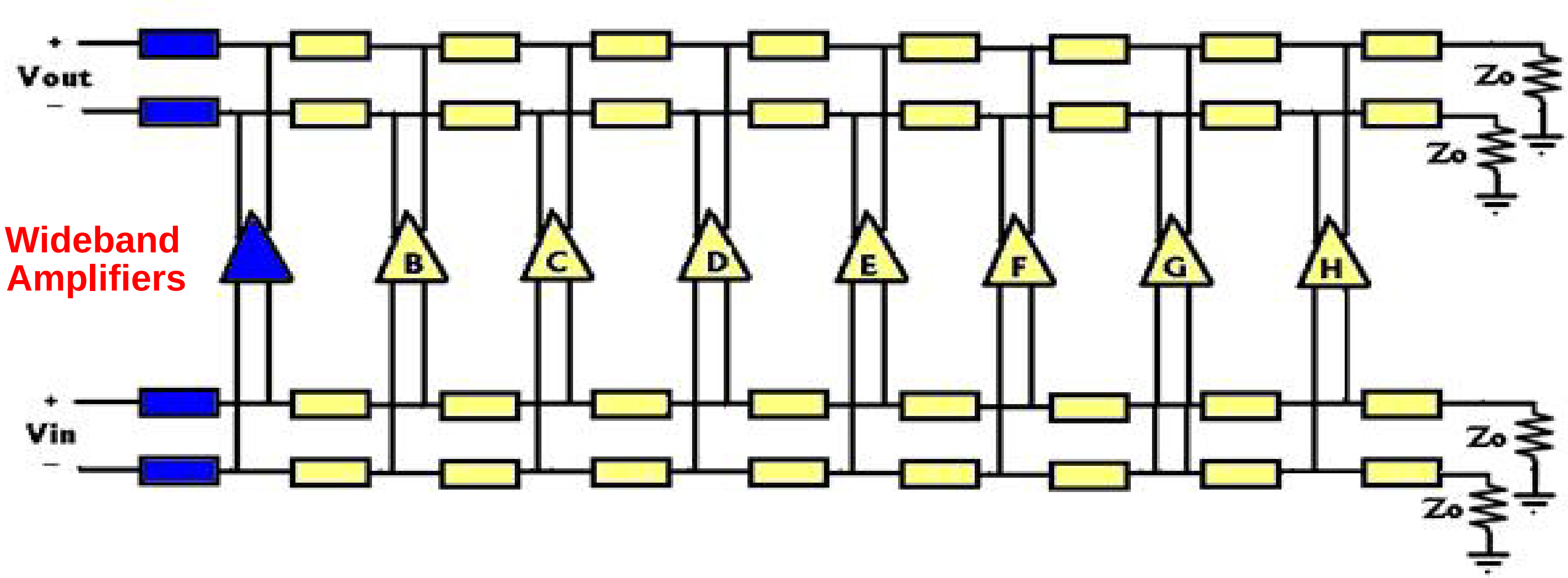



**Delay**
- 4-bit delay control
- 4ps resolution
- 64ps maximum

**Gain**
- 5dB variation
- 1dB resolution
- 10dB maximum

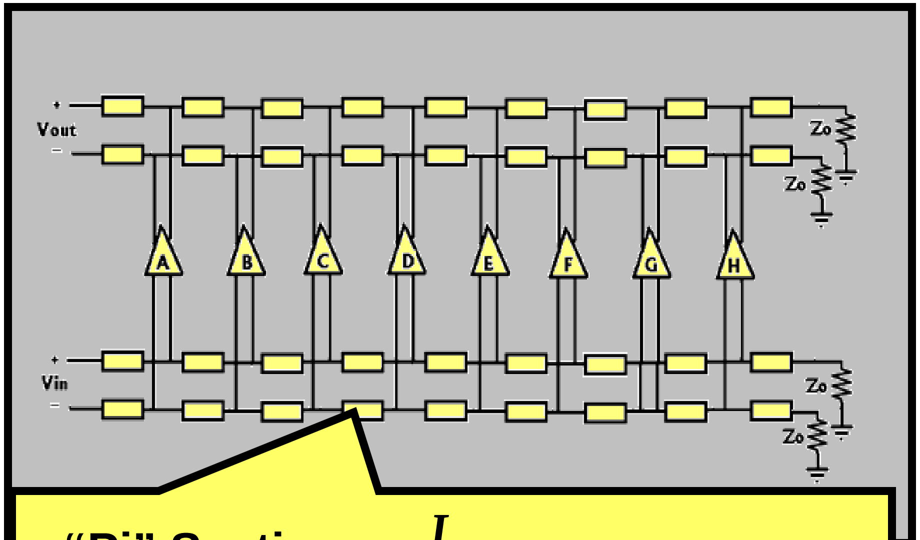
**Impedance**
- 50Ω input/output
- 50Ω inter-stage CPS

# 3-Bit Tapped Delay Trombone Line

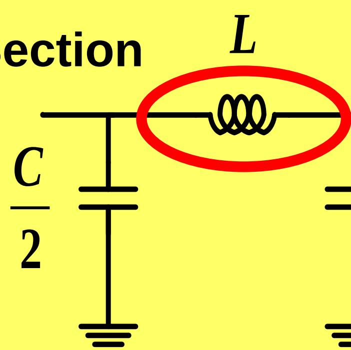



- Provides 3-bit (8 states) control with 4ps resolution
- Group delay variation is achieved by changing signal path
- Input and output are 50Ω matched

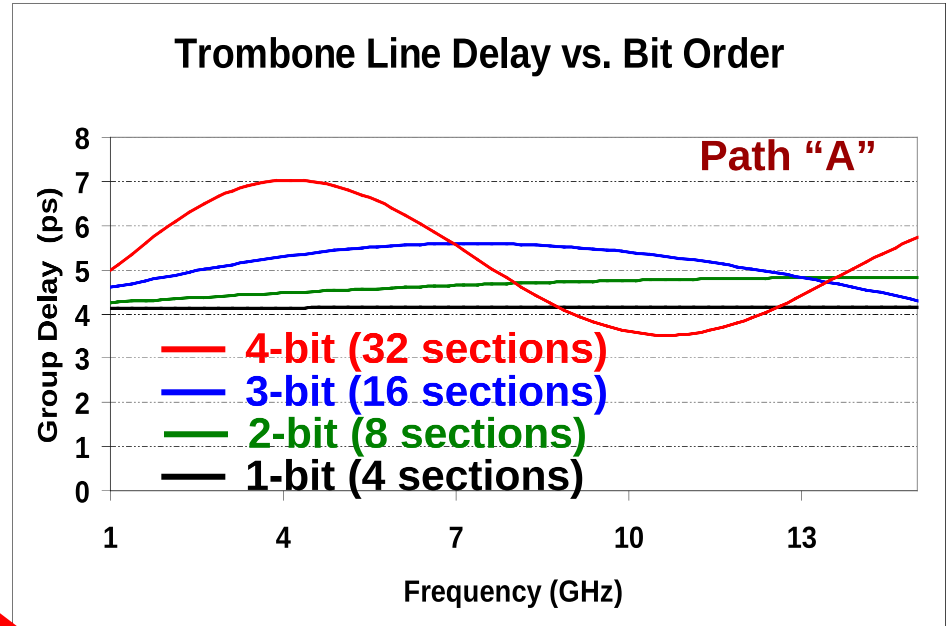
# Trombone Line Design Strategy

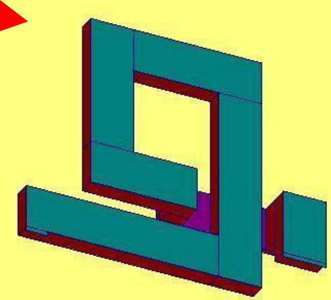



**"Pi" Section**



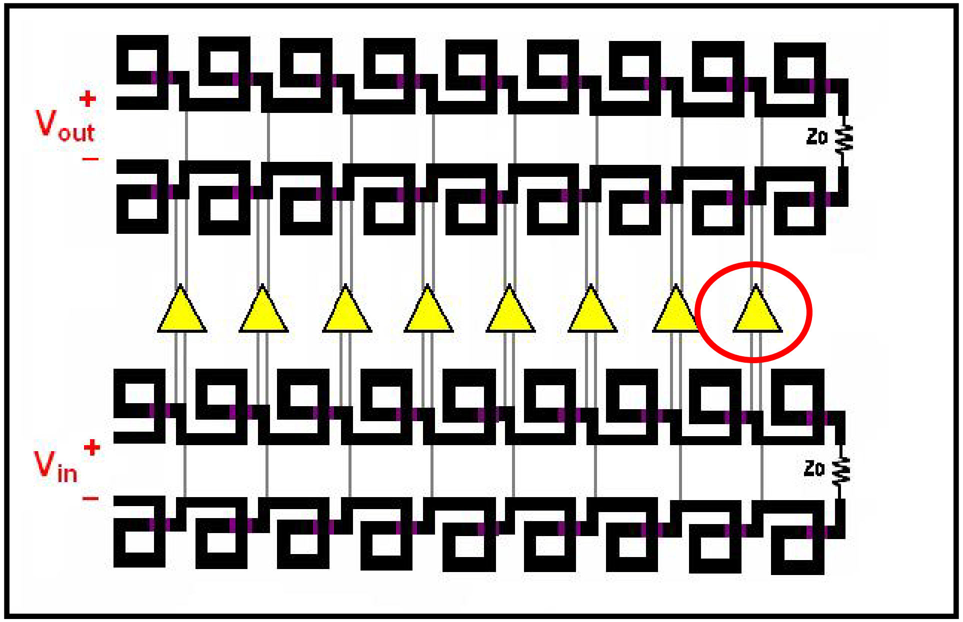

$$Delay = \frac{\tau}{2},\ \tau = 2\sqrt{LC},\ \omega_{cutoff} = \frac{2}{\sqrt{LC}}$$



**70μ X 55μ**

# Wideband Amplifier/Switch Design Criteria




- Act like a switch
- Maximize bandwidth and gain
- Maximum $C_{in}$ (12fF) set by delay resolution
- Maximize "Off" I/O isolation
- Minimize operating input impedance difference
  - $Z_{in}$("on") = $Z_{in}$("off")

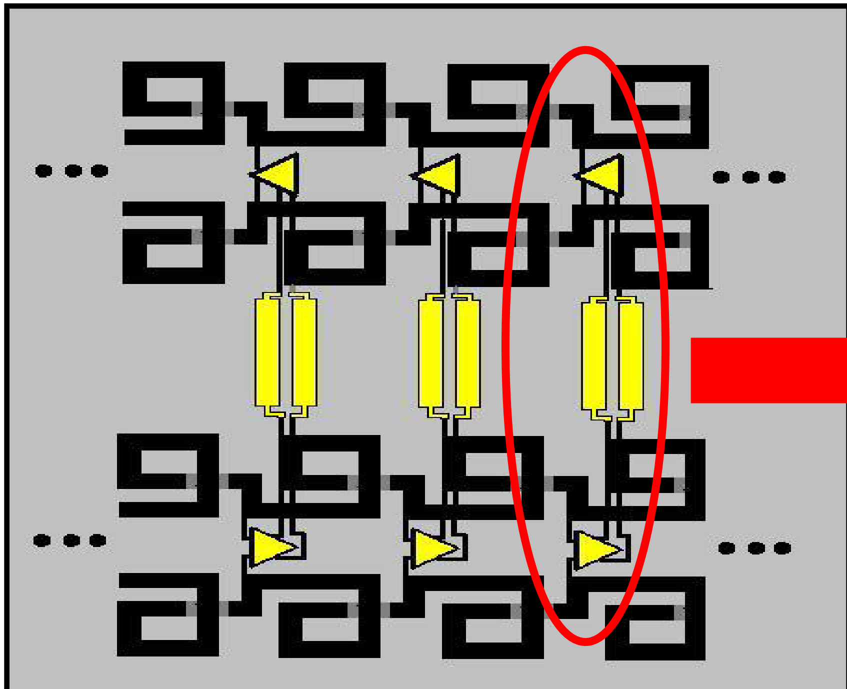
**Assuming one dominant pole**

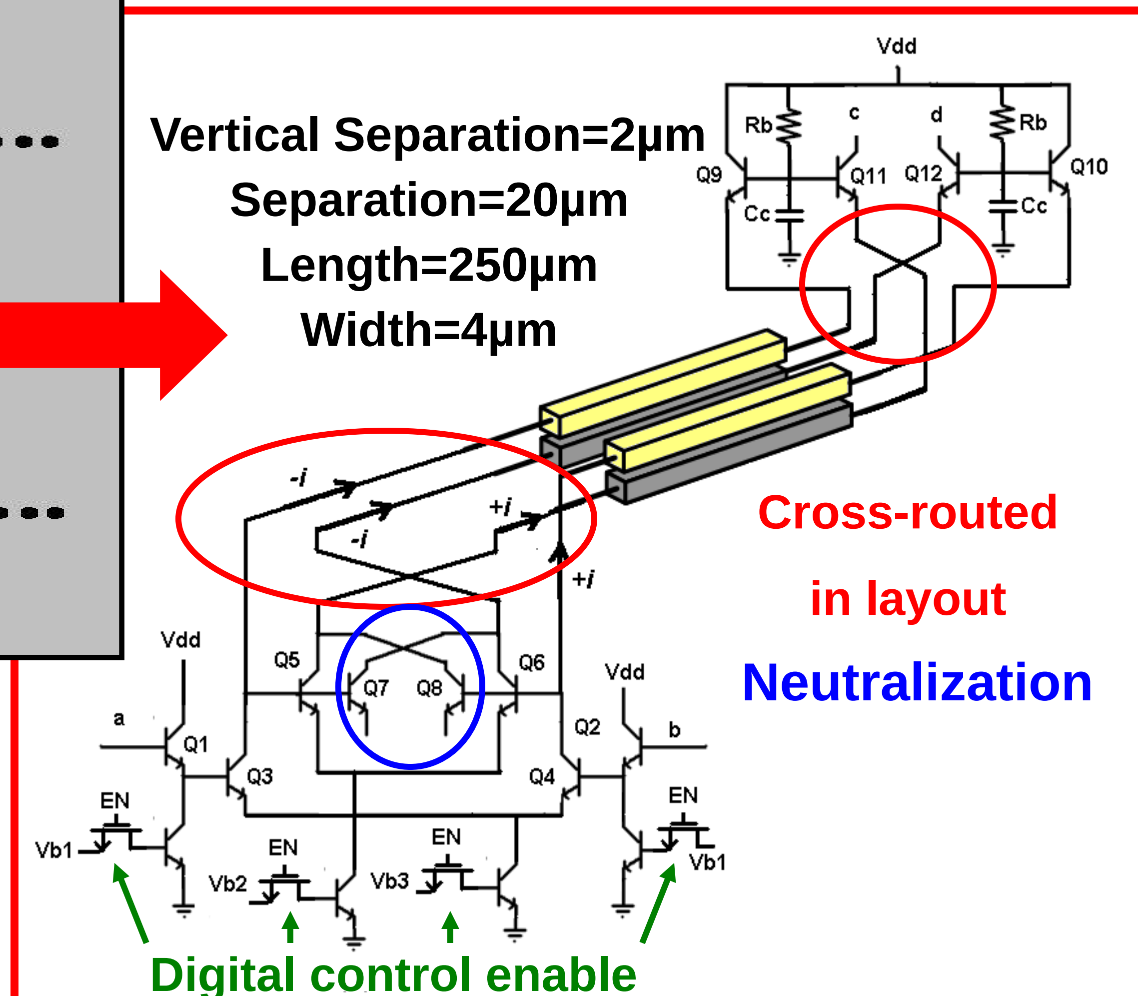
$$A_v = \frac{f_T \pi \tau_r}{4}$$

**$f_t$ required for unity gain**

$$f_T \approx 300GHz$$

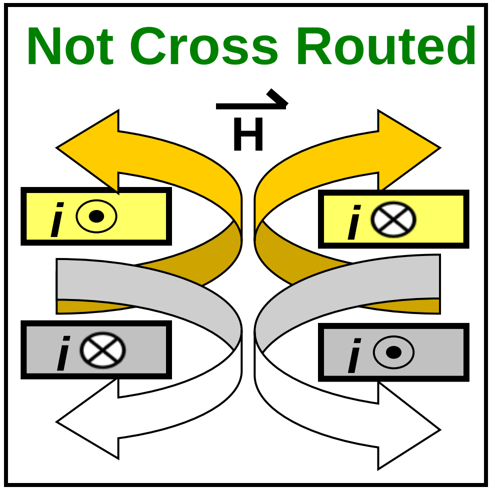
# Trombone Line Wideband Amplifier/Switch

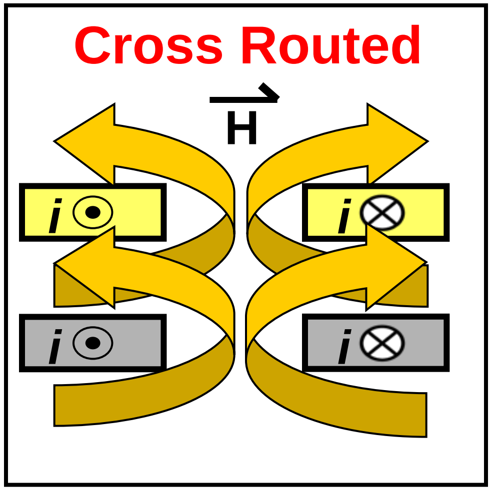


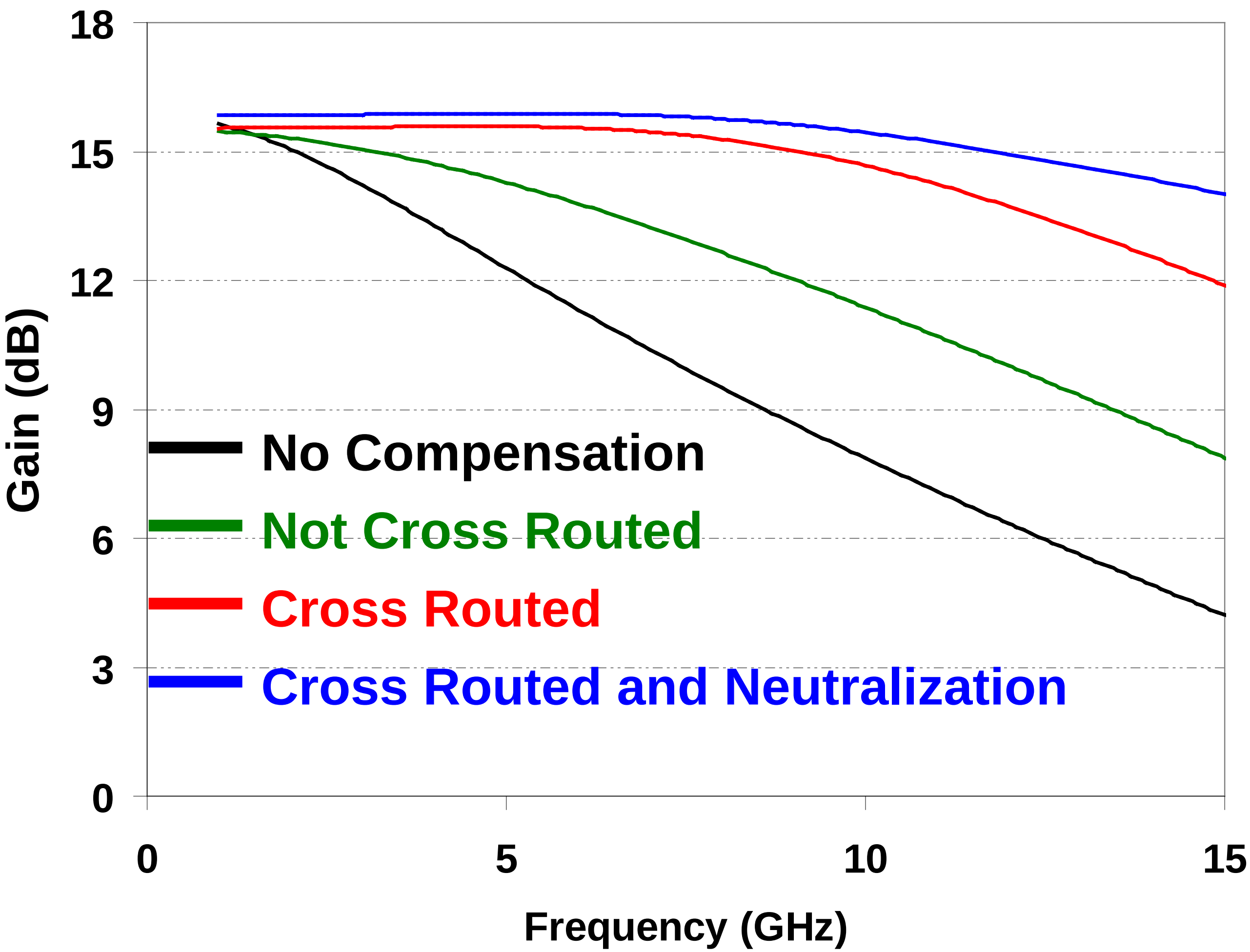



- Split layout architecture
  - −Coherent coupling CPS
- Neutralization

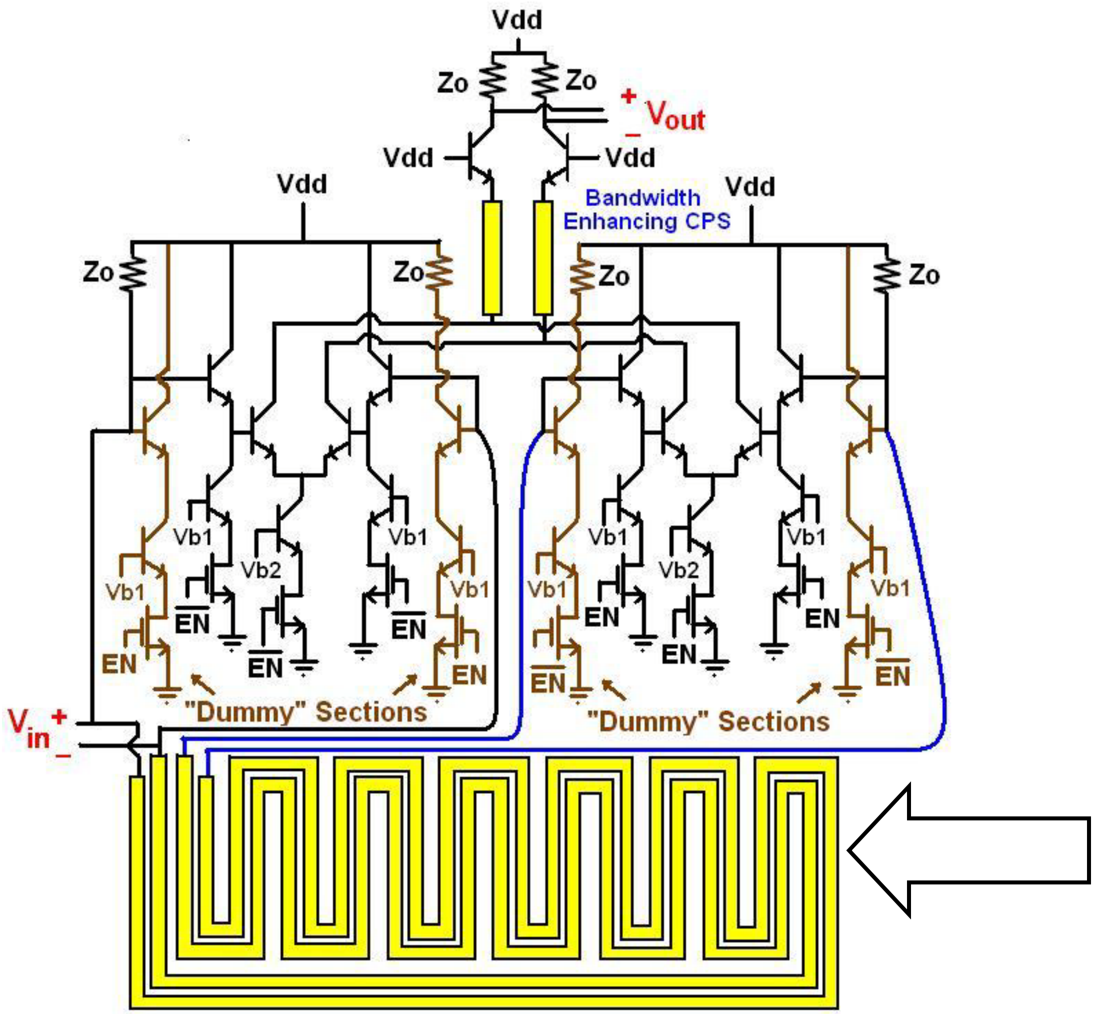
# Bandwidth Enhancement Techniques



# 1-bit Coarse Tuning Delay (32ps)




## MSB Delay (32ps)

- Broadband switch
- Split layout architecture
  - CPS shunt peaking
- “Dummy” structures
  - Constant impedance

## MSB CPS Delay Line

Length = 4.9mm

$Z_0 = 100\Omega$

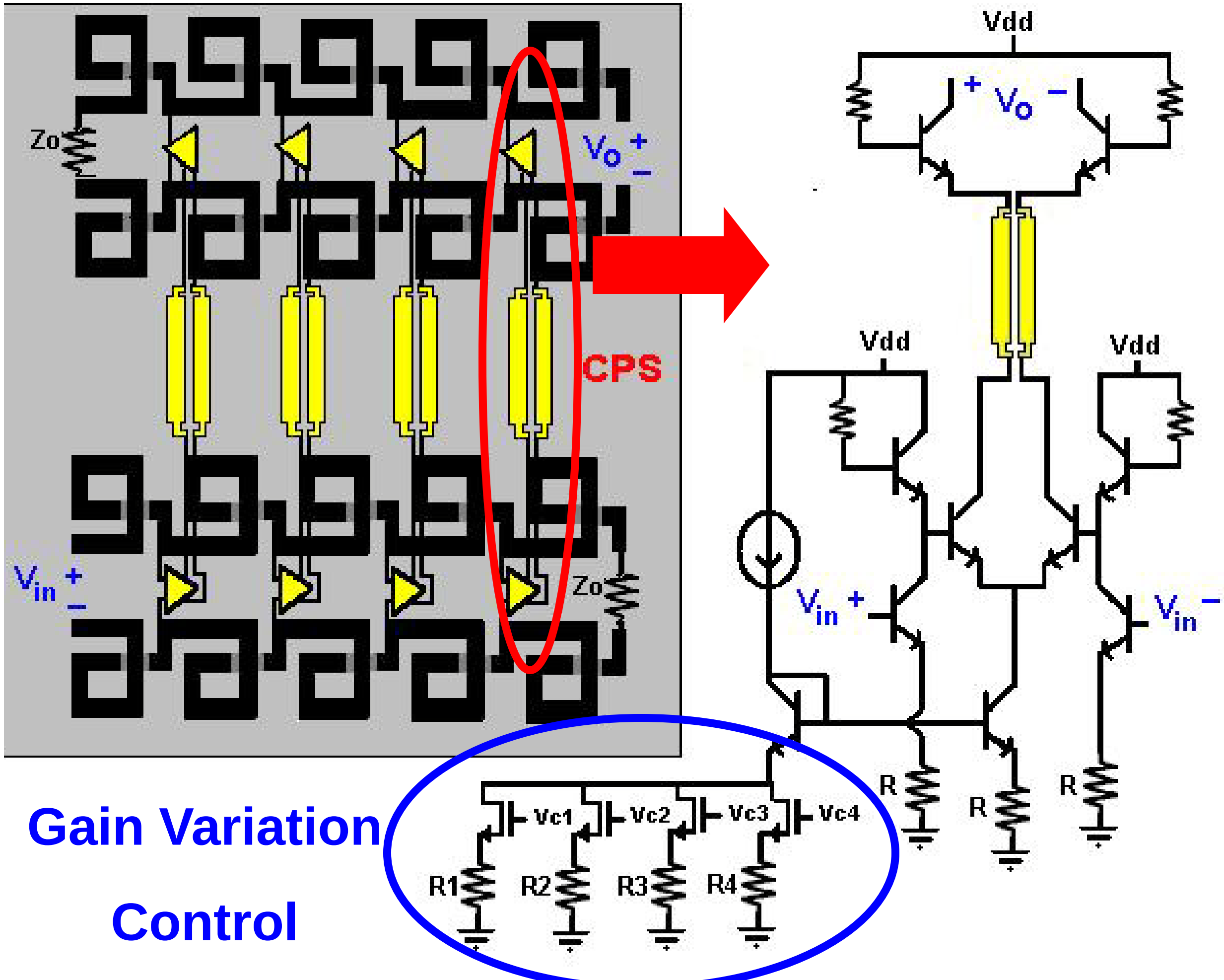
$\varepsilon_{eff} = 5$

Spacing = 10µm, Width = 10µm

$\alpha$(1GHz) = 0.113dB/mm

$\alpha$(11GHz) = 0.205dB/mm

# Variable Gain Distributed Amplifier (VGDA)

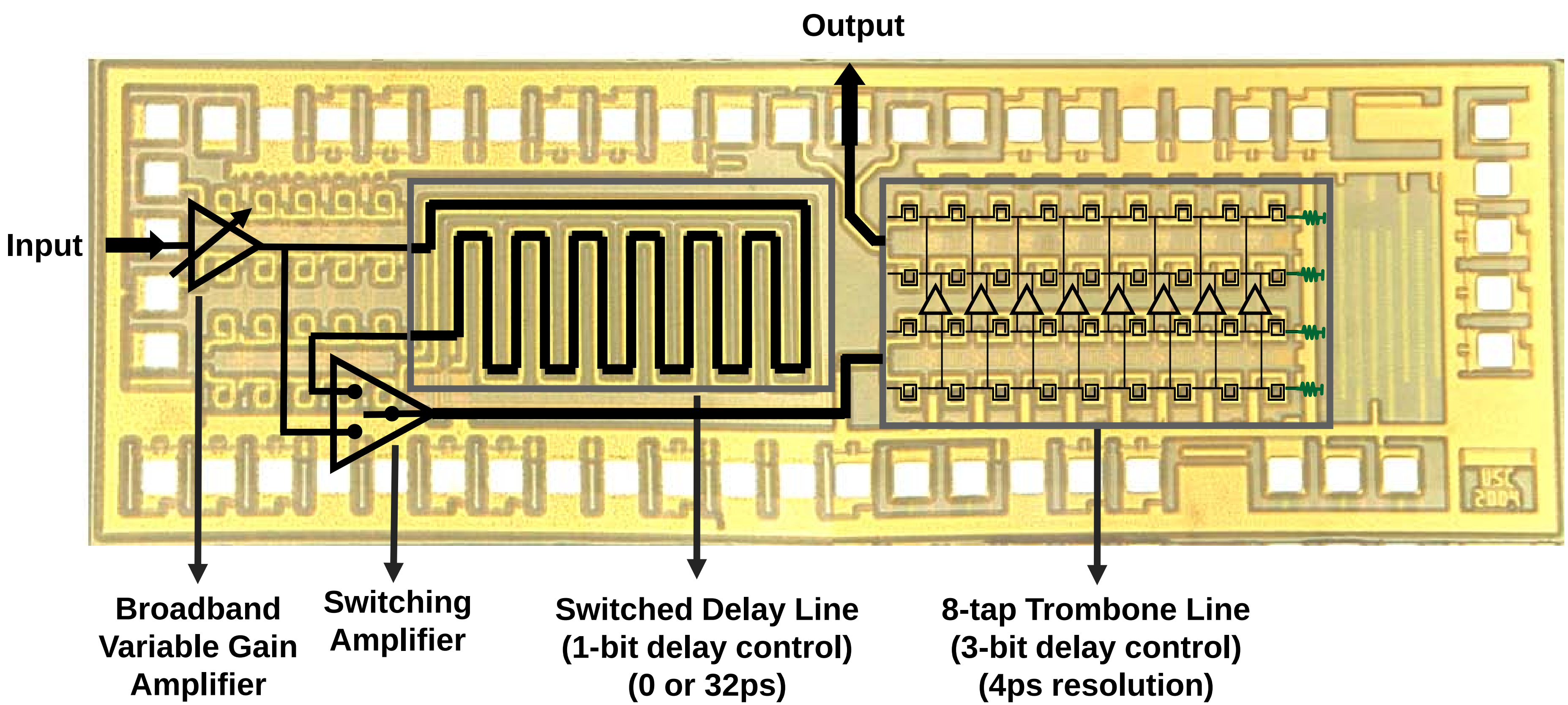



**Gain Variation Control**

## Design Criteria

- 5dB gain variation in 1dB steps
- Split architecture
  - CPS shunt peaking
- Compensates for propagation loss in trombone line
- Gain variation is achieved by manipulating current mirror references

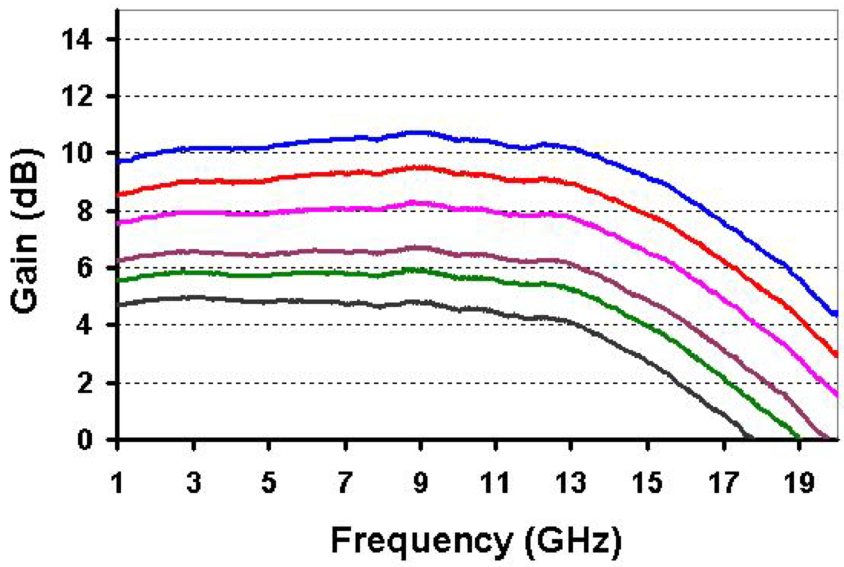
# 1-15GHz 4-bit VTTD SiGe Beam-Former



# Measured Magnitude and Phase Response

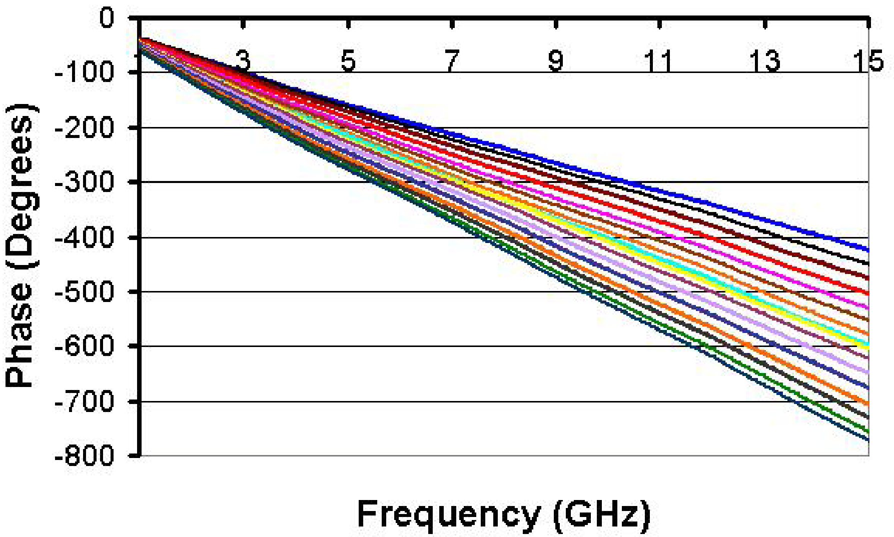
## Gain Control

**Lowest delay setting**




## Phase (Delay) Control

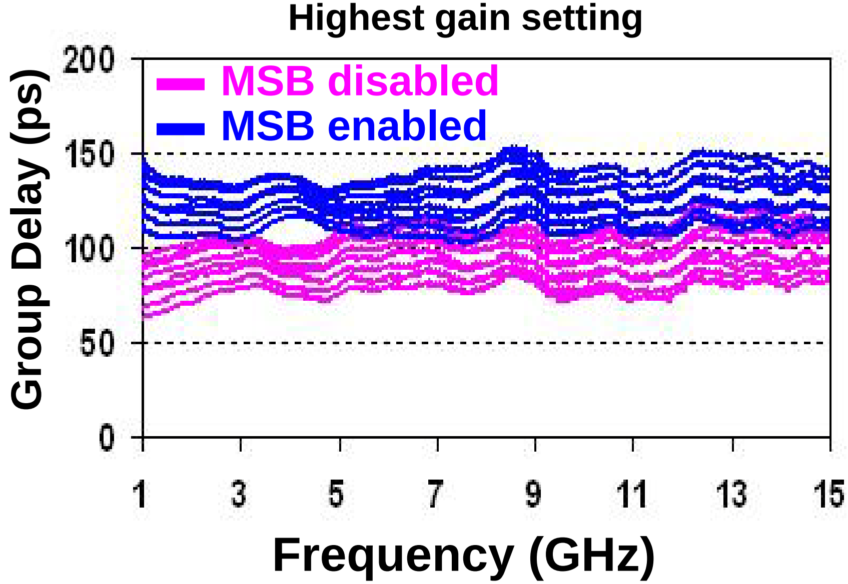
**Highest gain setting**




- 15GHz bandwidth for lowest delay setting
- 5dB gain variation in 1dB steps (VGDA)

