4.5: Electronic THz Pencil Beam Forming and 2D Steering for High Angular-Resolution Operation: A 98×98 Unit, 265GHz CMOS Reflectarray with In-Unit Digital Beam Shaping and Squint Correction

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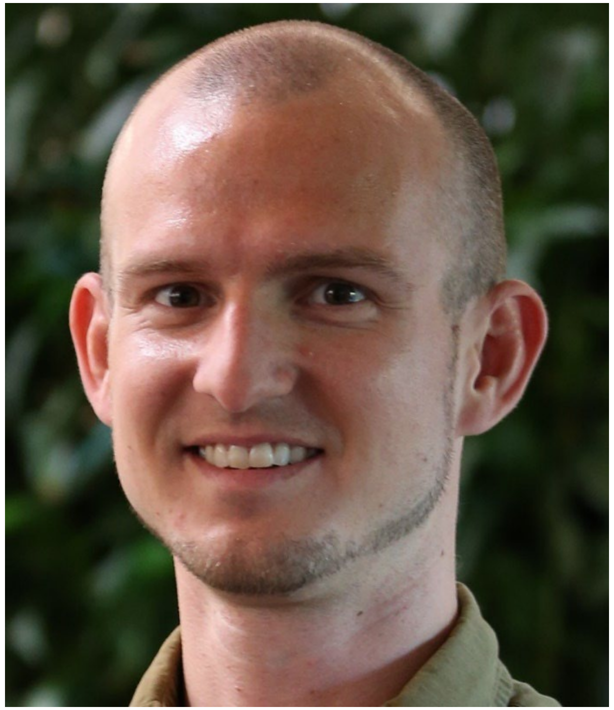
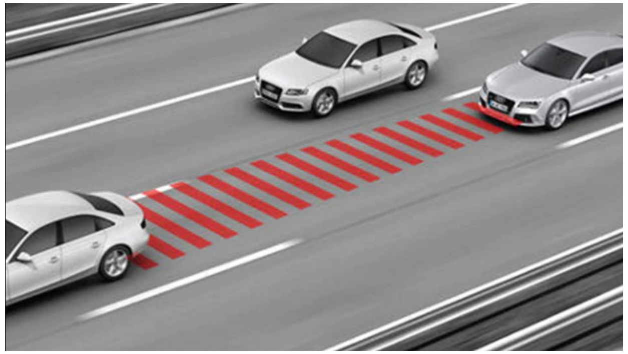
Speaker Bio: Nathan Monroe

- **Education**
  - S.B., MIT EE | 2013
  - M. Eng. MIT EE | 2017
  - Ph.D., MIT EE | 2021
- **Professional Experience**
  - Microsoft Xbox Sensor Development 2013-2015
- **Research Interests**
  - THz antenna arrays
  - THz radar

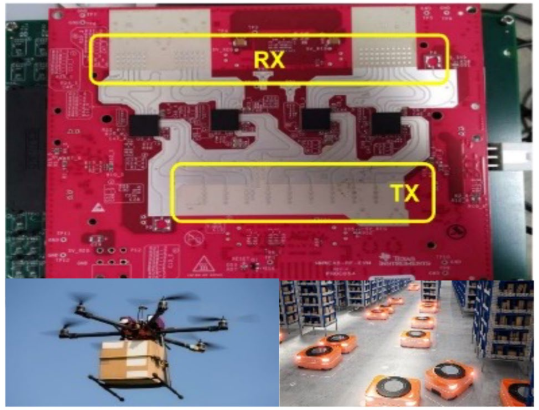


Sensing in Autonomous Vehicles

- Vision is key for autonomous vehicles
- From object detection to recognition



- ✓ High angular resolution
- × High cost
- × Mechanical scanning
- × Poor robustness to weather

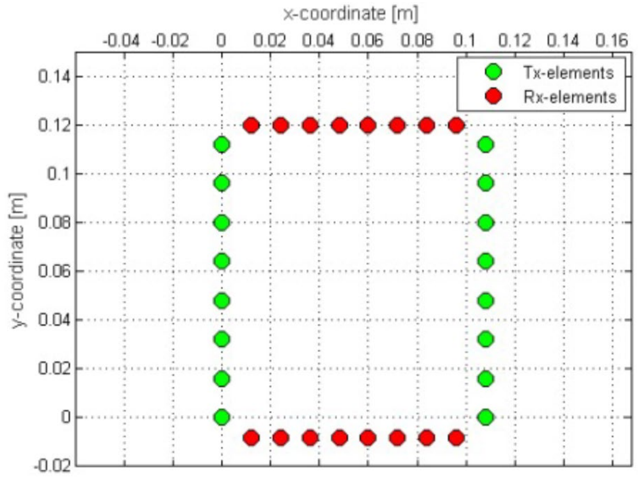


- ✓ Low cost, long range
- ✓ All-weather operation
- × Low 2D angular resolution
- × Large size

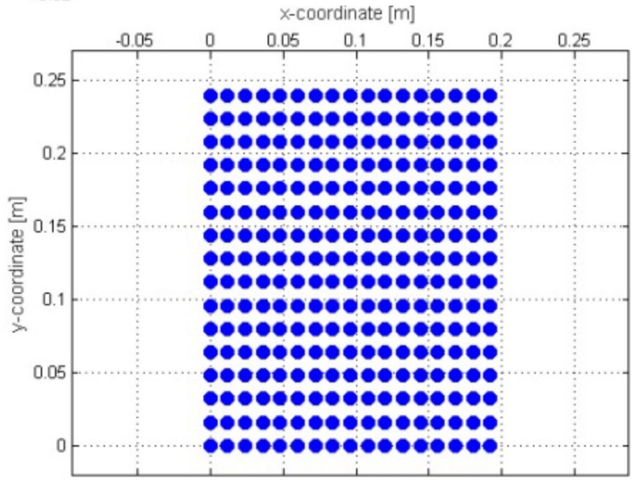
MIMO Radar: Practicality Issues

- ✓ Low cost, long range
- ✓ All-weather operation
- ✓ Small size

- ✘ Low 2D angular resolution
- ✘ Clutter issues
- ✘ Interference concerns



Physical Array



Virtual Array

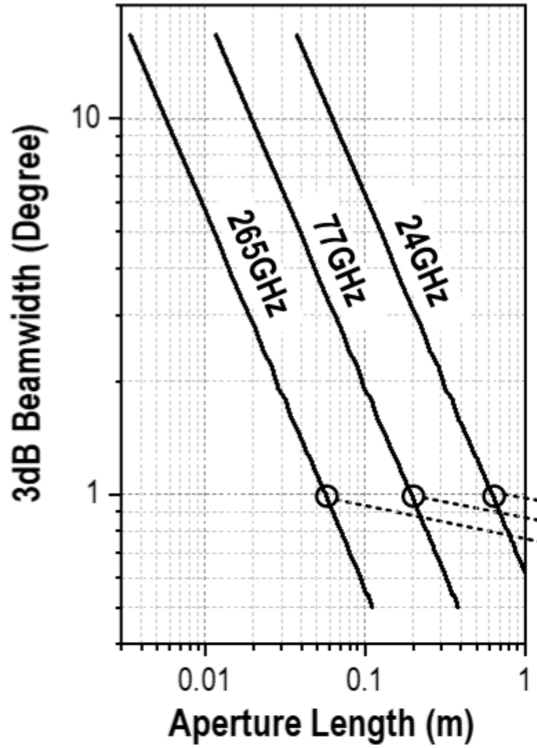
[Mietzner 2017]

Imaging Radar: The Case for THz

100x100px image ➔ 1^o beam

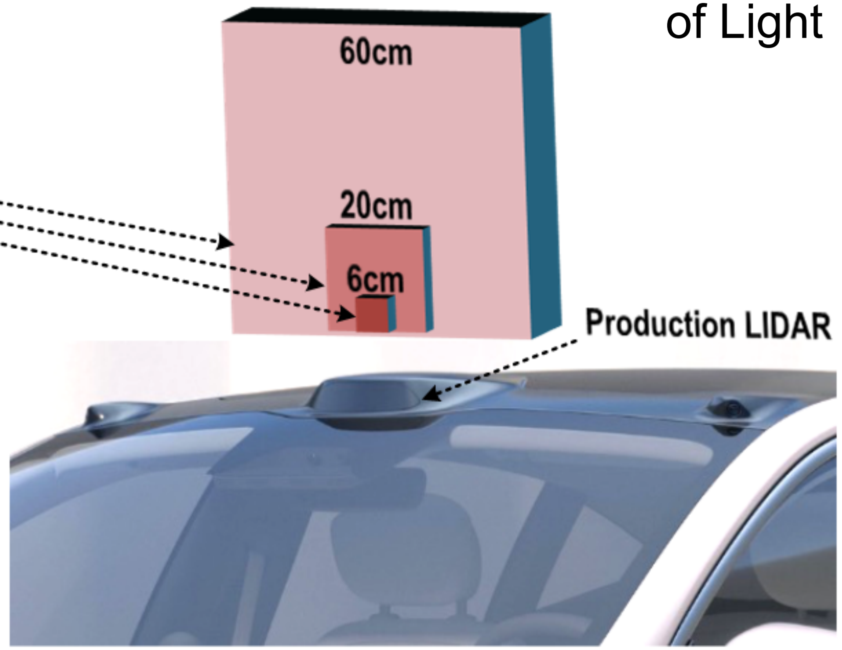
Imaging Radar: The Case for THz

100x100px image ➔ 1^{o} beam



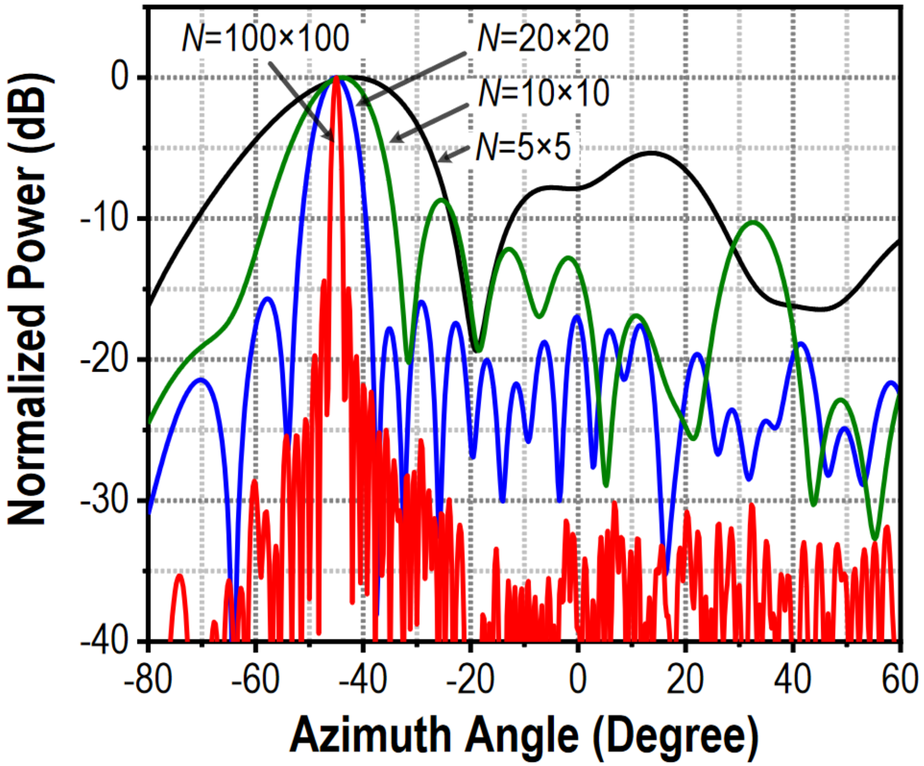
Beam Directivity → D; Aperture Area → A; Frequency → f; Speed of Light → c

$$D = \frac{4\pi A f^2}{c^2}$$



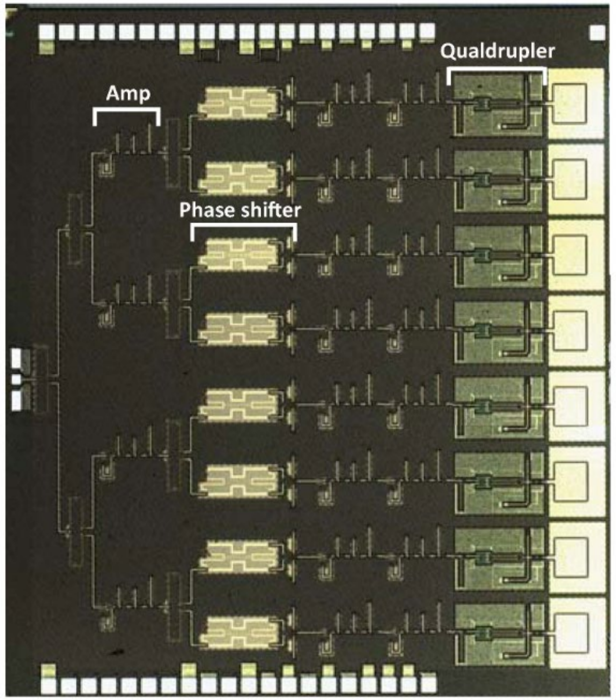
THz Array: Implementation Challenges

- 1º beam ➔ 100x100 antennas
- RF Power Distribution
  - ✘ High loss
  - ✘ Routing complexity/congestion
  - ✘ Phase synchronization
- Phase control issues

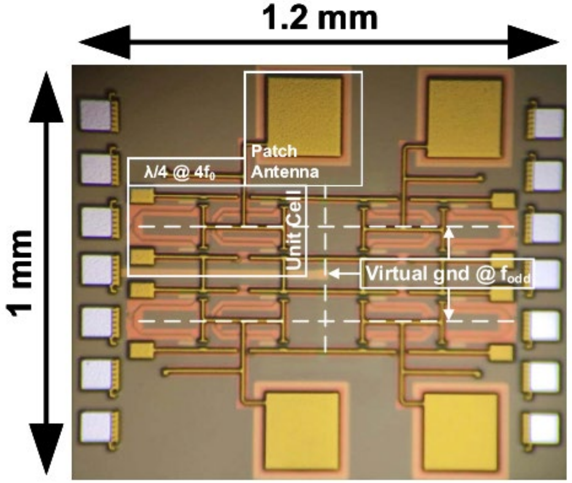


THz Phase Shifter Limitations

- Insertion Loss ~10dB
- Power ~ 10mW
- Size ➔ λ/2 footprint
- Phase/Amplitude errors
- Narrowband
- One-directional



