ANALOG DEVICES

Beamforming Technology Advancements for Phased Array Radar Systems

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Agenda

Phased array radar market trends

RF front-end ICs dictate radar performance

Beamforming technology advancements

ADI beamforming IC solutions

Takeaways

Phased Array Radar Market Trends

	Projected 2030 Market Size	CAGR
Conventional Radar	$8B to 9B*	4% to 5%*
Active Phased Array Radar	$13B[1] to 15.94B[2]	8.7%[1] to 9.79%[2]

PLATFORMS

Airborne

Naval

Ground

Space Based

FREQUENCY BANDS

S-Band

X-Band

L-Band

C-Band

Others (Ku-, Ka-, E-Bands)

APPLICATIONS

Surveillance

Weather Monitoring

Air Traffic Control

Space Situational Awareness

Automotive & Industrial

TECHNOLOGY DRIVERS

GaN Power Amplifiers

Highly integrated BFICs

Multi-Ch. Data Converters

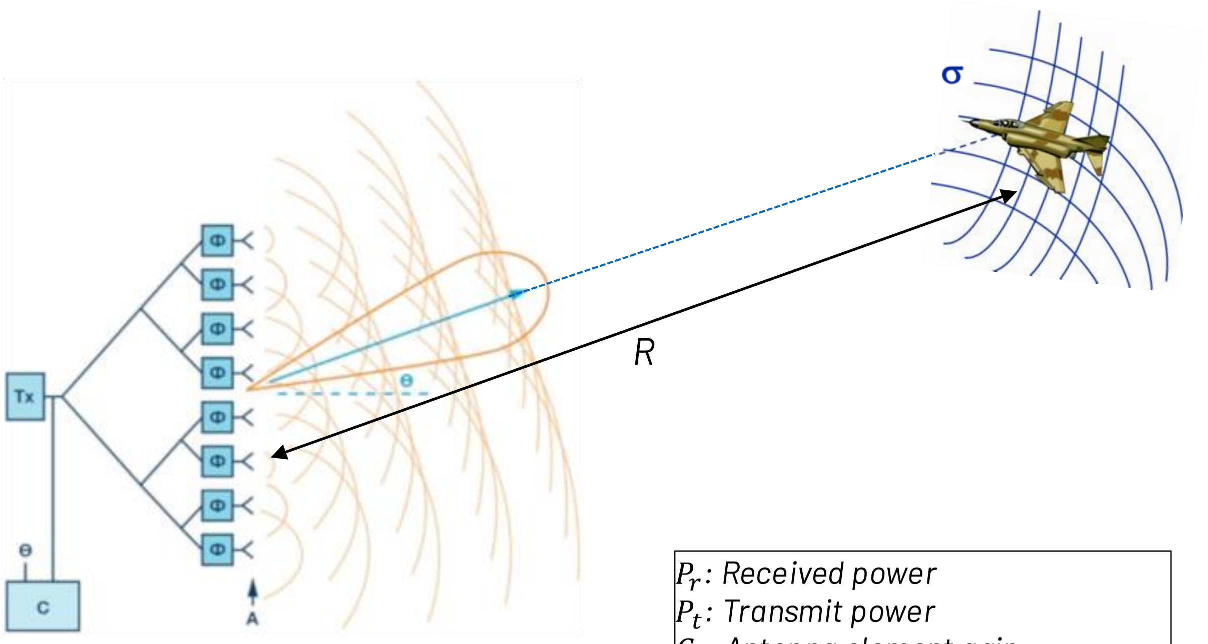
Integration of AI/ML for Target Recognition & Feature Enhancements

* Copilot summary

[1] Active Phased Array Radar Market Report 2030 by Strategic Market Research (Copilot summary)

[2] Global Active Phased Array Radar Market Size Study … Forecasts 2022-2032: GII Research (Copilot summary)