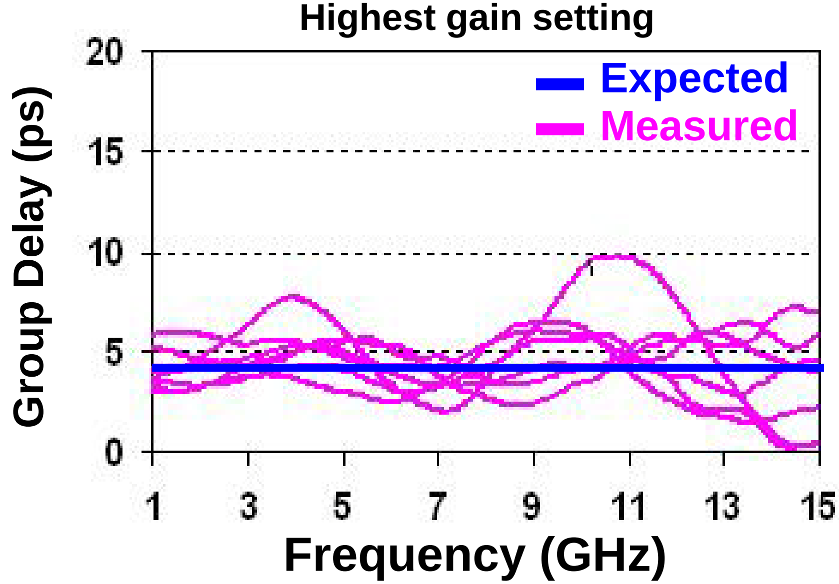
# Measured Group Delay

## Group Delay Variation



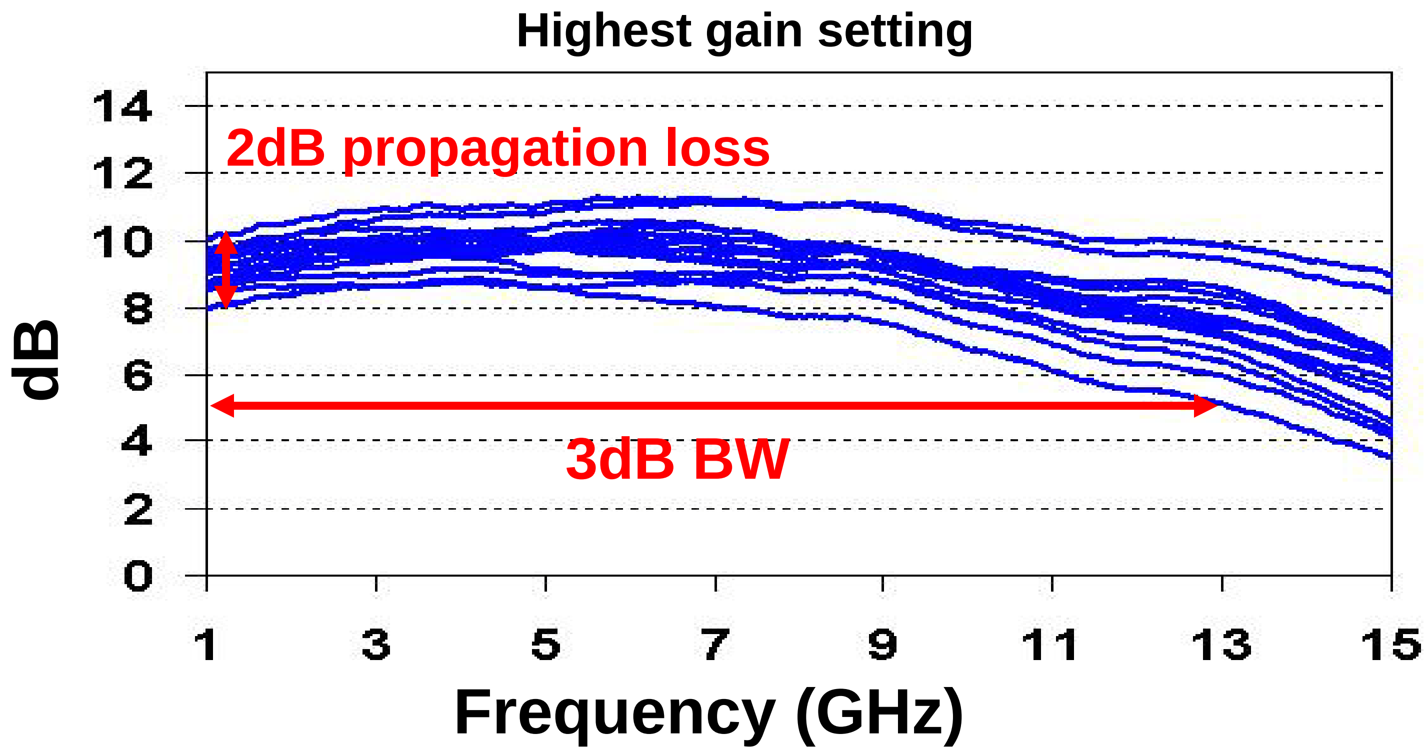

## Group Delay Difference

### (Between Adjacent Settings)




Group delay variation is caused by inductor Q and the difference between $C_{in}$("Off") and $C_{in}$("On") of the wideband amplifiers.

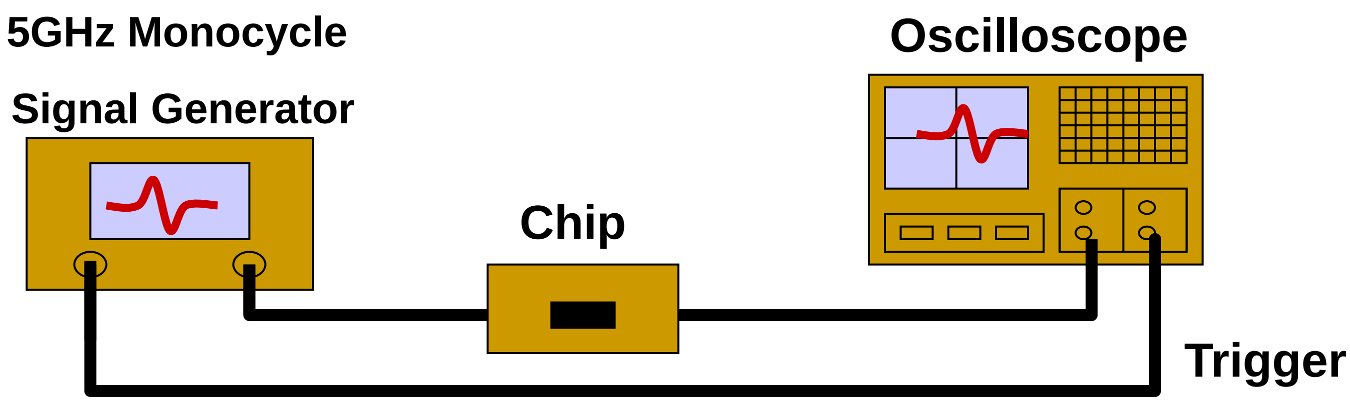
# Measured Gain for Various Delay Settings

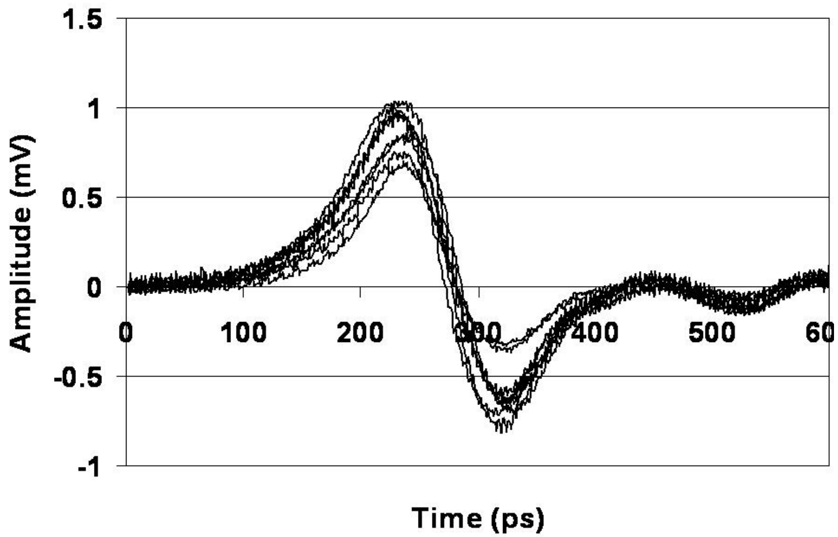


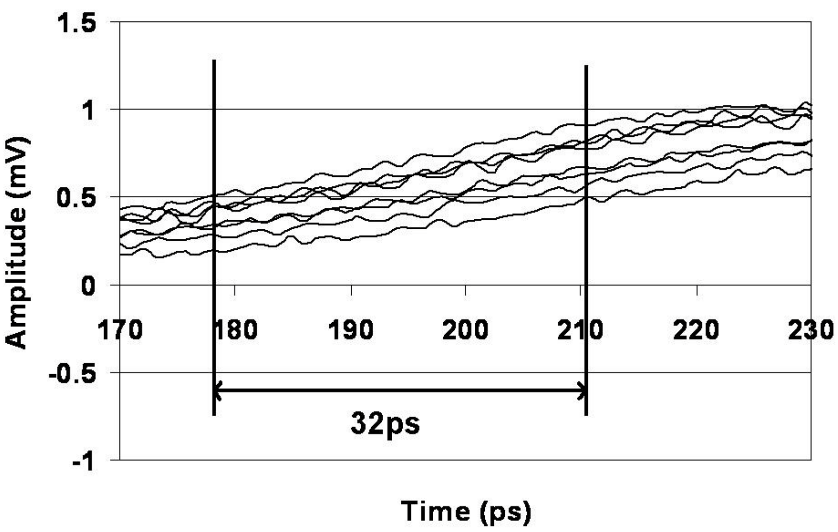

- Inductor Q results in propagation loss
- 13GHz worst case bandwidth for largest delay setting

Gain difference can be compensated in VGDA (5dB in 1dB steps).

# Time Domain Measurements



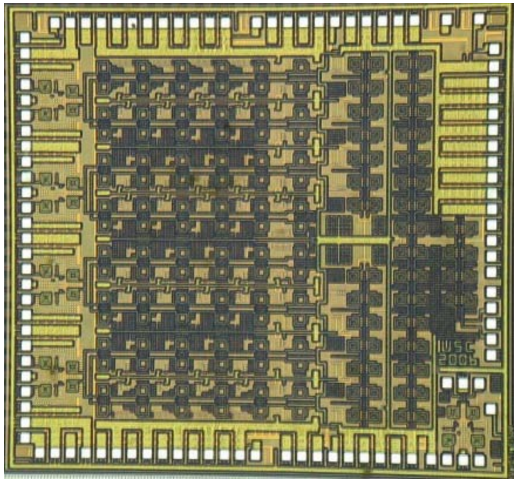



# SiGe Beam-Former Performance Summary

| Parameter | Result |
|---|---|
| UWB delay resolution | 4ps |
| Total achievable delay | 64ps |
| Worst case -3dB bandwidth | 13GHz |
| Gain peaking over bandwidth | 1dB |
| Gain difference over delay settings | 2dB |
| Maximum system power gain | 10dB |
| Power gain tuning range | 5dB in 1dB steps |
| UWB steering resolution (expected) | 7° (4 elements) |
| Power consumption | 87.5mW (2.5V) |
| Area | 2.5mm X 0.9mm |
| Technology | 0.18µm BiCMOS SiGe |

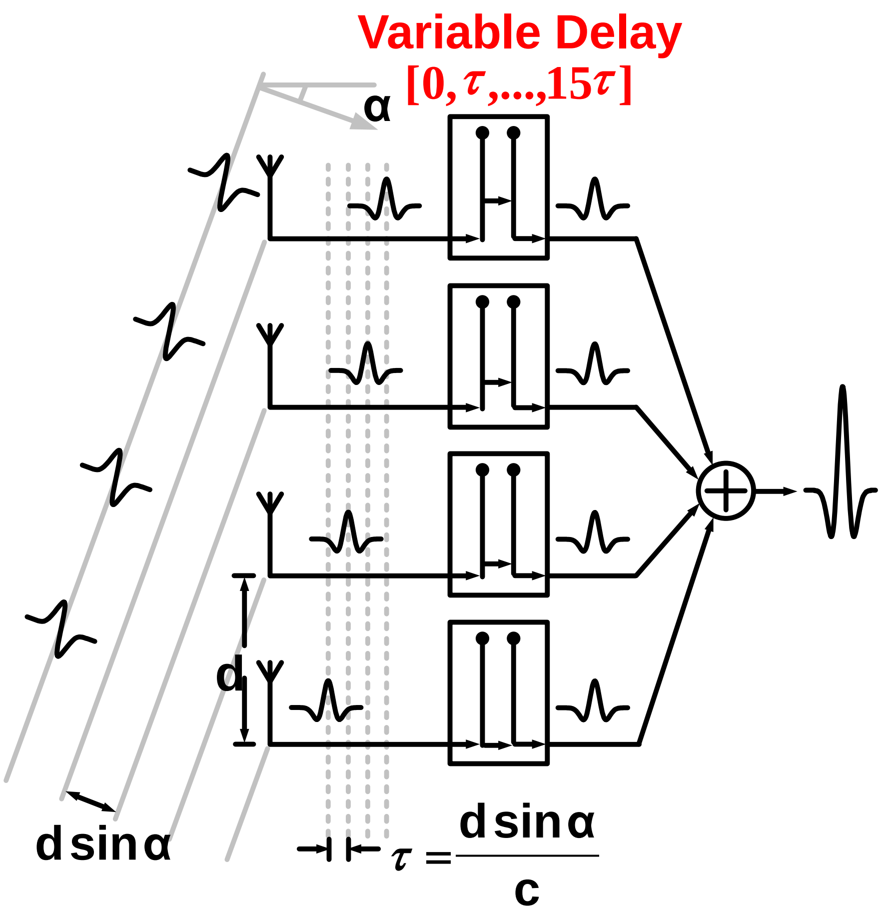
# 1-15GHz 4-Channel Receiving Beam-former in 0.13μm CMOS



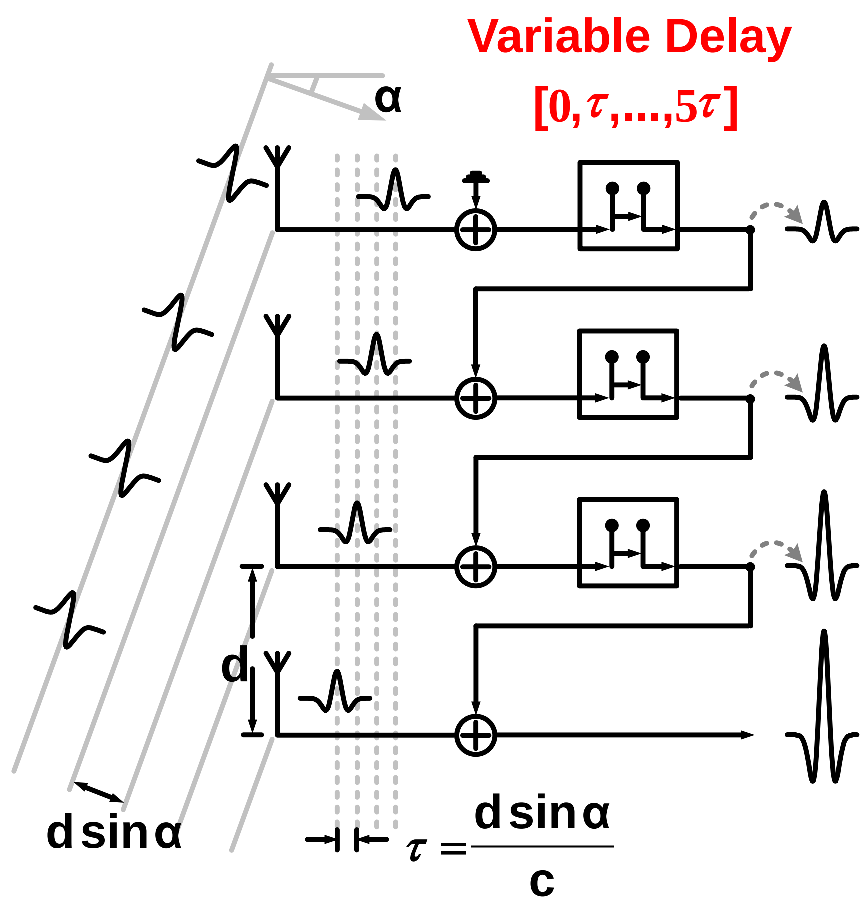
**T. Chu, J. Roderick, and H. Hashemi, "A Fully Integrated 4-Channel Ultra-Wideband Beam-former in 0.13μm CMOS using a Path-Sharing True Time Delay Architecture"** ***IEEE International Solid-State Circuits Symposium*** **Digest of Technical Papers, San Francisco, CA, pp. 426-427, February 2007.**

# Path-Sharing TTD Array Architecture

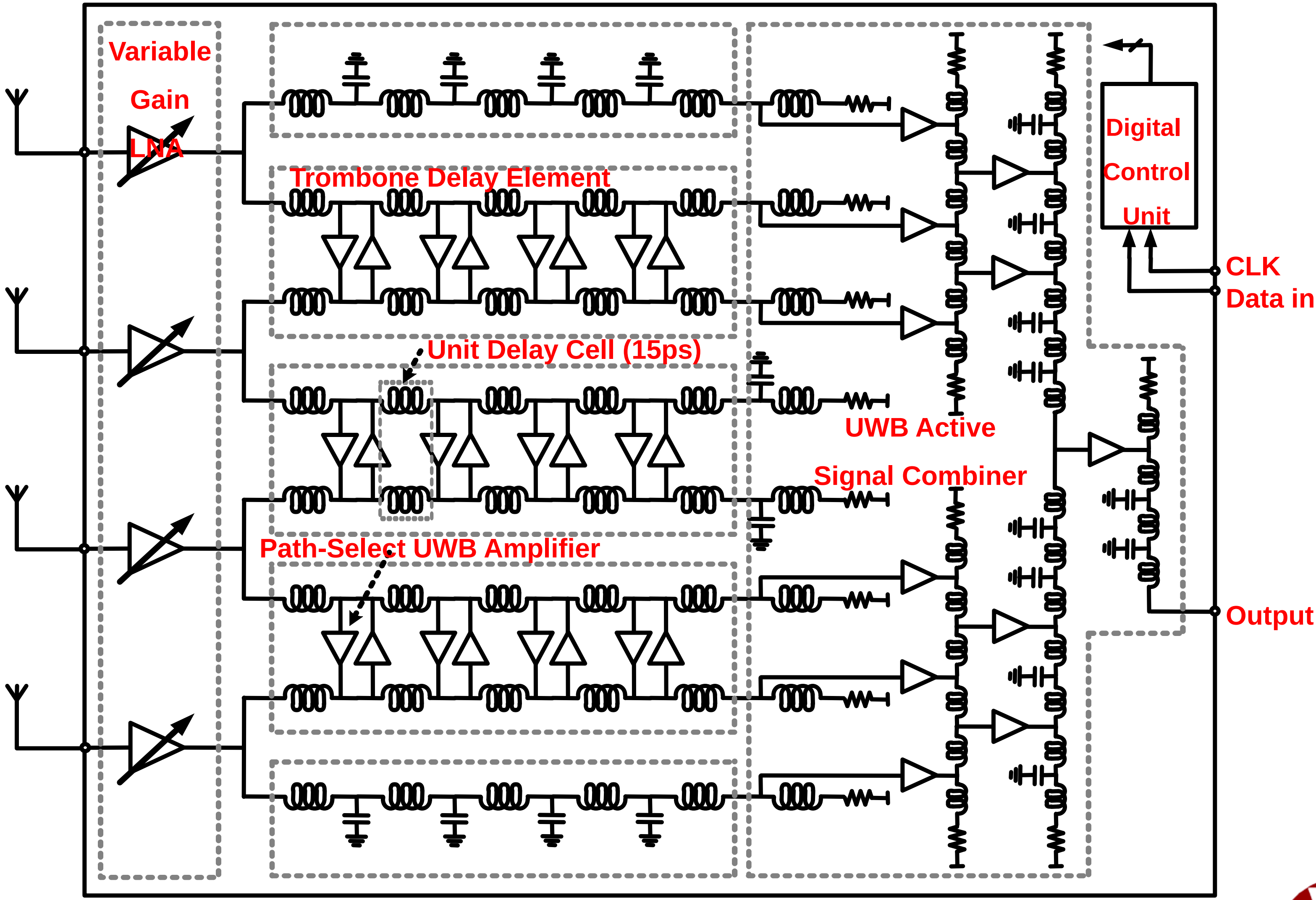
## Conventional TTD Array Arch.



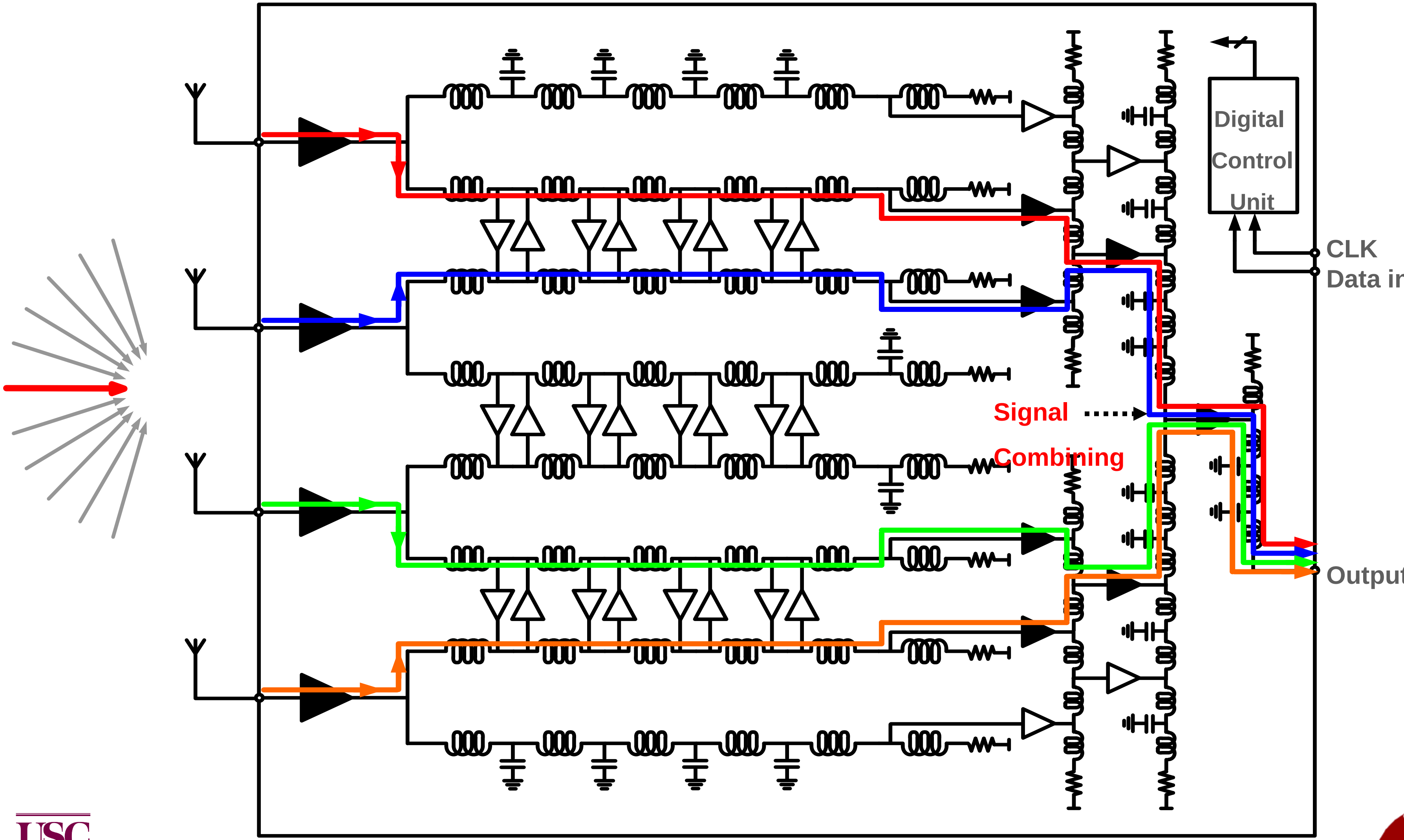

## Path-Sharing TTD Array Arch.



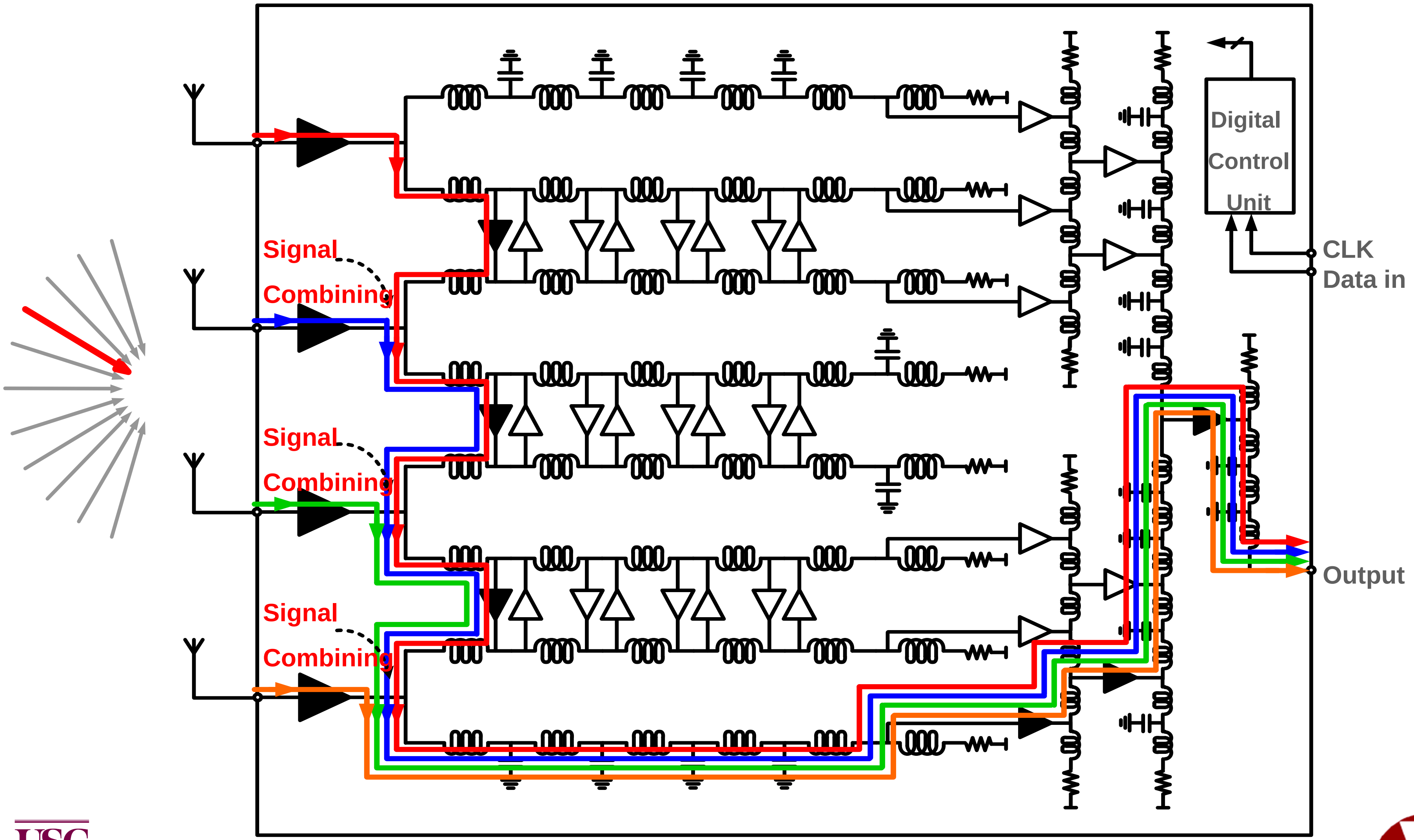
# Path-Sharing Timed-Array: Block Diagram



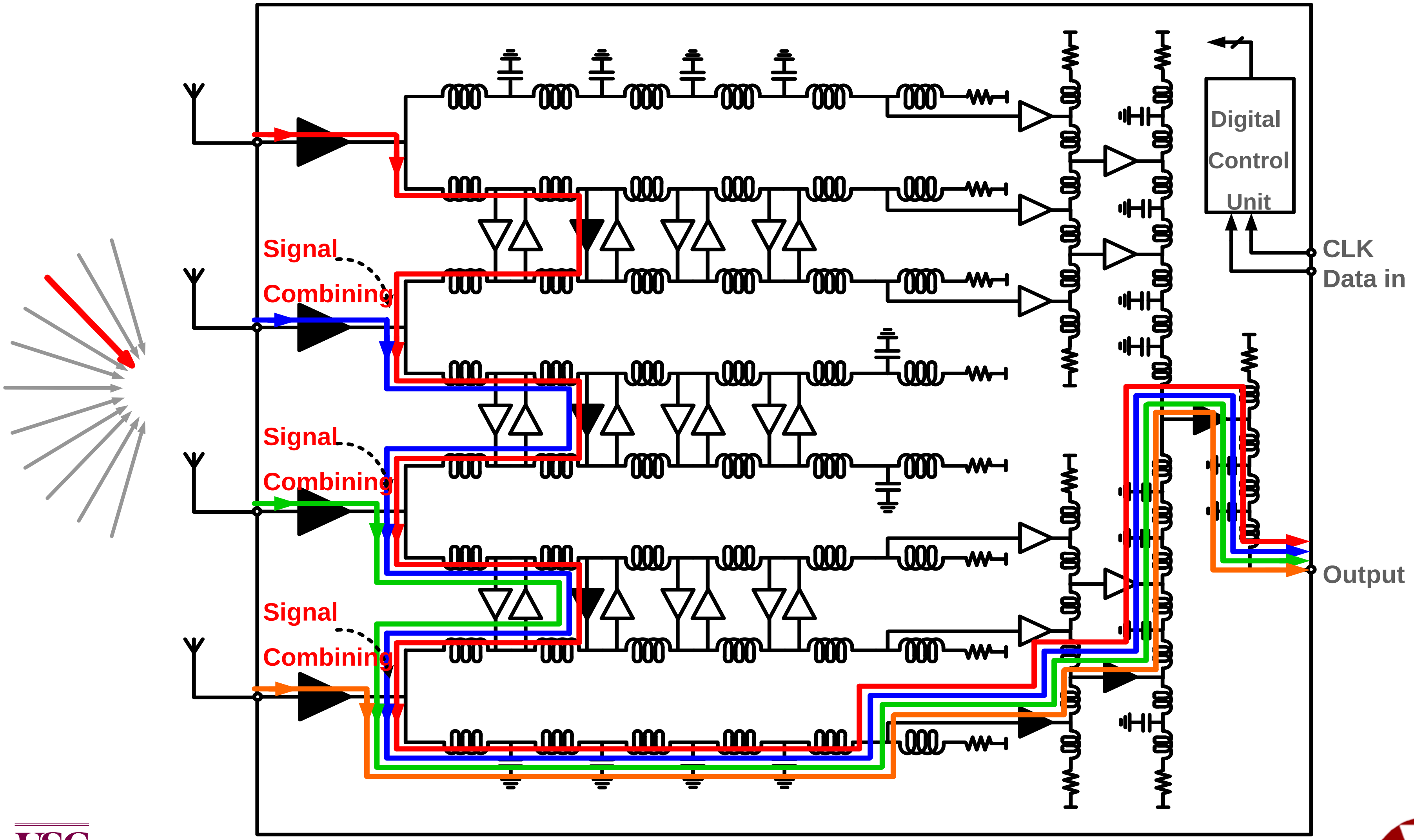
# Signal Flow for Normal Incident Angle



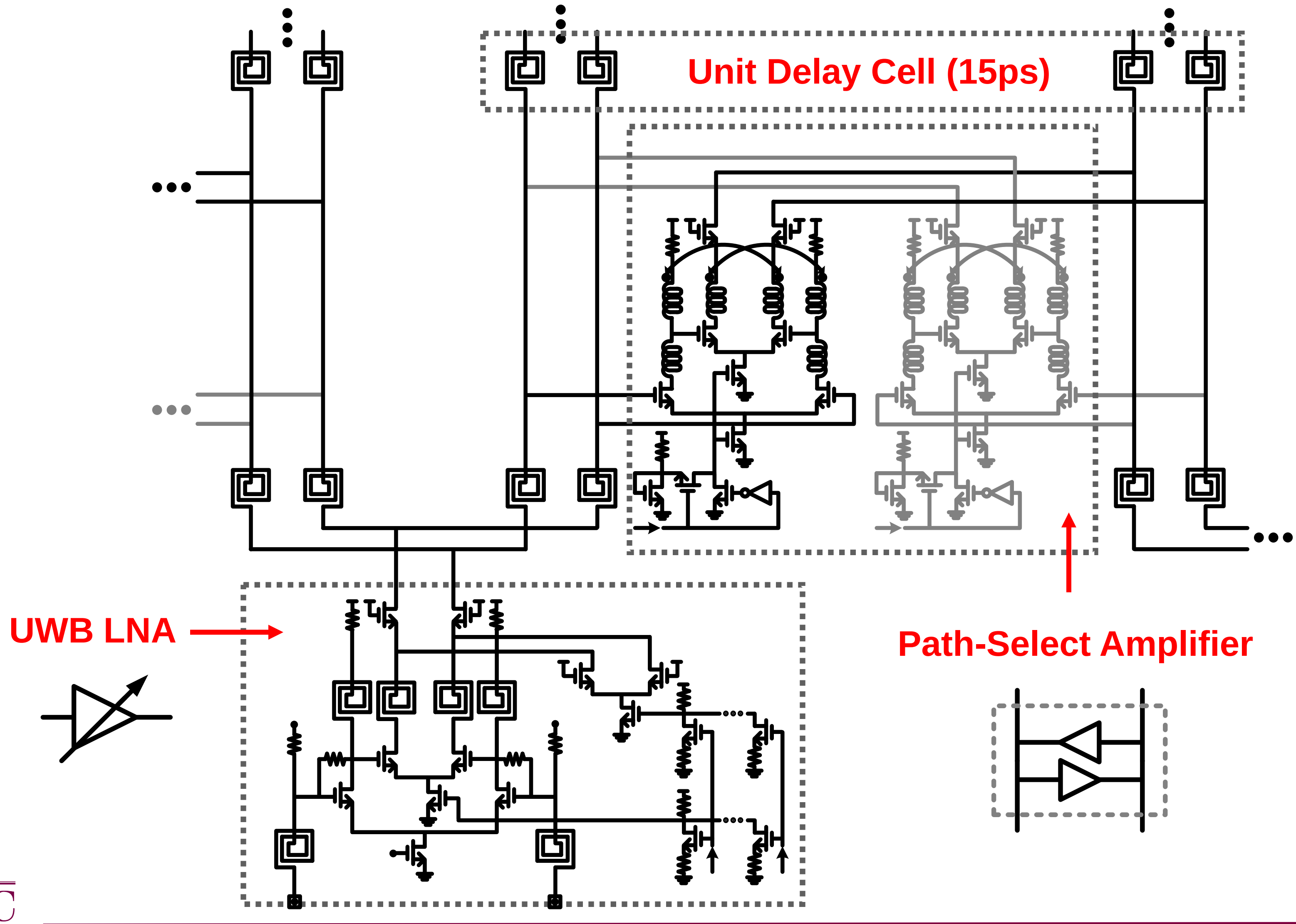
# Signal Flow for 2nd Incident Angle (30ps)