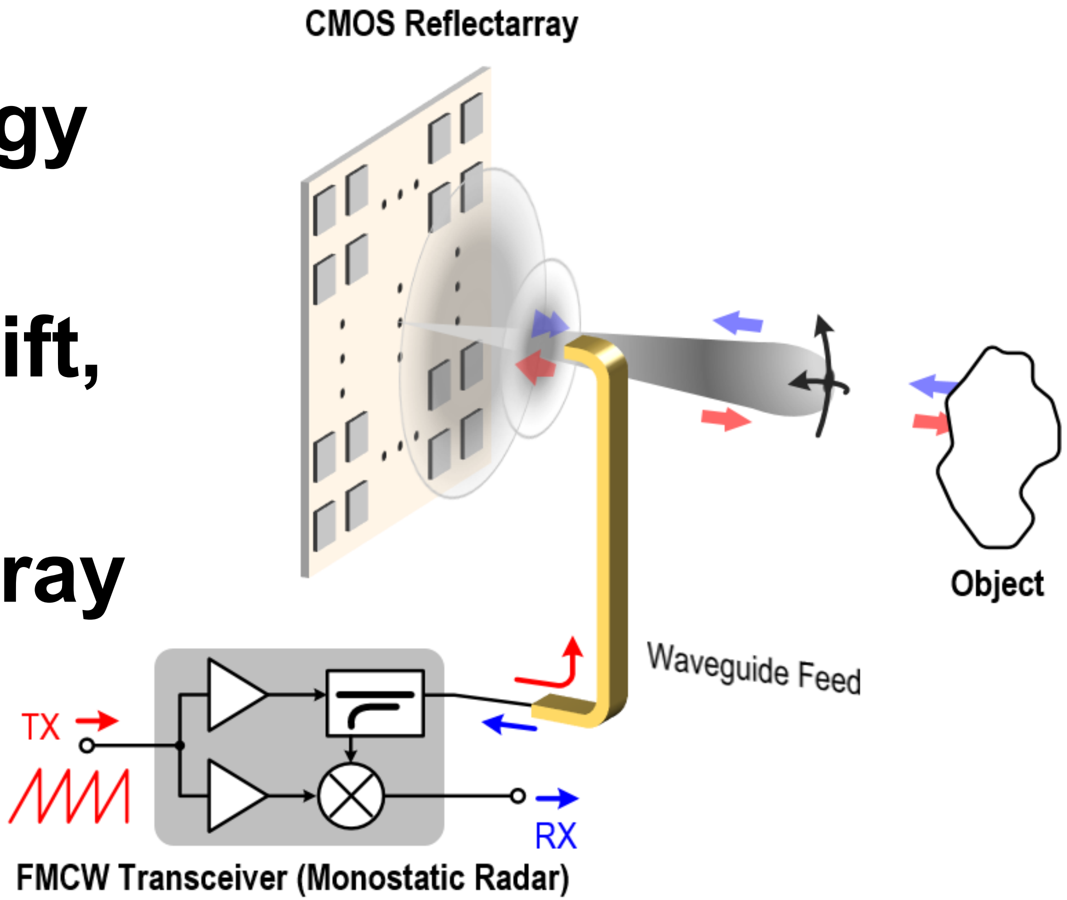
Yang et al, MTT 2015



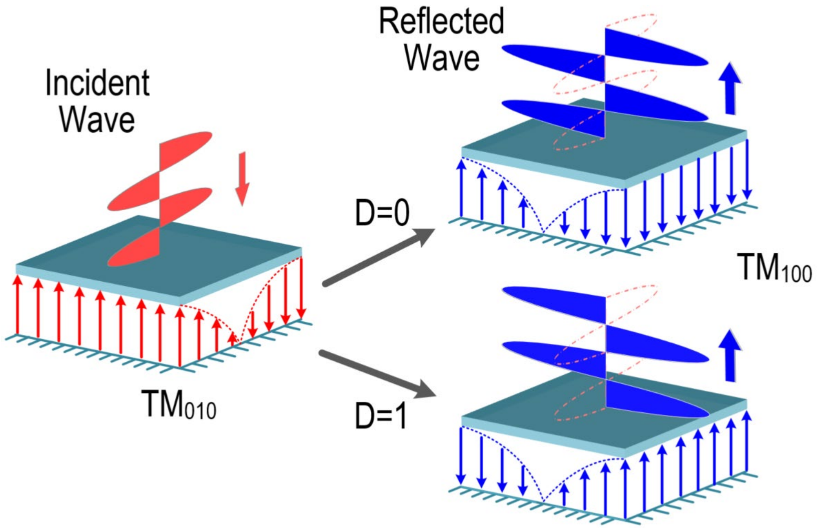
Jalili et al, JSSC 2019

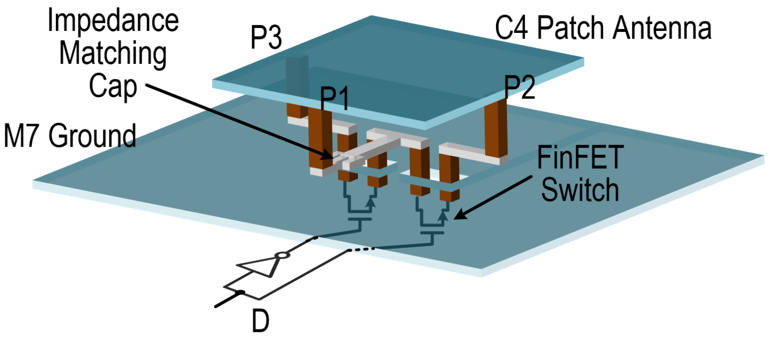
Reflectarray:
A Reconfigurable Mirror

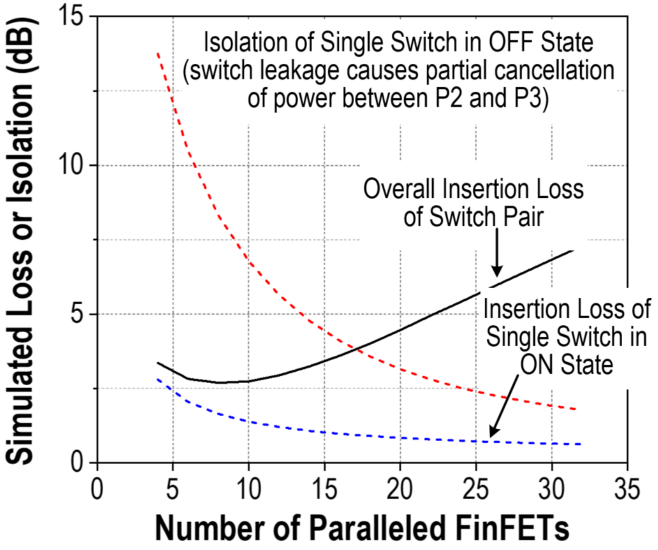
- Feed antenna radiates energy onto antenna array
- Elements receive, phase shift, radiate
- Advantages over phased array
  - Reduced distribution losses
  - Phase synchronization
  - No complex RF routing



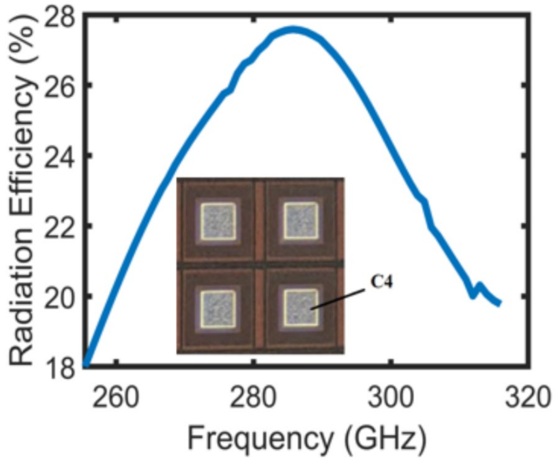
One Bit Phase Shifter Concept







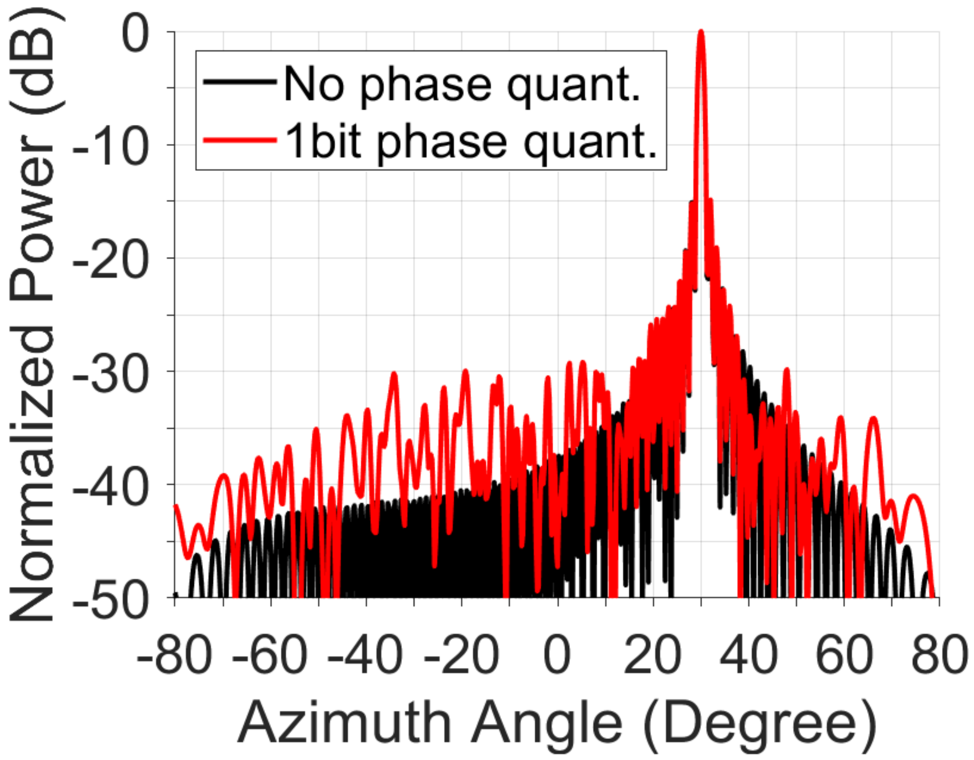
- **Quantize phase to 0° or 180°**
  - Two passive FET switches
  - Feed opposing sides of antenna
- **Tradeoffs: switch sizing**
  - Insertion loss vs isolation



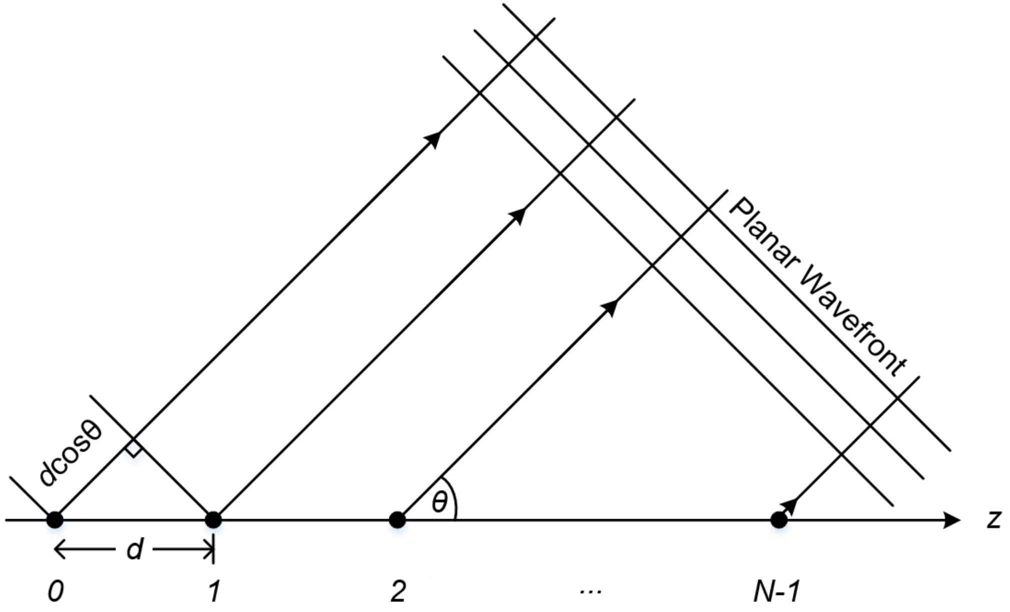
Q. Yu et al, IEDM 2020

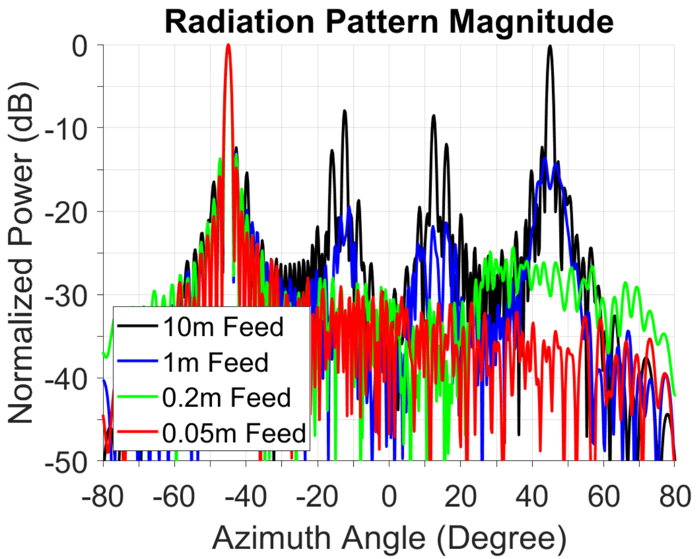
One Bit Phase Shifter Considerations

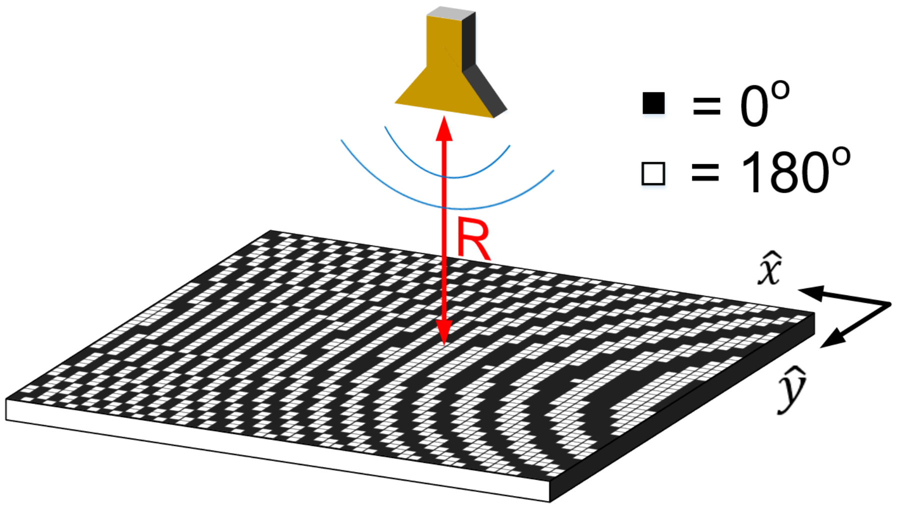
- ✓ No static DC power
- ✓ Low THz loss ~3dB
- ✓ Small area >10x10 μm^2
- ✓ No phase/amplitude errors
- ✗ Phase quantization ➔ sidelobes