Radar: Radio Detection and Ranging: Maximizing Range



*

P_r: *Received power*
P_t: *Transmit power*
G_e: *Antenna element gain*
N: *Number of elements*
λ: *Wavelength*
σ: *Radar cross section (RCS)*
R: *Range*
T_s: *System noise temperature*
B: *Noise bandwidth*
L: *System losses*

For a phased array radar antenna with N elements:

$$P_r = \frac{P_t\, N^2\, G_e^2\, \lambda^2\, \sigma}{(4\pi)^3\, R^4}$$

$$\mathrm{SNR} = \frac{P_t N^2 G_e^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k T_s B L}$$

$$R_{\max} = \left[\frac{P_t\, N^2 G_e^2\, \lambda^2\, \sigma}{(4\pi)^3\, k\, T_s\, B\, L\, \mathrm{SNR}_{\min}}\right]^{1/4}$$

Range scales as $\sqrt{N}$, ¼ power of P_t & inverse ¼ power of T_s

For large range:

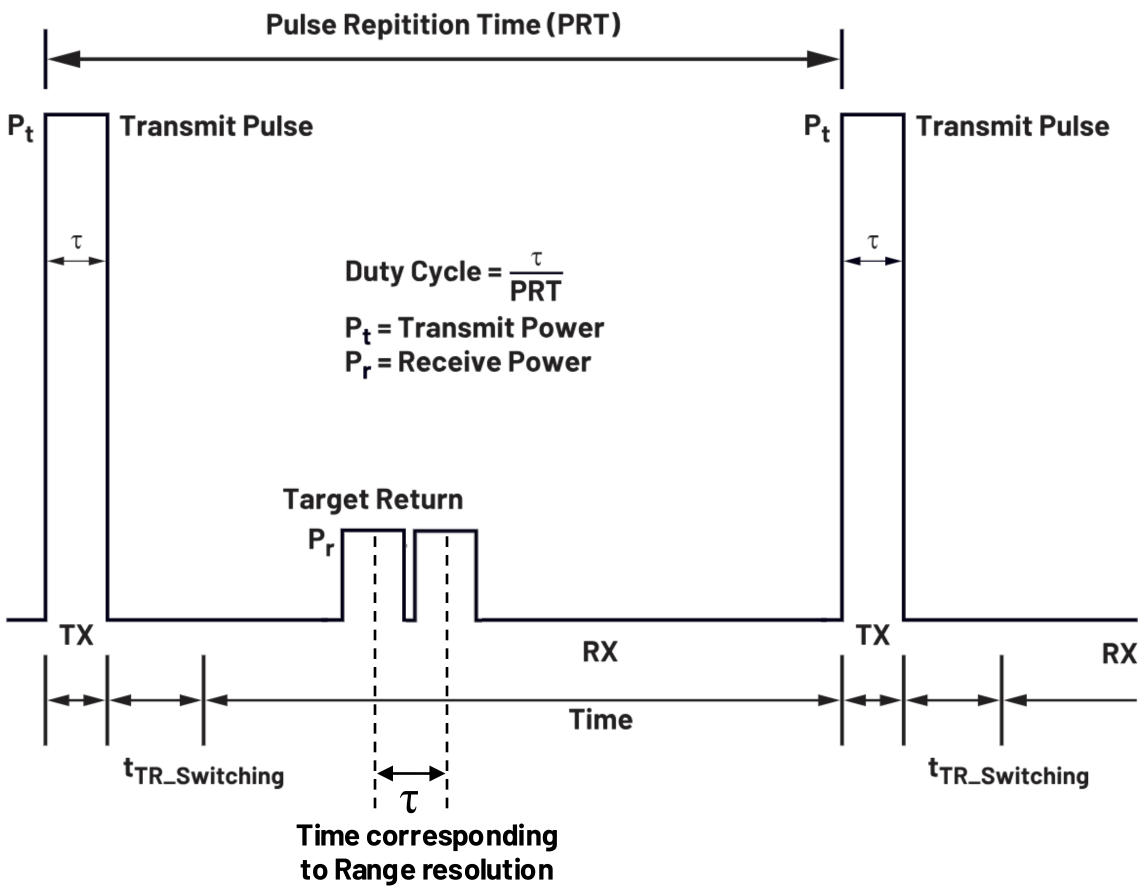
Increase array size

Increase Tx Power

Improve Rx Noise Figure

*Beamforming ICs Simplify Phased Array Antenna Design: Keith Benson, ADI (Microwave Journal)