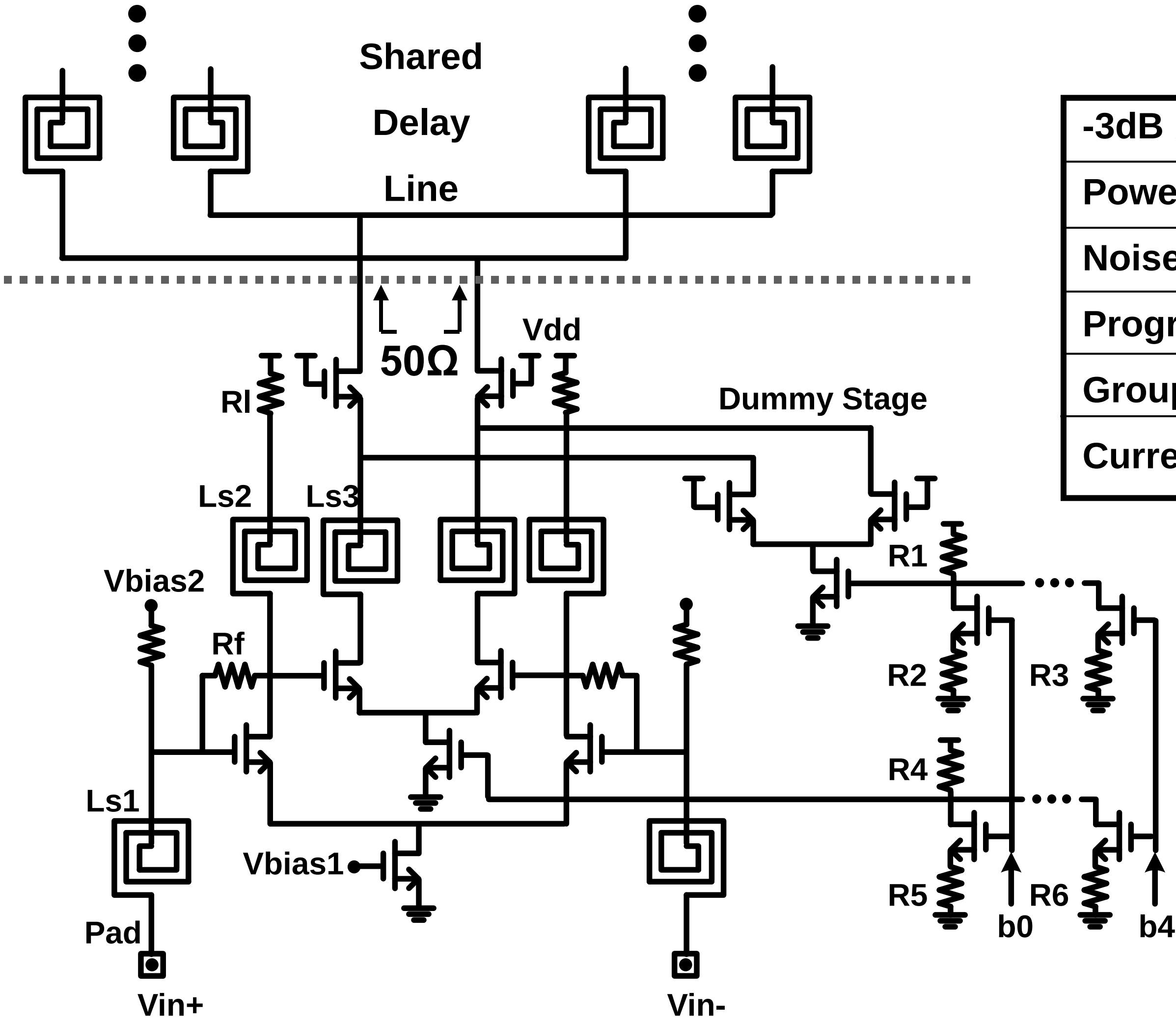
# Signal Flow for 3rd Incident Angle (45ps)



# Circuit Schematics



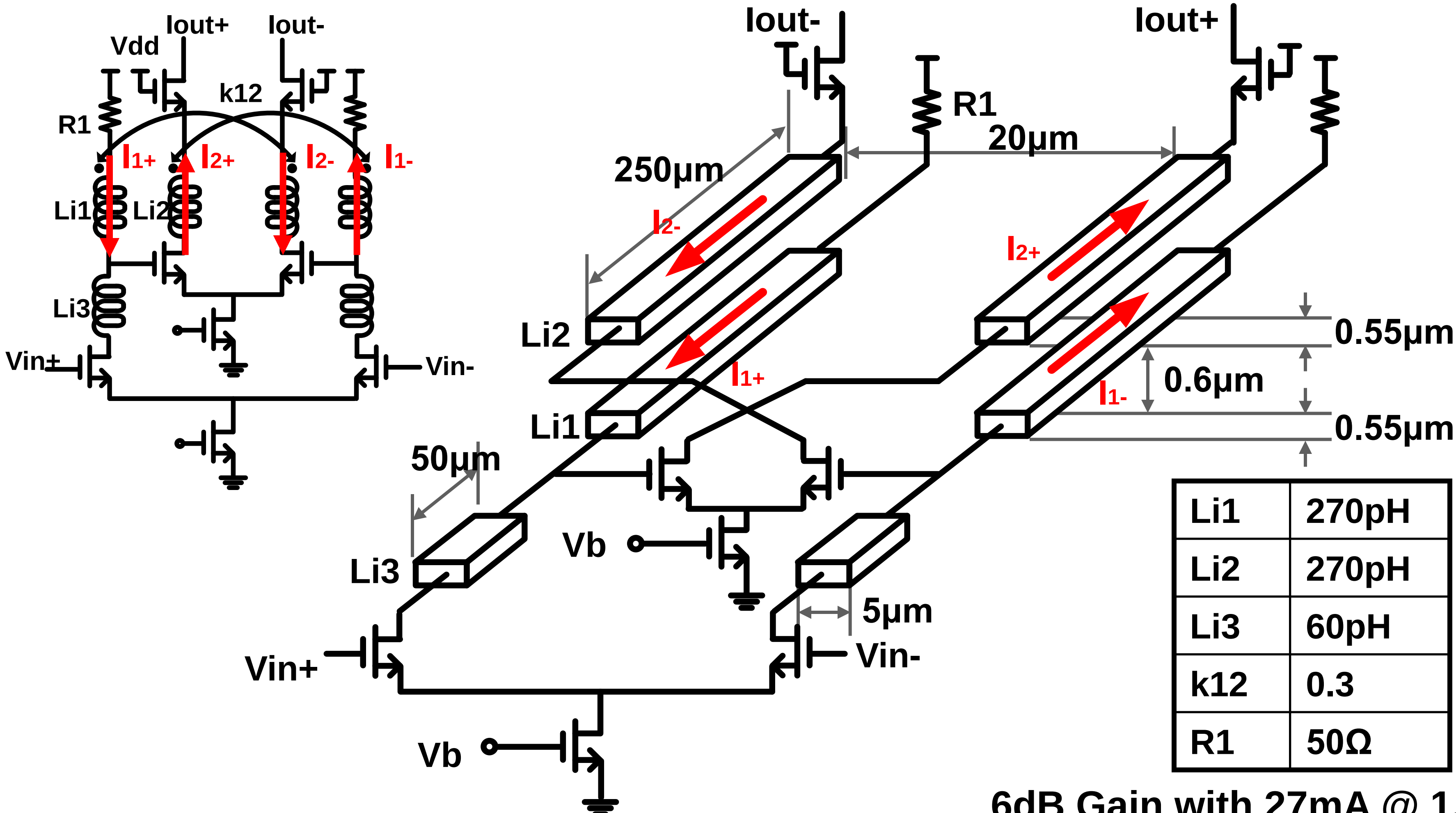
# UWB Front-end Low-Noise Amplifier




| | |
|---|---|
| -3dB bandwidth | 15GHz |
| Power gain | 10dB |
| Noise figure | <4dB |
| Programmable gain | 5dB /1dB |
| Group delay variation | <5ps |
| Current Consumption | 40mA @1.5V |

| | |
|---|---|
| Ls1 | 350pH |
| Ls2 | 350pH |
| Ls3 | 350pH |
| Rf | 340Ω |
| Rl | 57Ω |

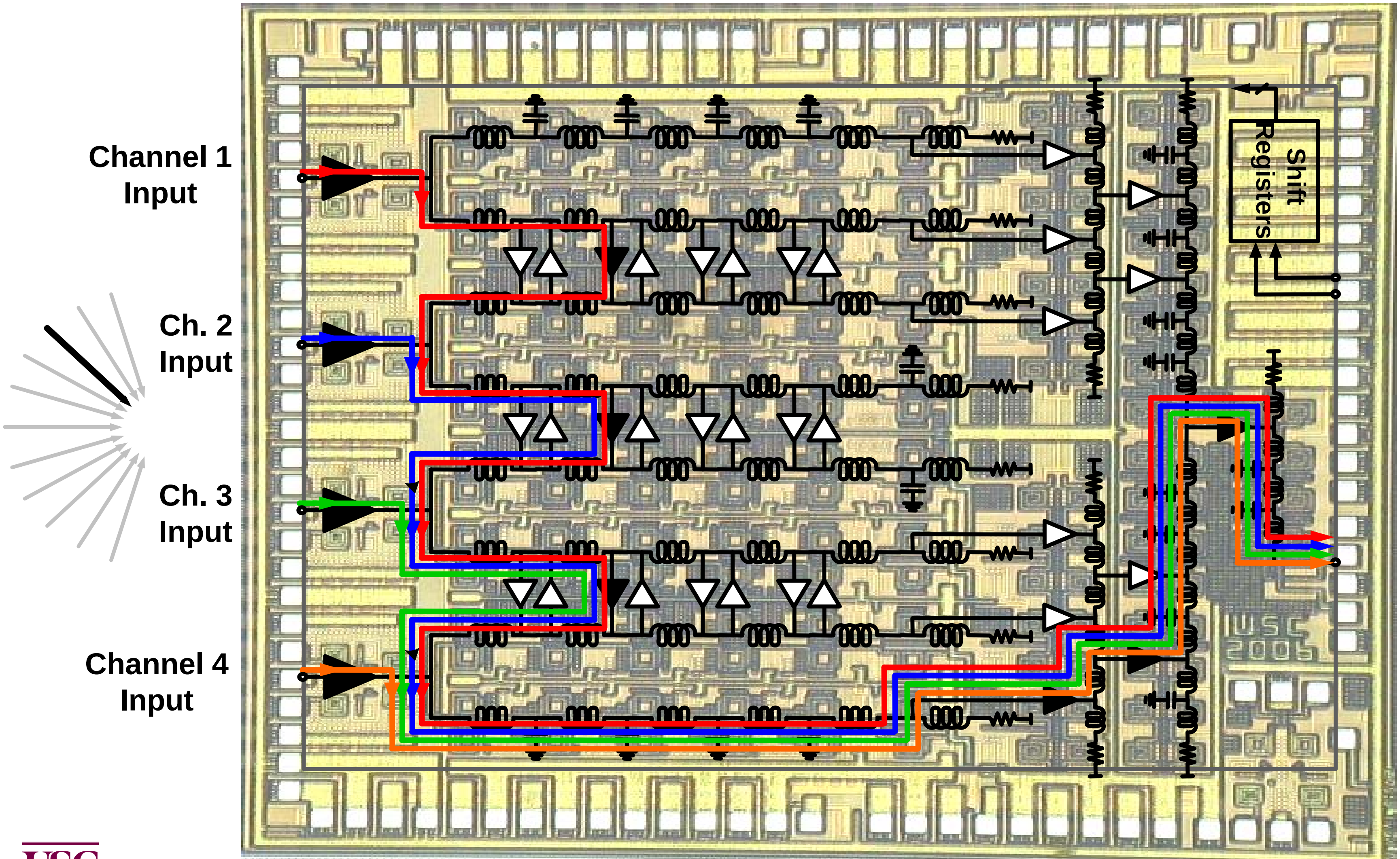
# UWB Path-Select Amplifier



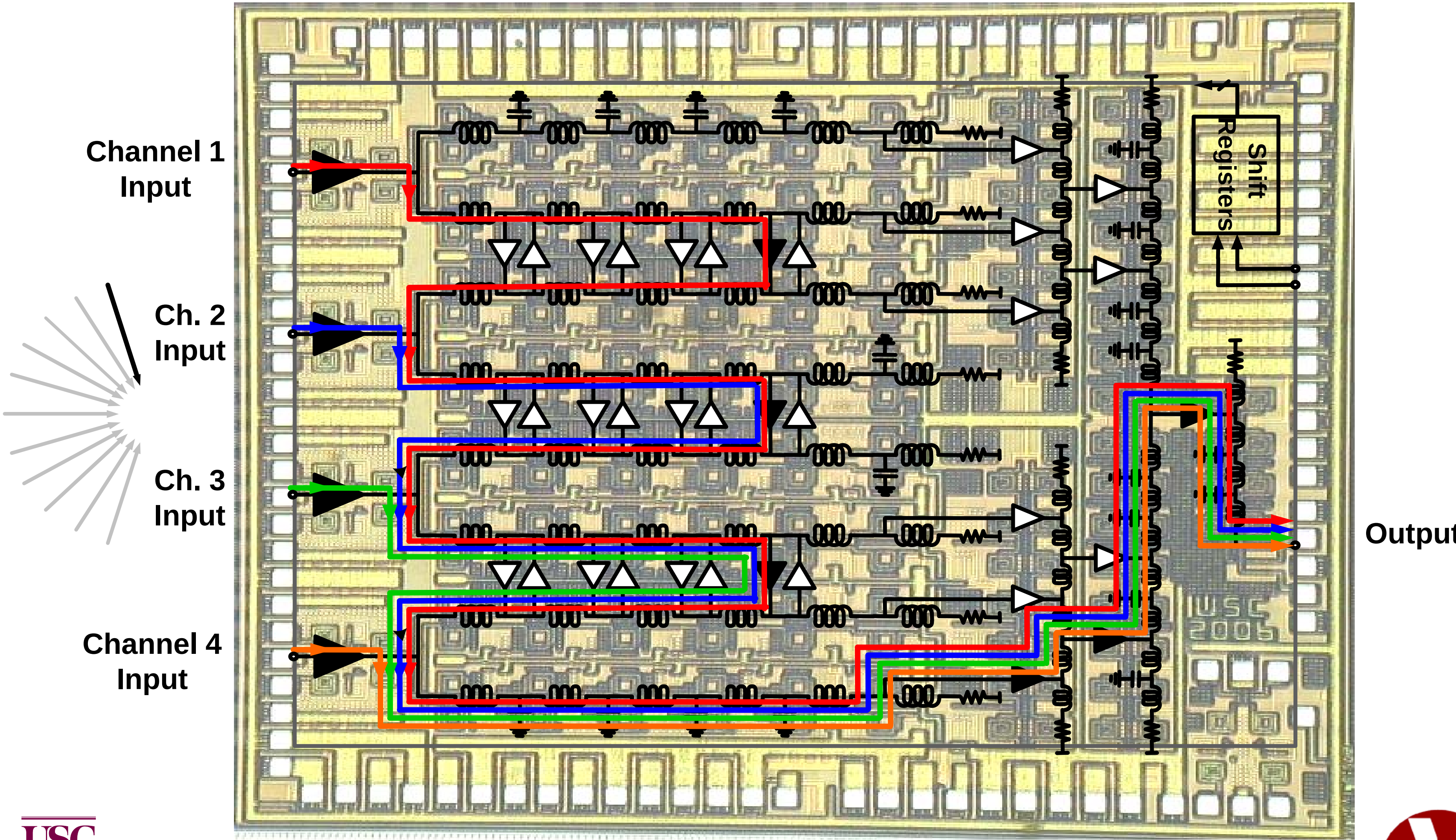

| | |
|---|---|
| Li1 | 270pH |
| Li2 | 270pH |
| Li3 | 60pH |
| k12 | 0.3 |
| R1 | 50Ω |