One Bit Reflectarray

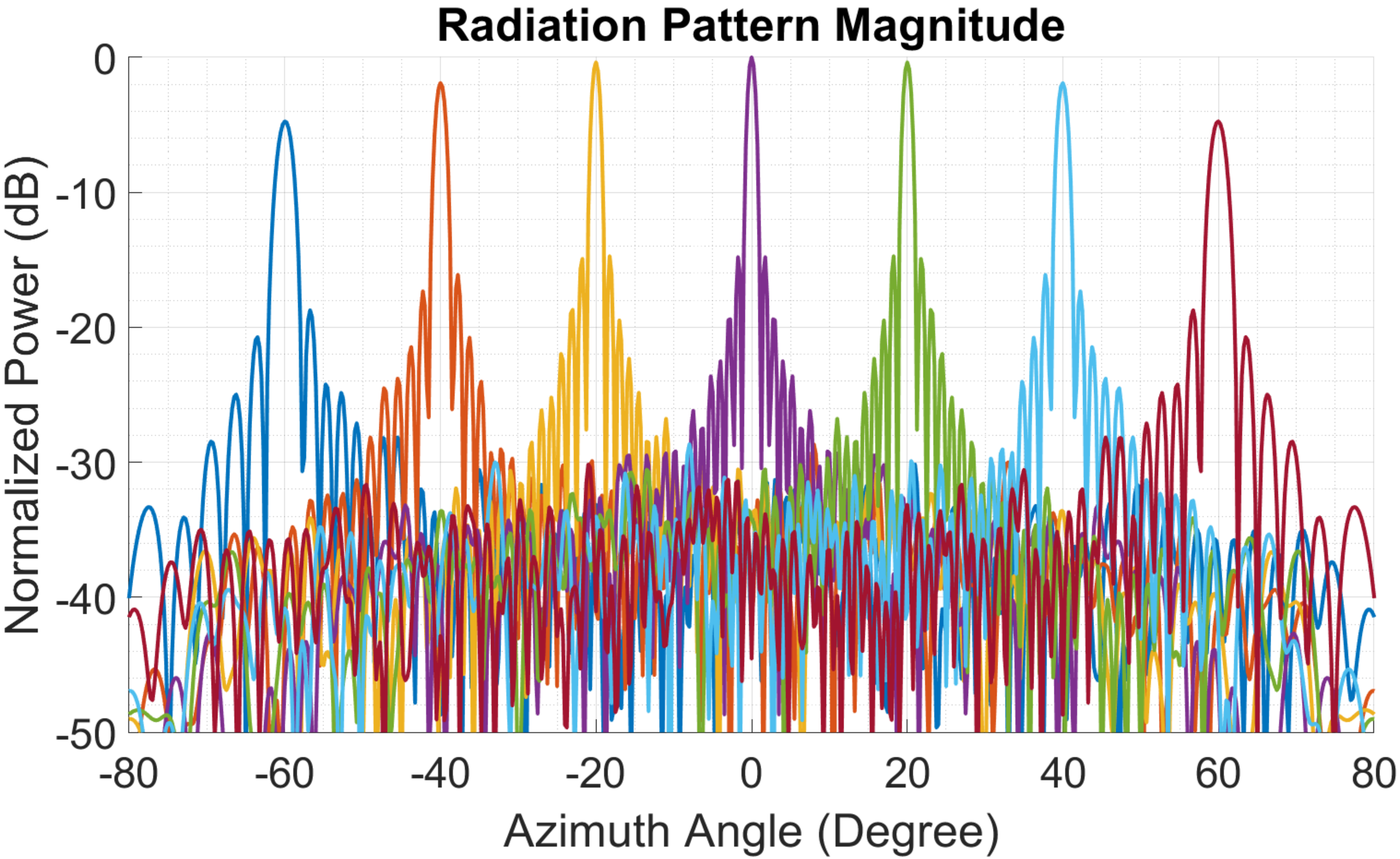




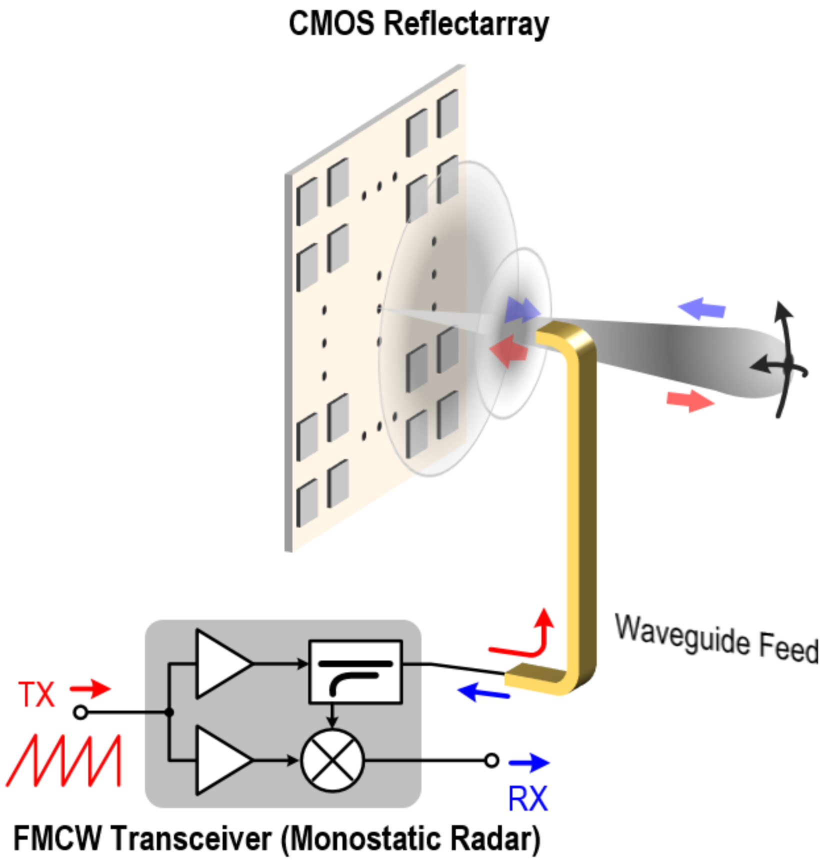


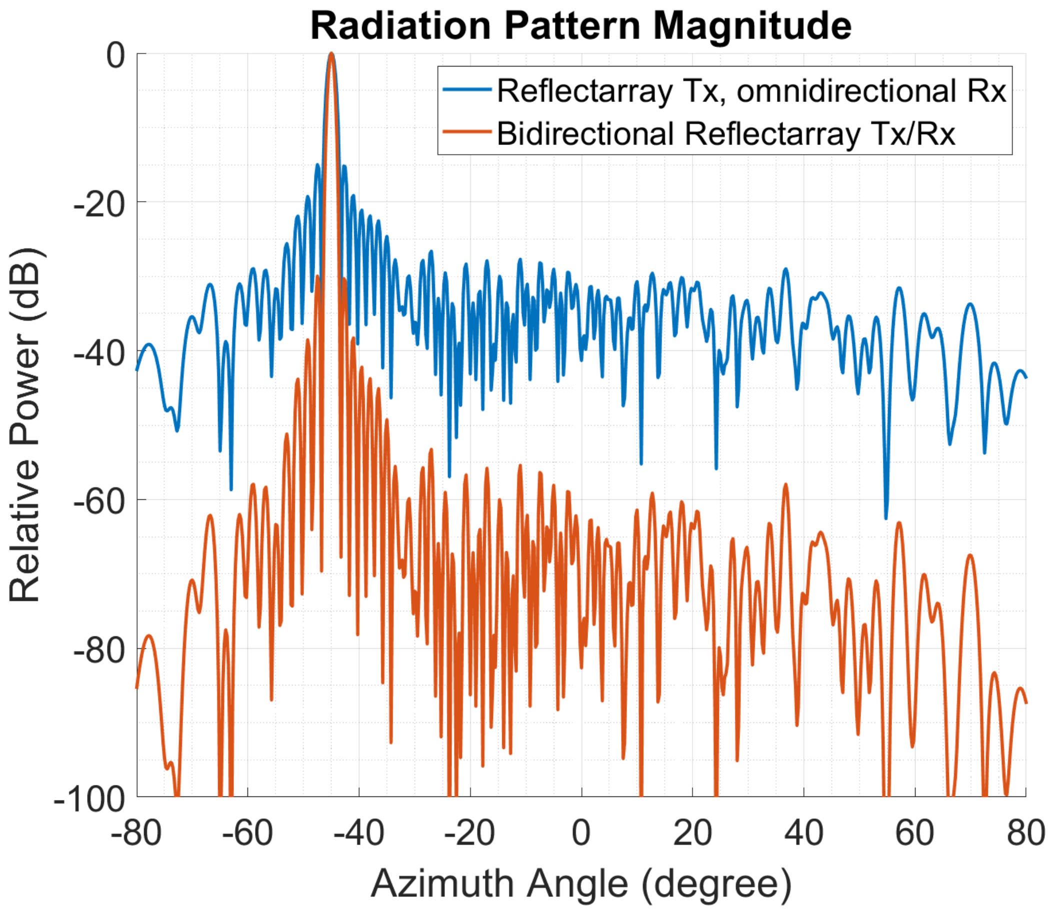
Array Factor		DFT
$AF = \sum_{m=0}^{N-1} I_m e^{jm\psi}$	⟷	$X_{2\pi}(\omega) = \sum_{n=-\infty}^{\infty} x[n]e^{-j\omega n}$
$\psi = kd\cos\theta$	⟷	ω

One Bit Reflectarray: Sim. Radiation



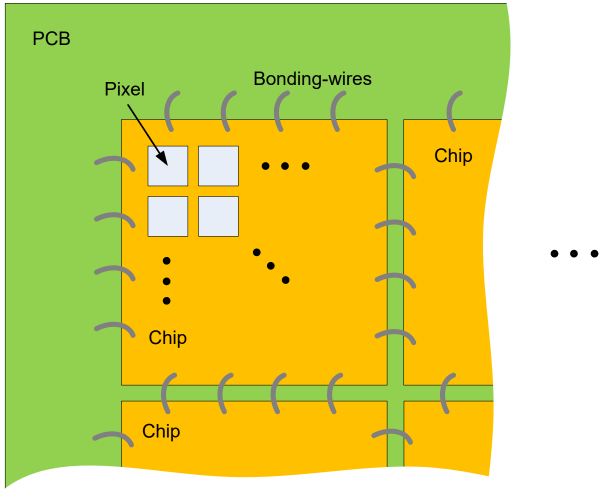
Advantages of a Bidirectional Phase Shifter

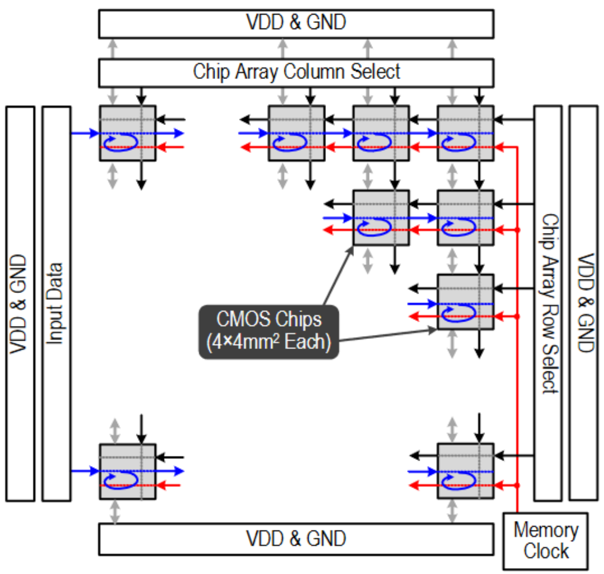




Tiled Chips for Scalable Architecture

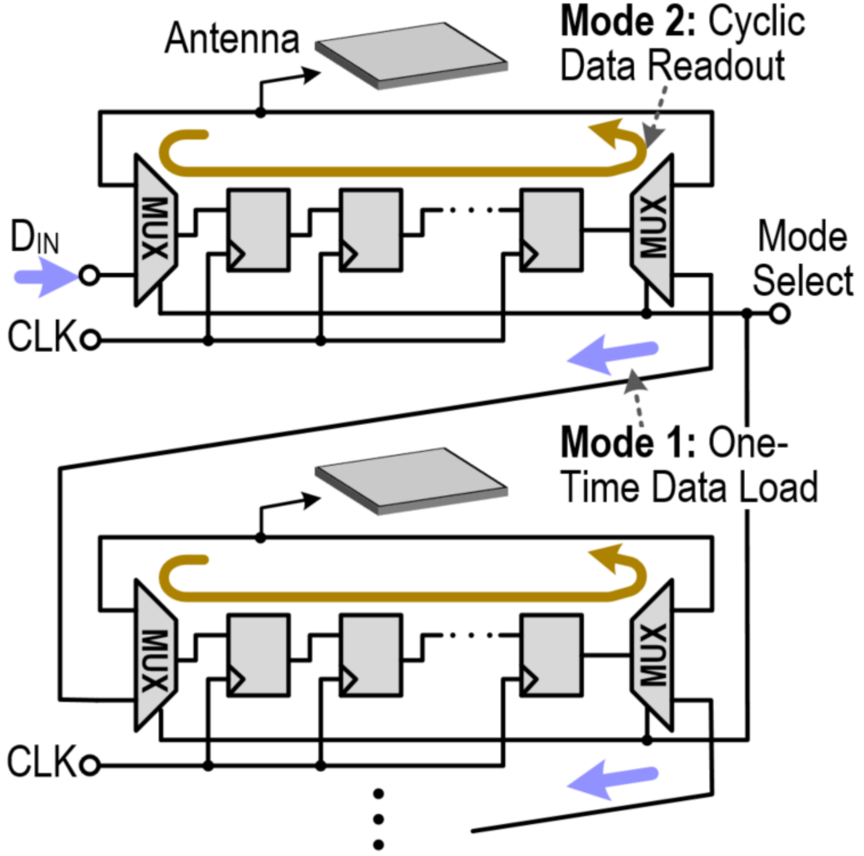
- Single chip with 7x7 antennas
- Tile chips on PCB for large array
  - Wirebond stitching
  - Antenna spacing maintained
- Scalable architecture
  - Arbitrary array sizes
  - Individual chip addressing
    - Robust architecture
    - Bypass defects