How Timing Affects Performance: Blind Range and Resolution



Minimum detectable range (blind range) = $(\tau + t_{TR\_Switching}) \times (c/2)$

- Pulse width and T/R switching time of 0.1μs each results in a **blind range** of 30m

Range resolution, $\Delta R = \tau \times (c/2)$

- 0.1μs pulse width results in range resolution of 15m
- Shorter pulse improves resolution, longer pulse improves SNR

Pulse compression breaks this trade-off

Compression Ratio (CR) $= B \cdot T$; where B = BW, T = pulse duration

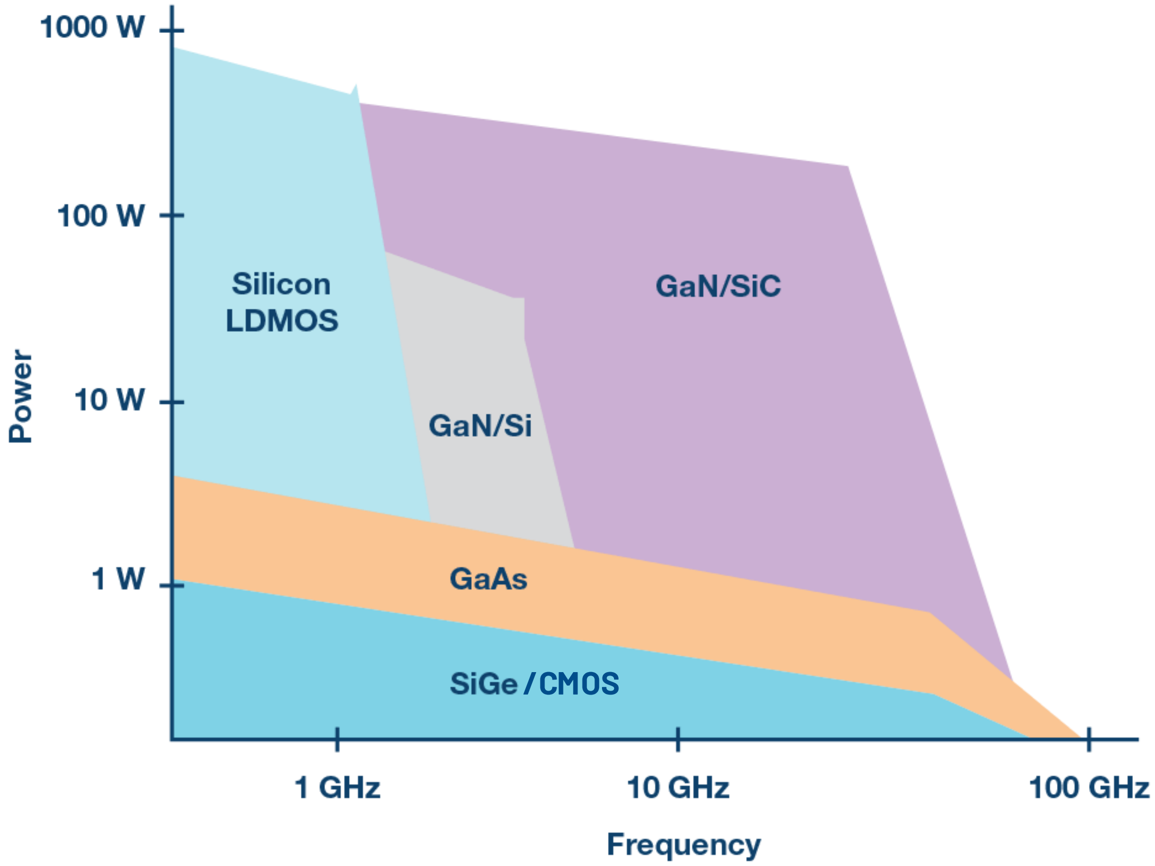
Processing gain, $G = B \cdot T \Rightarrow 10\log_{10}(BT)$ dB