**6dB Gain with 27mA @ 1.5V**

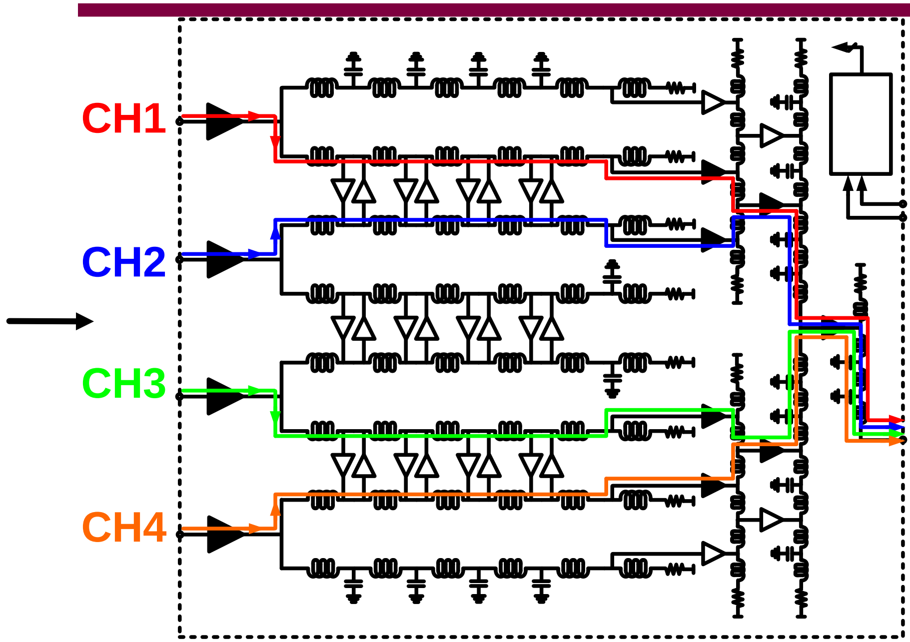
# 4-Element TTD Path-Sharing CMOS RX

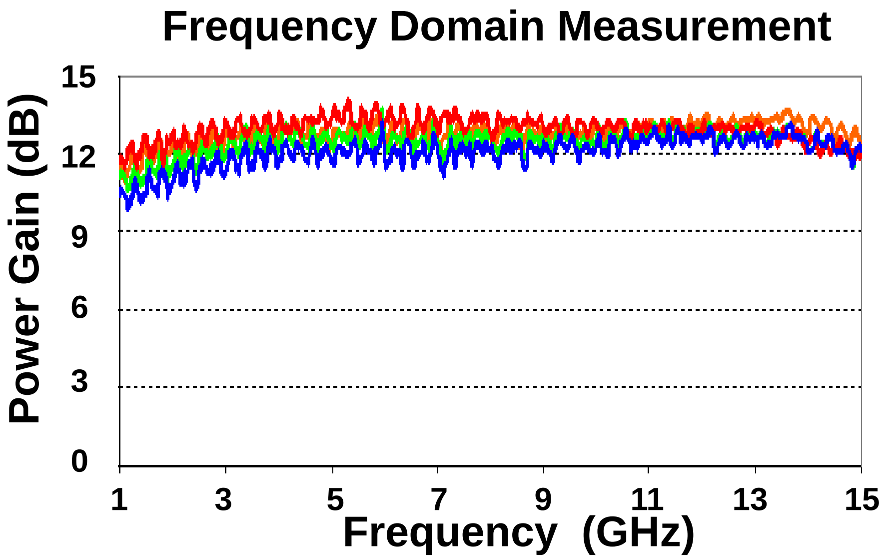


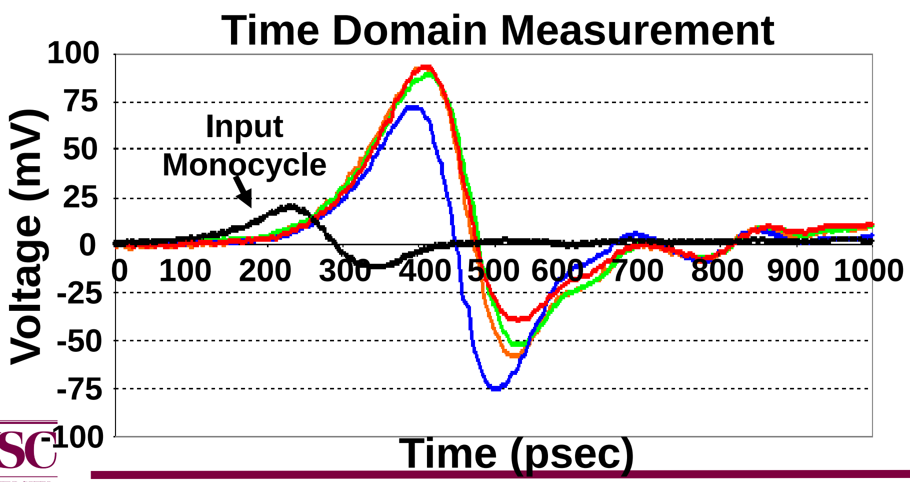
# 4-Element TTD Path-Sharing CMOS RX

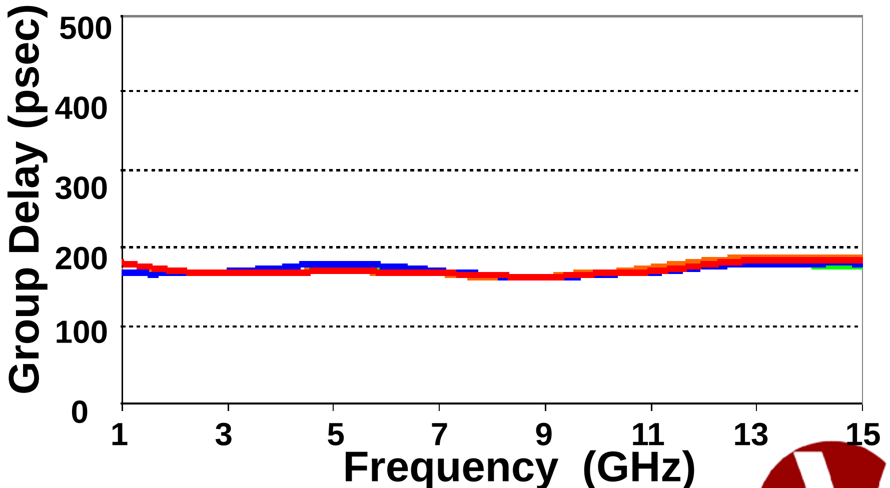


# Measurement Results: 0 Delay Setting

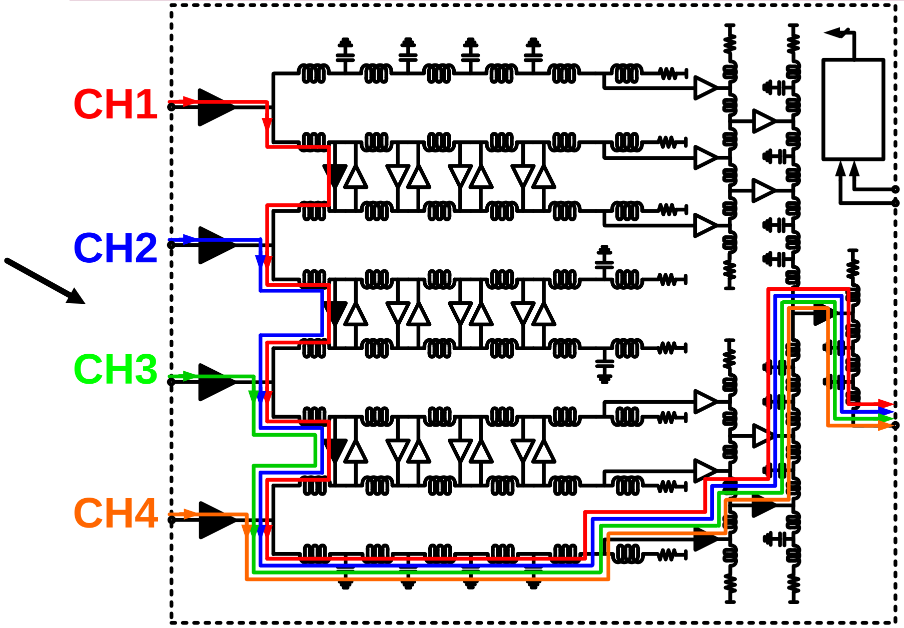


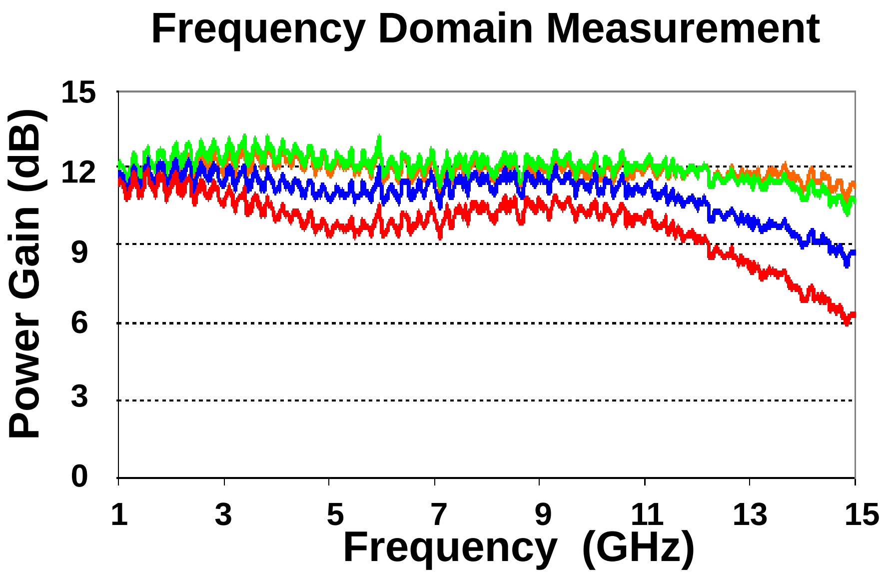



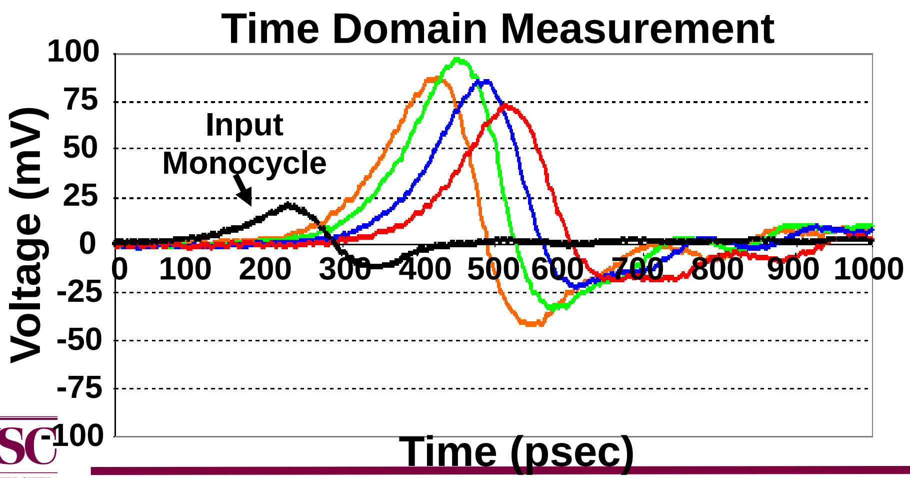



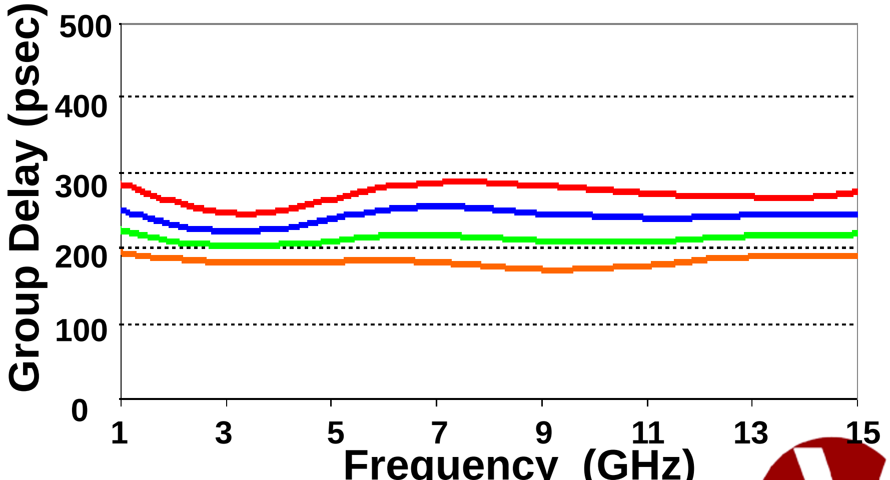



# Measurement Results: 30ps Delay Setting

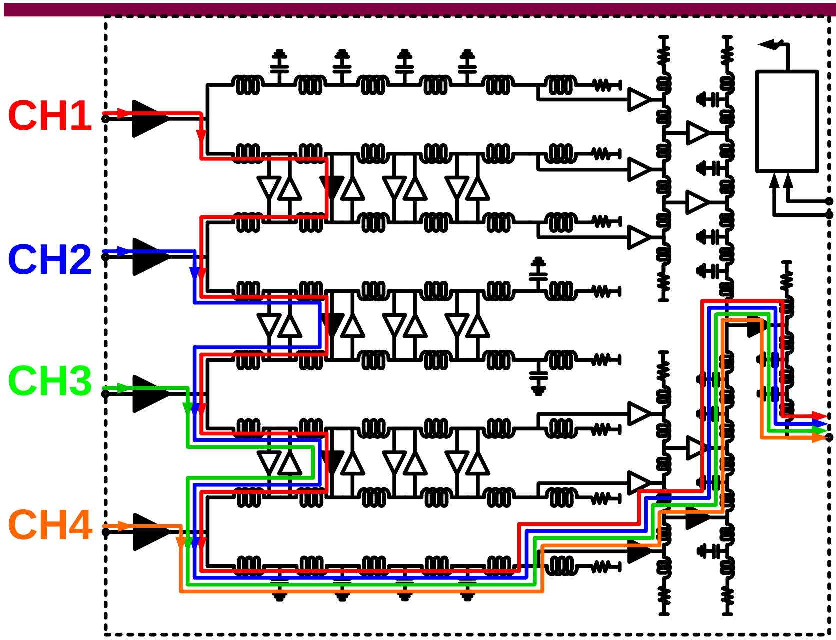


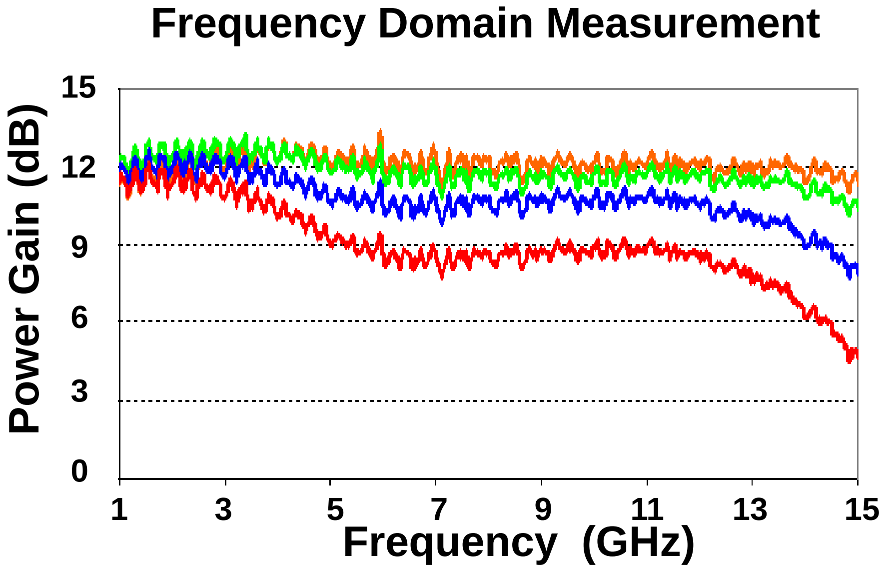



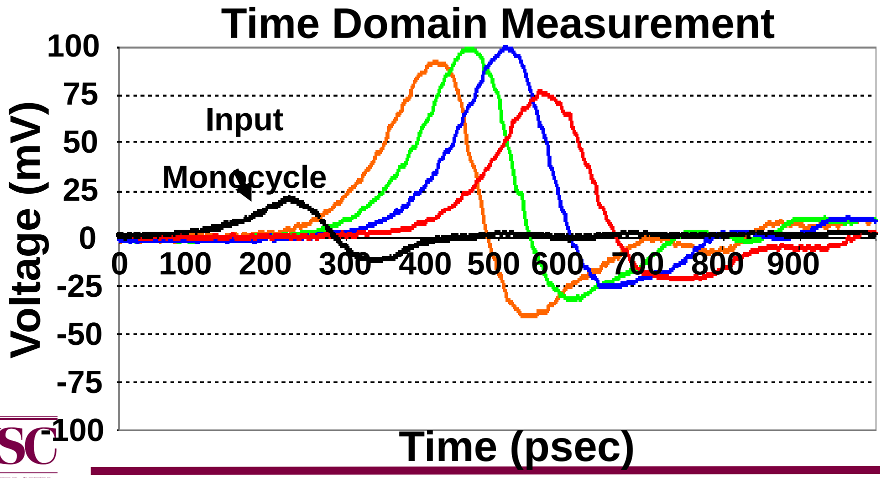



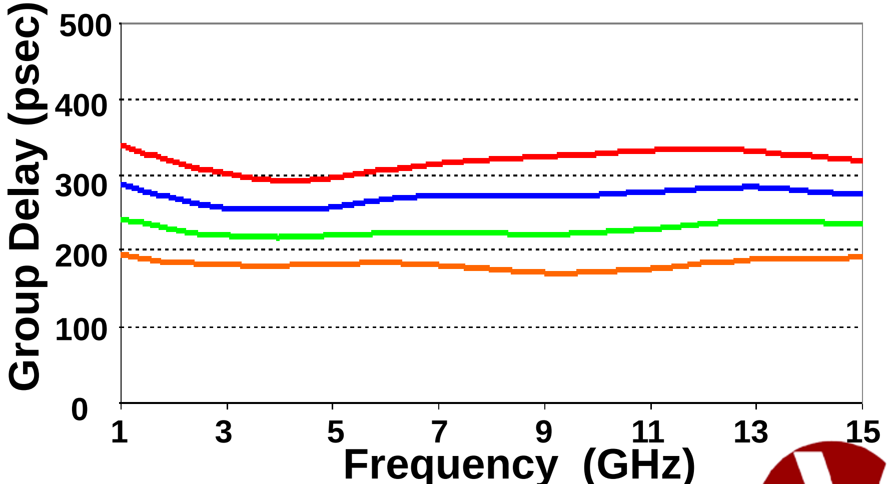



# Measurement Results: 45ps Delay Setting

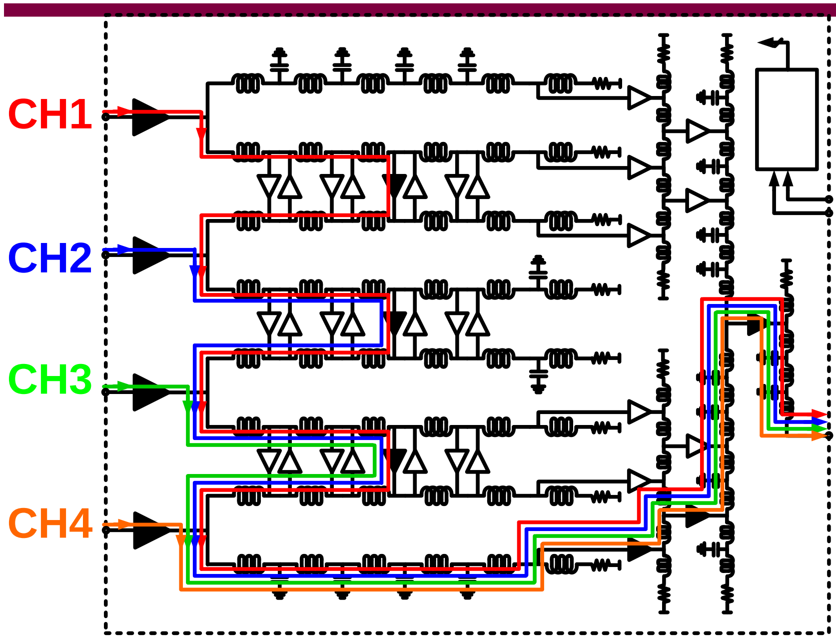


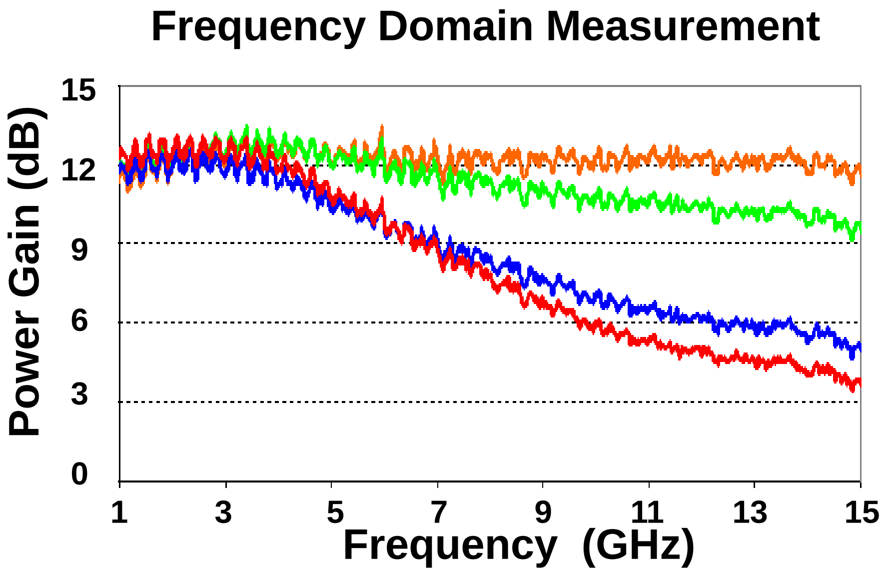



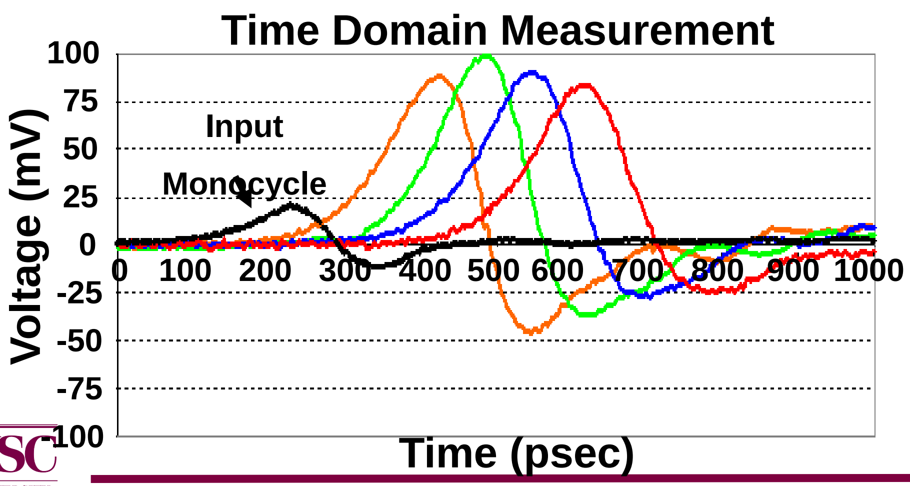



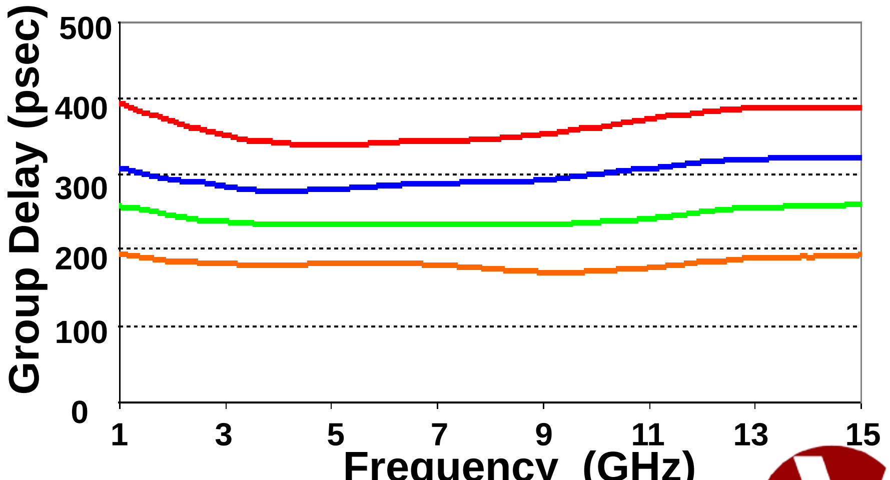



# Measurement Results: 60ps Delay Setting

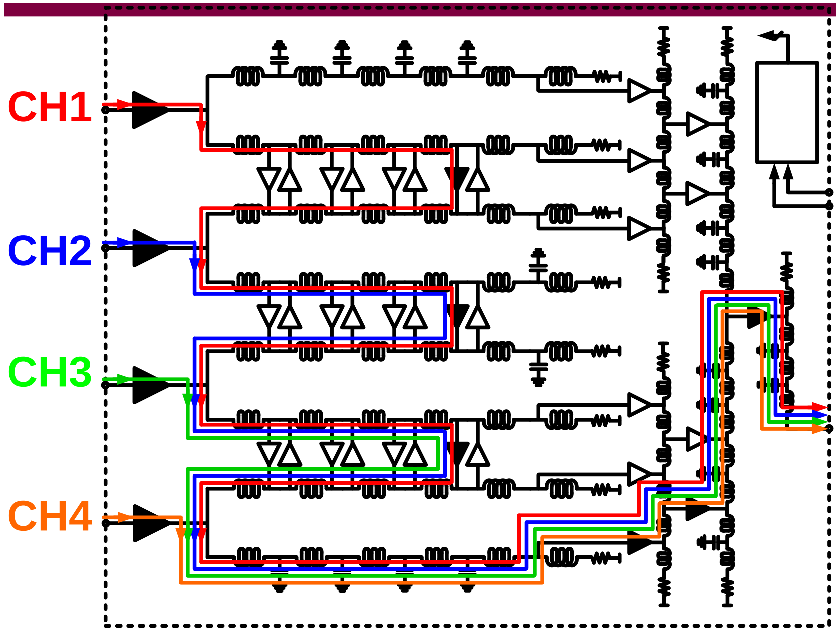


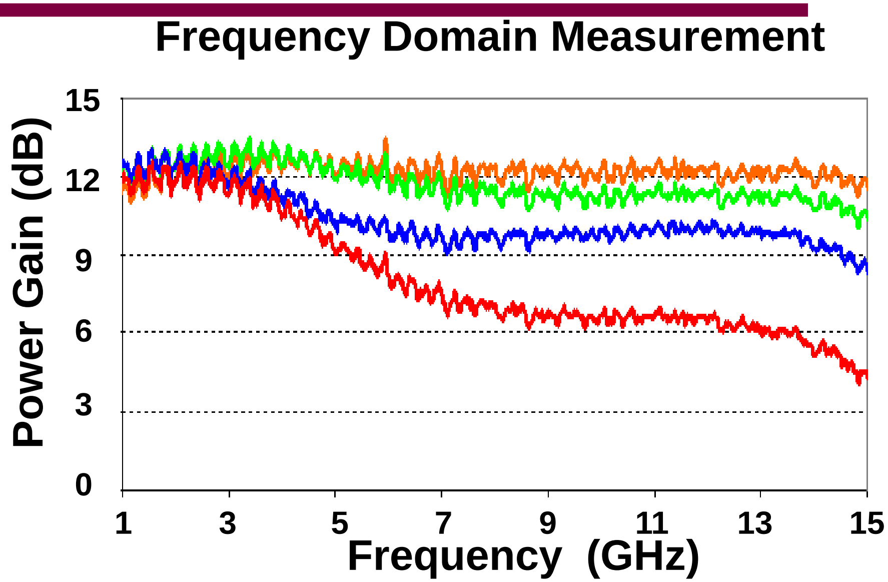



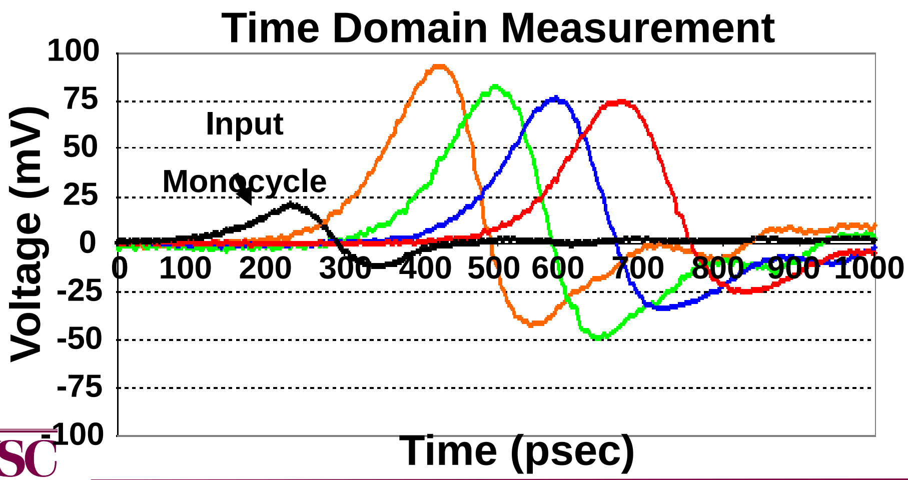



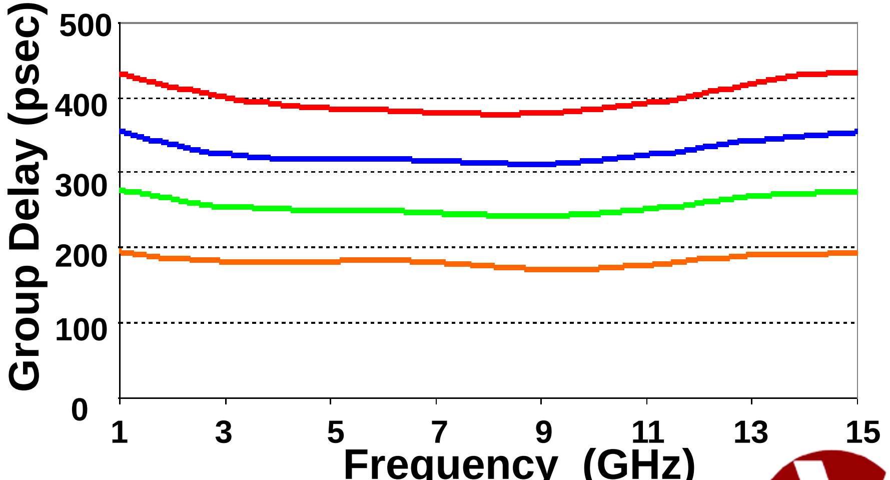



# Measurement Results: 75ps Delay Setting

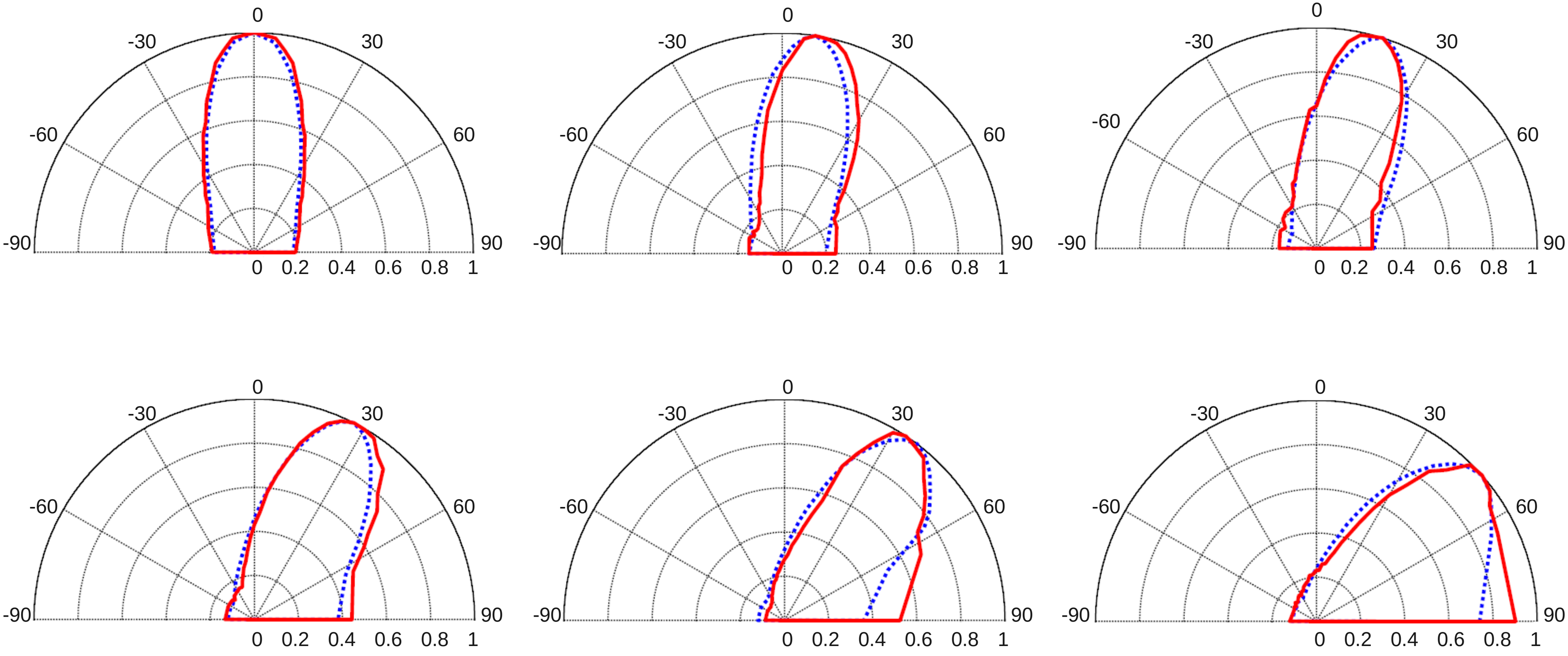


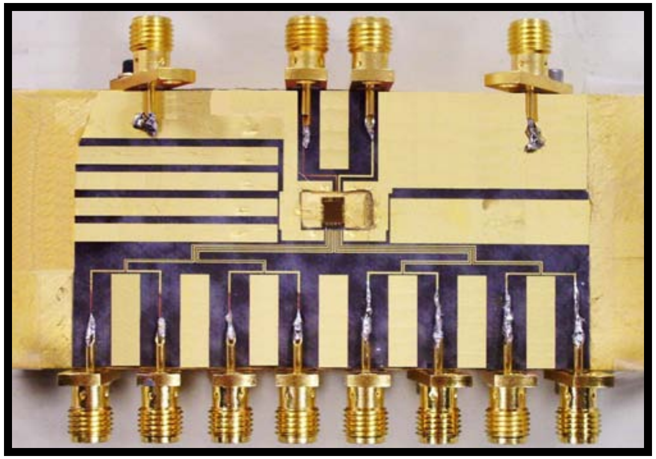



# Inferred Patterns based on Chip Meas.

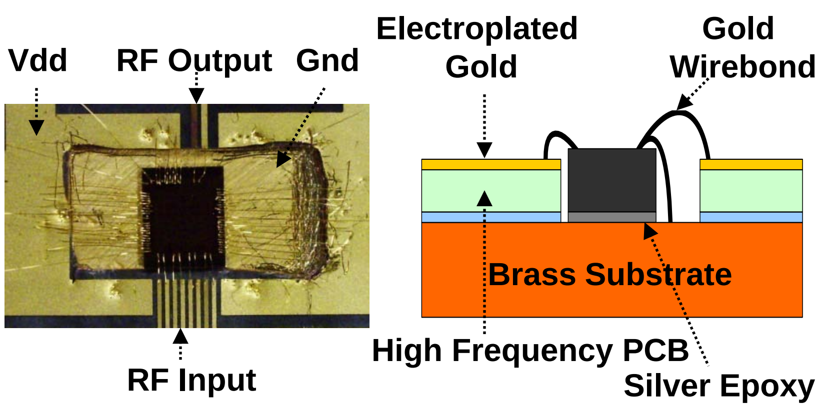


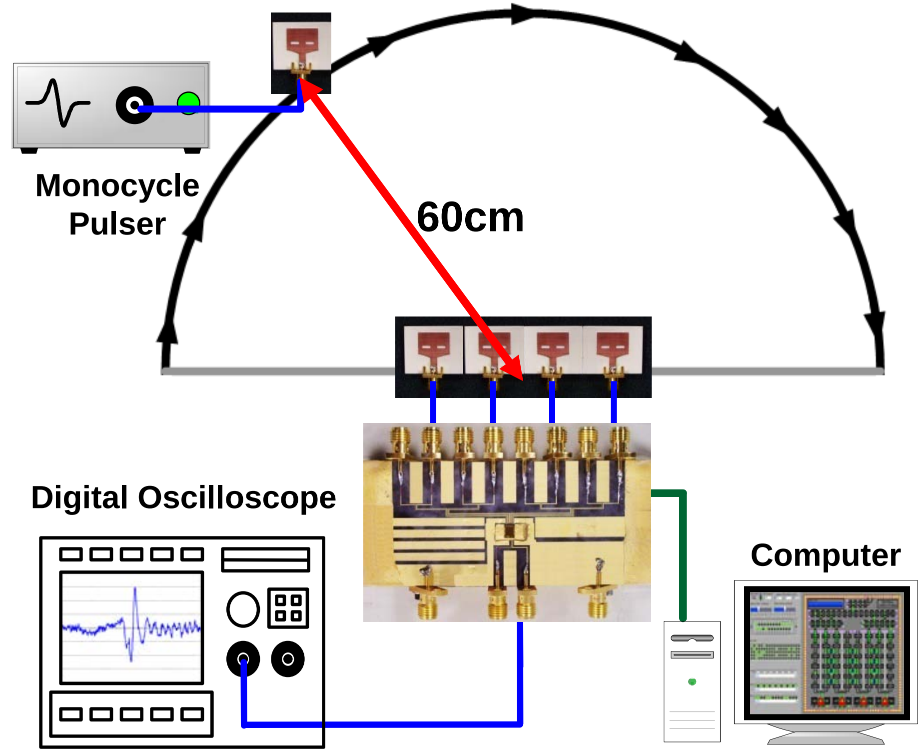

Red lines represent inferred array patterns with 3cm antenna spacing.
Blue lines represent inferred array patterns with 6cm antenna spacing.

# Wireless Array Measurement Setup

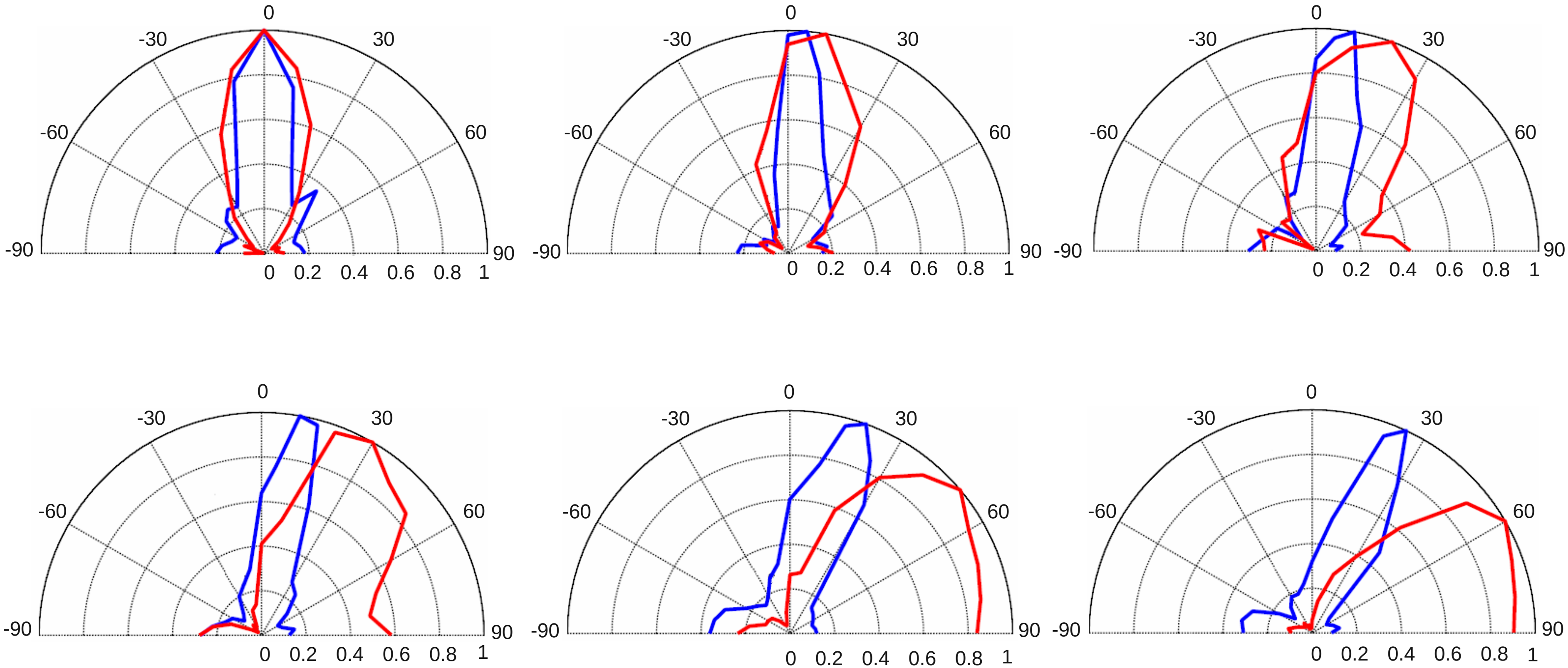


Microwave Package



# Measured Wireless Array Patterns




Red lines represent measured array patterns with 3cm antenna spacing.

Blue lines represent measured array patterns with 6cm antenna spacing.

# Measurement Performance Summary

### *UWB Front-End*

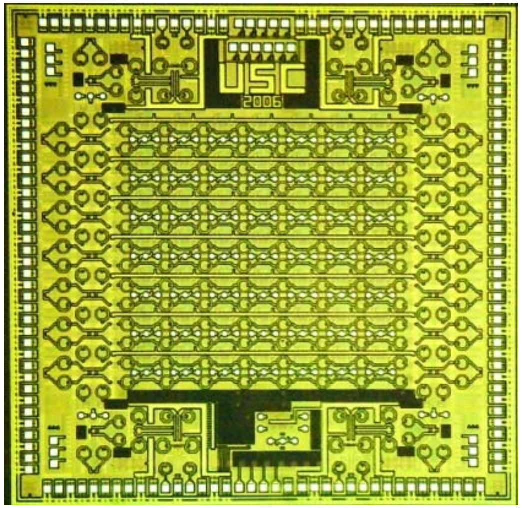
| | |
|---|---|
| -3dB Bandwidth | 15GHz |
| Power gain | 10dB |
| Noise-Figure (1GHz – 15GHz) | 2.9 dB – 4.8dB |
| Programmable gain | 5dB in 1dB steps |
| Group delay variation | < 5ps |
| Power dissipation | 40mA @1.5V |

### *Complete 4-Channel UWB Beam-former*

| | |
|---|---|
| -3dB Bandwidth (normal incident angle) | 18GHz |
| Total array gain | 24dB |
| UWB true time delay resolution | 15ps |
| Beam steering spatial resolution | $9^{\circ}$ (antenna separation = 30mm) |
| Maximum beam steering spatial angle | $45^{\circ}$ (antenna separation = 30mm) |
| Total number of available beams | 11 (3.5bits) |
| Power dissipation@1.5V | 370mA |

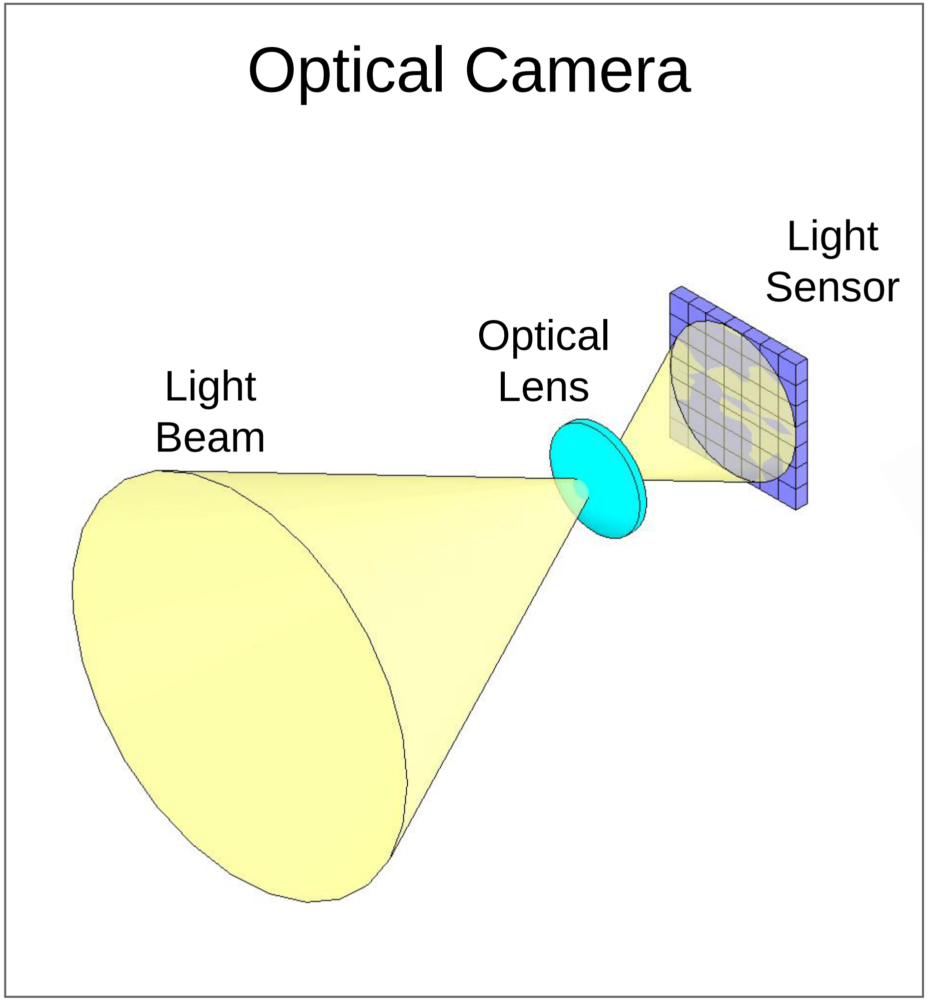
| | |
|---|---|
| Total number of on-chip spiral inductors | 188 |
| Technology | 0.13µm CMOS |
| Die Area | 3.2mm x 3.1mm |

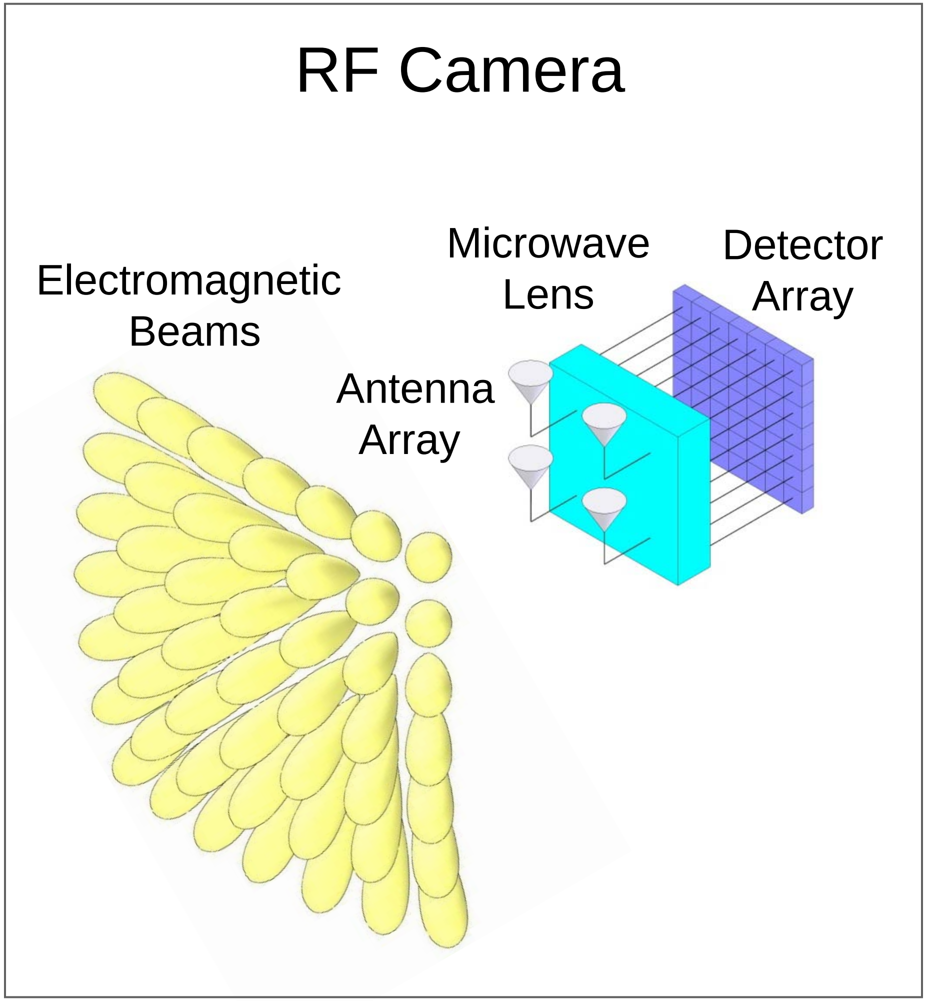
# 1-15GHz 2x2-Channel 7x7-Beam Receiving Array in 0.13μm CMOS



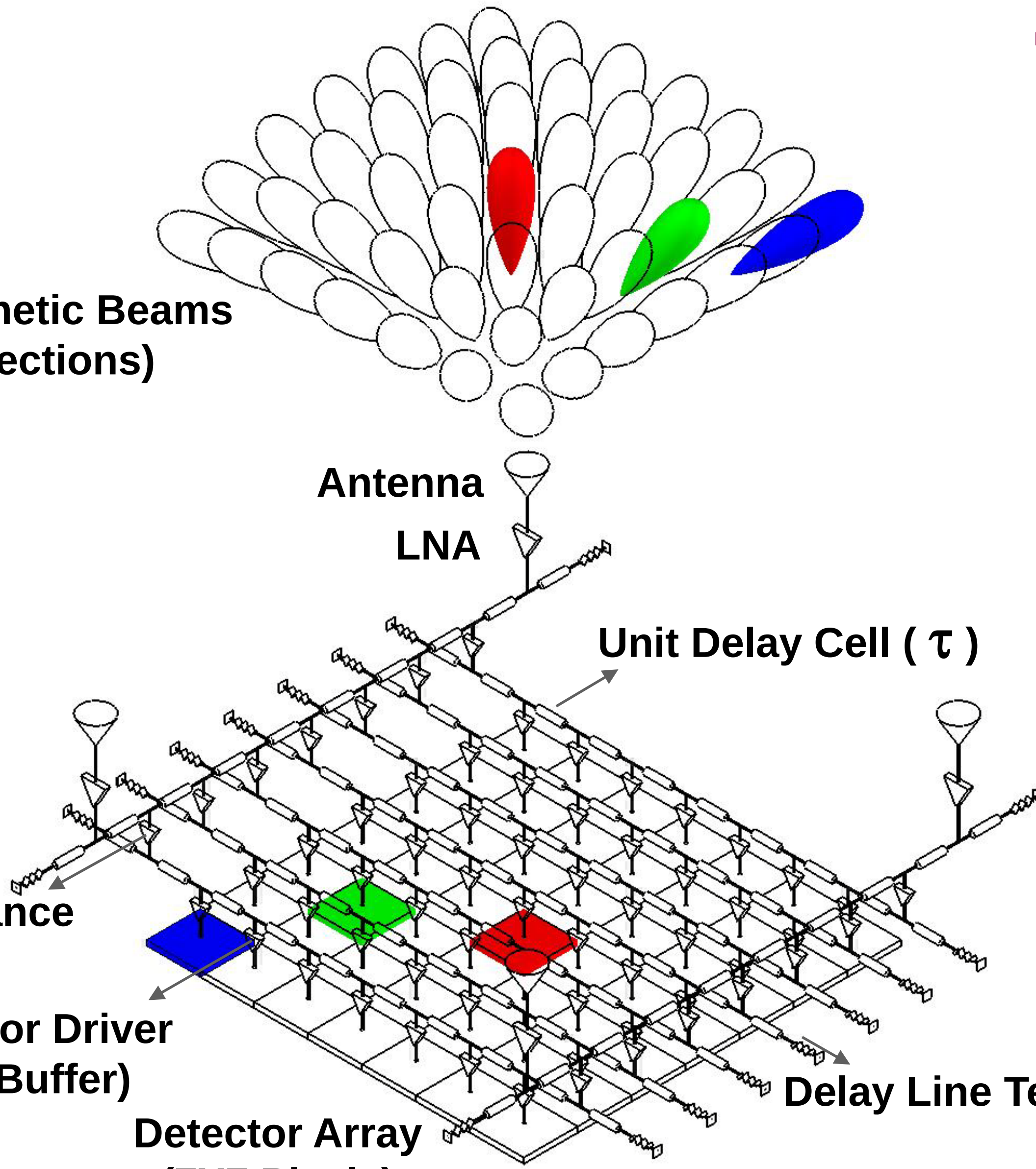

**T. Chu and H. Hashemi, "A CMOS UWB camera with 7x7 simultaneous active pixels", in *IEEE International Solid-State Circuits Conference* Digest of Technical Papers, pp. 120-121, February 2008.**

# Optical Versus RF Camera Analogy

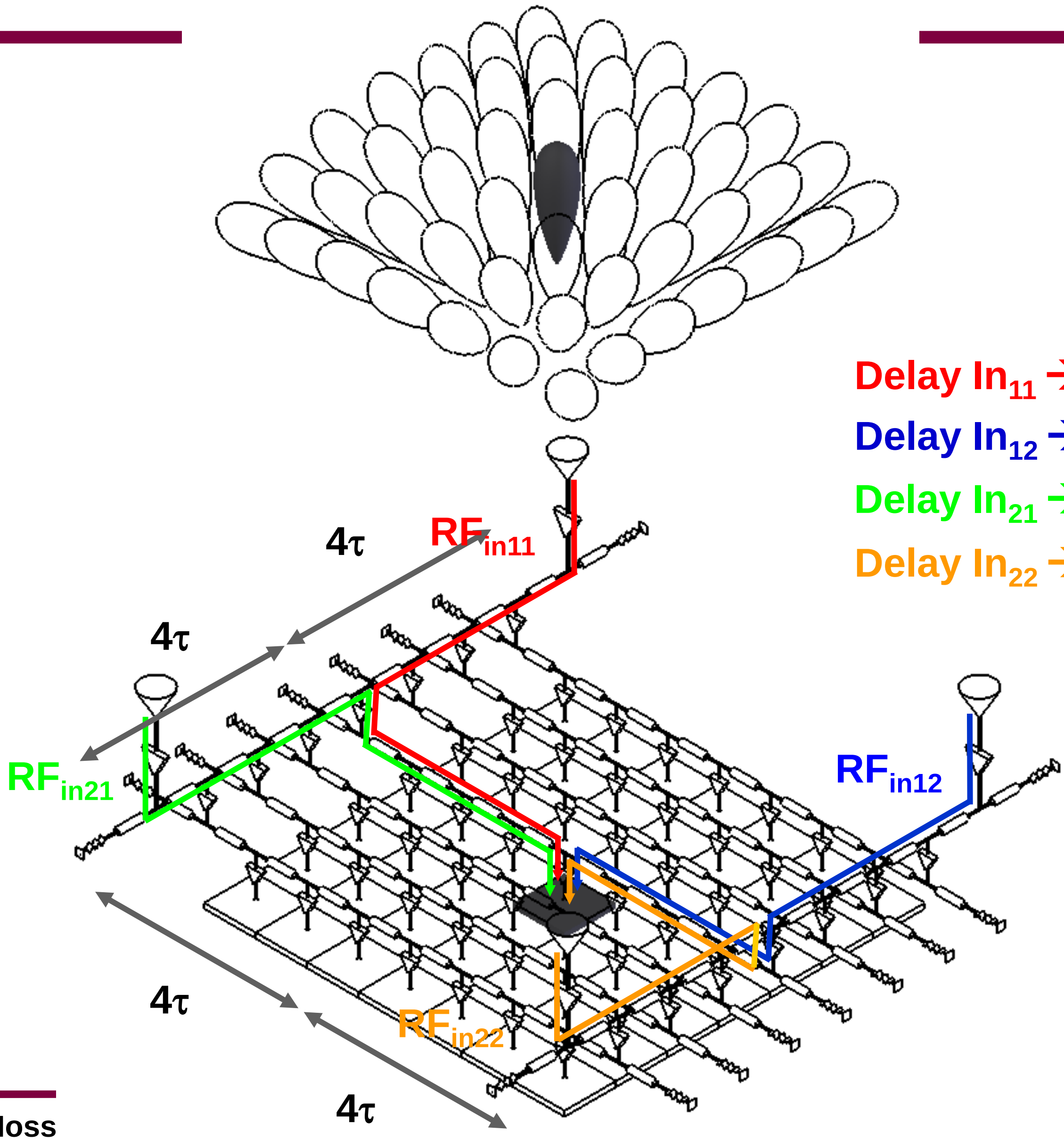


# Multi-Beam TTD Architecture: RF Camera



# Signal Flow for Output 44



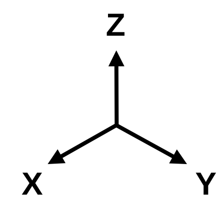

X-direction    Y-direction

$\text{Delay In}_{11} \rightarrow \text{Out}_{44} = 4\tau + 4\tau = 8\tau$

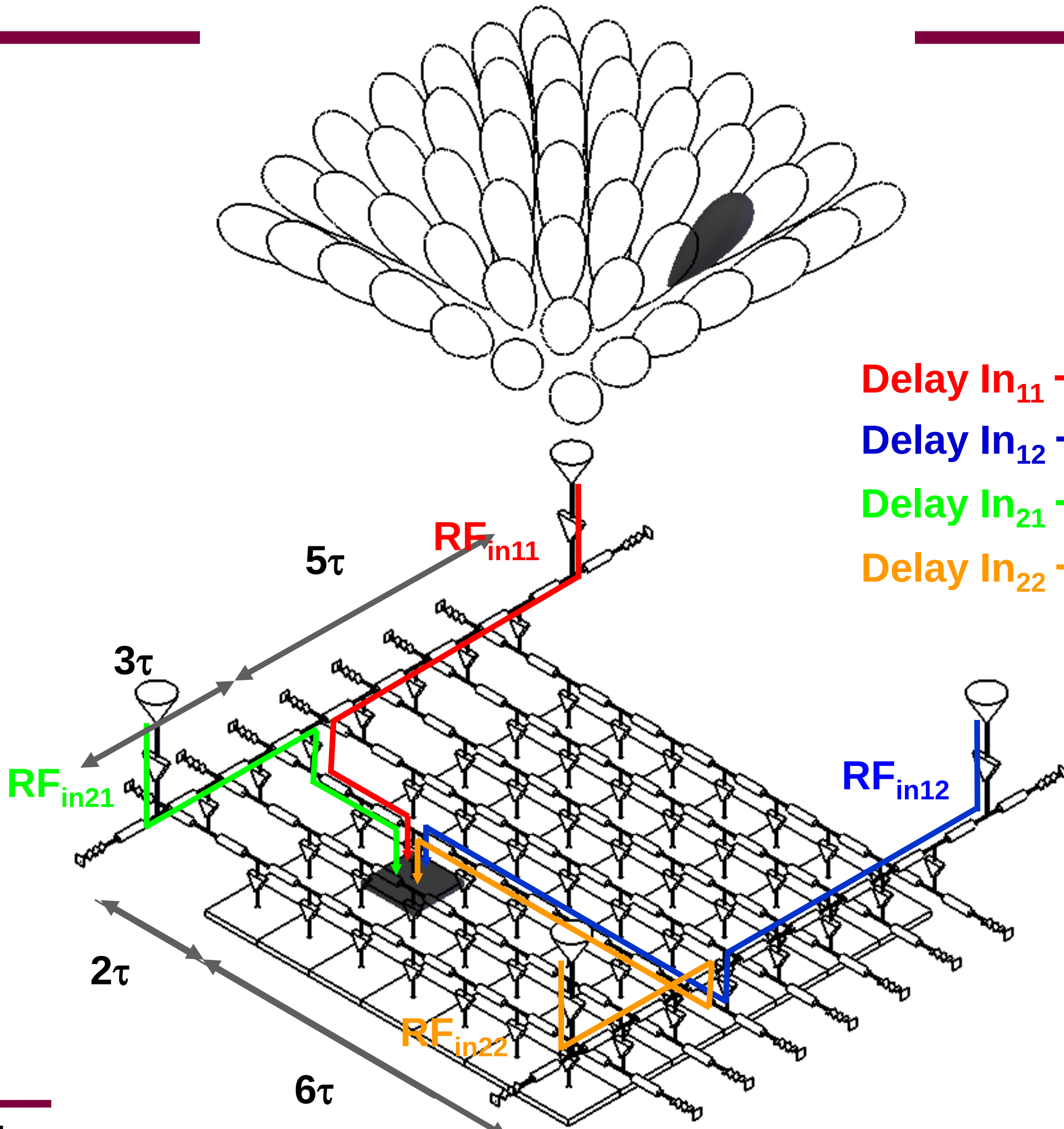
$\text{Delay In}_{12} \rightarrow \text{Out}_{44} = 4\tau + 4\tau = 8\tau$