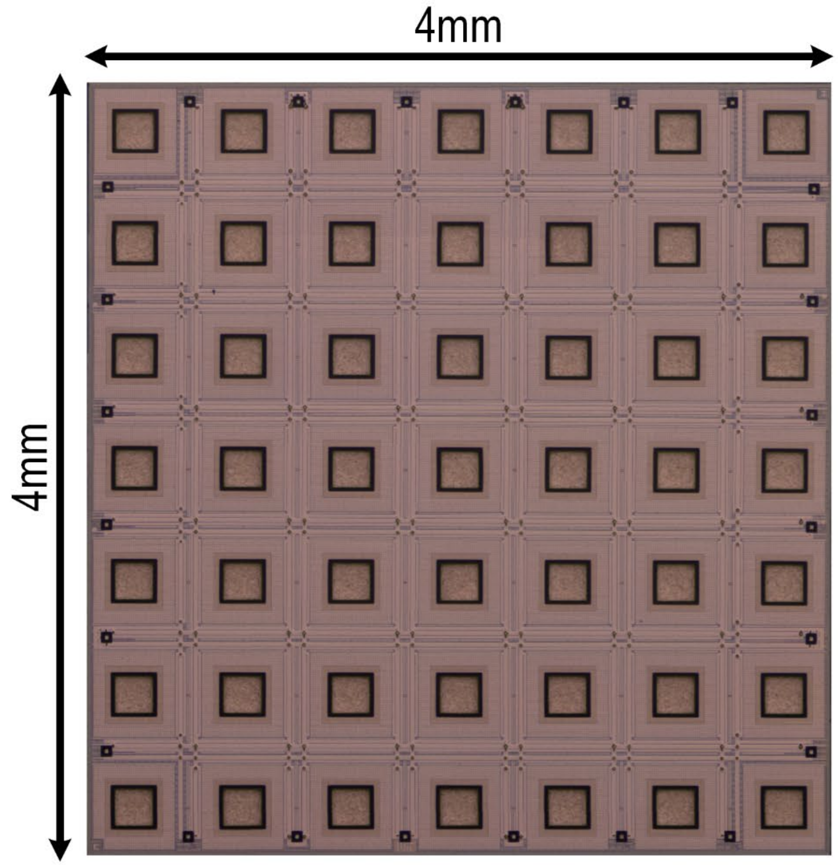


In-Unit Memory for Phase Control

- **80kb memory per antenna**
  - Shift register
- **Phases pre-computed**
  - Pre-loaded at startup
- **Master clock cycles array**
- **Addresses digital bandwidth issues**
- **Enables performance enhancing algorithms**