$\tau_{\text{compressed}} \approx \frac{1}{B}$; Range resolution $\Delta R = \frac{c}{2B}$

For shorter blind range & better resolution

- **Reduce T/R switching time**
- **Employ pulse compression**

Process Technologies for Radar Front-End ICs



Combination of high frequency and high power is not achievable on Si technologies

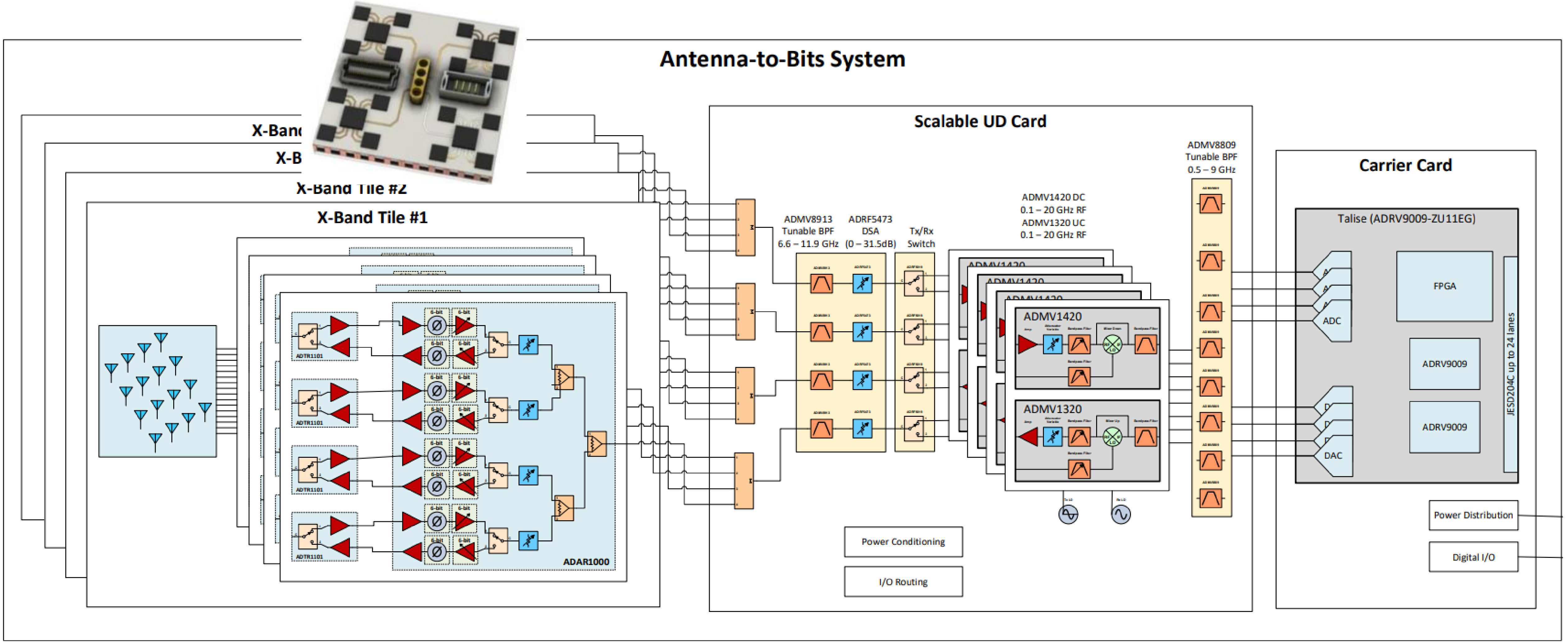
- Fine line, high-speed devices have lower breakdown voltages
- Power combining reduces efficiency
- Si is excellent for beamforming ICs needing high level of integration and moderate transmit output power