$\text{Delay In}_{21} \rightarrow \text{Out}_{44} = 4\tau + 4\tau = 8\tau$

$\text{Delay In}_{22} \rightarrow \text{Out}_{44} = 4\tau + 4\tau = 8\tau$



# Signal Flow for Output 52



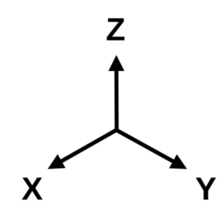

X-direction　　Y-direction

$\text{Delay In}_{11} \rightarrow \text{Out}_{52} = 5\tau + 2\tau = 7\tau$

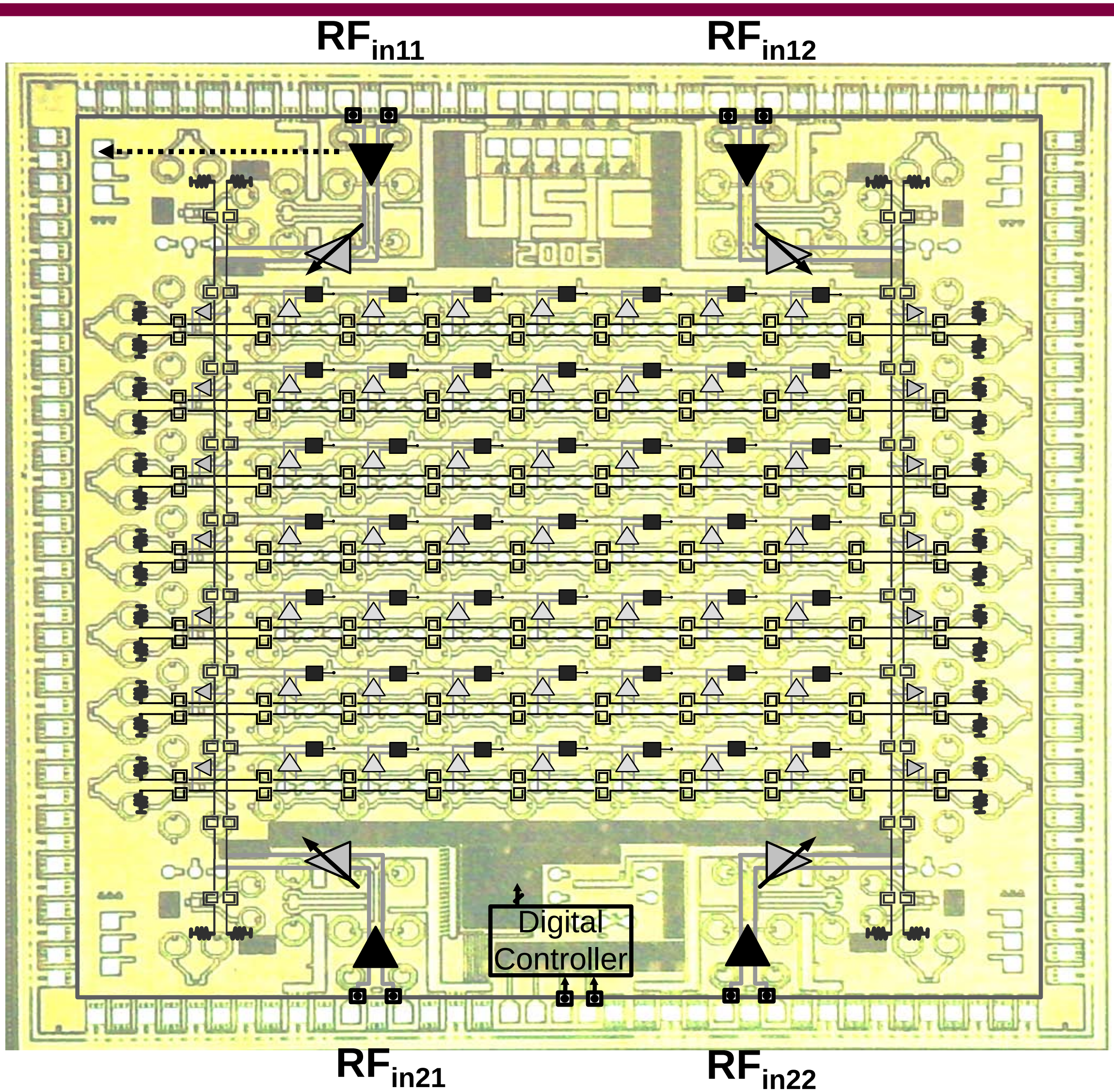
$\text{Delay In}_{12} \rightarrow \text{Out}_{52} = 5\tau + 6\tau = 11\tau$

$\text{Delay In}_{21} \rightarrow \text{Out}_{52} = 3\tau + 2\tau = 5\tau$

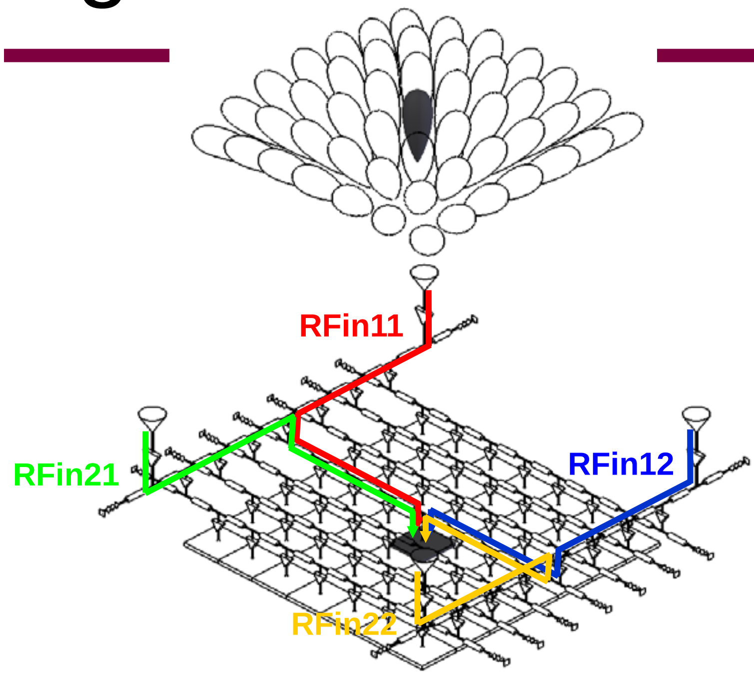
$\text{Delay In}_{22} \rightarrow \text{Out}_{52} = 3\tau + 6\tau = 9\tau$



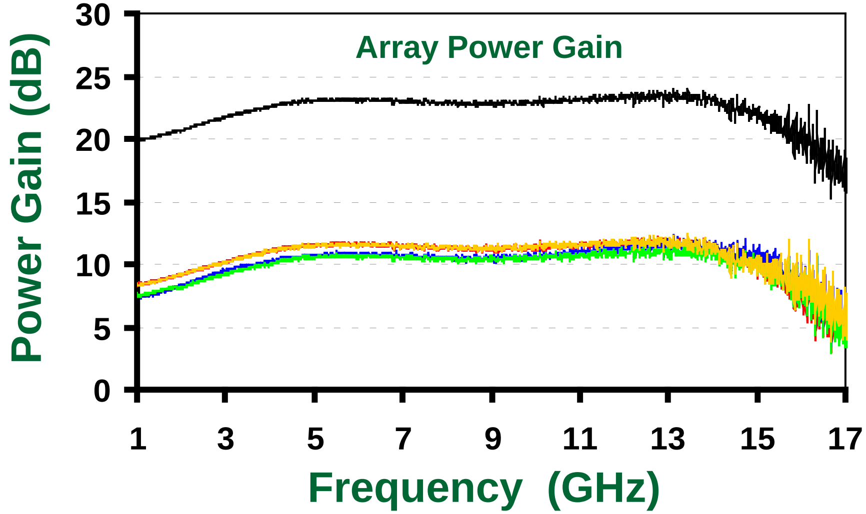
# 2x2-Element TTD CMOS RX with 7x7 Outputs



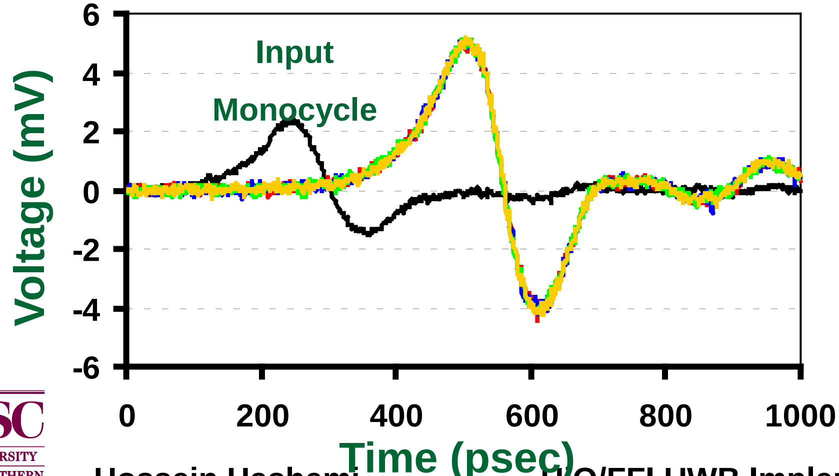
# Single-Channel Measurements for Pixel 44

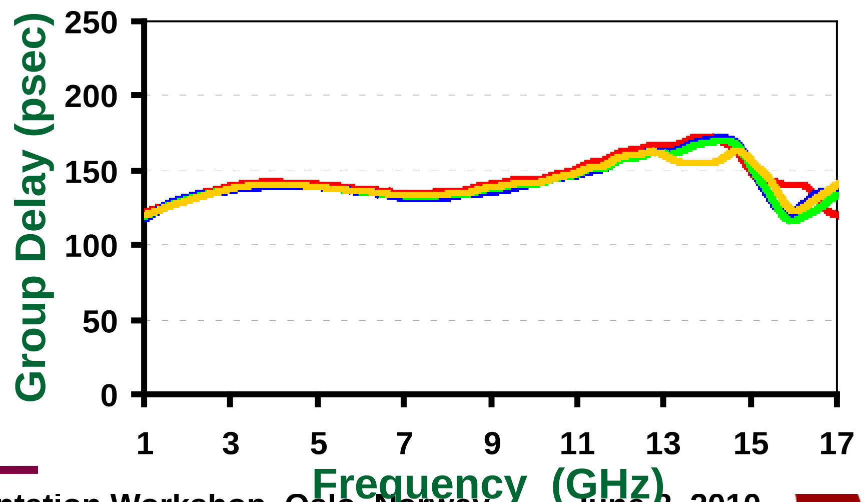



## Frequency Domain Measurement

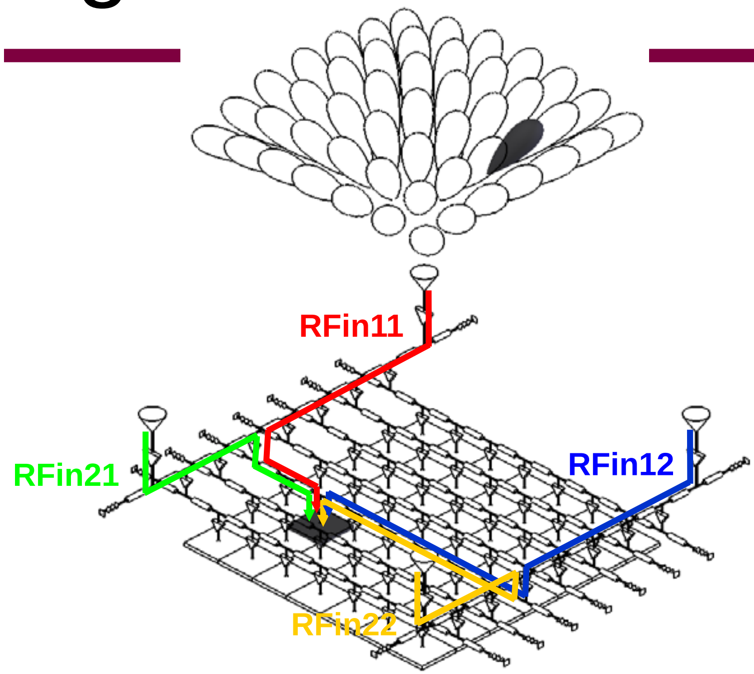



## Time Domain Measurement

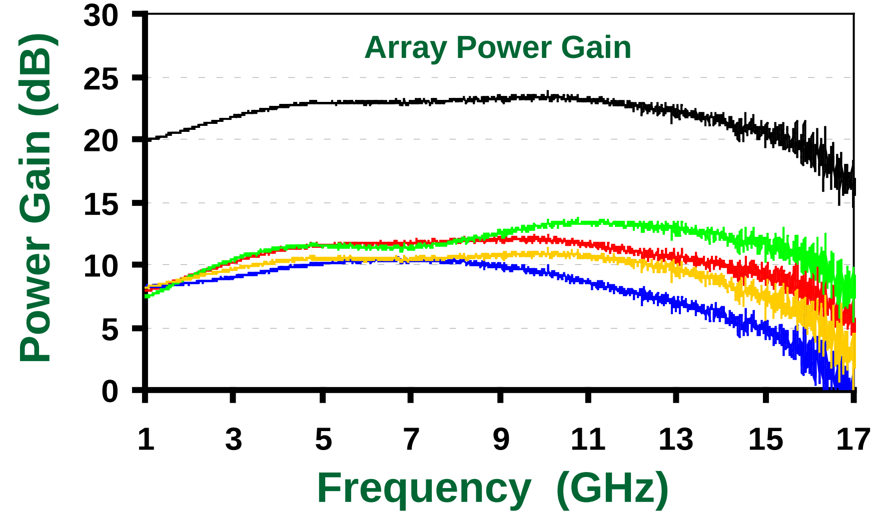


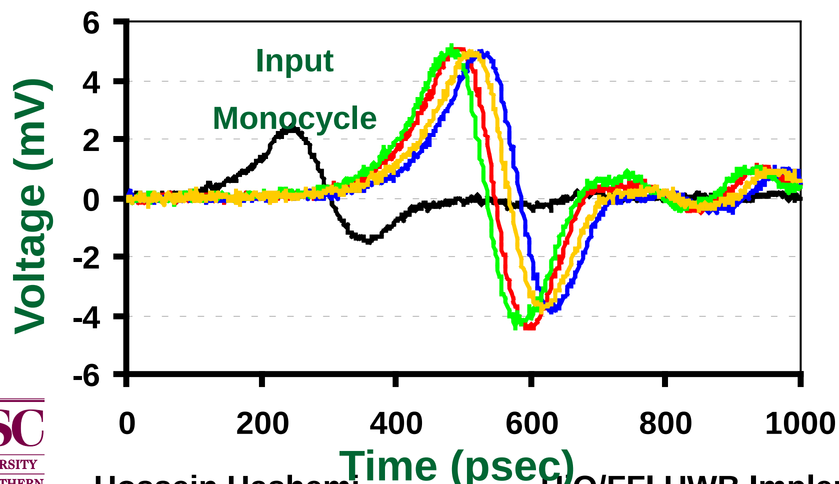
# Single-Channel Measurements for Pixel 52

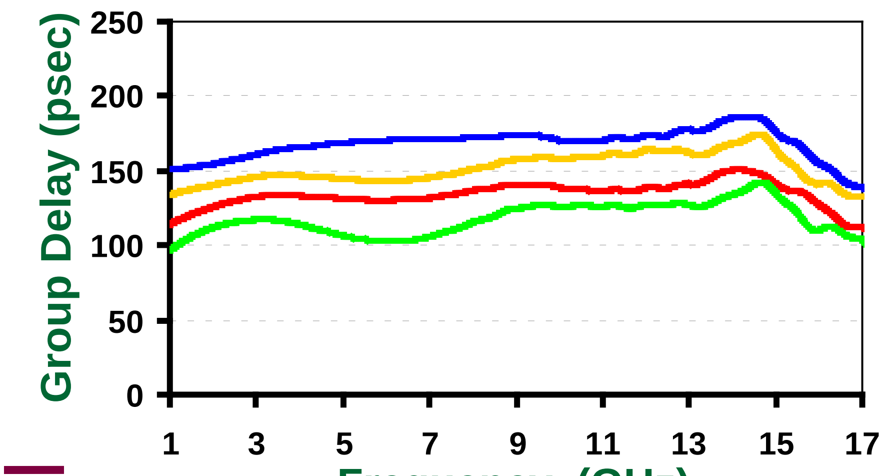



## Frequency Domain Measurement

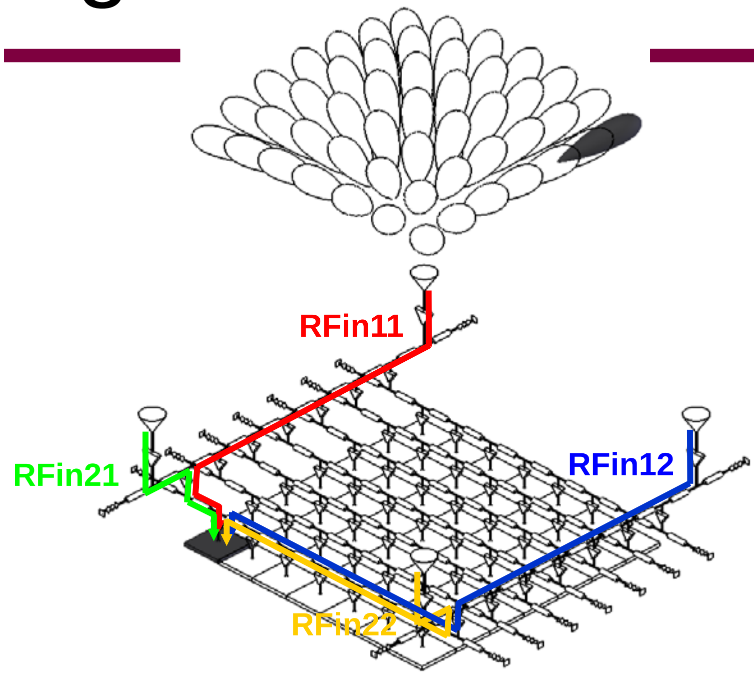



## Time Domain Measurement

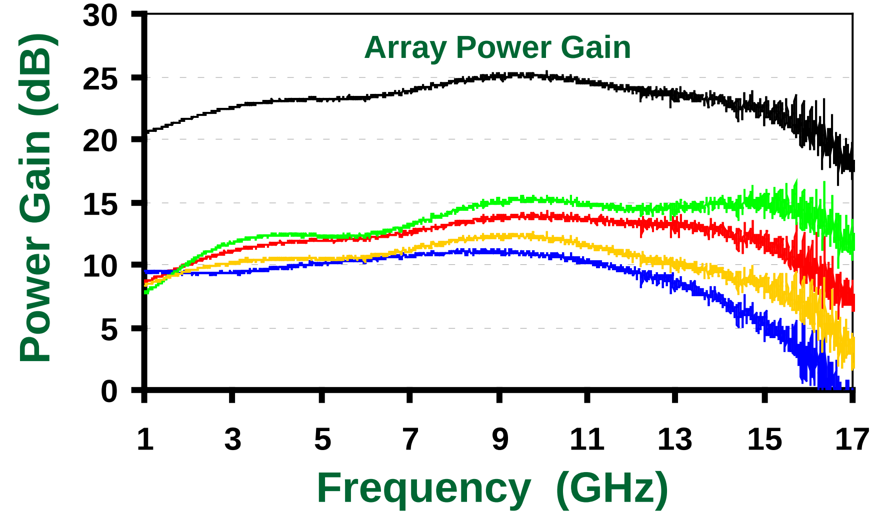


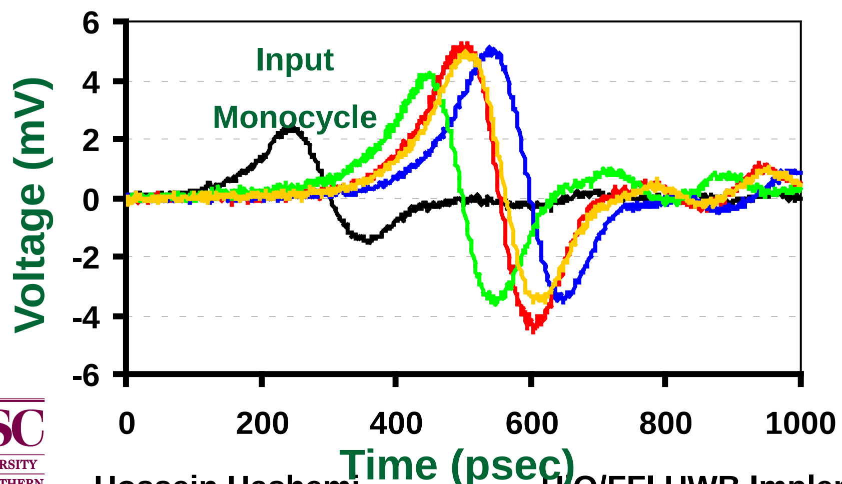
# Single-Channel Measurements for Pixel 71

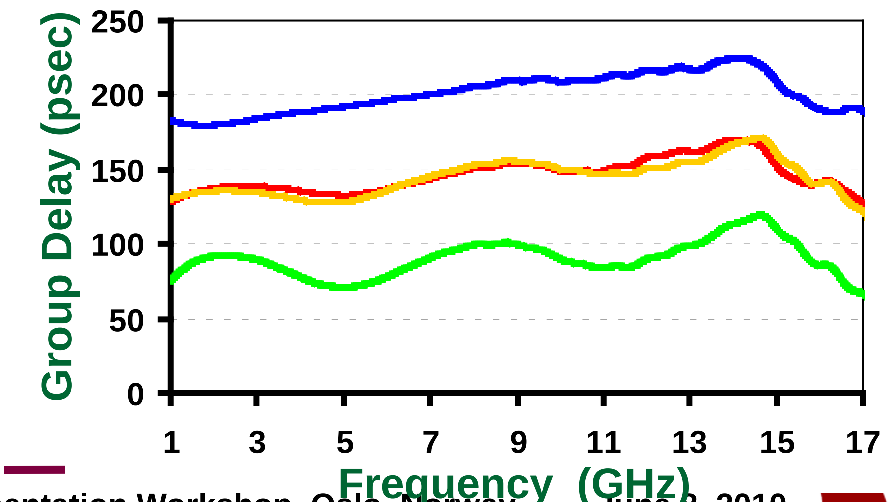



## Frequency Domain Measurement

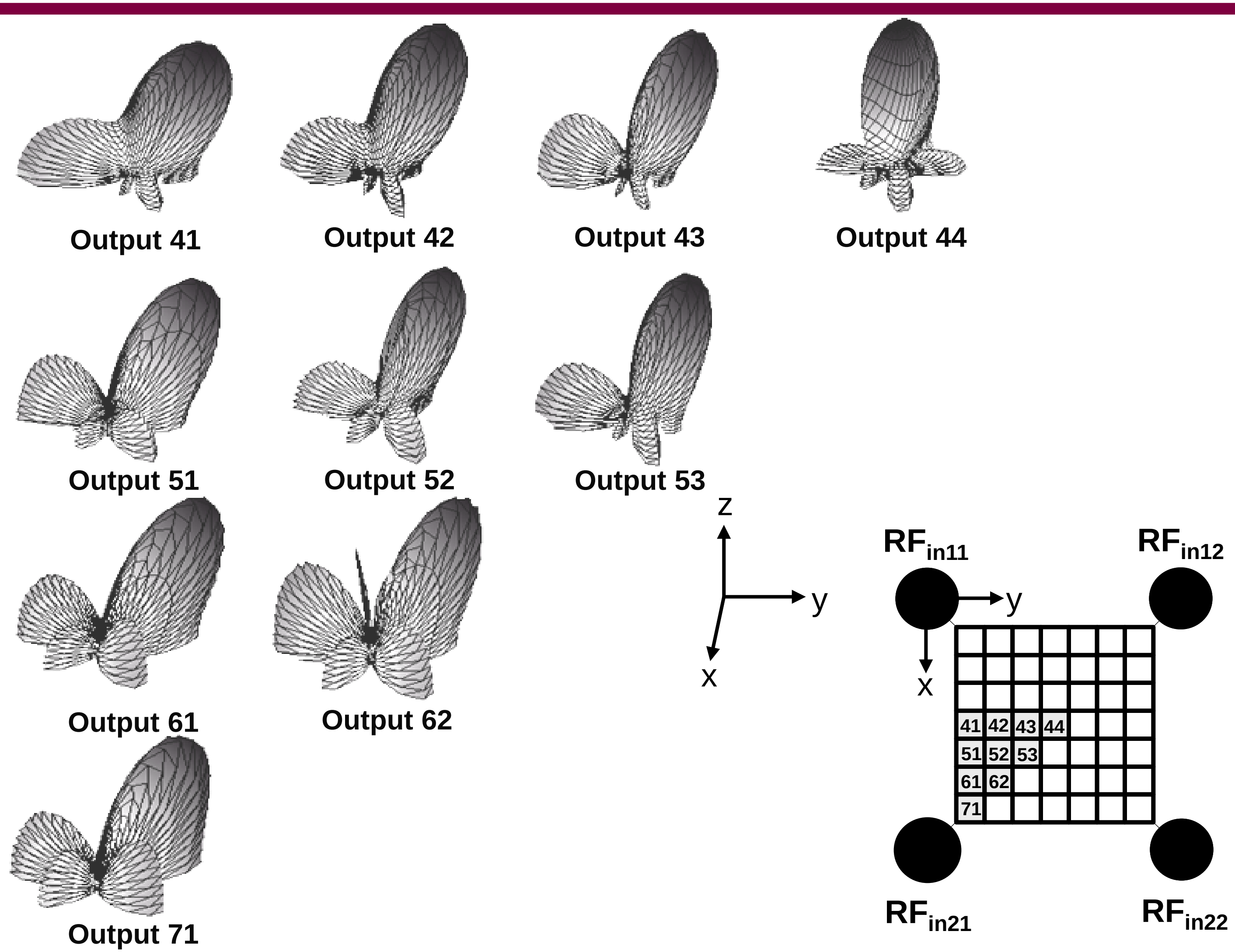



## Time Domain Measurement

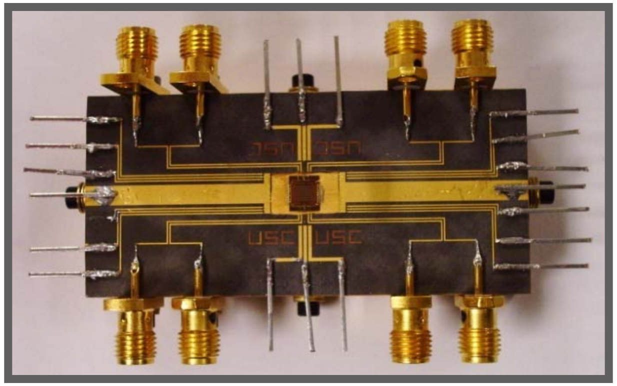


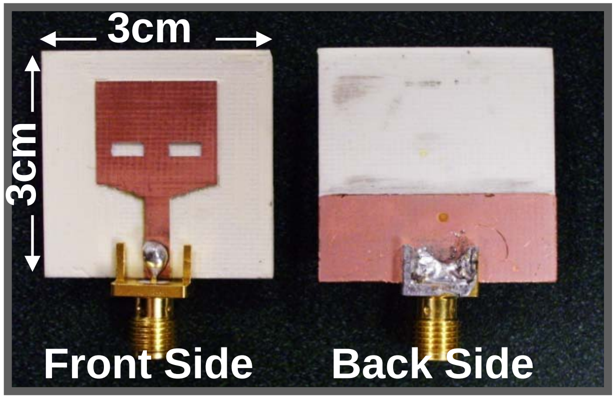



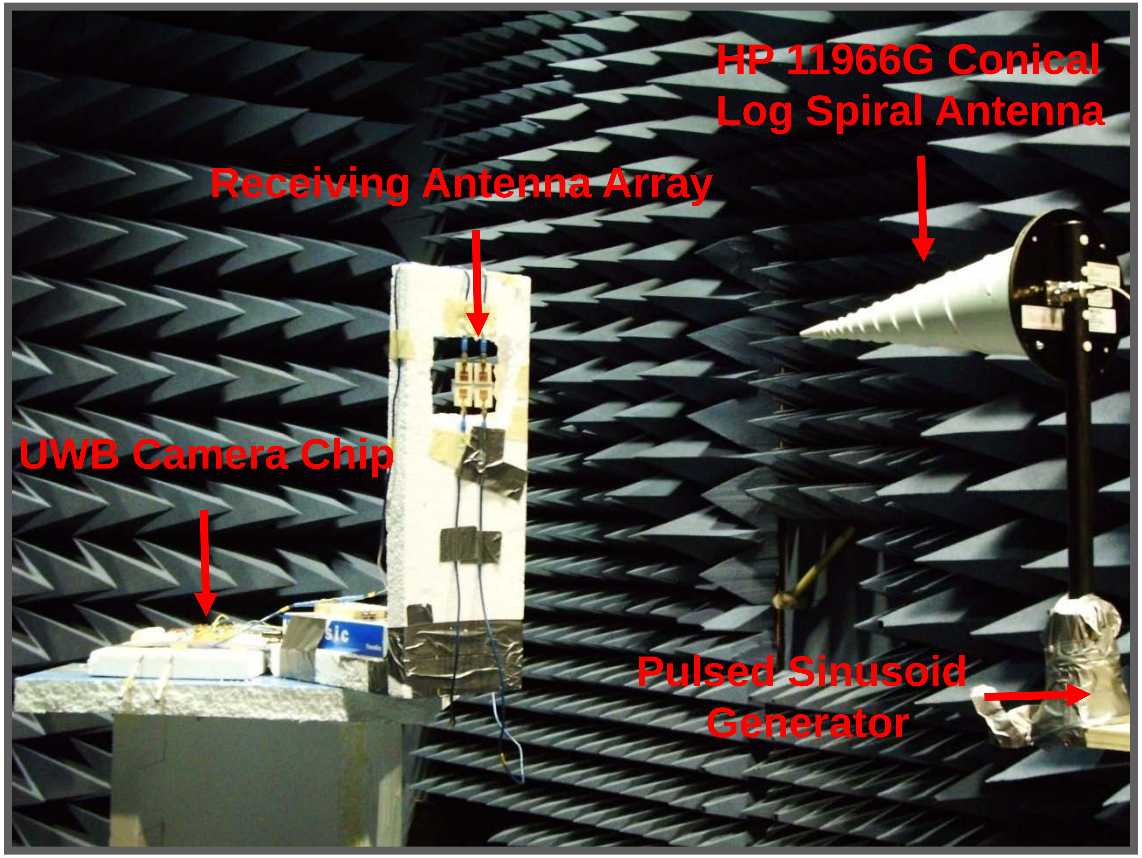
# Synthesized Array Patterns (from meas.)