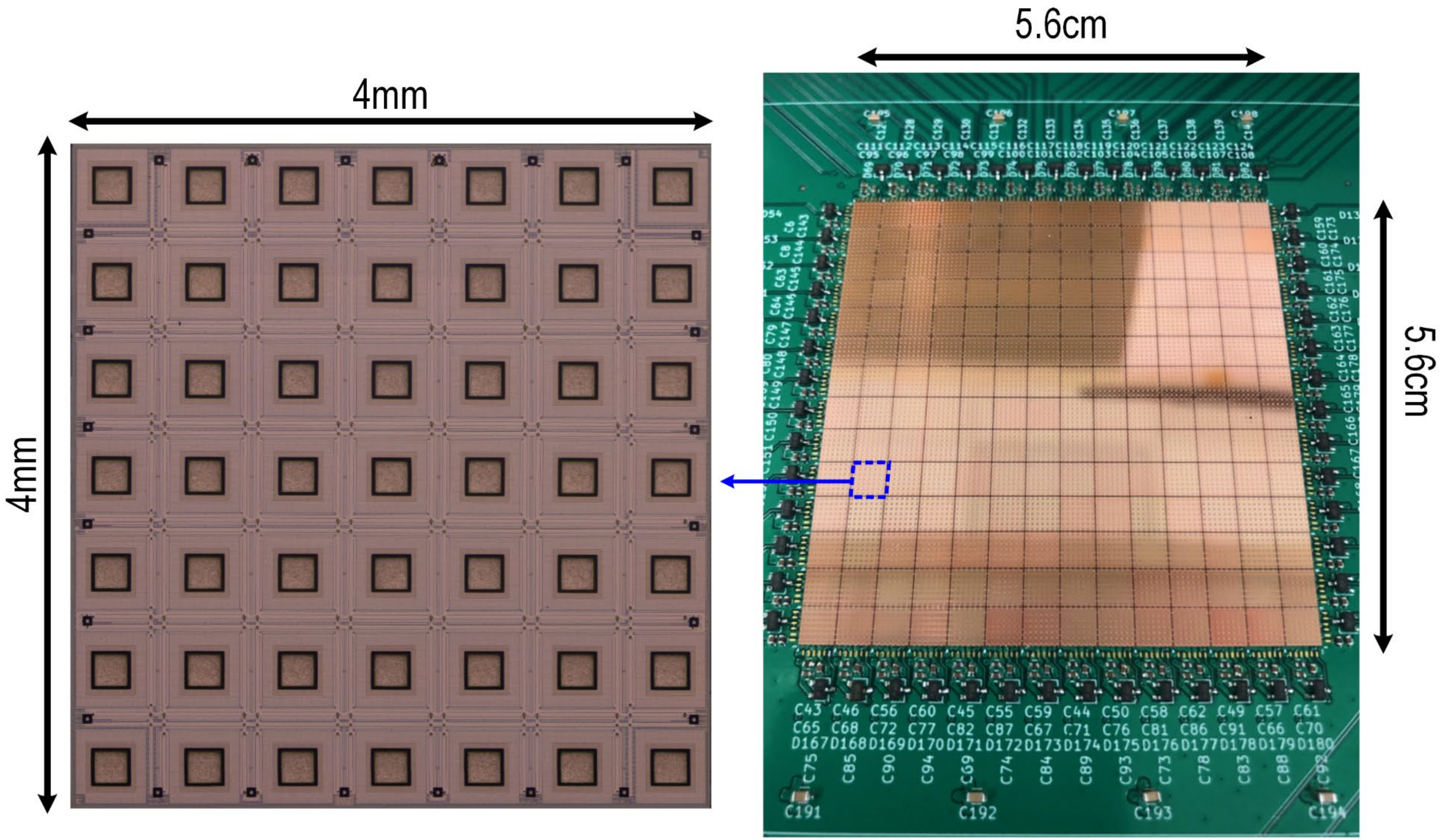


265GHz Reflectarray Die Photo



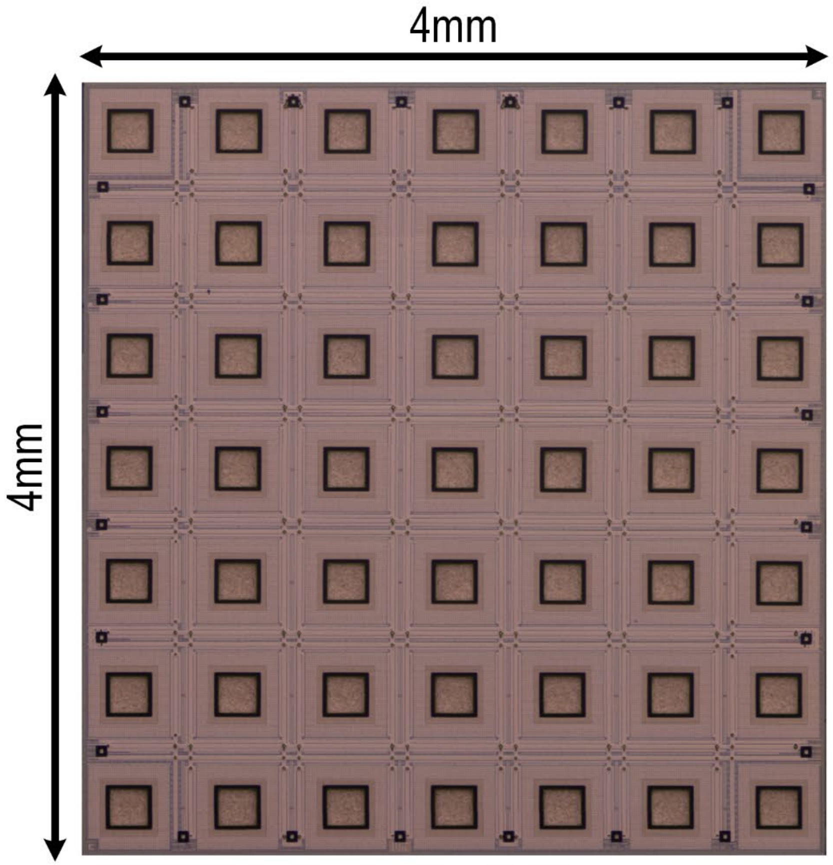
Intel 22nm FinFET

98 × 98 Antenna Reflectarray

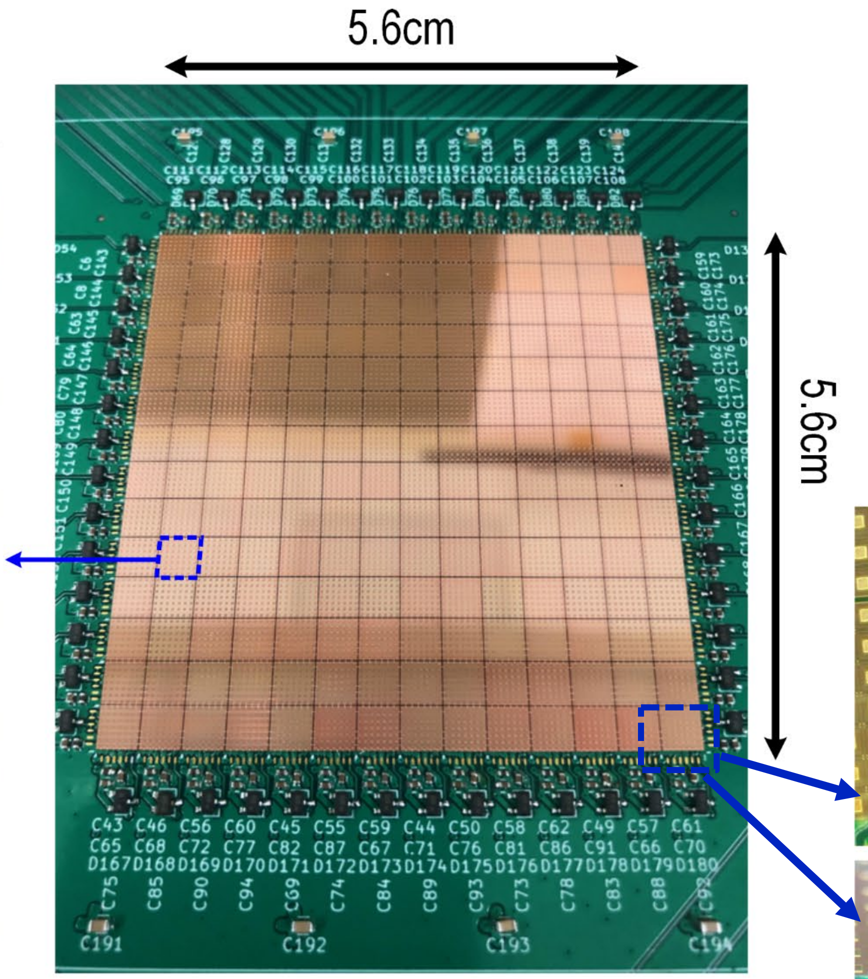


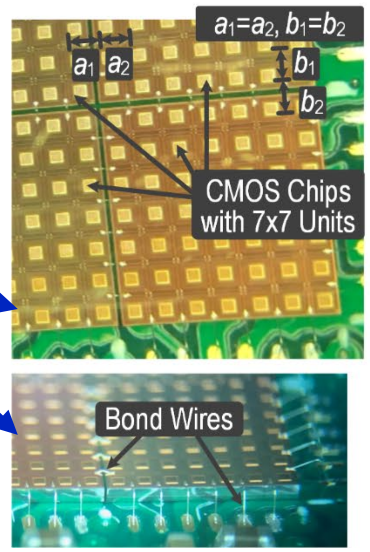
Intel 22nm FinFET

98 × 98 Antenna Reflectarray



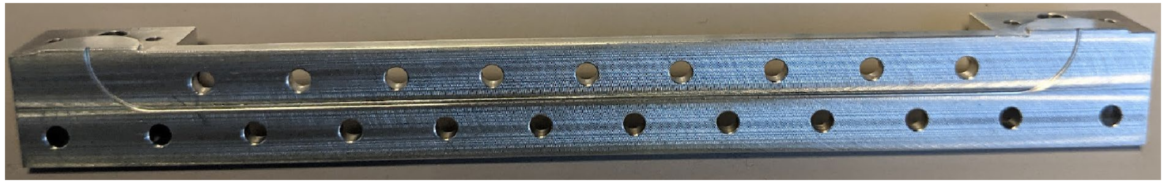
Intel 22nm FinFET

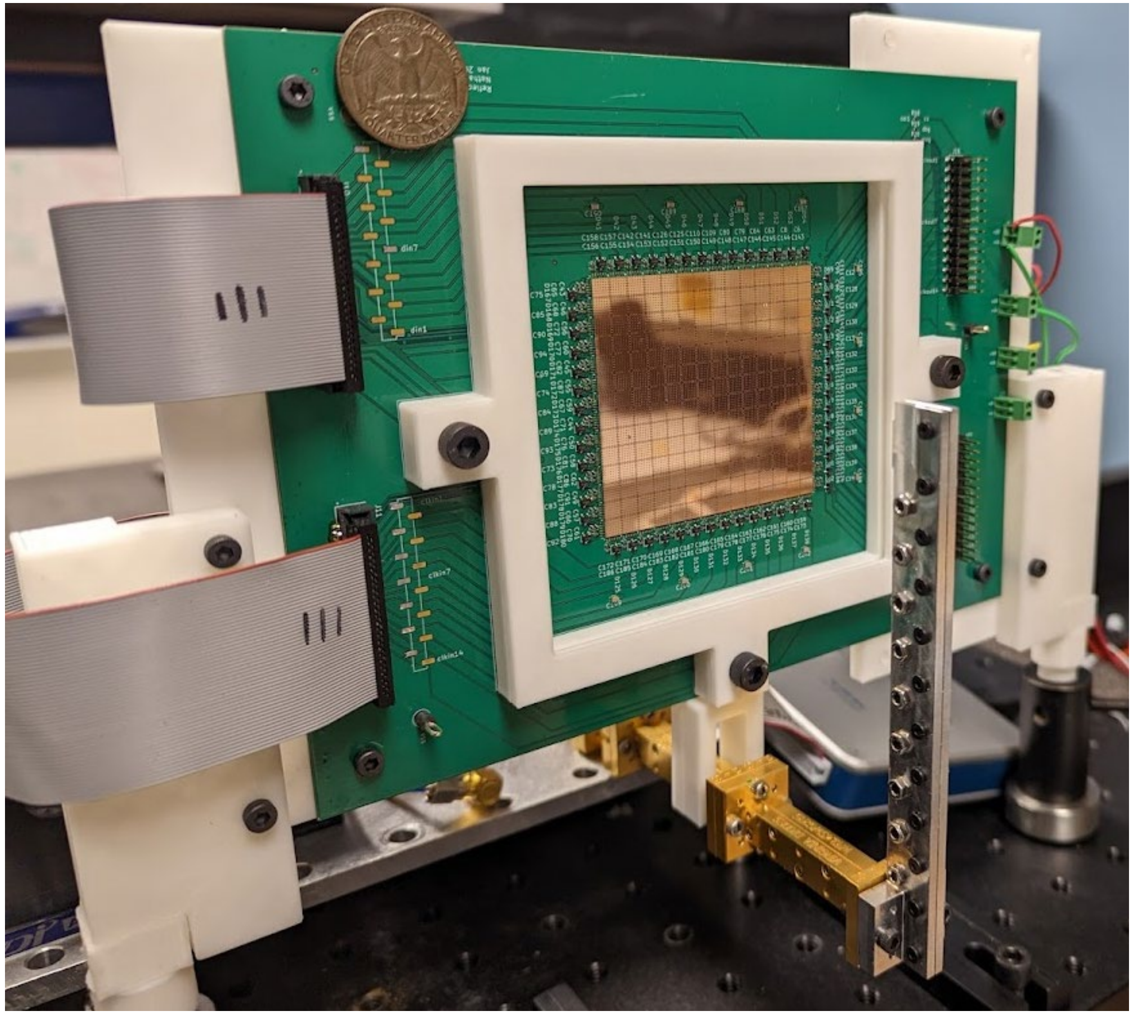




Assembled Reflectarray

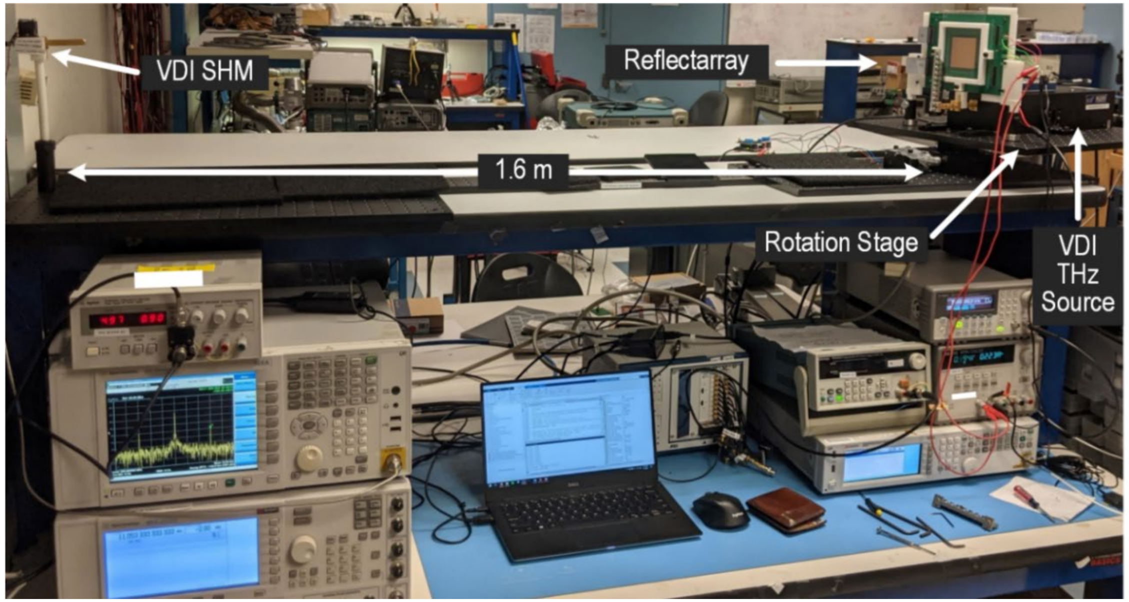
- 265GHz VDI source
- Custom CNC WR3.4 feed
  - 5.8cm feed distance

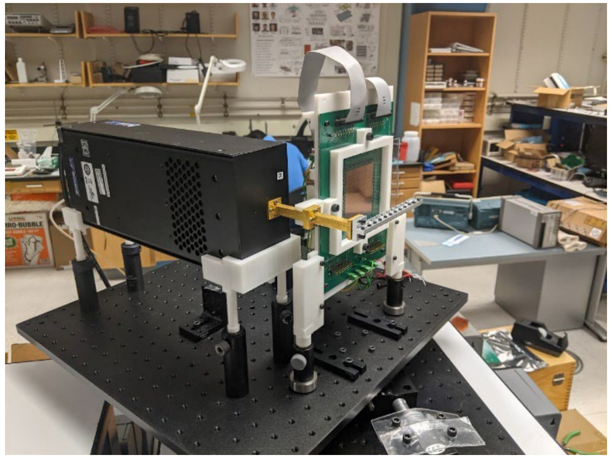


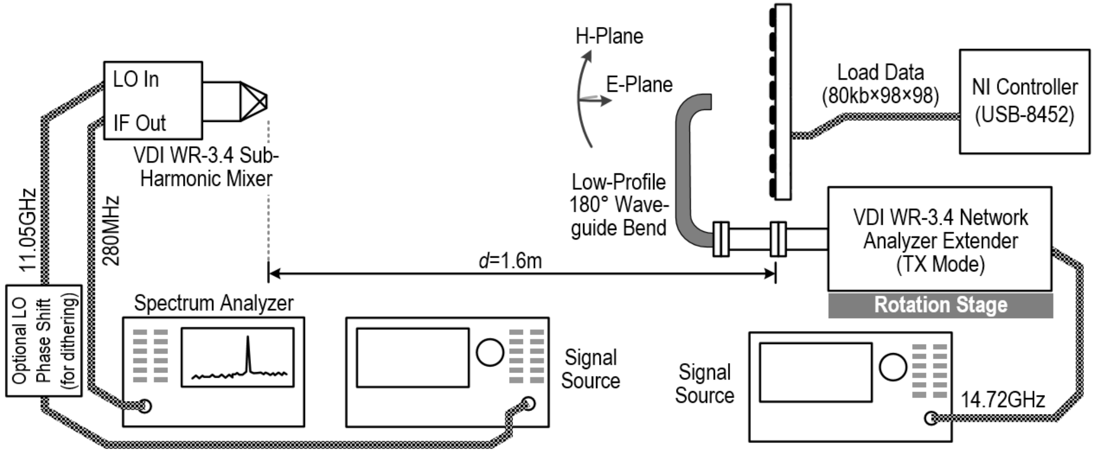


Testbench

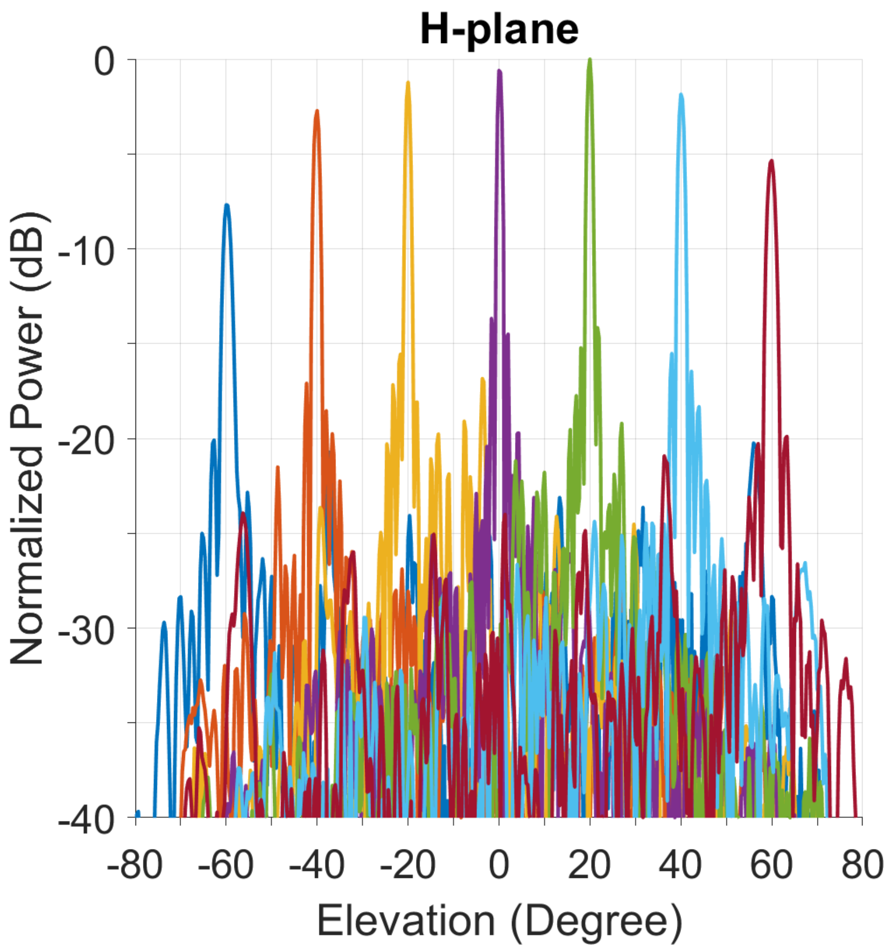
- **Motorized rotation stage**
  - 0.25° steps
- **Static receiver at 1.6m**
  - VDI WR3.4 SHM
- **E-plane/H-plane cuts**