GaN is a better technology for high-power applications

GaAs LNAs for better noise figure

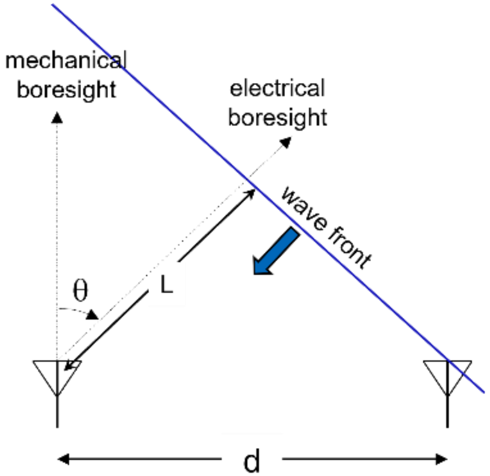
CMOS SOI for high-power T/R switches

Hybrid Beamforming: High-Level Block Diagram



TRM (ADTR1101) BFIC (ADAR1000) ADI tunable filter, Att. & Sw. UDCs (ADMV1320/1420) Multi-ch. ADC/DAC

Beamforming: Time Delay vs. Phase Shifter: Beam Squint



Θ: beam steering angle
Δt: incremental time delay between elements
$\Delta\phi$: incremental phase shift between elements
L: incremental propagation distance between elements
d: distance between elements
c: speed of light

$L = d \sin\theta$

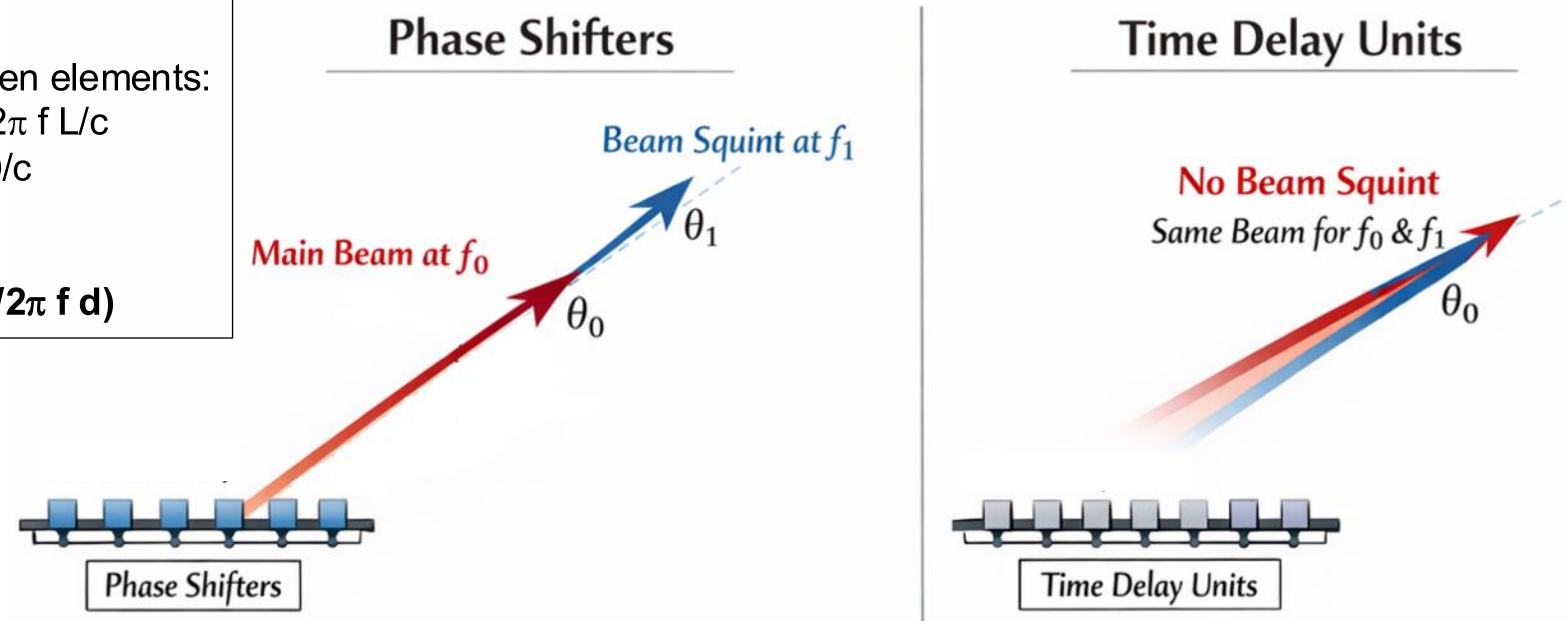
For phase shift between elements:

$\Delta\phi = 2\pi L / \lambda = 2\pi f L/c$

$\Delta\phi = 2\pi f d \sin\theta/c$

Solving for θ:

$\boldsymbol{\theta = \arcsin(\Delta\phi\, c/2\pi f d)}$



$L = d \sin\theta$

For time delay between elements:

$\Delta t = L/c$

$\Delta t = d \sin\theta/c$

Solving for θ :

$\boldsymbol{\theta = \arcsin(\Delta t\, c/d)}$

Beamformer Technology Advancements

Low power consumption

Passive TDU/phase shifters and DSA

Wider RF bandwidth for multifunction arrays

High transmit output power, low noise figure

High-channel count to enable dual polarized antennas

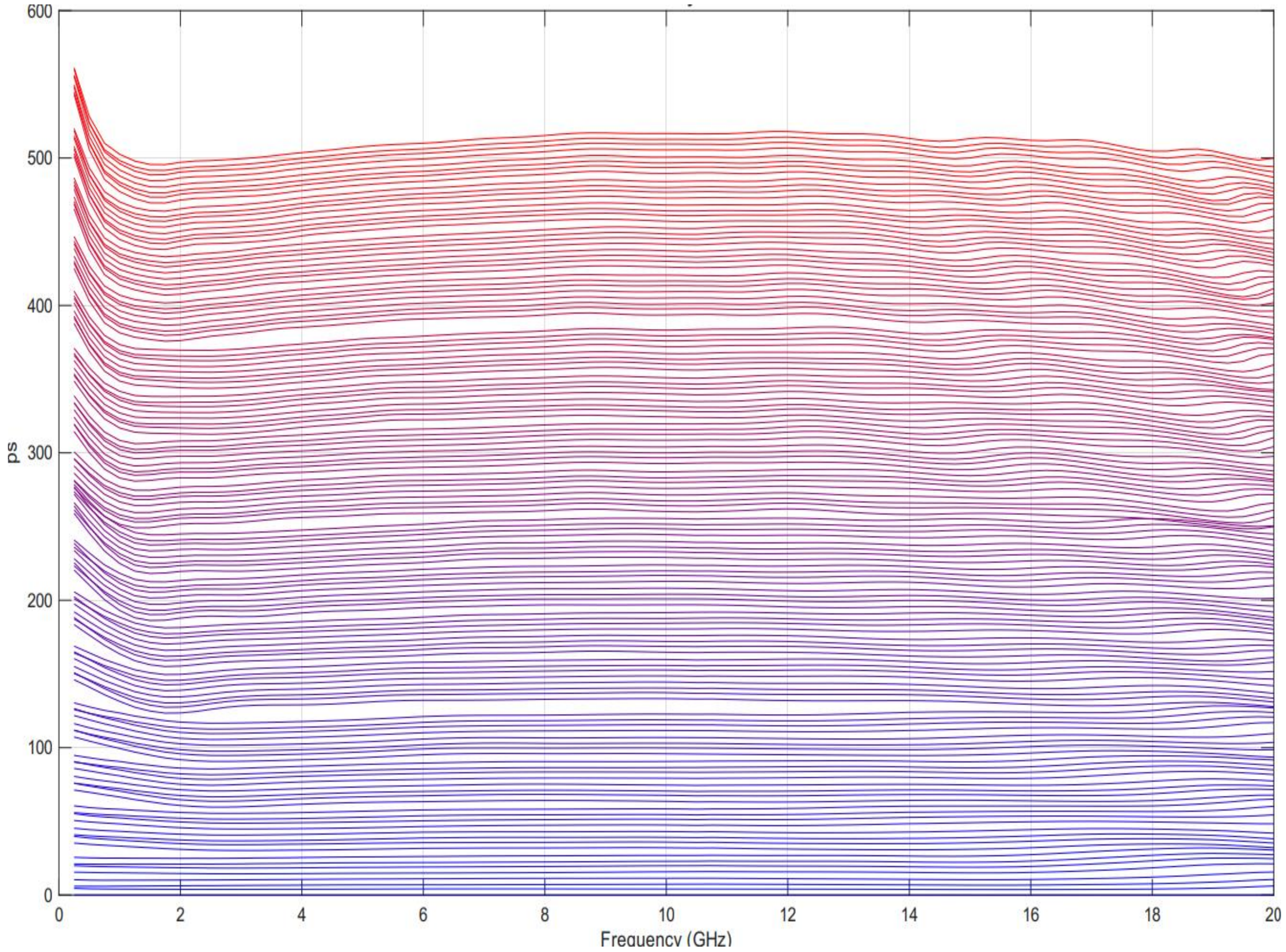
Integrated fast switching gate drivers

Integrated receiver limiters

On-chip beam state memory for faster scanning

Better thermals with WLCS packaging

ADAR4002 (0.5GHz to 19GHz, 508ps TDU) Time Delay Response



Packaging Advancements: Embedded Package

Interconnect evolution

Gold wire → Cu wire → Solder ball interconnect → Cu pillar interconnect → ?

Interconnect without interconnect: embedded package

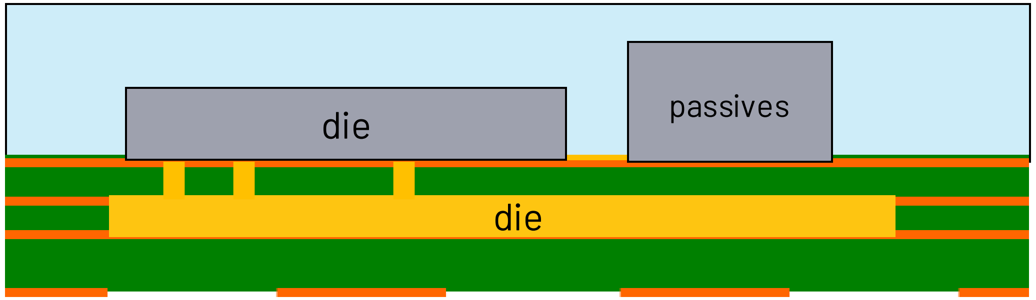
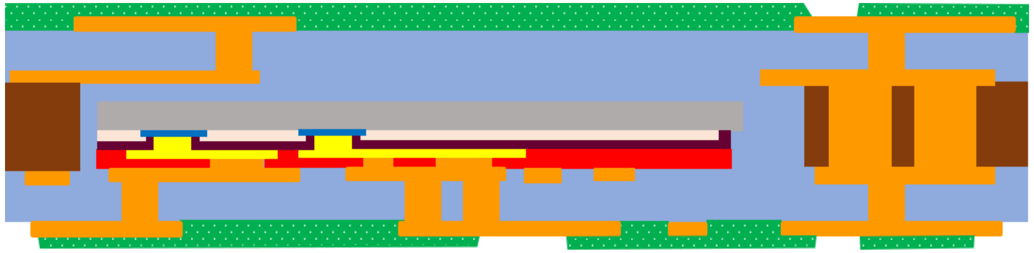