# UWB RF Camera Measurement Setup

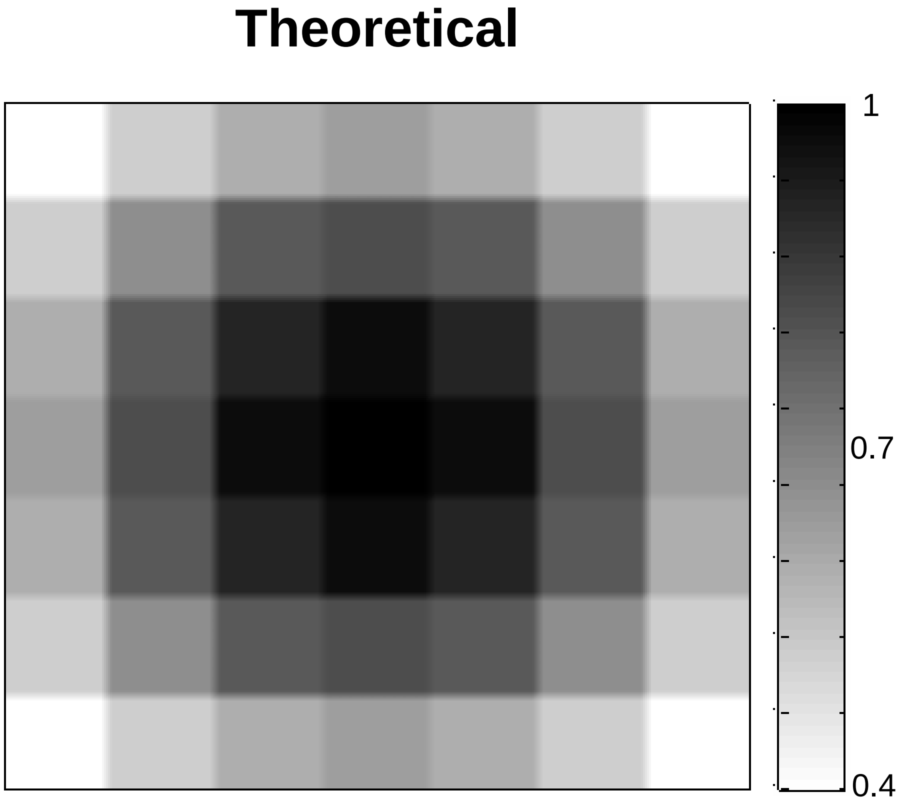


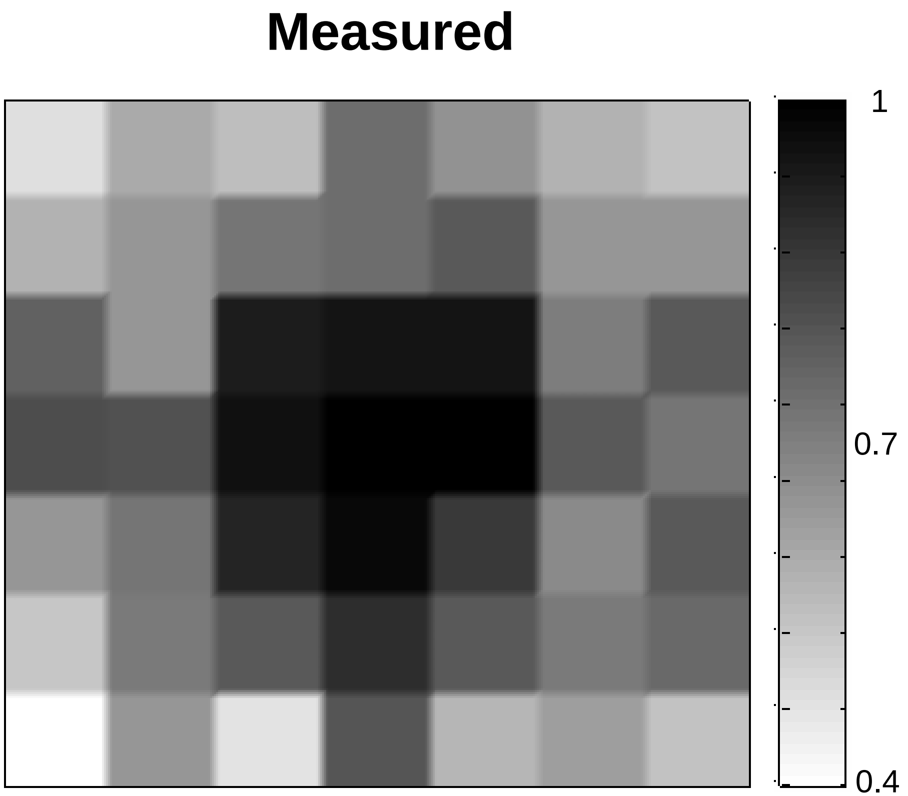



Z. Low, et. al, AWPL'05

# Measured Performance

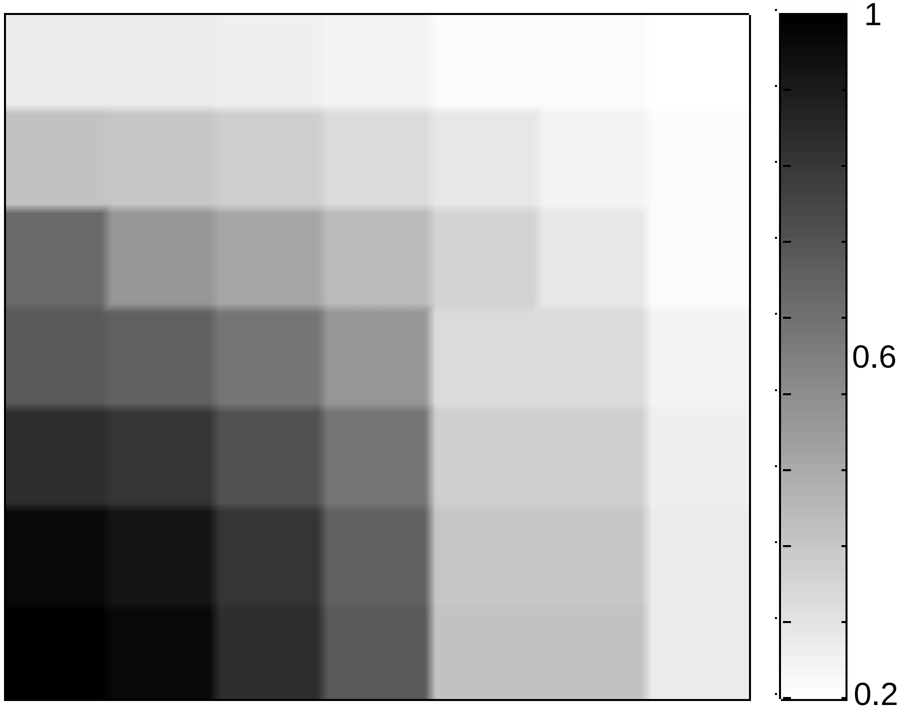


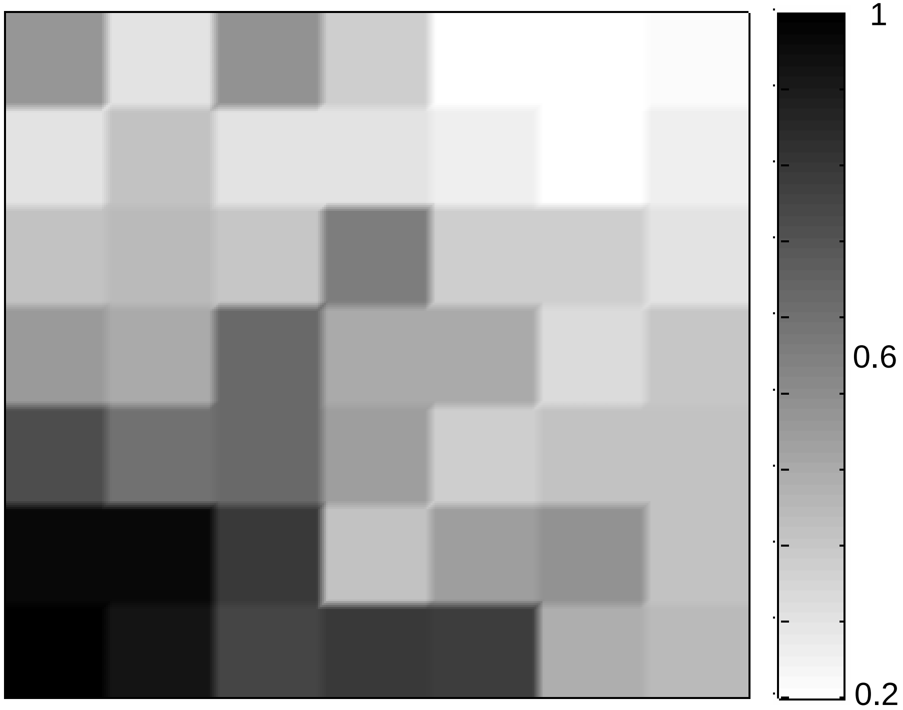

Maximum intensity is at the center pixel (pixel 44).

# Measured Performance

**Theoretical**




**Measured**

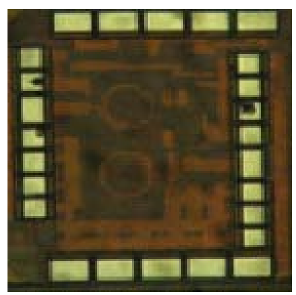


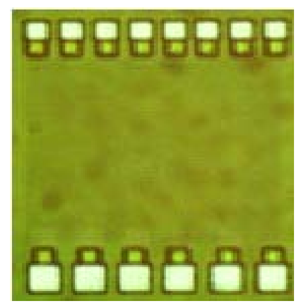

Maximum intensity is at the bottom left corner pixel (pixel 71).

# Performance Summary

| | |
|---|---|
| -3dB Bandwidth (normal incident angle) | 15GHz |
| Total array gain | 24dB |
| Noise-Figure (1GHz – 14GHz) | <5.8dB (single channel worst case) |
| 1 dB Compression Point (input power) | -24dBm@1GHz, -26dBm@15GHz |
| UWB true time delay resolution | 17.5ps |
| UWB Camera spatial resolution | $10^{\circ}$ (antenna separation = 30mm) |
| Total number of available beams | 7x7 simultaneously |
| Power dissipation@1.5V | 945mW |
| Technology | 0.13μm CMOS |
| Die Area | 4.1mm x 4.1mm |

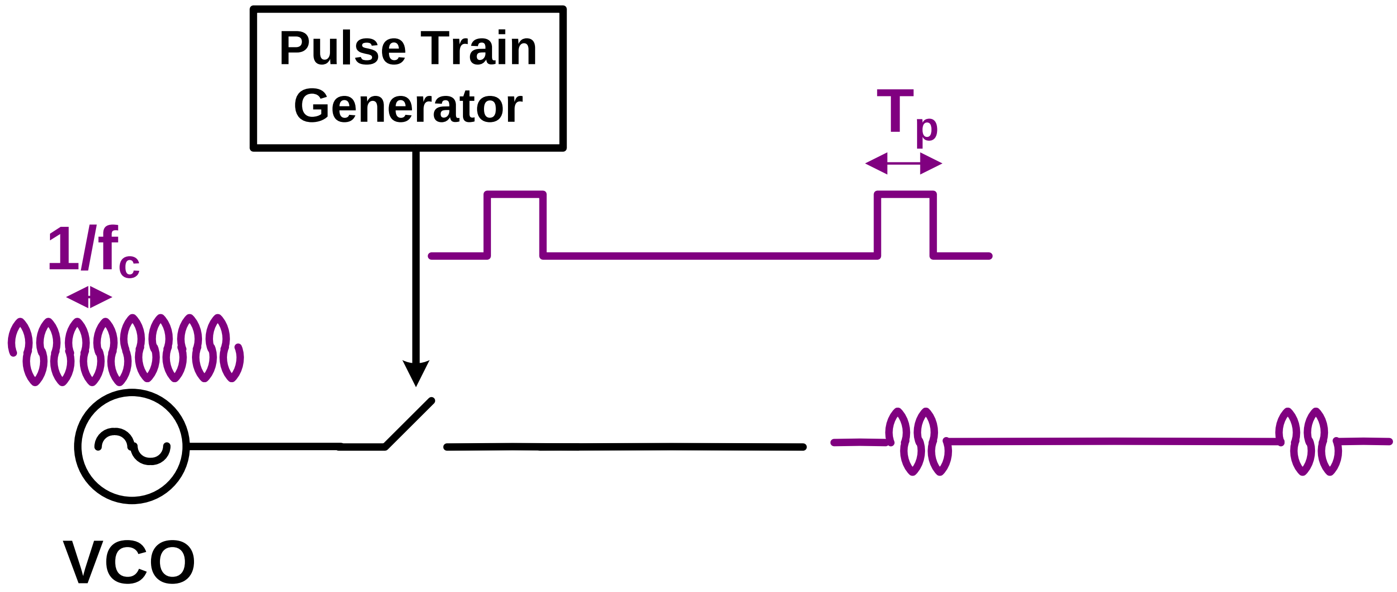
# UWB Timed-Array Transmitter





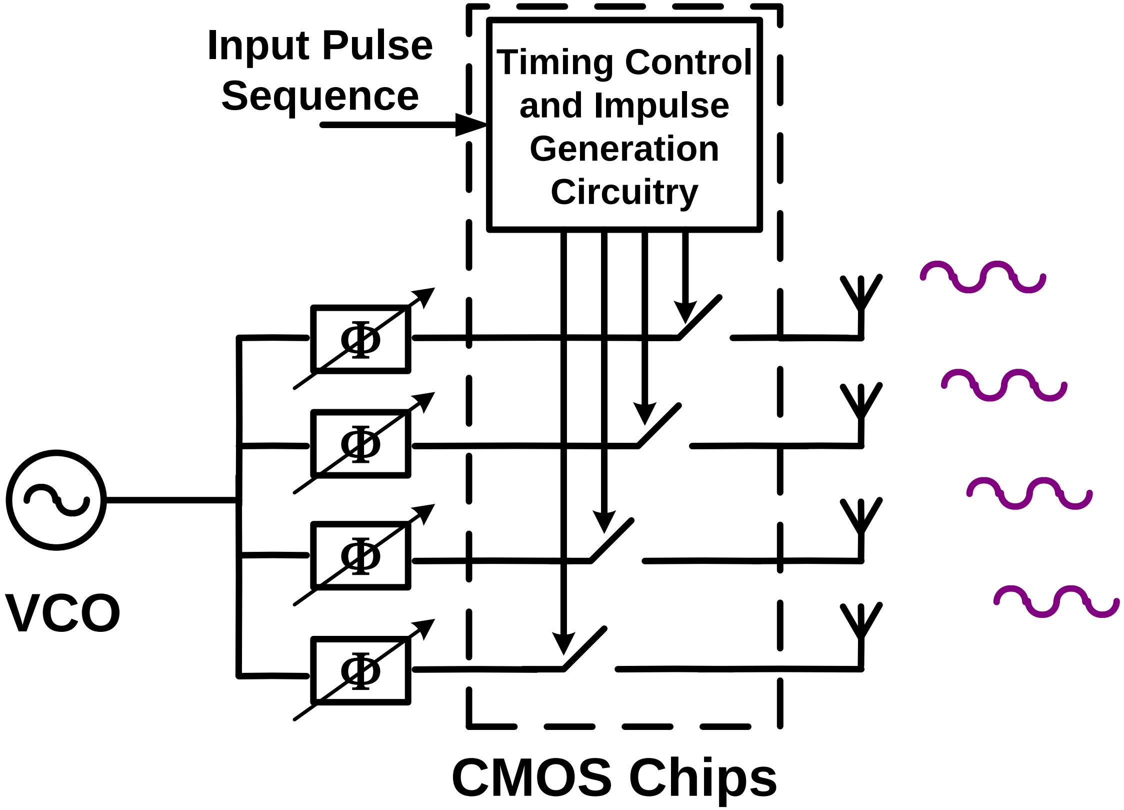
**Z. Safarian, T. Chu, and H. Hashemi, “A 0.13μm CMOS 4-channel UWB timed-array transmitter chipset with sub-200ps switches and all-digital timing circuitry”, in *IEEE Radio Frequency Integrated Circuits Conference Digest of Papers*, Atlanta, GA, pp. 601-604, June 2008.**

# Conceptual UWB Signal Generation



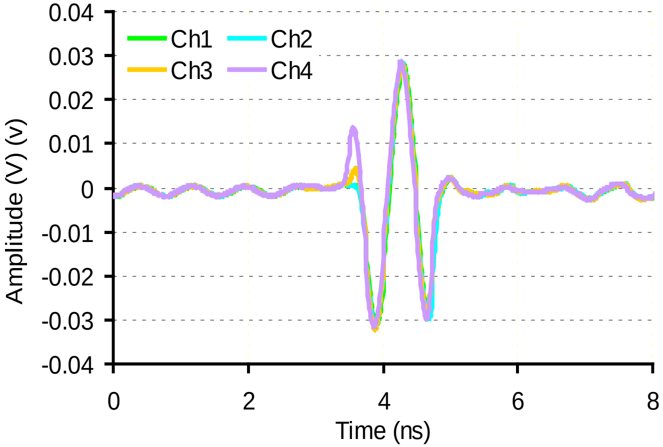

- Center frequency dictated by VCO or synthesizer
- Bandwidth dictated by pulse-width (pulse generator)
- Information can be in pulse position (PPM) and/or in instantaneous frequency (FH)

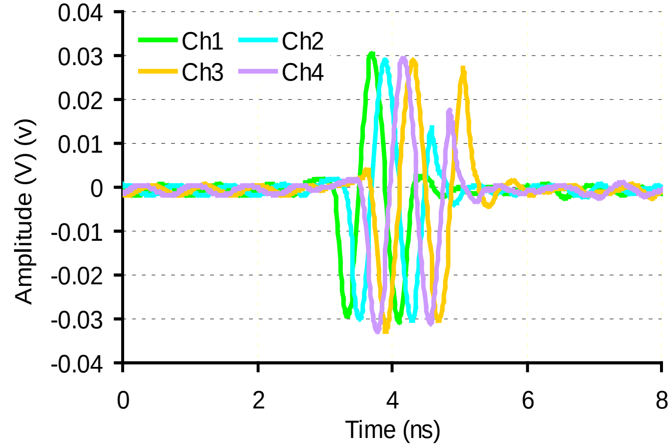
# An UWB Timed-Array Transmitter Chipset

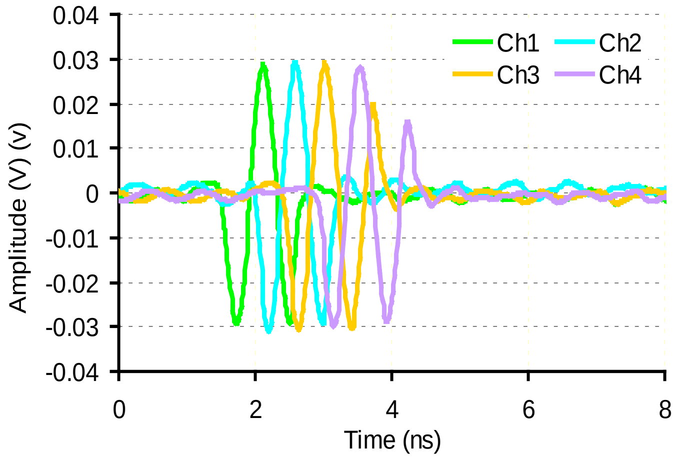


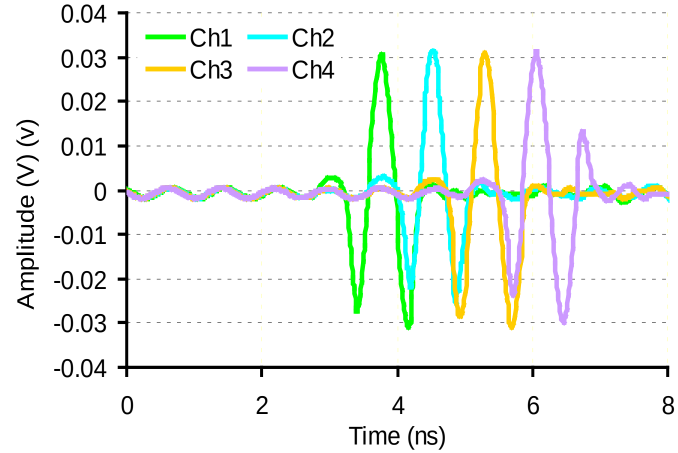

- Phase shifters guarantee transmitted signals from all channels are identical (big deal in UWB signals).

# Measured Timed Pulses at 1.3GHz

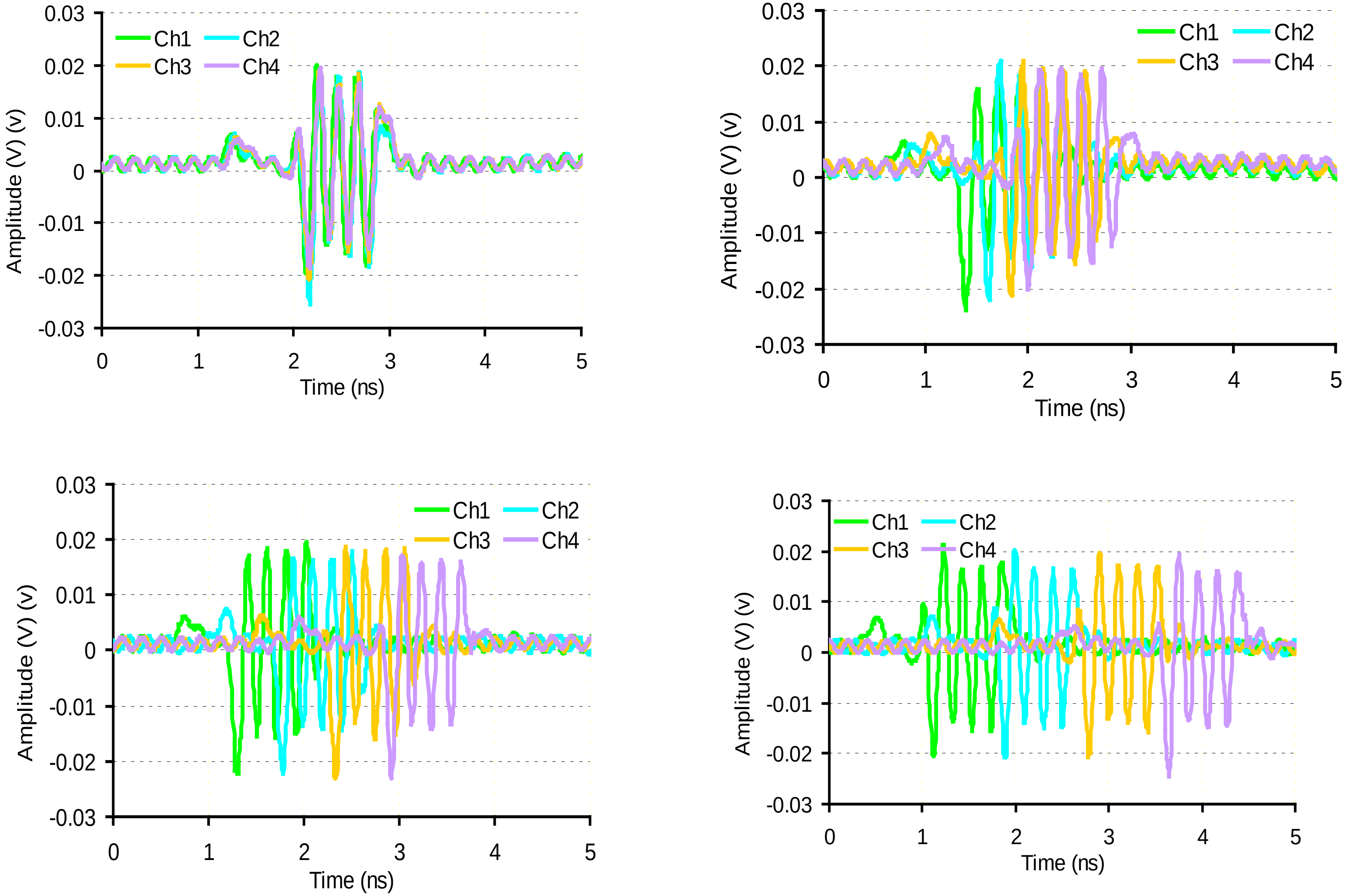


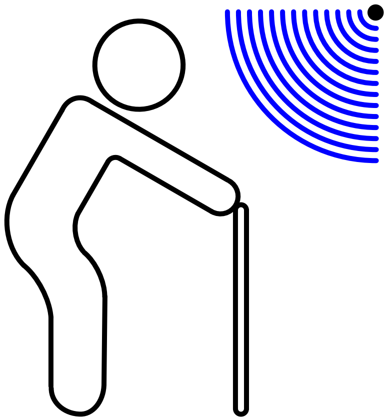



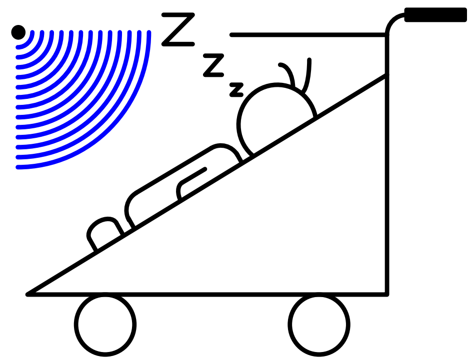
# Measured Timed Pulses at 5GHz



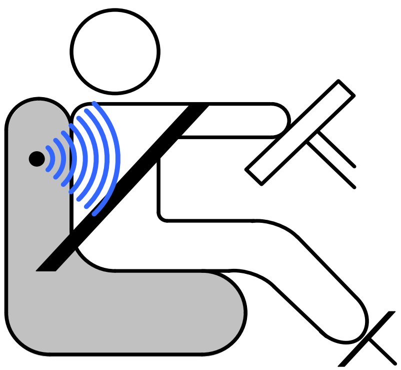
# Human Feature Detection using UWB

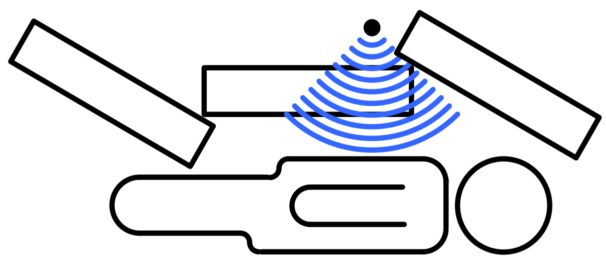
# Non-Contact Wireless Sensing Applications