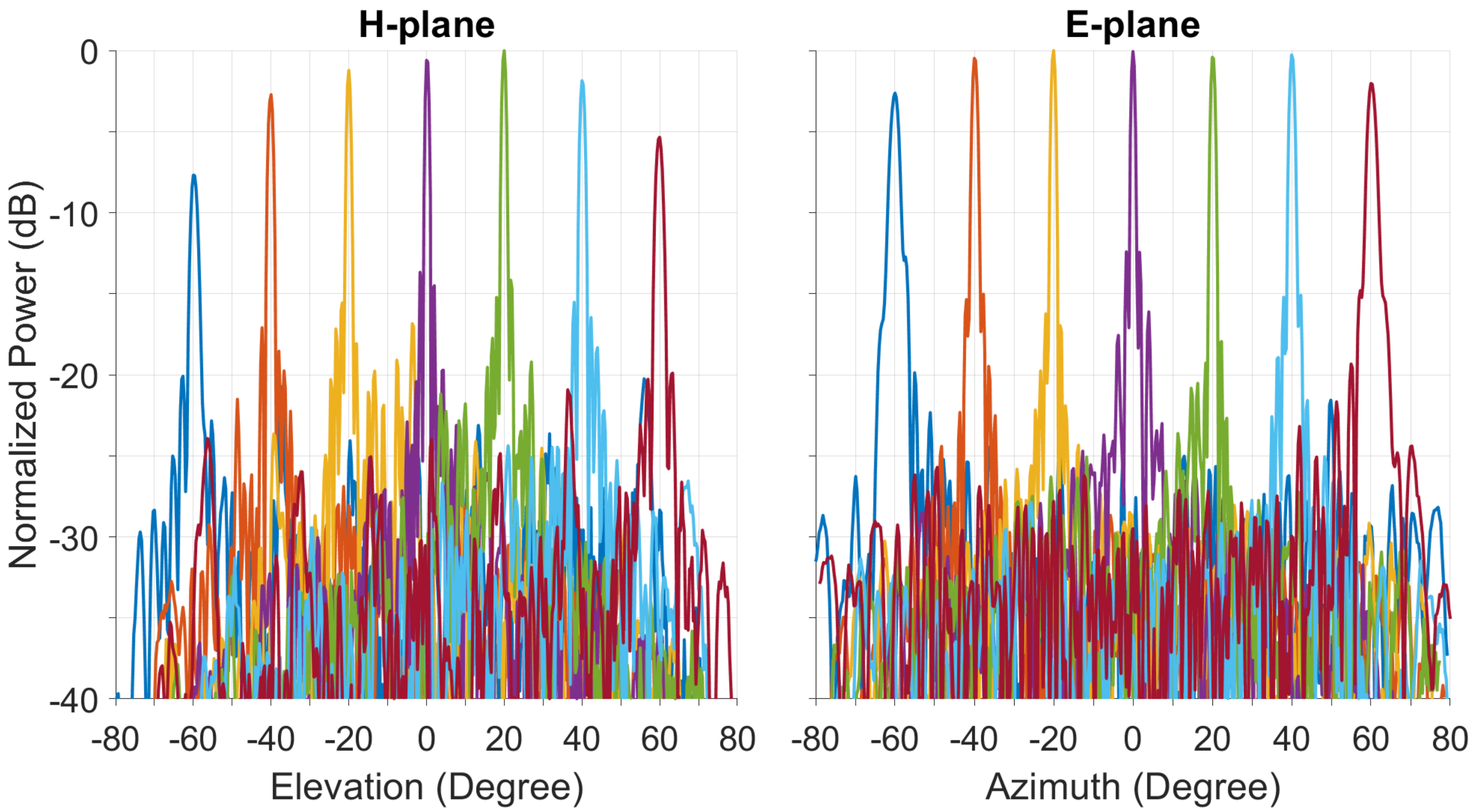




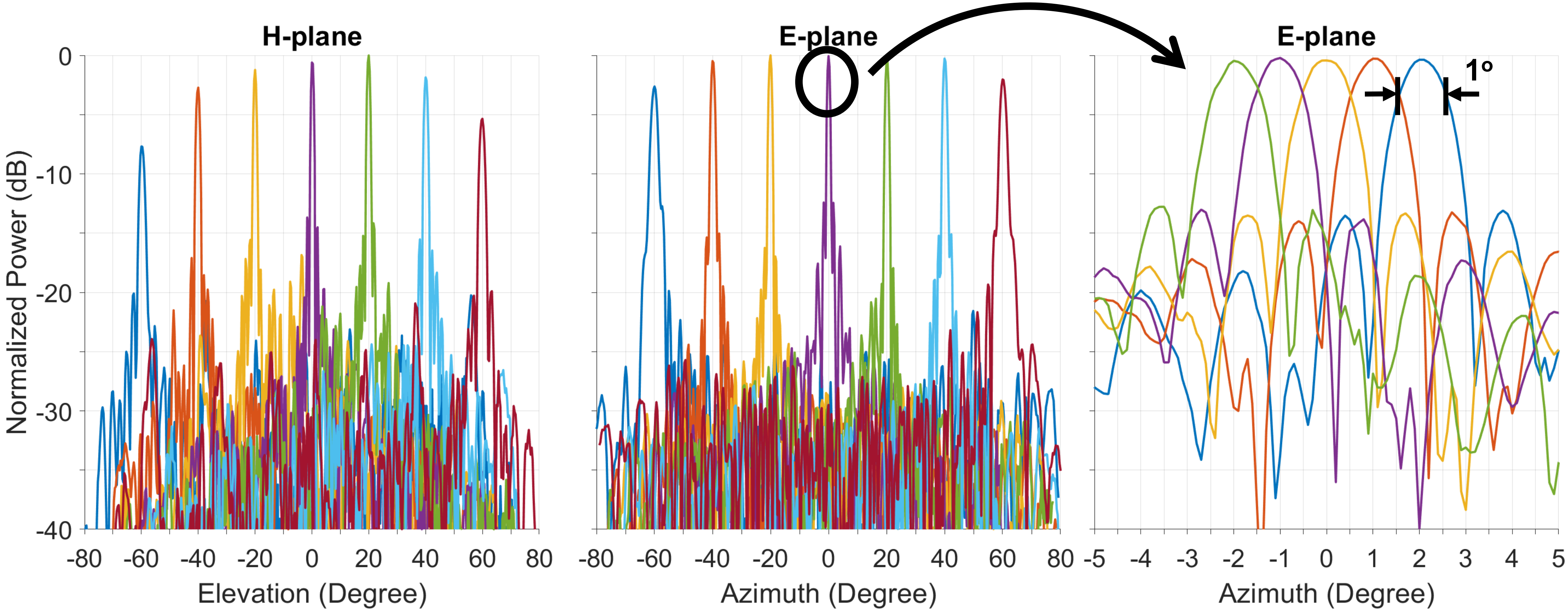
Measured Radiation Patterns



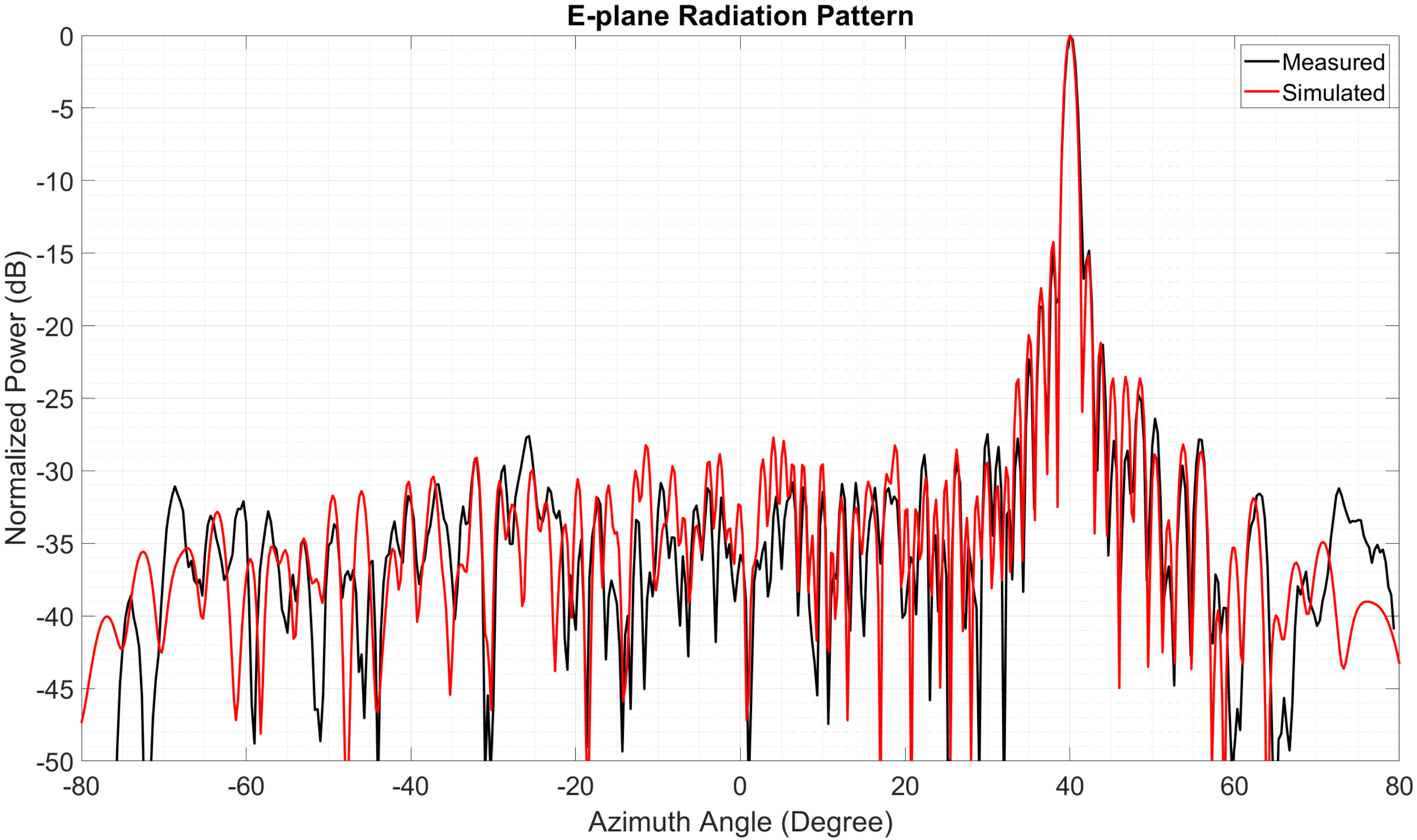
Measured Radiation Patterns



Measured Radiation Patterns

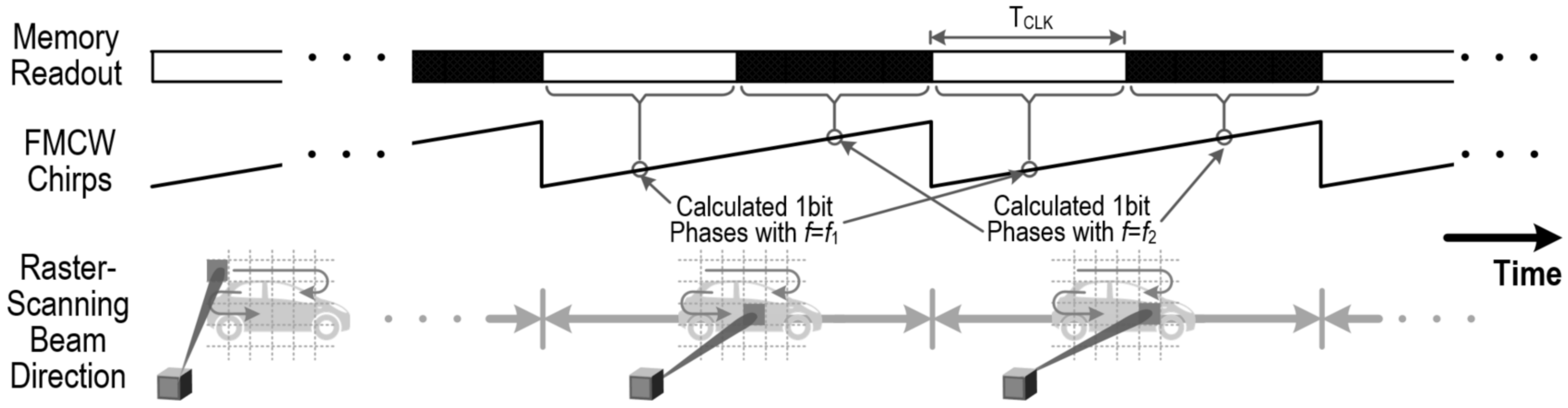


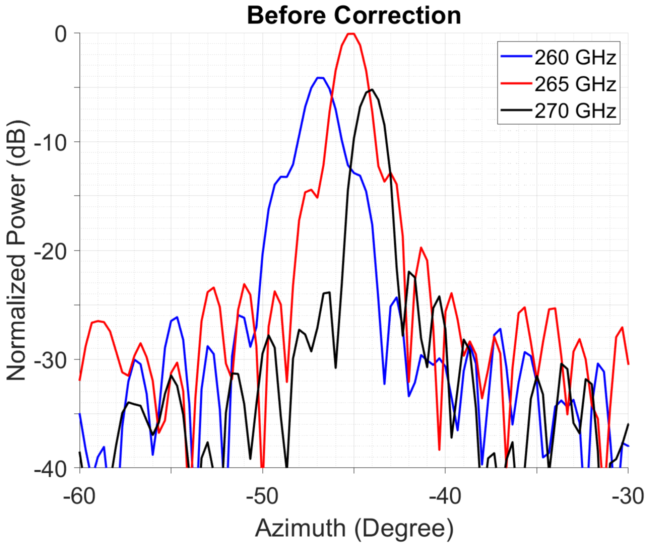
Measured/Simulated Radiation

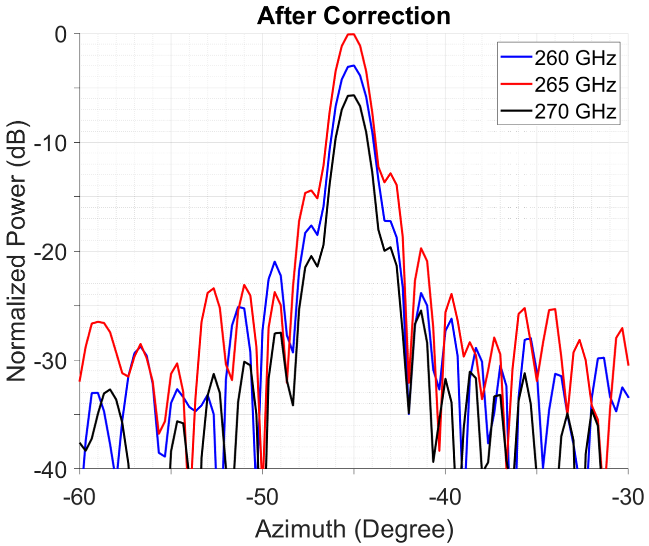


Beam Shaping: Squint Correction

- **Required phases change during FMCW chirp**
  - Beam squint reduces resolution
- **Use memory to update phases during chirp**

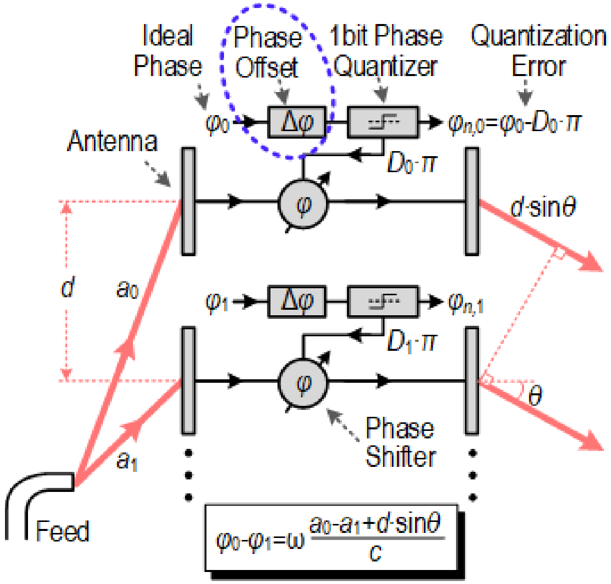


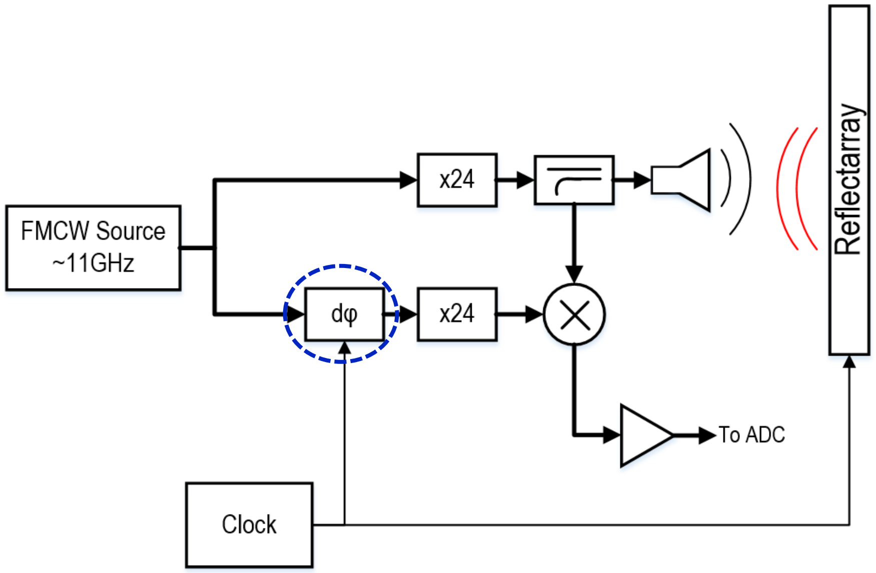




Beam Shaping: Sidelobe Reduction

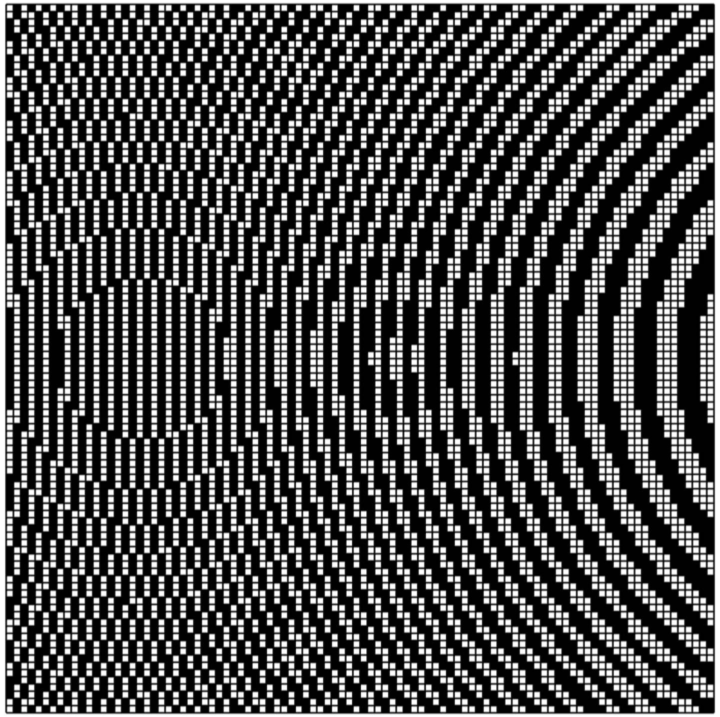
- **Time varying offset added before quantization[3]**
  - Scramble quantization error in sidelobes ➔ average out
  - Mainlobe phase offset is de-embedded at receiver
  - Needs fast change in antenna phases ➔ enabled by memory