Illustration of an embedded package with die-to-die vertical connection



Details of a typical embedded substrate

Embedded package advantages

Functionalizing the substrate

- Vertical connection with reduced length (parasitic resistance and inductance)

Alternative to the flip-chip package

- EM improvement
- Flexible die connection design and placement

Reduced footprint of a package

ANALOG DEVICES

ADI Beamforming IC products

Radar/TDD

ADAR1000
Half-Duplex
X- and Ku-Band (8GHz to 16GHz)
1×4 T/R BFIC

Wideband TDU

ADAR4002
0.5GHz to 19GHz,
Bidirectional
508psec TDU

ADAR4000/ADAR4001
2GHz to 18GHz, 508psec
TDU, 1×4 Full Duplex Tx/Rx
BFICs

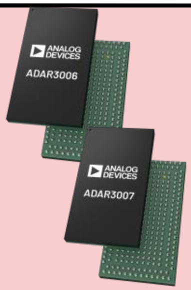
T/R Modules

ADTR1101
Freq: 8GHz to 12GHz
Tx Pout: 37dBm (5W)
Pkg: 5mm × 5mm LGA

ADTR1104
Freq: 8GHz to 12GHz
Tx Pout: 39.5dBm (9W)
Pkg: 5mm × 5mm LGA

ADTR1107
Freq: 6GHz to 18GHz
Tx Pout: 25dBm
Pkg: 5mm × 5mm LGA

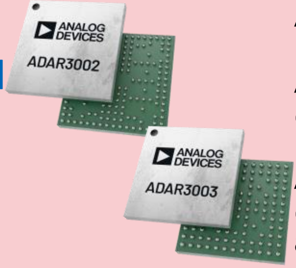
Satcom Payloads



ADAR3006/ADAR3007
Ku Band Full Duplex
16 Channels, 4×4
ADAR3006: 10.7GHz to 12.75GHz
ADAR3007: 13.75GHz to 14.6GHz

ADAR3000/ ADAR3001
Ka-Band Full Duplex
16 Channels, 4×4
ADAR3000: 17GHz to 22GHz
ADAR3001: 27GHz to 31GHz

Satcom Terminal



ADAR3002/ADAR3003
Ka Band Full Duplex
ADAR3002: 17GHz to 21GHz (RX)
16 Channels, 8×2
ADAR3003: 27GHz to 31GHz (TX)
8 Channels, 1×8

ADMV4680
Satcom Ku-Band 1×4
T/R BFIC

Comms. T/R BFICs

ADMV48281
24GHz to 30GHz
2×8 T/R BFIC

ADMV1228
24GHz to 30GHz
2×8 UDC + BFIC

ADMV49281
37GHz to 44GHz 2×8
T/R BFIC

Wilkinson Power Combiner/Splitter

ADAR5000
4 - Way Wilkinson
17GHz to 32GHz

ADAR5001
2 - Way Wilkinson
10GHz to 40GHz

Takeaways and Future Trends

APAR is the backbone of modern airborne, naval, ground-based, weather and spaceborne radars

- Multiple simultaneous beams and modes - search, track, imaging
- Adaptive patterns: interferer nulling, sidelobe shaping

Miniaturized front-end electronics enables scalable flat panel arrays

- GaN amplifiers and high-channel count Beamformer ICs

Digital beamforming and signal processing breakthroughs

- ML/AI assisted target recognition, clutter suppression, and adaptive beam steering

Emerging application and active research areas

- SAR (Synthetic Aperture Radar) for:
  - Defense ISR applications on UAVs and satellites
  - Terrain structural information for mineral exploration, oil spill boundaries on water, sea, and ice hazard maps
- Rapid volume scanning using AESA for fast-evolving storms, tornado genesis, and microbursts

<u>Parting thought:</u>

"Our scientific power has outrun our spiritual power. We have guided missiles and misguided men." – Dr. *Martin Luther King Jr.*