Wireless Health Sensor



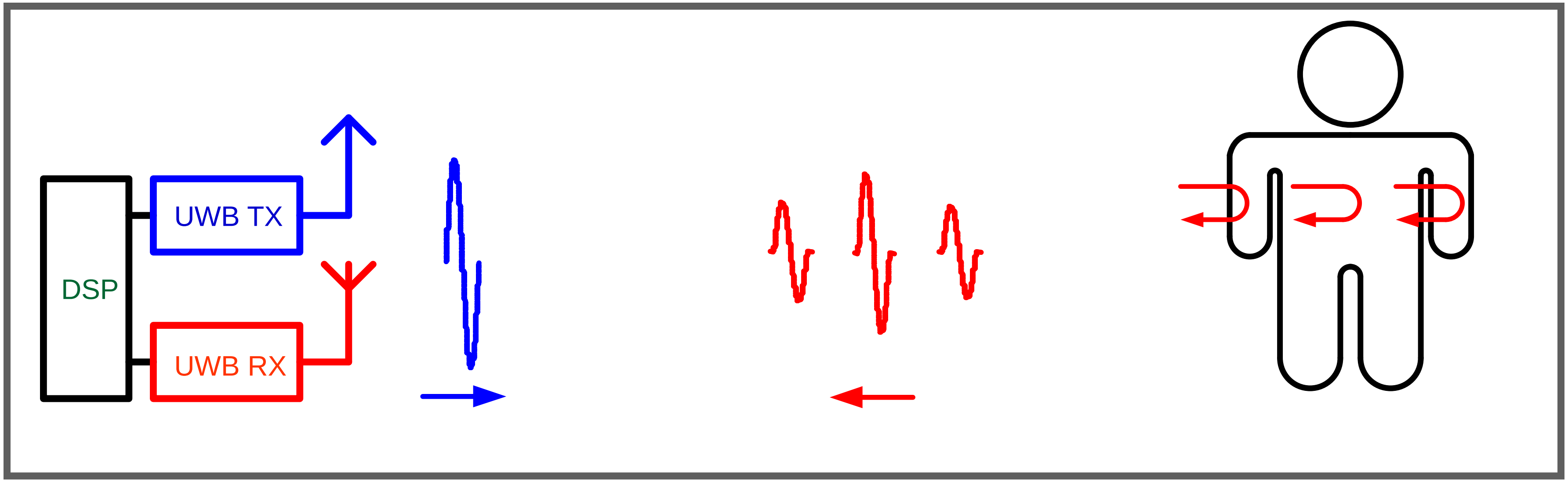
Baby Health Monitor

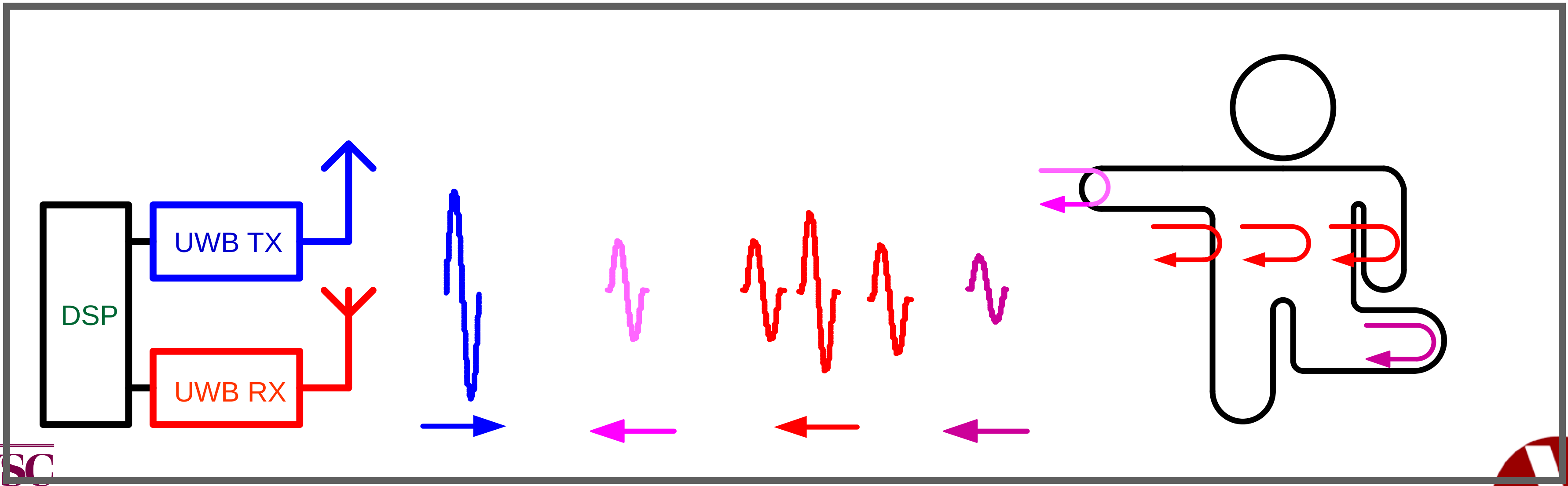

Driver Condition Monitor


Wall Penetrating Radar

Surveillance Radar

# Ultra-Wideband Human Gait Monitoring

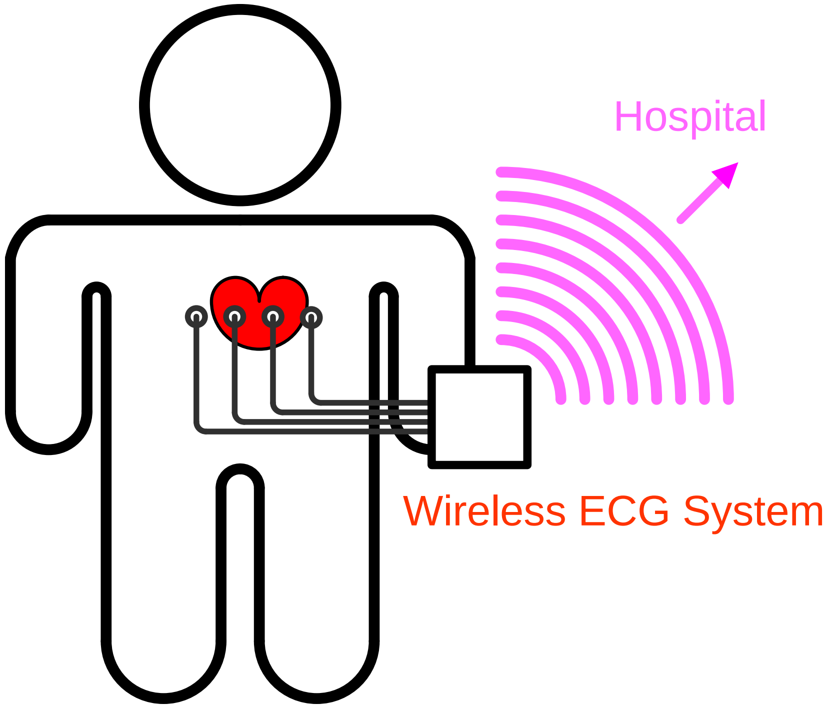


# Non-Contact Wireless Healthcare Sensing

## Contact

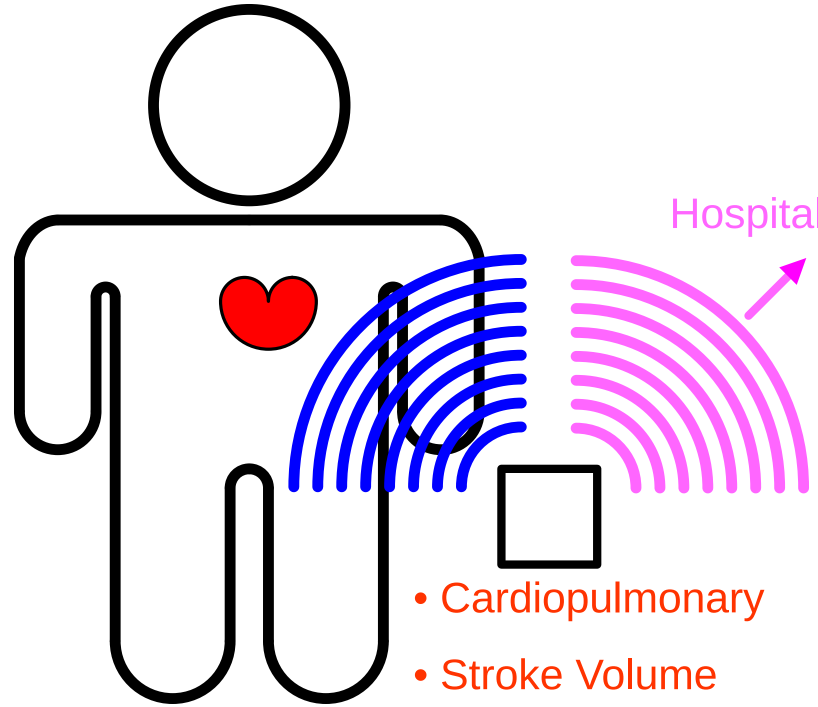
Wireless ECG System




http://www.lifesynccorp.com/

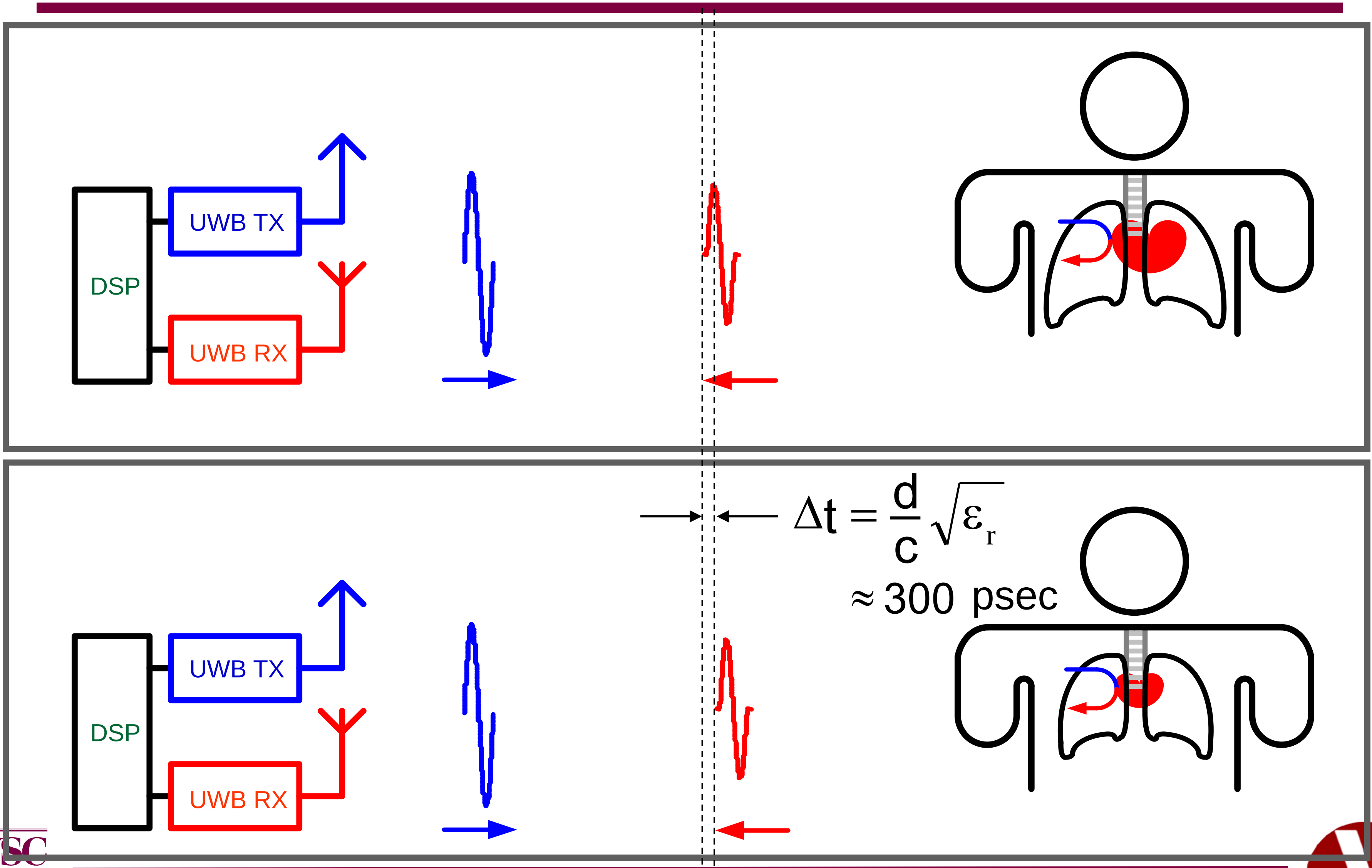
## Non-contact

Wireless Sensing System




- Cardiopulmonary
- Stroke Volume
- Localization
- Gait Analysis

# UWB Cardiopulmonary Monitoring



# Human Feature Detection and Tracking

**Wireless Sensor**

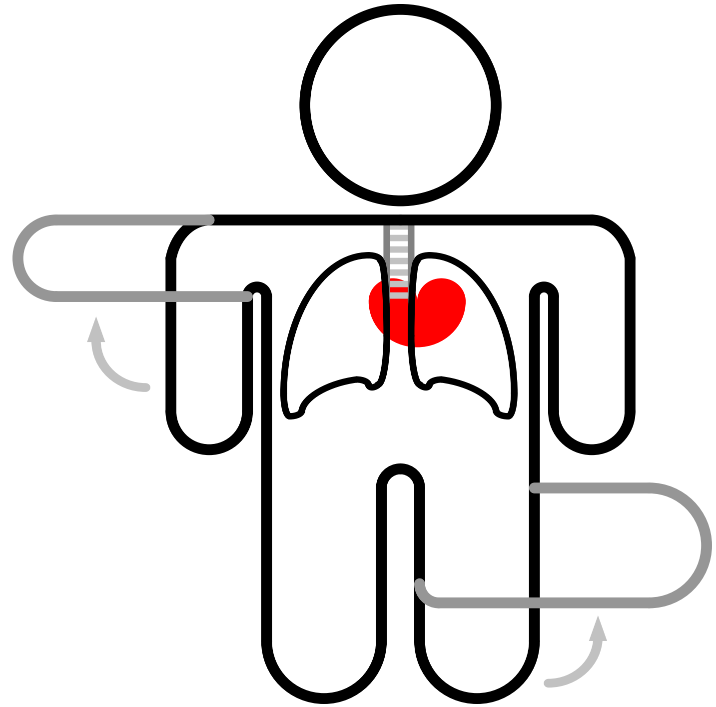
**Human Features**

**UWB Sensor** ⇄

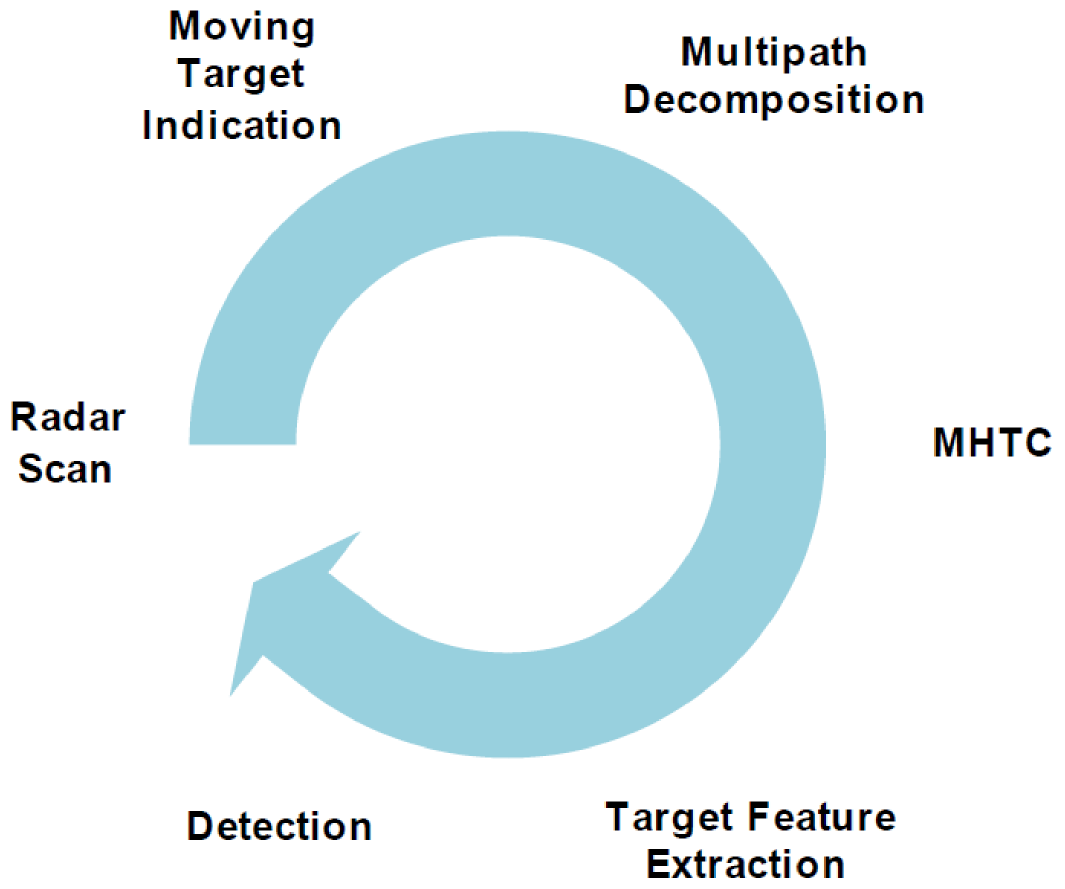
**Cardiac Activity**

**Breathing**

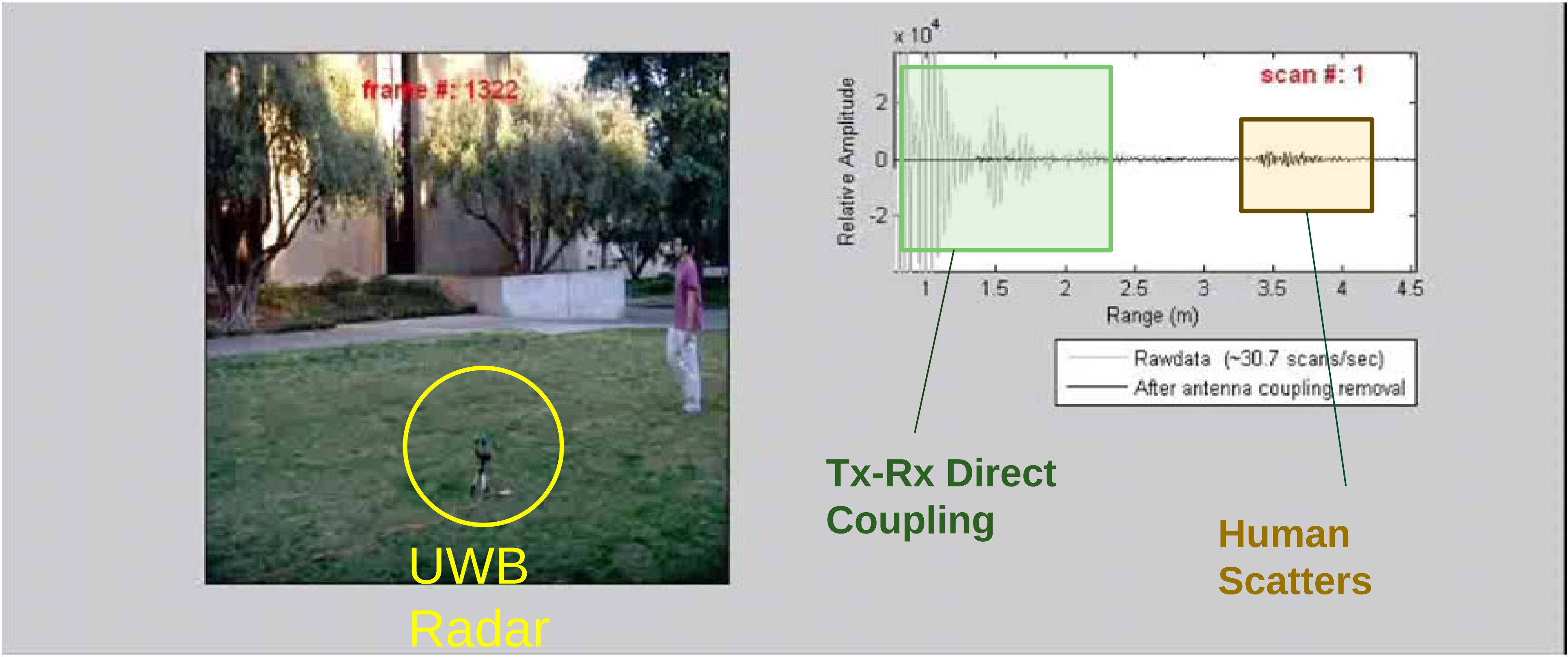
**Gait**



# Overview of the Algorithm



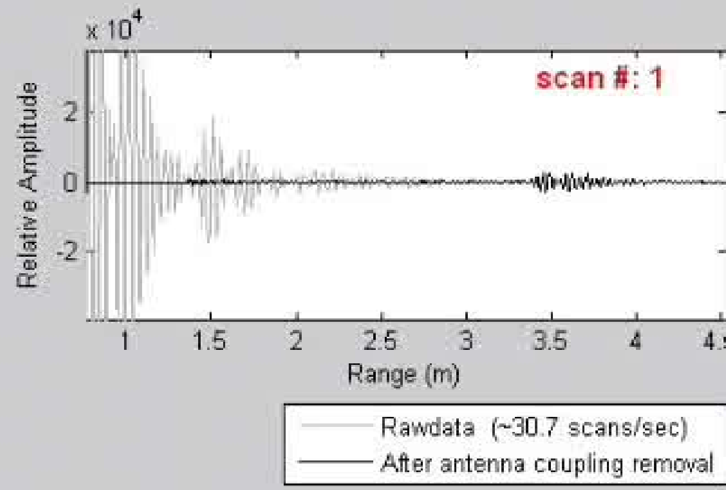
# Walking Human



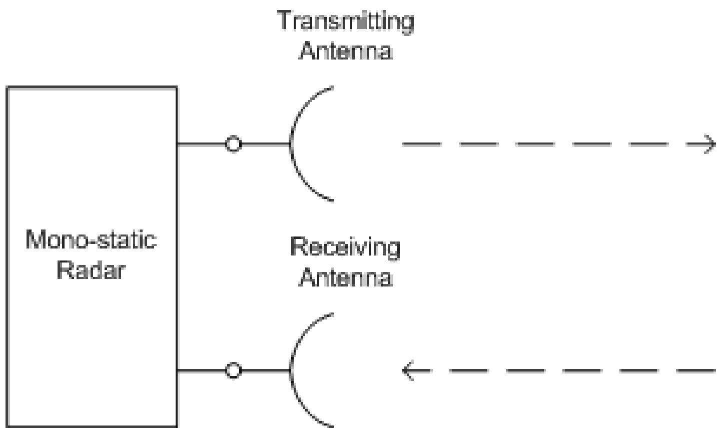

**Commercial UWB radar is used to verify the developed algorithms.**

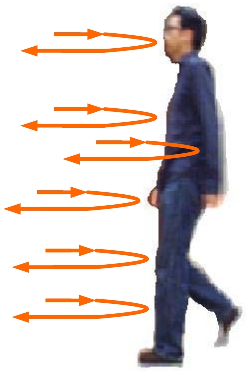
**Signal processing is off-line at this point.**

# Walking Human

# Multipath Decomposition



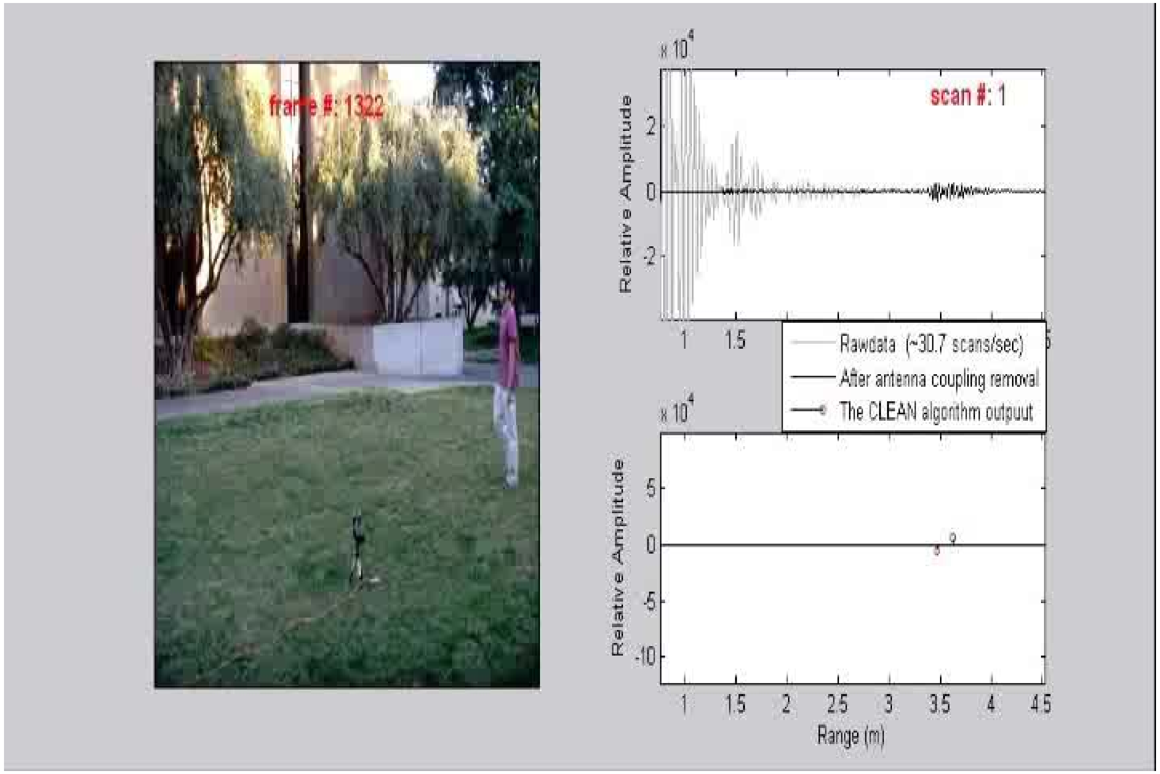
$$w(t) \approx \sum_{j=1}^{L} a_j p(t - n_j)$$

Path amplitude

Waveform template

Time-of-arrival (TOA)

# Walking Human (Cont'd)




$$w(t) \approx \sum_{j=1}^{L} a_j p(t - n_j)$$

Path amplitude

Waveform template

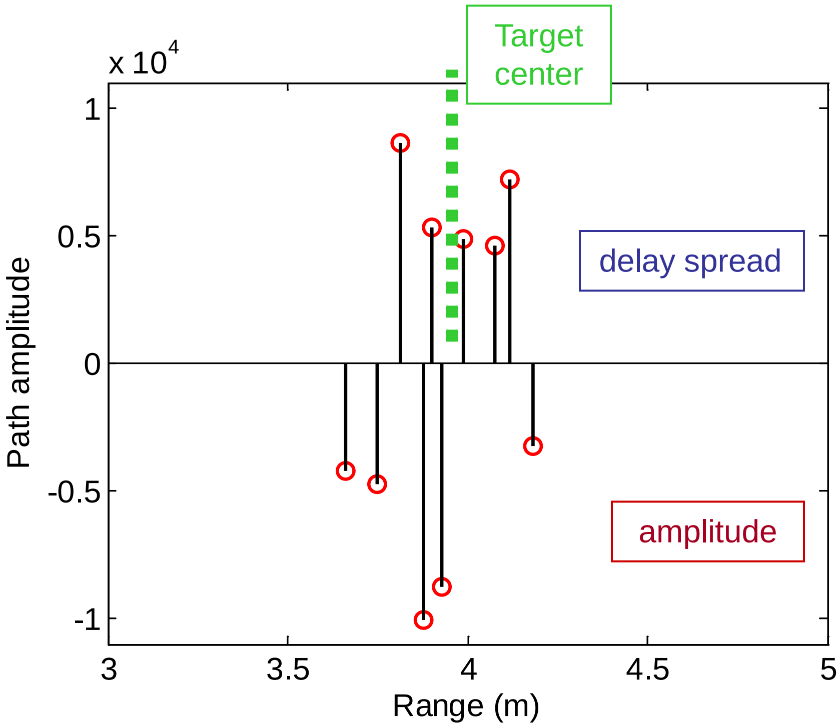
Time-of-arrival (TOA)

# Human Feature Detection Basics

- **Maximum amplitude, RMS range spread, and velocity features can be useful for discriminating humans from common clutter caused by stationary objects as well as moving objects such as small animals, cars and bicycles.**

- **Human breathing and heartbeat signatures can also be exploited.**
  - **Detecting cardiopulmonary features in a dynamic environment is challenging.**

# Feature Extraction & Detection




$$\Lambda(\Theta) = \frac{p(a_{max}|\mathcal{H}_1)p(R_{rms}|\mathcal{H}_1)}{p(a_{max}|\mathcal{H}_0)p(R_{rms}|\mathcal{H}_0)} \underset{\mathcal{H}_1}{\overset{\mathcal{H}_0}{\lessgtr}} T_D$$

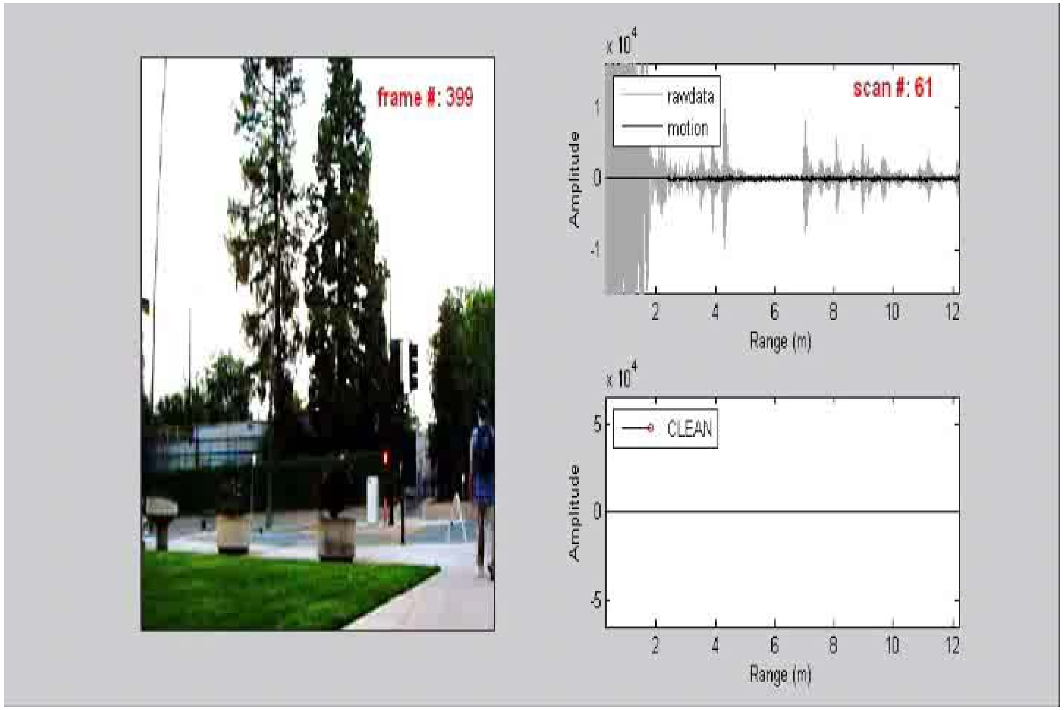
$\mathcal{H}_0$ : the target is non-human
$\mathcal{H}_1$ : the target is human.

$$\begin{aligned} p(a_{max}|\mathcal{H}_1) &= f_{\mathcal{N}}(x; 104.6, 3.70^2), \\ p(a_{max}|\mathcal{H}_0) &= \frac{1}{12}, \quad \text{for} \quad a_{max} \in [93, 105], \\ p(R_{rms}|\mathcal{H}_1) &= f_{\mathcal{N}}(x; 0.1157, 0.0316^2), \\ p(R_{rms}|\mathcal{H}_0) &= f_{\mathcal{N}}(x; 0.0303, 0.0120^2), \end{aligned}$$

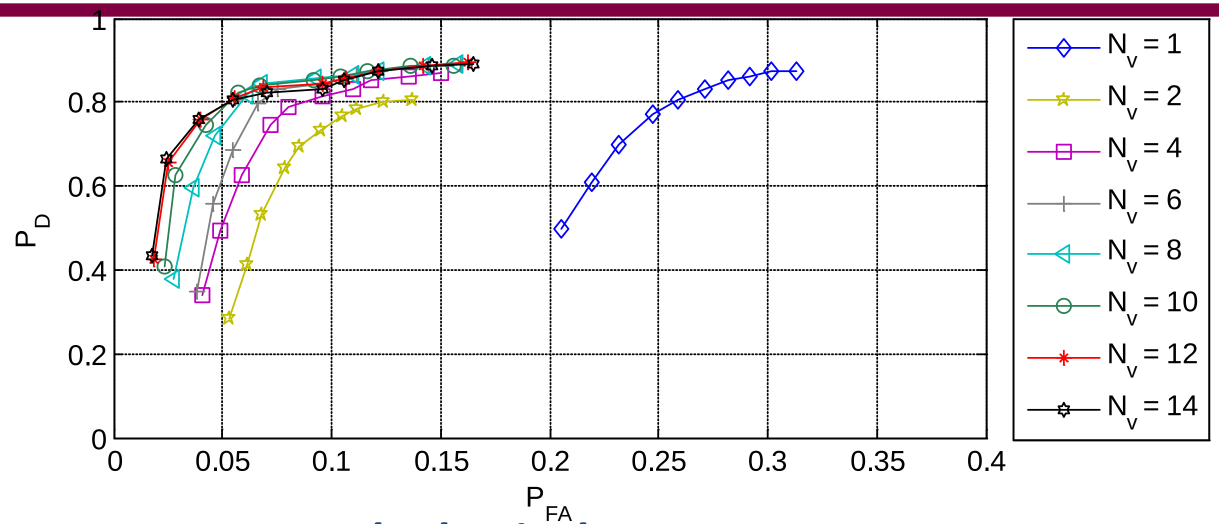
- **Basic detector**: Likelihood Ratio Test (LRT) only for maximum amplitude and RMS range spread features
- A *voting method** is applied to detector output to integrate information over time

*pick the majority over $N_v$ recent detector outputs

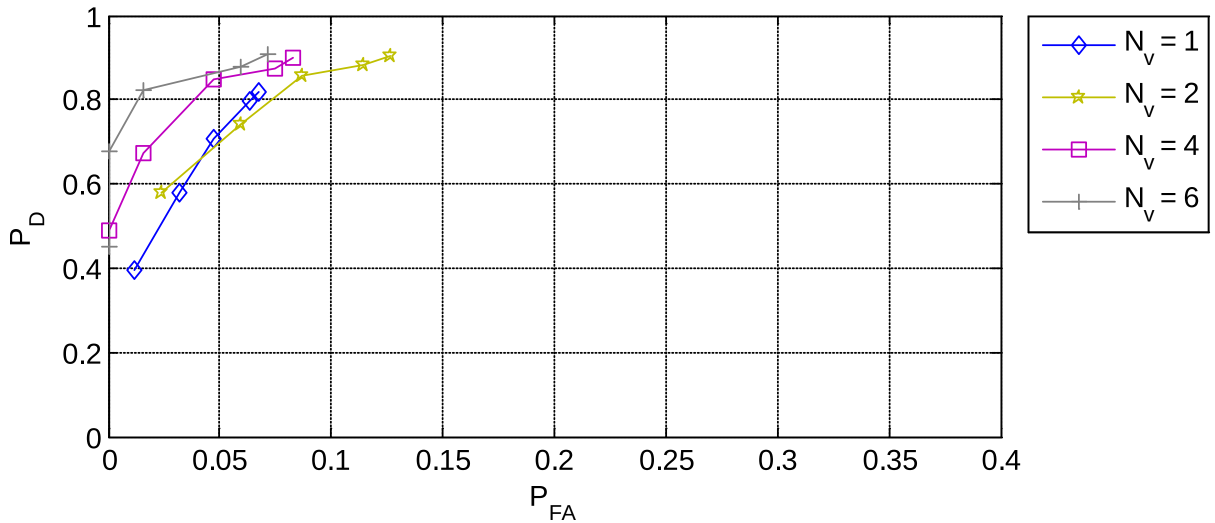
# Experimental Results



# Result: $P_D$~ 82.4% for $P_{FA}$~ 1.6%

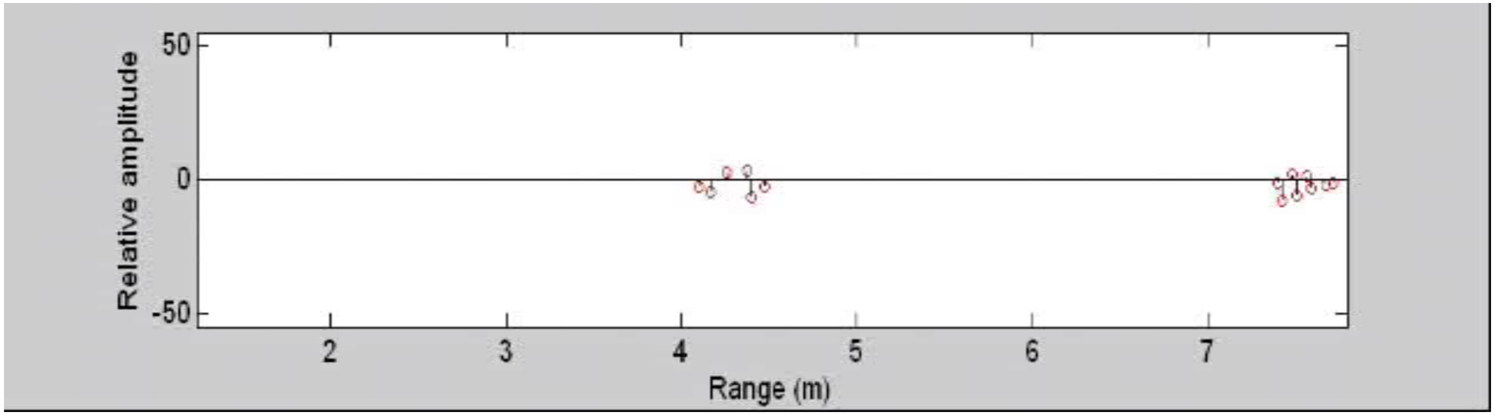



*The basic detector*



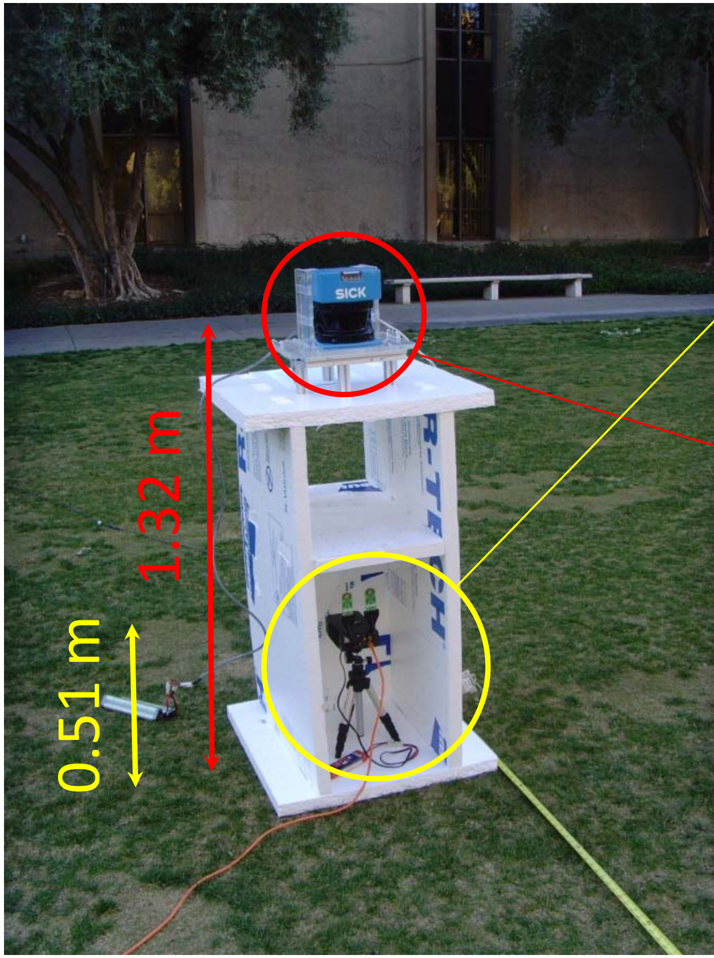

*The MHT detector (with the velocity feature)*

# Human Tracking




- Quantify the relationship between the scattering pattern produced by a human and his location (modeling problem)
- Use the segmented data to track human target(s) (tracking problem)
- Segment the returned signal properly into intervals that isolate the scatter components from individual targets, and associate each multipath component to its generating target (data association problem)

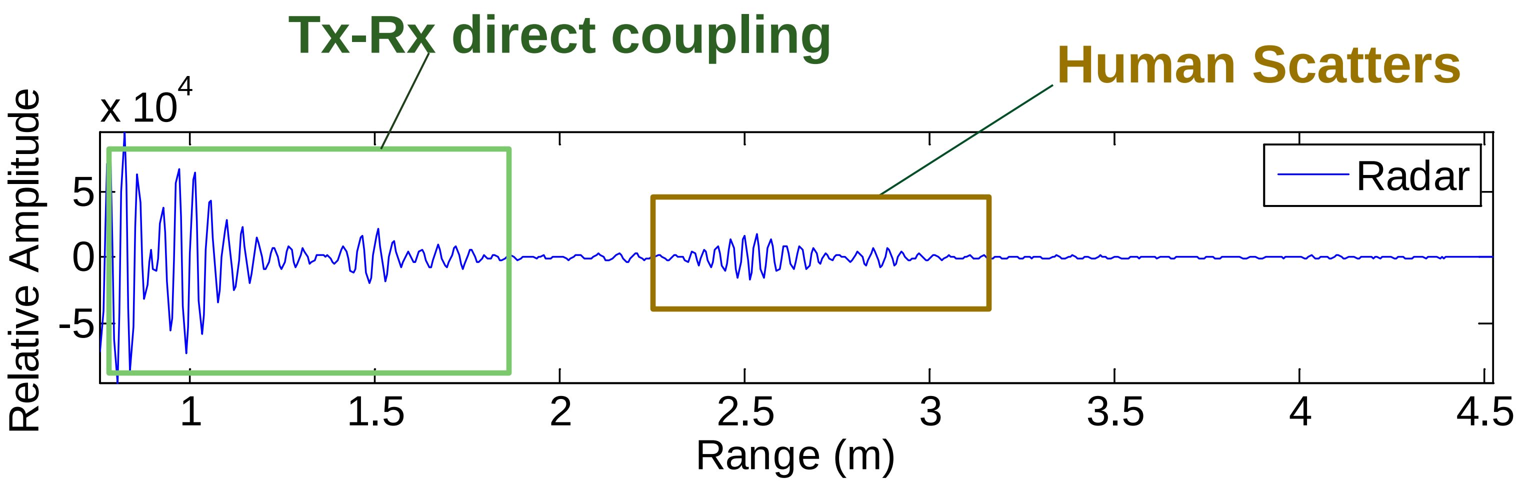
# Human Tracking Measurement Setup

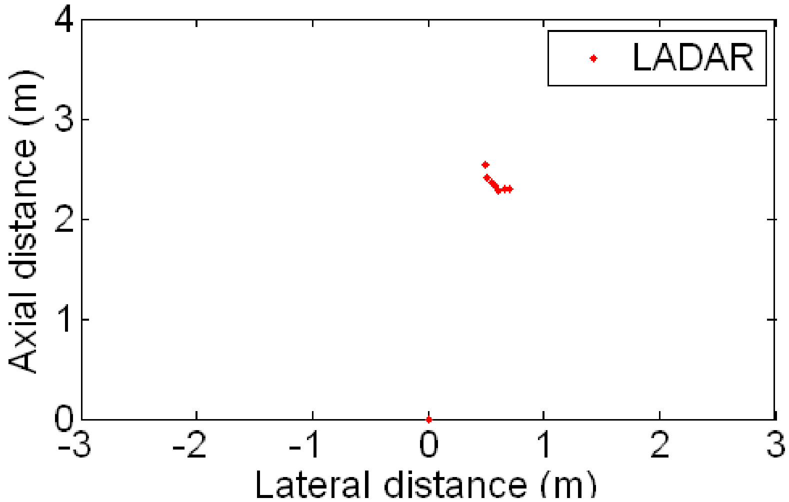



- **Time Domain PulsOn 210 UWB Radar**
  waveform sampling period: 41.33 ps
  scanning frequency: 30.7 scans/sec,
  # of scans recorded: 3720 scans

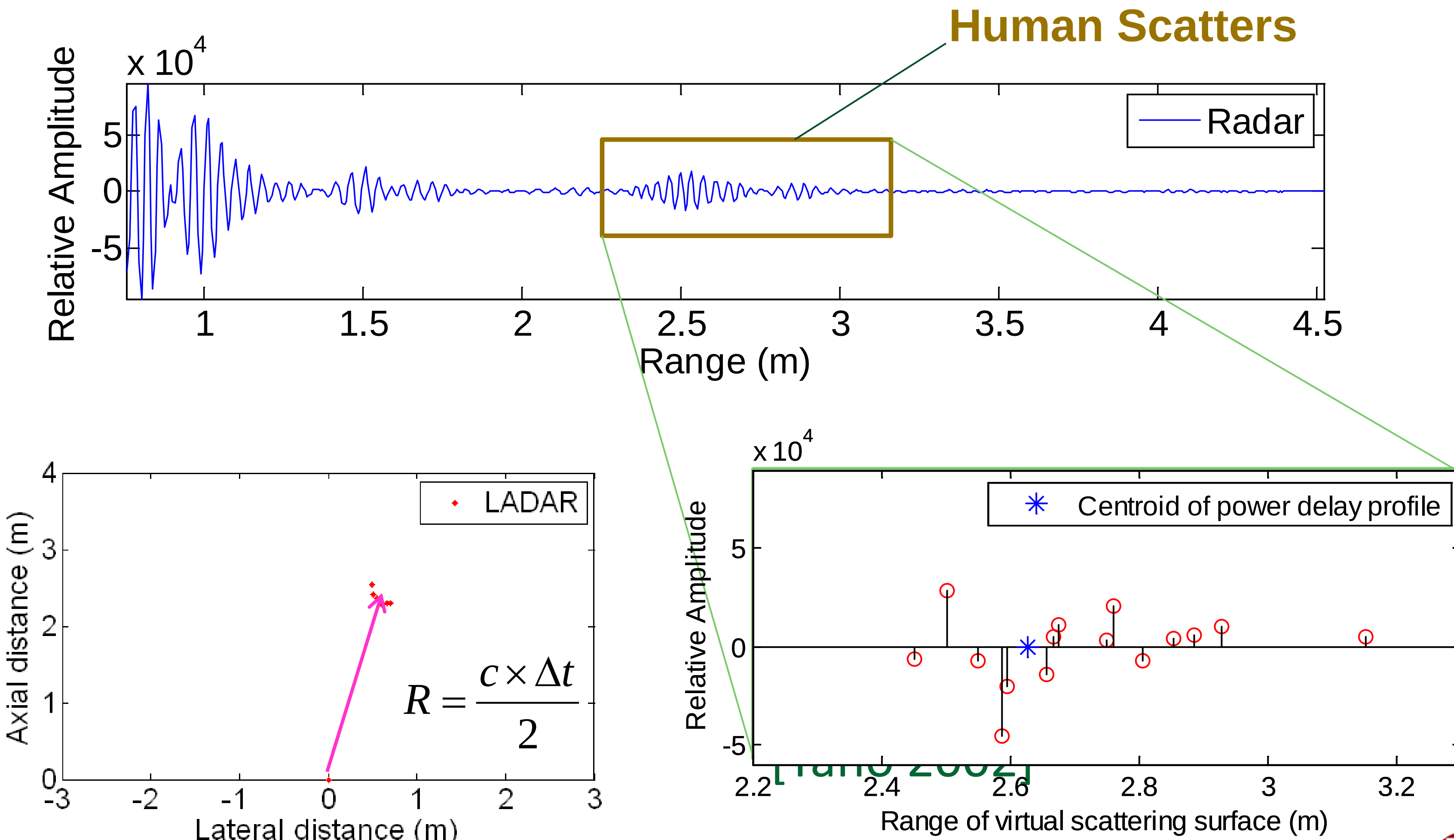
- **SICK AG short range LADAR**
  (collocated *reference*)
  operating frequency: 75 scans/sec
  on every angle from $0^o$ to $180^o$
  around chest level high