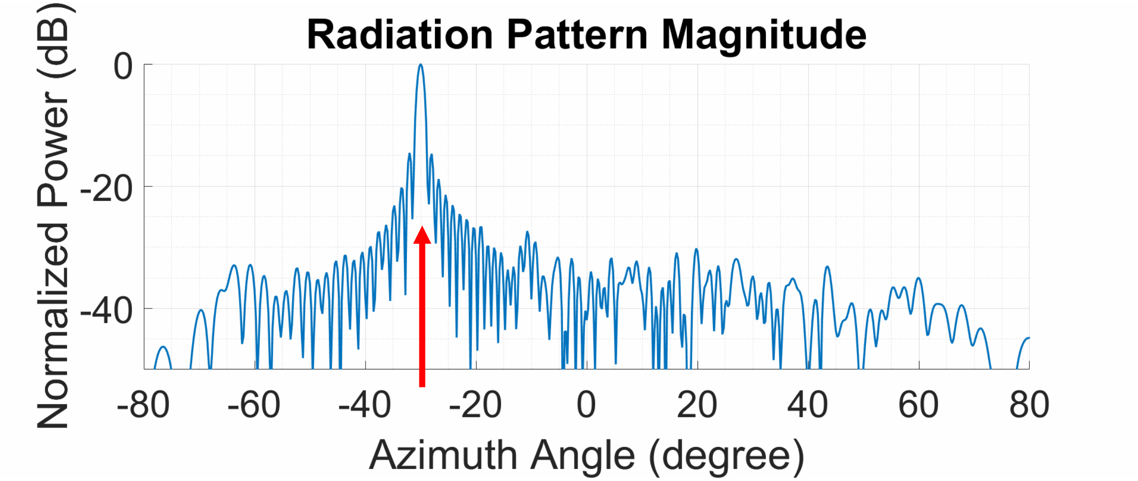


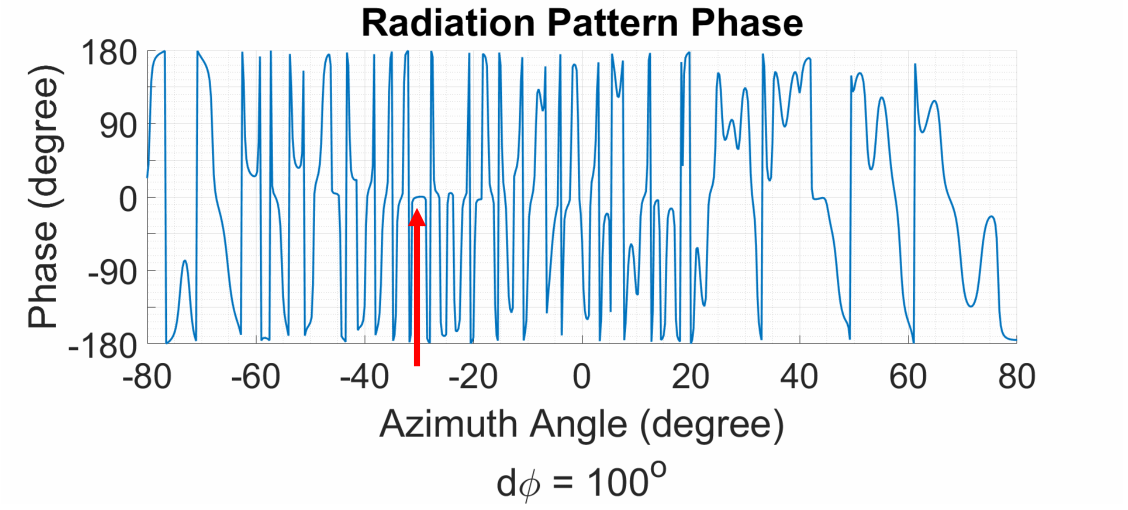


Beam Shaping: Sidelobe Reduction

Quantized Phases

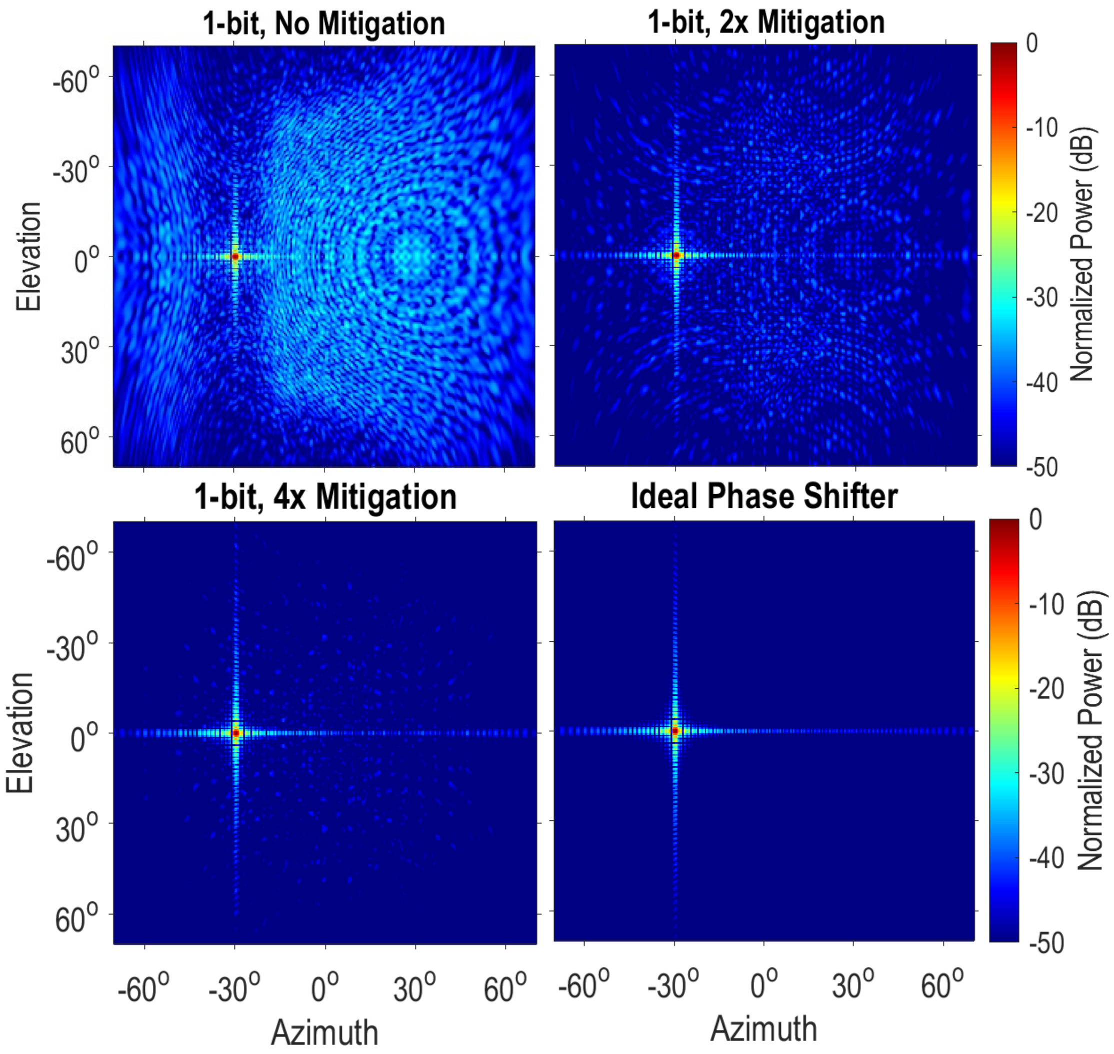






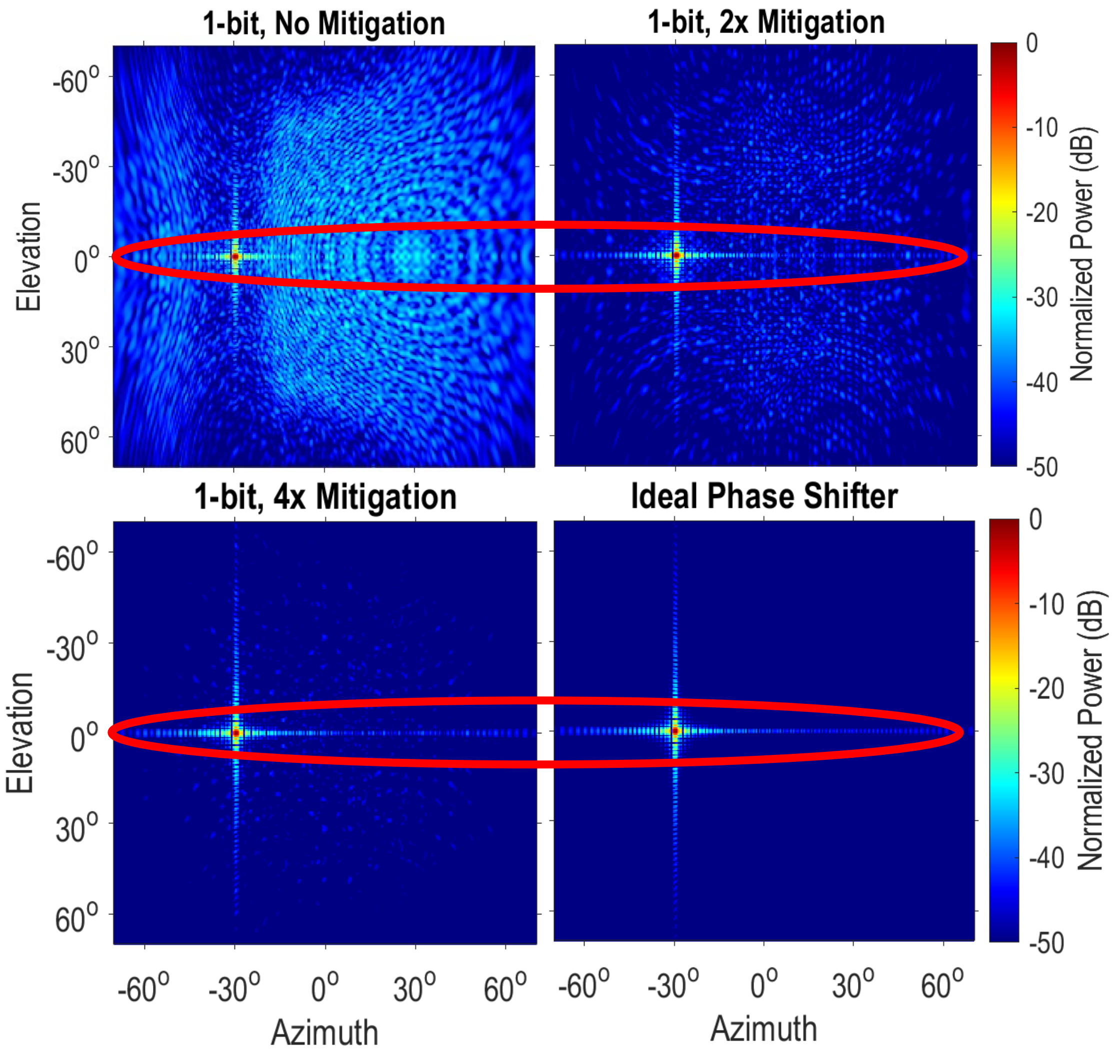
Beam Shaping: Sidelobe Reduction

Simulated 2d pattern

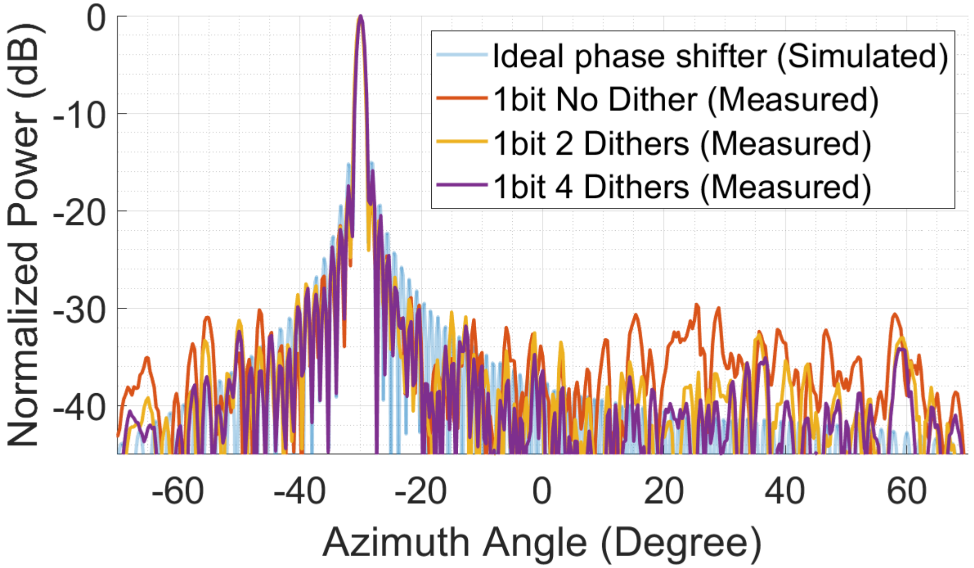


Beam Shaping: Sidelobe Reduction

Simulated 2d pattern



Measured cut

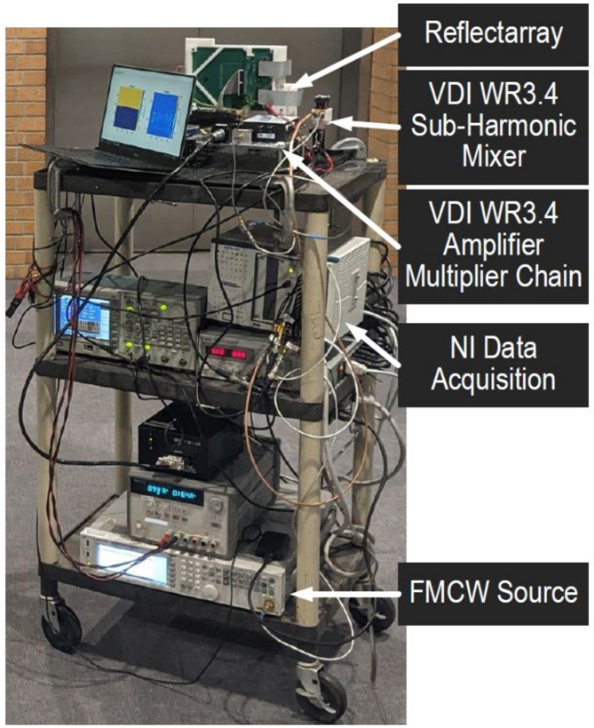


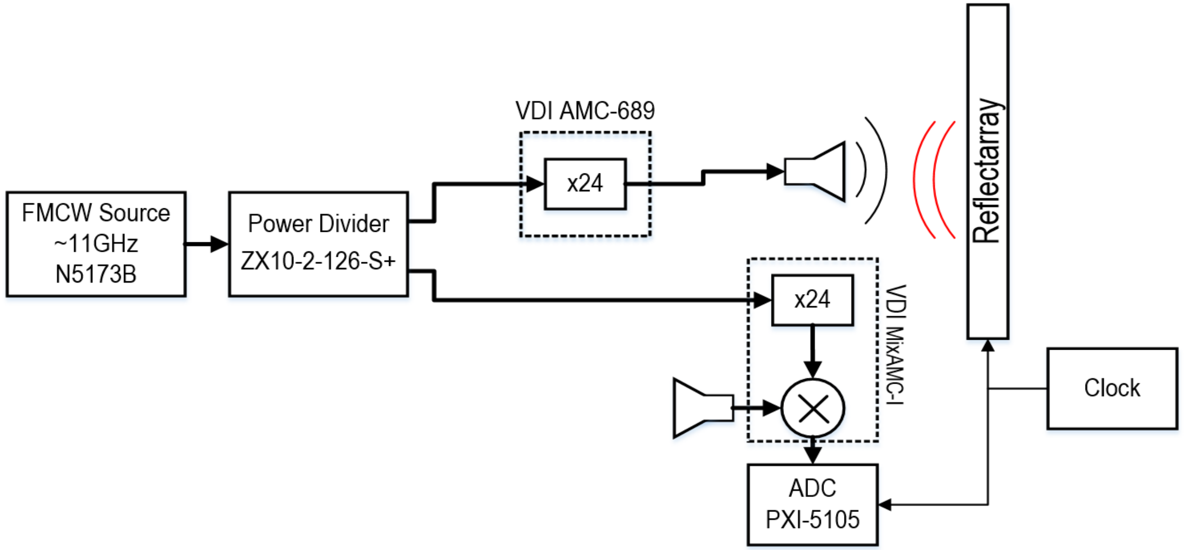
Integrated Sidelobe Power