# Human Scattering Measurement

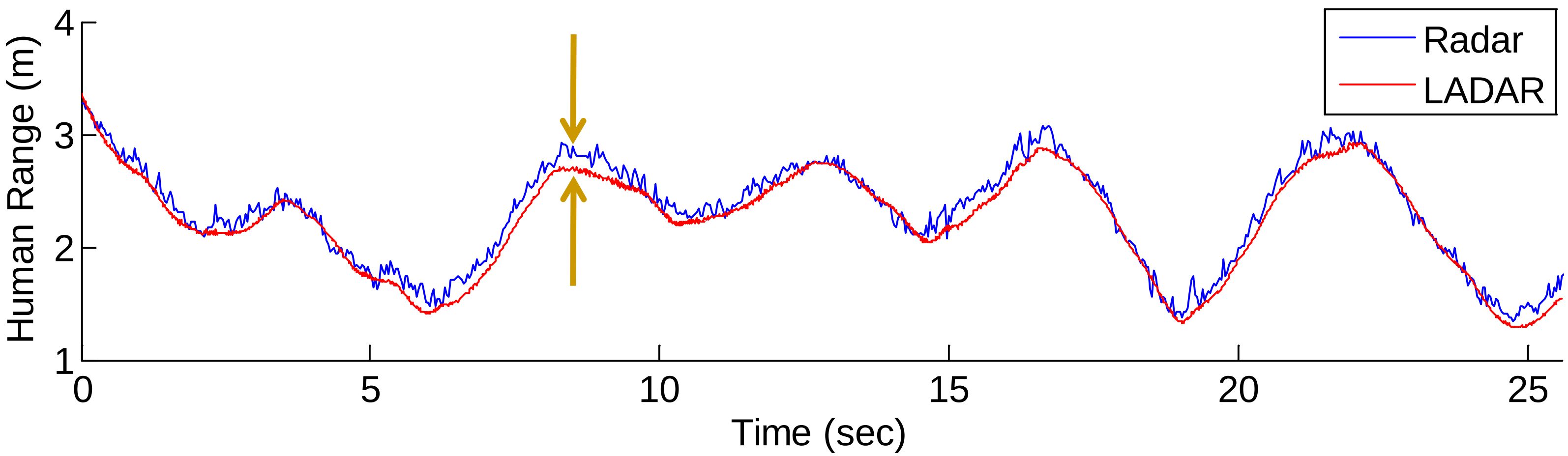


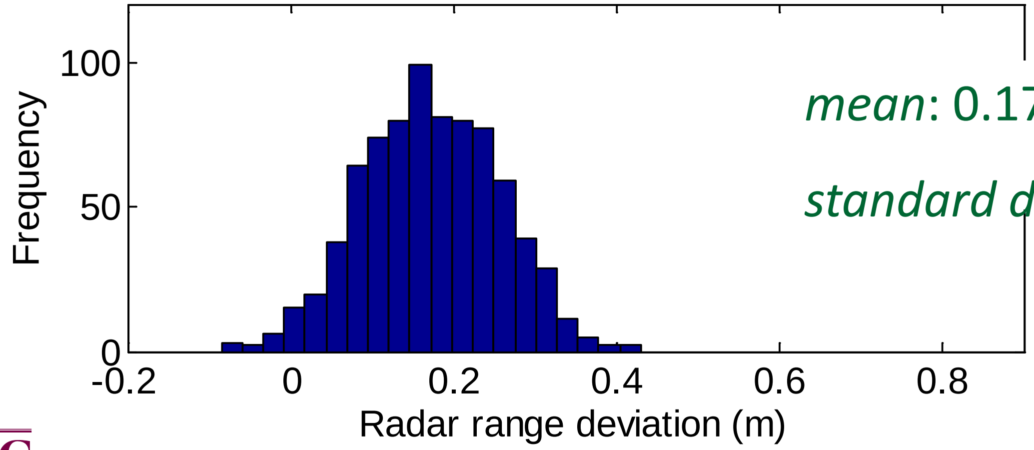




# Human Range Test



# Human Range Test (786 scans)



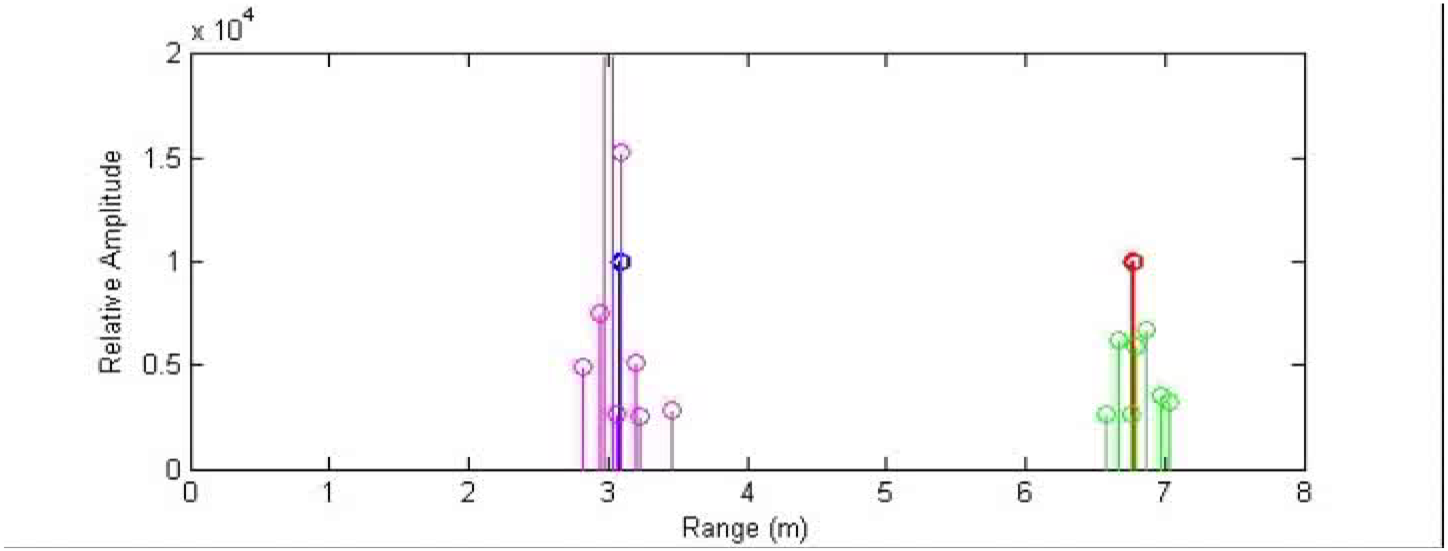




*mean*: 0.1722 m,

*standard deviation*: *0.0841 m*

# Conclusion on Fixed # of Human Tracking

- **UWB mono-static radar multipath scatters from walking humans can be modeled as a point process.**
- **A Kalman Filter framework via an EM mixture model framework can accurately track a fixed number of human.**

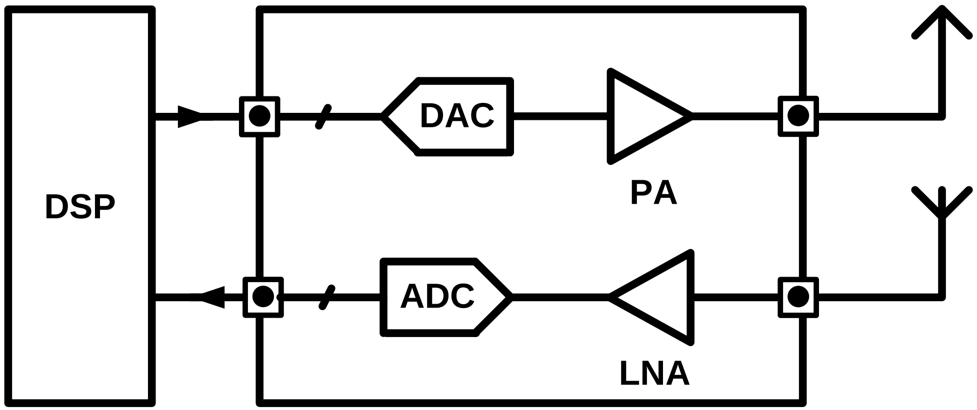


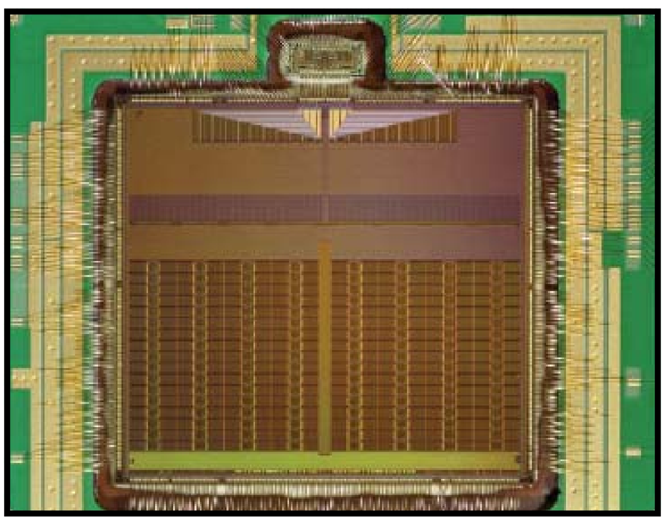
# Human Detection in Poor Visibility

**Human detector performance**

| Conditions | $P_D$ | $P_{FA}$ |
|---|---|---|
| Rainy | 97 % | 0 % |
| Dusty | 93 % | 0 % |
| NLOS | 97 % | 0 % |
| Foggy | 97 % | 0 % |

# Real-Time Oscilloscope (All-Digital Radar)



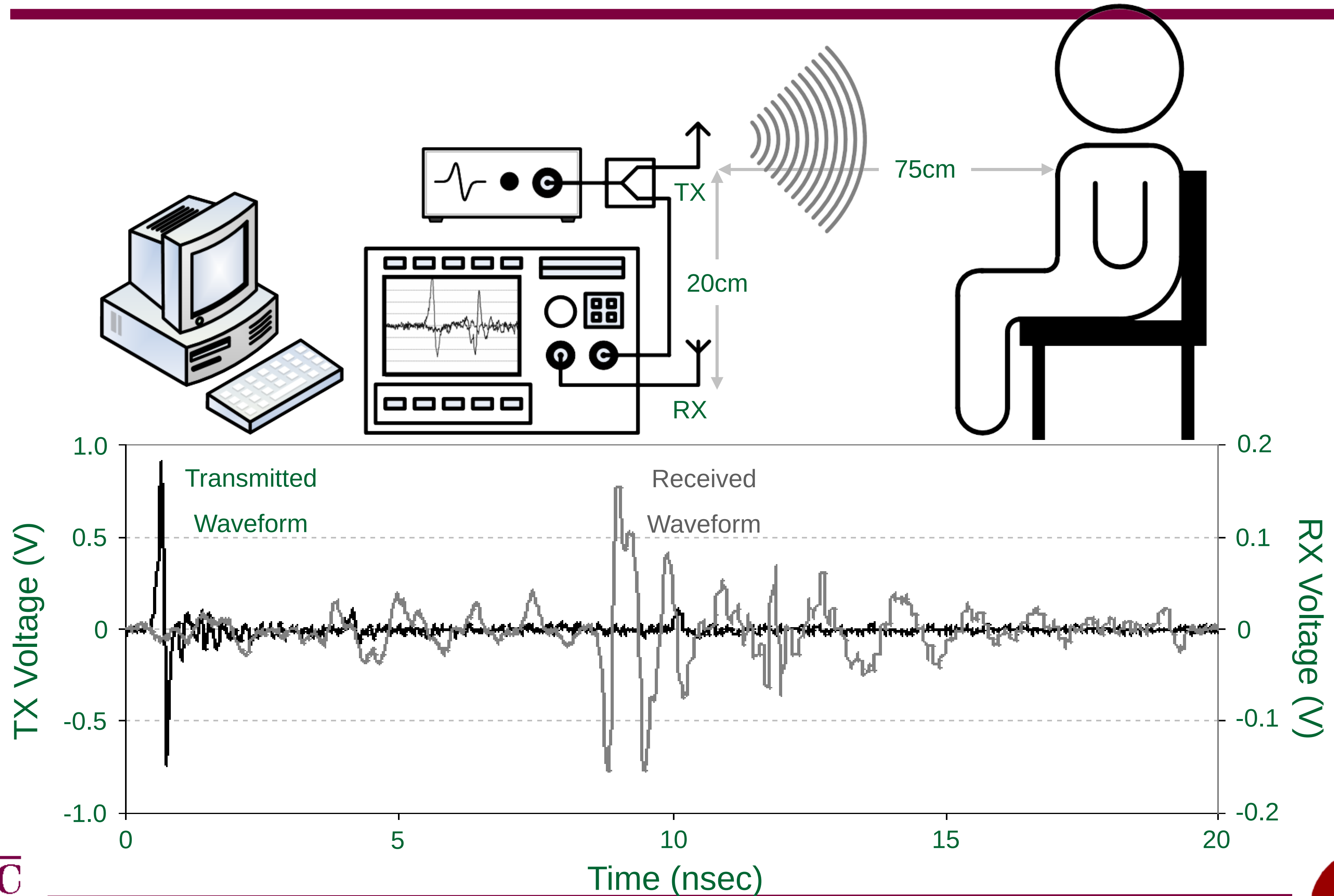



Agilent 20GSa/sec 8-bit ADC Module

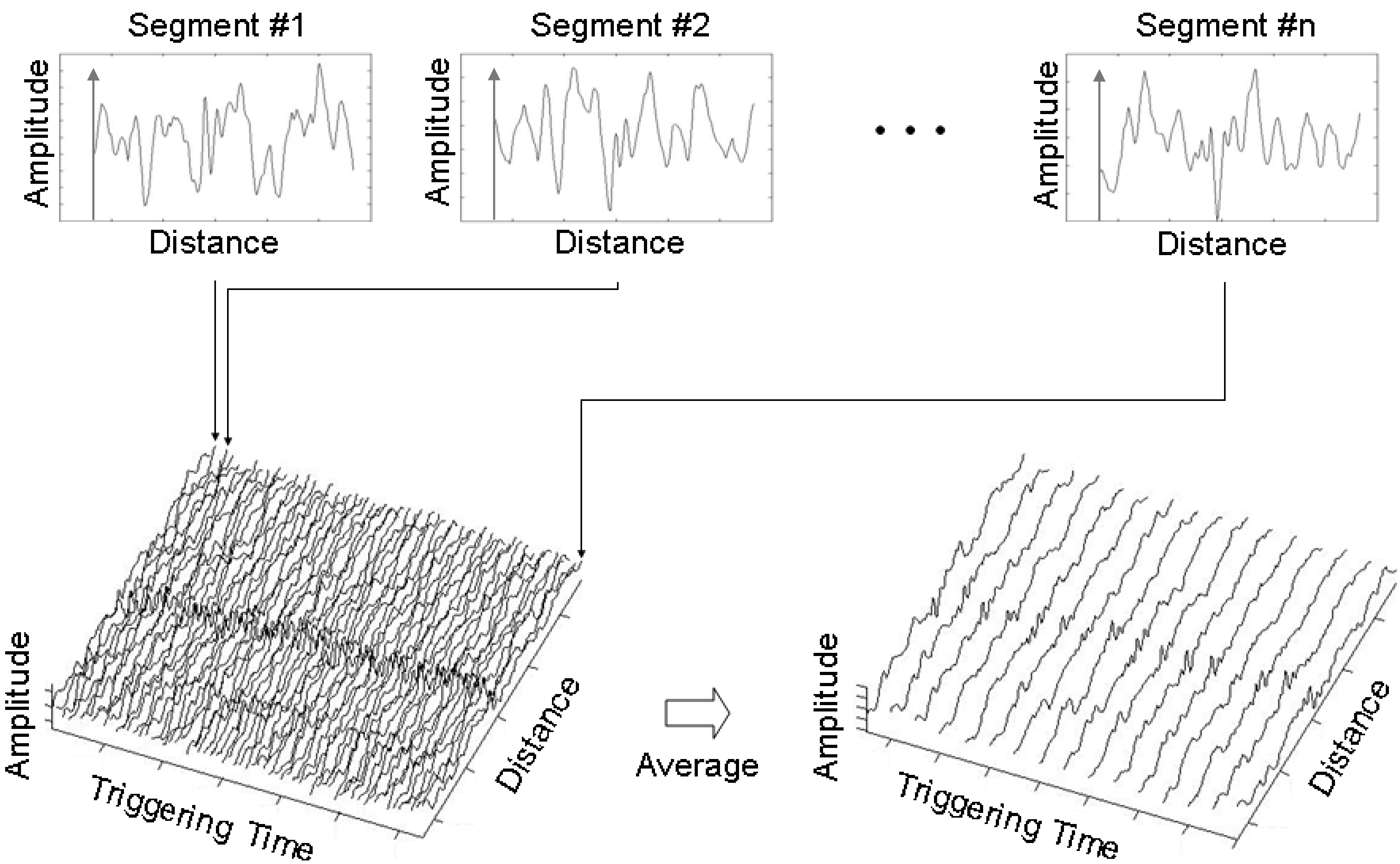
RF Buffer : 0.18μm SiGe
1mm X 2mm
1K transistors
1W

ADC : 0.13μm CMOS
14mm X 14mm
50M transistors
9W

# Wireless Measurements with Oscilloscope

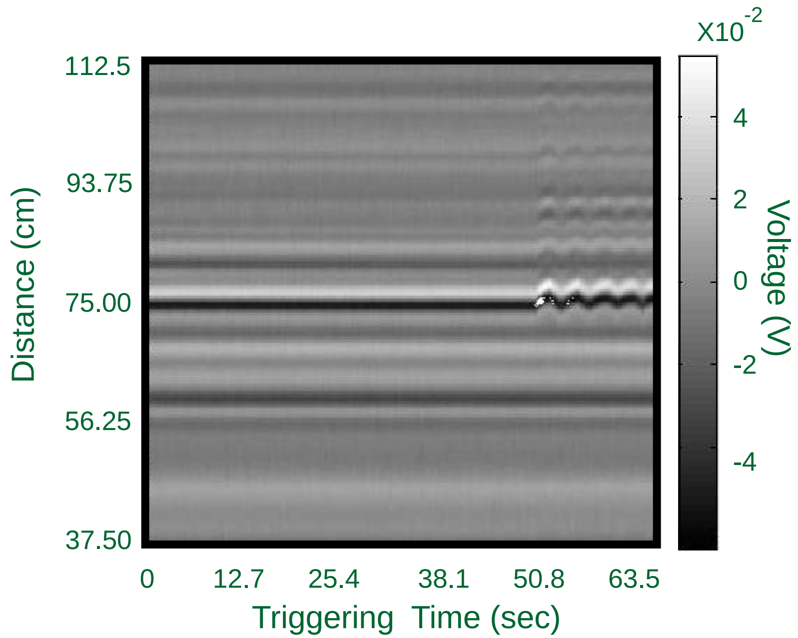


# Wireless Measurement (Cont.)

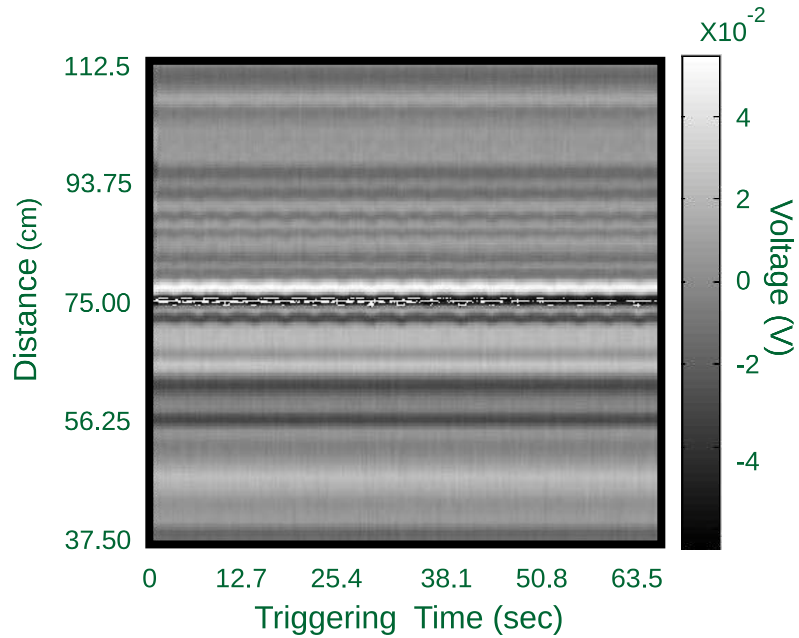


# Wireless Measurements (Cont.)

Discontinuous Breathing

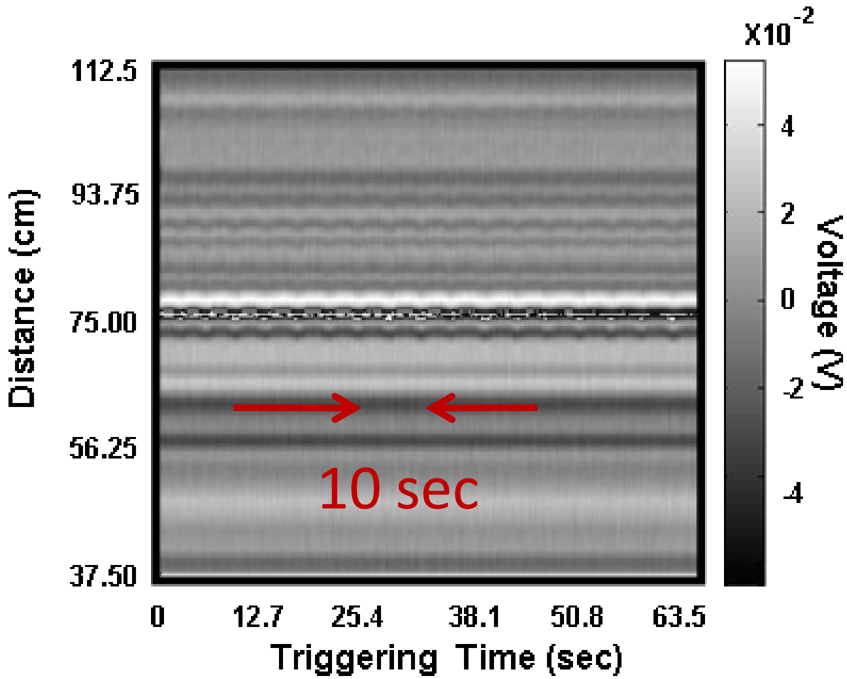



Continuous Breathing

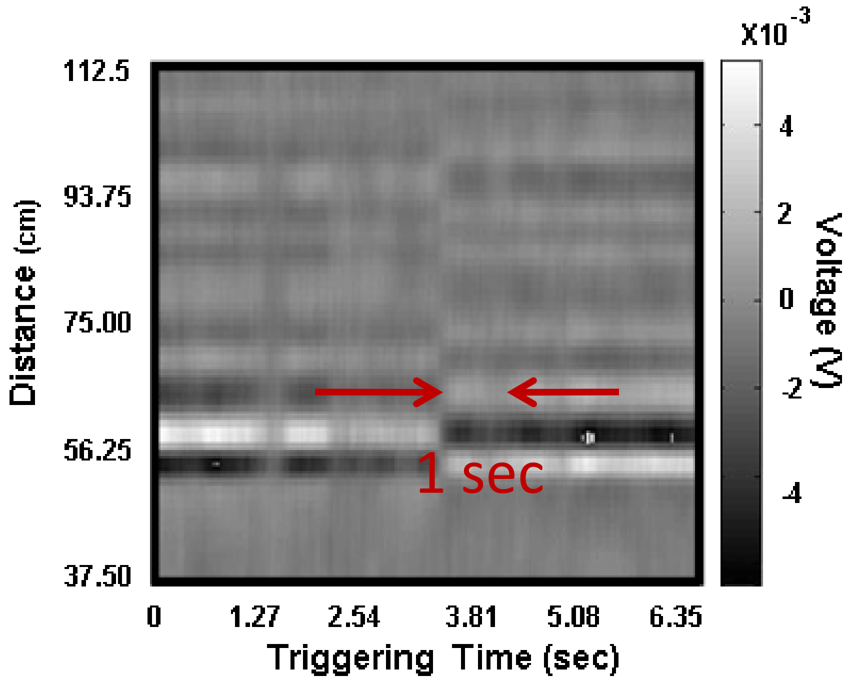



| | |
|---|---|
| Pulse Repetition Frequency = 1 kHz | Number of Total Segments = 65536 |
| Sampling Rate = 40 Gsa/sec | Number of Segments Averaged = 256 |

# Wireless Measurements (Cont.)



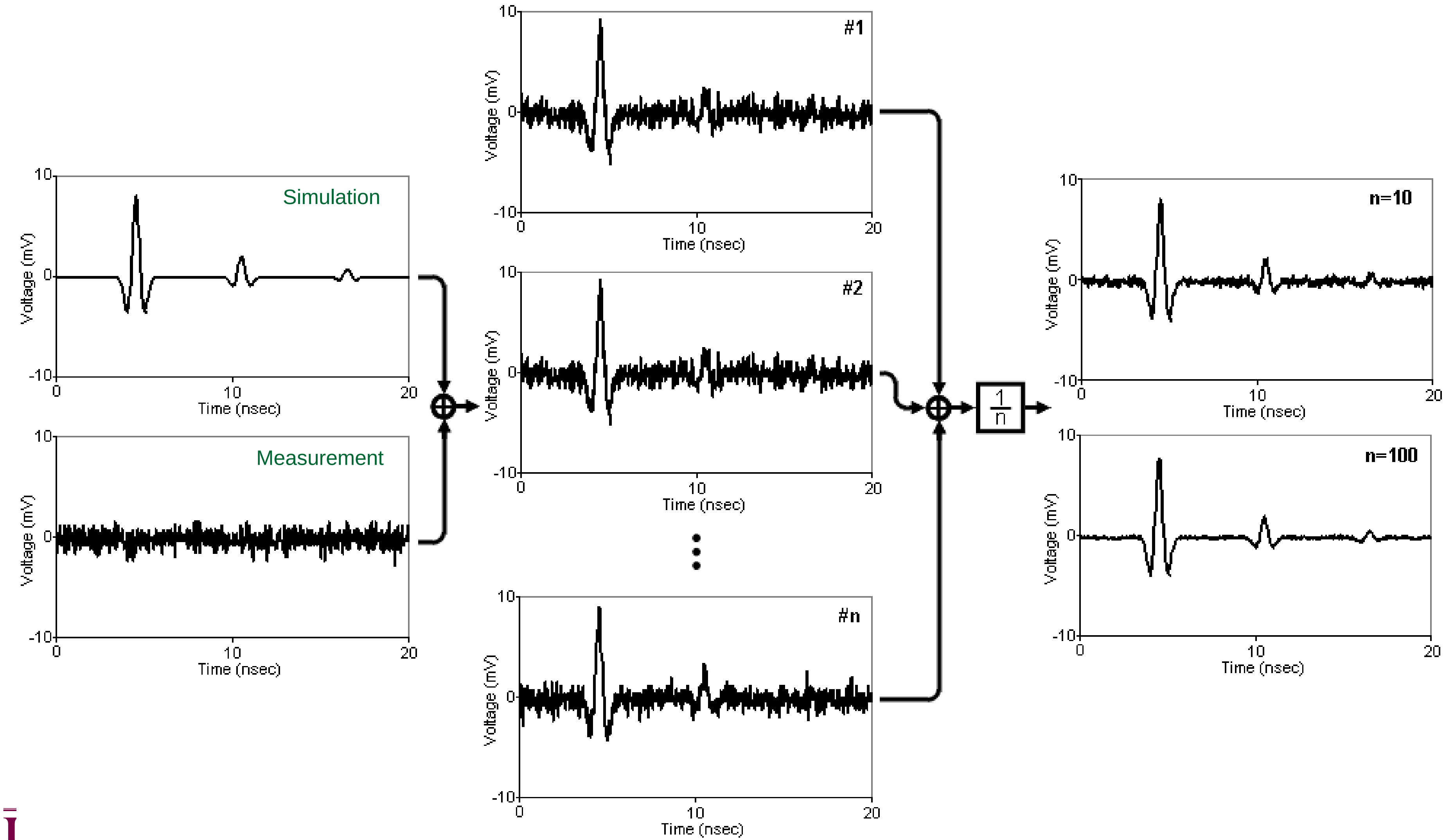

*Measured breathing pattern*




*Measured heartbeat pattern*

Quasi-periodicity can be measured by harmonic component analysis and/or auto correlation

# Signal-to-Noise Ratio

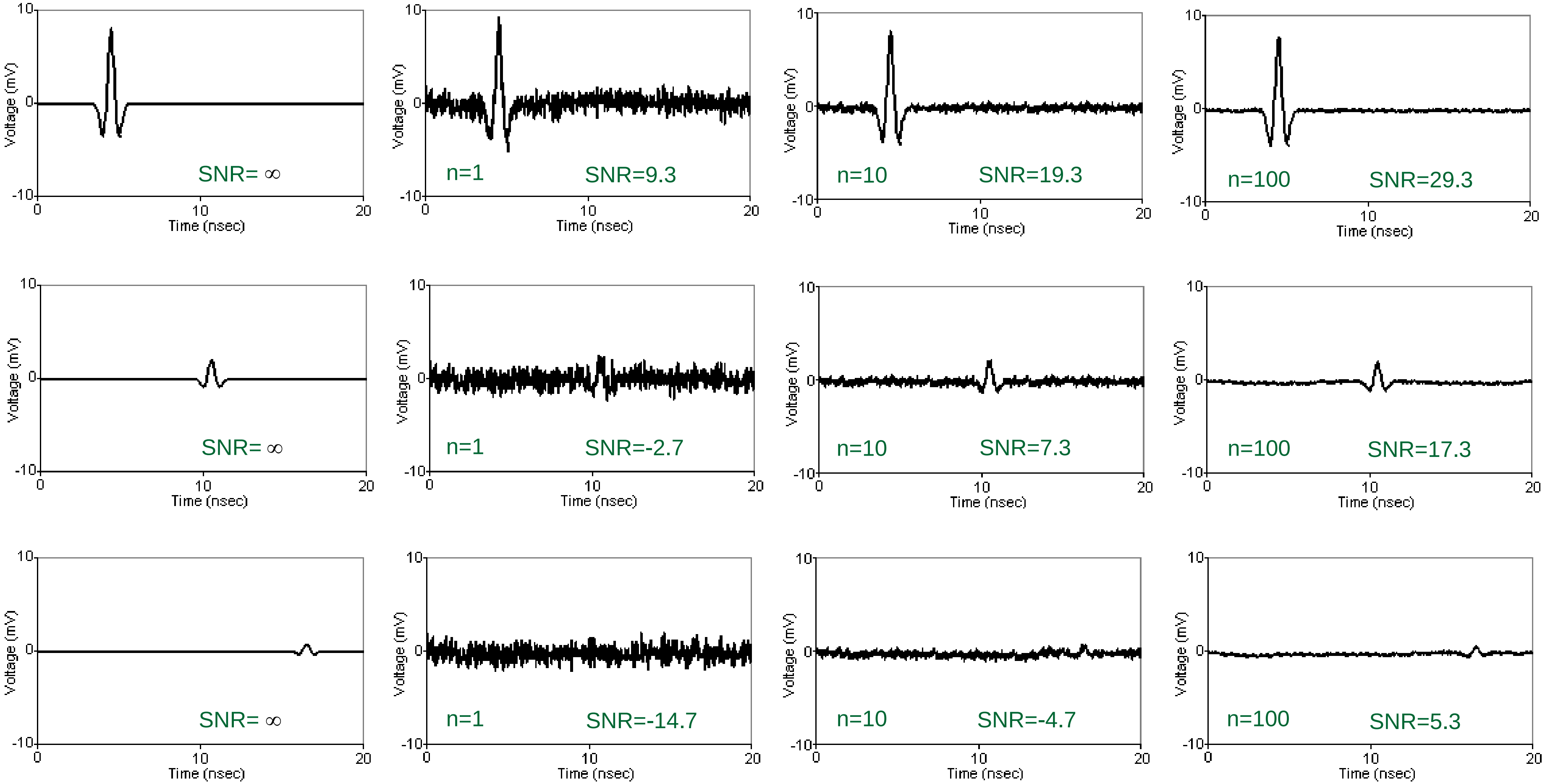


# Signal-to-Noise Ratio (Cont.)

$$SNR_1 = \frac{\text{Energy of Single Pulse over Pulse Repetition Time}}{\text{Noise Power}}$$

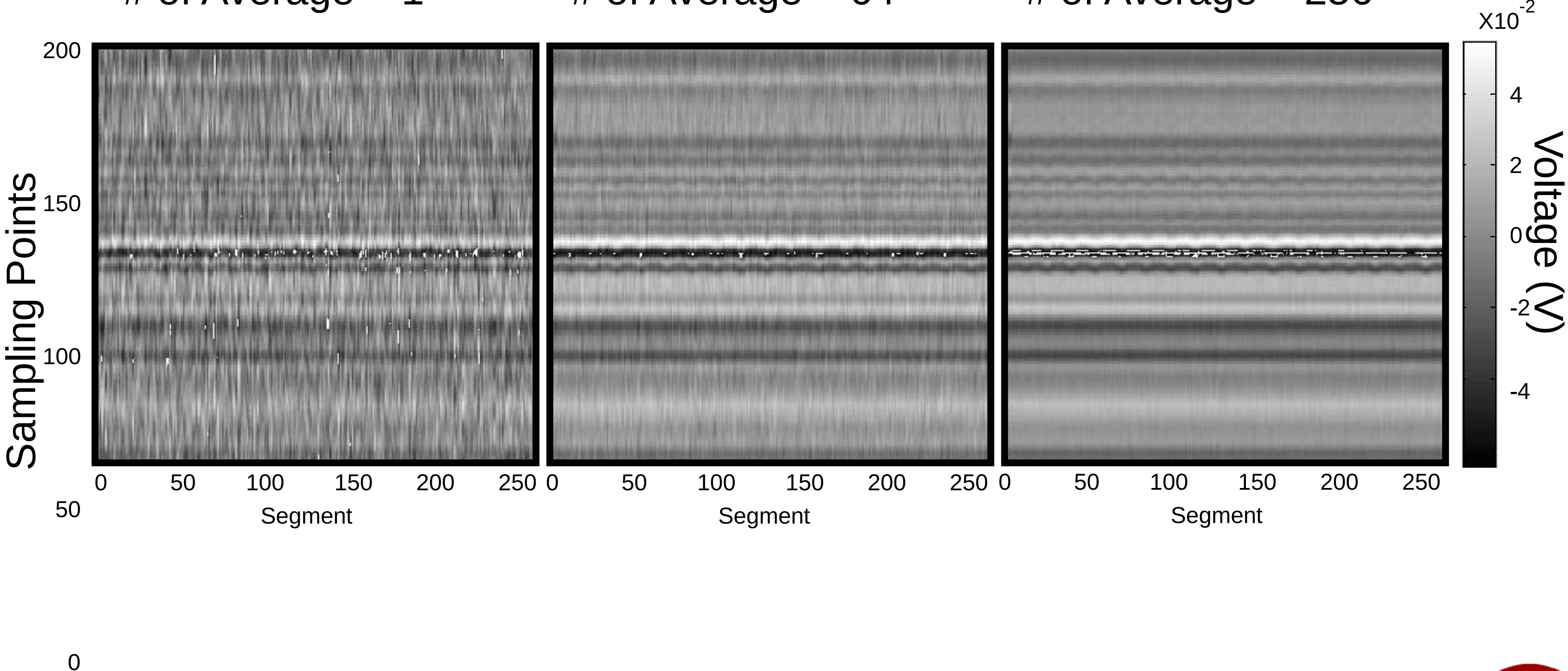
$$SNR_2 = \frac{\text{Energy of Single Pulse over Pulse Time Width}}{\text{Noise Power}}$$

$$SNR_2 = SNR_1 + 10\log\left(\frac{\text{Pulse Repetition Time}}{\text{Pulse Time Width}}\right)$$



# Signal-to-Noise Ratio (Cont.)

| Breathing | Breathing | Breathing |
|---|---|---|
| SNR = 16dB | SNR = 28dB | SNR = 40dB |
| PRF = 4Hz | PRF = 64Hz | PRF = 1kHz |
| # of Average = 1 | # of Average = 64 | # of Average = 256 |



# Conclusion: Looking Forward

# Selected UWB Research Challenges

- **All-Digital UWB Arrays**
  - **Advantages**: leveraging on technology scaling (higher speed + smaller area)
  - **Challenges**: low-power sampling & signal processing
- **Collaborative UWB Sensors**
  - **Advantages**: scalable; wide coverage; robust to single-point failures
  - **Challenges**: synchronization
- **Multi-Modal Sensing (UWB + …)**
  - **Advantages**: increased reliability & robustness; play to the strength of each sensing modality
  - **Challenges**: lower the cost, power consumption, and form-factor; multi-modal signal processing
- **Advanced Signal Processing for Reliable UWB Sensing**

# Commercial Future of UWB Sensing

**Commercial success of UWB sensing will be determined by**

- **Reliability**
- **Cost**
- **Power Consumption**
- **Form Factor**

**<u>Reminder</u>:**

**Commercial communication applications are much more forgiving. (In US, cell phone calls drop all the time! WLAN connections can be poor, so what?)**

**Most envisioned commercial sensing applications cannot tolerate a single failure (e.g., healthcare, safety, security). Hence, lawyers become more important that technologists! People's perception can make-it or break-it!**