↓ 4.6dB

Imaging Radar Demo

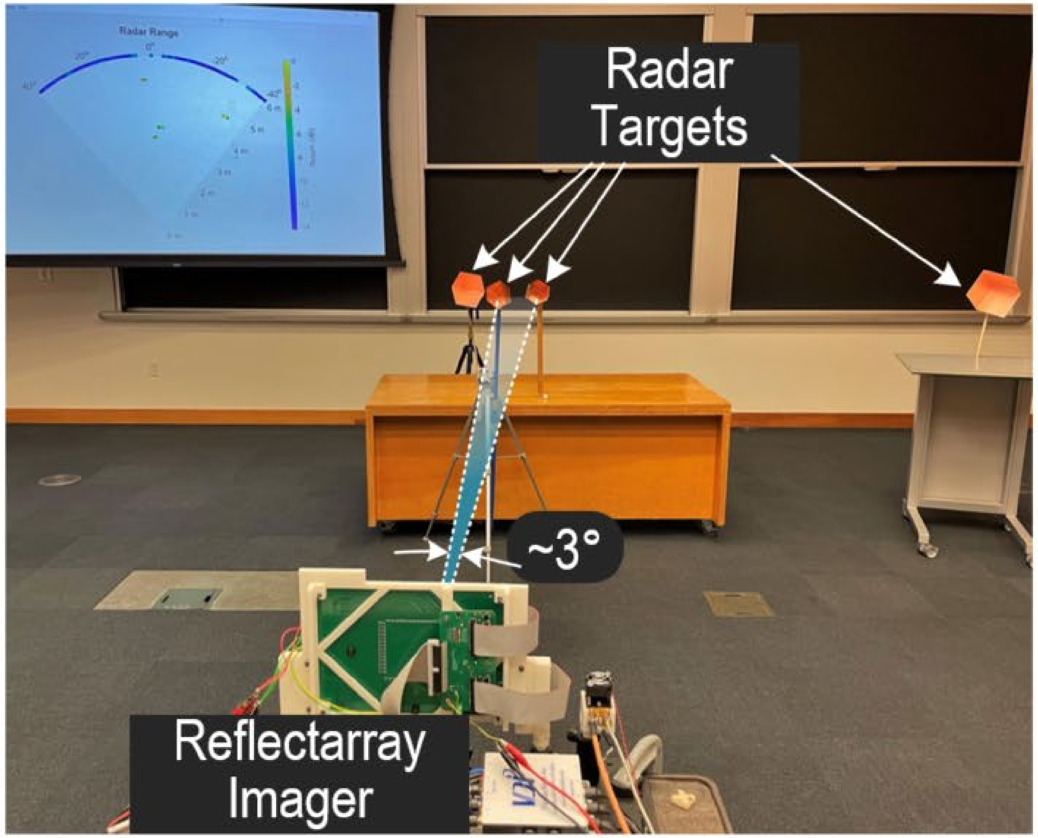
- Raster FMCW beam across scene
- Depth samples at each point
- Process IF into radar image



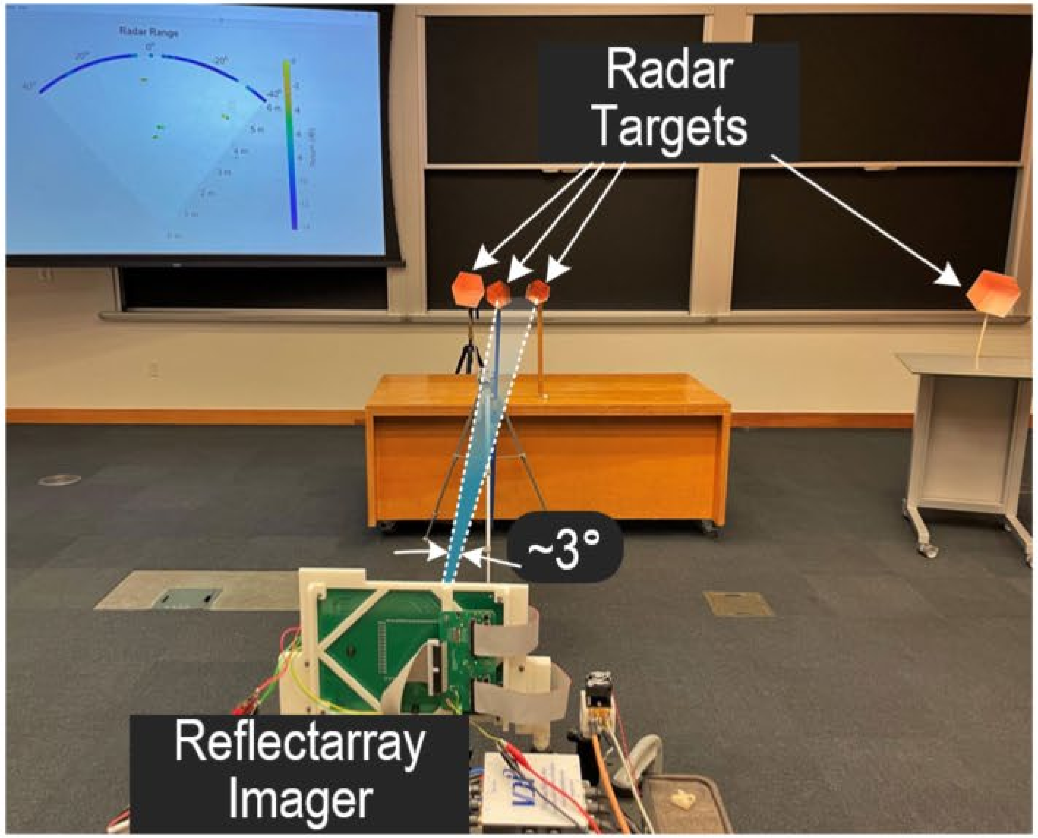


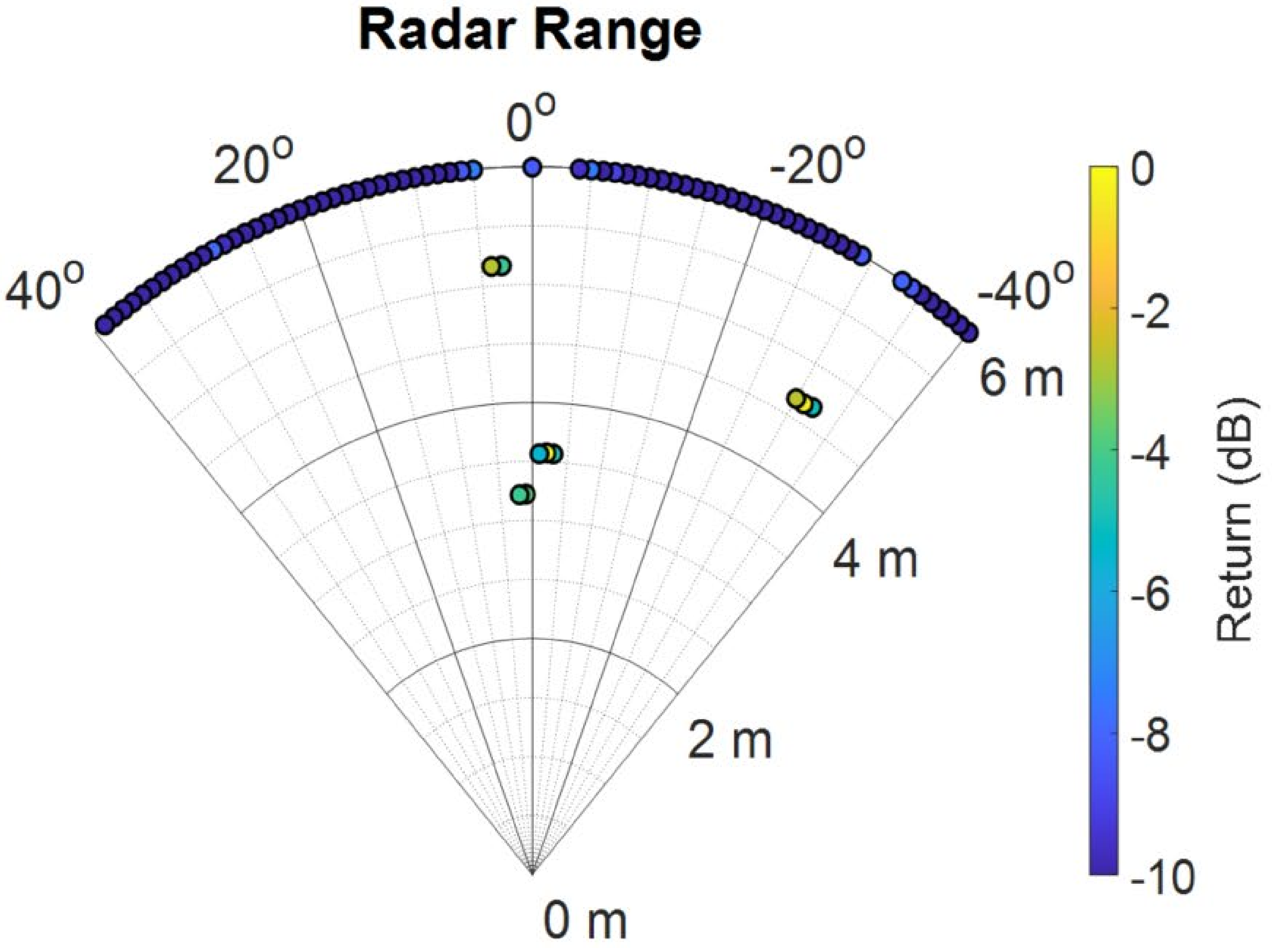
Parameter	Value
Chirp rate (MHz/μs)	62.5
Transmit Power (dBm)	20
Transmit Bandwidth (GHz)	1.92
Frequency (GHz)	263~265
Range Resolution (cm)	7.8
Pixel Integration Time (ms)	15

2D Radar Imaging



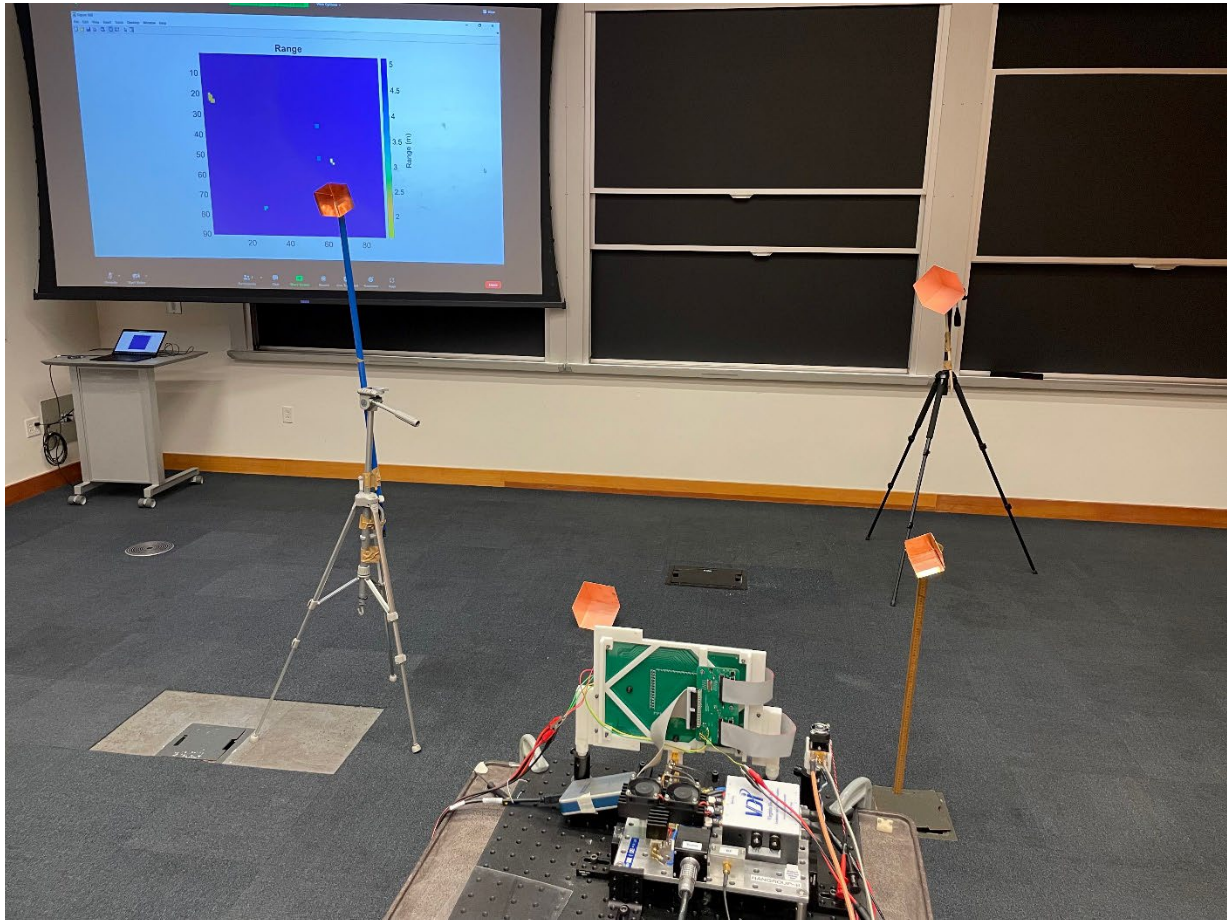
2D Radar Imaging



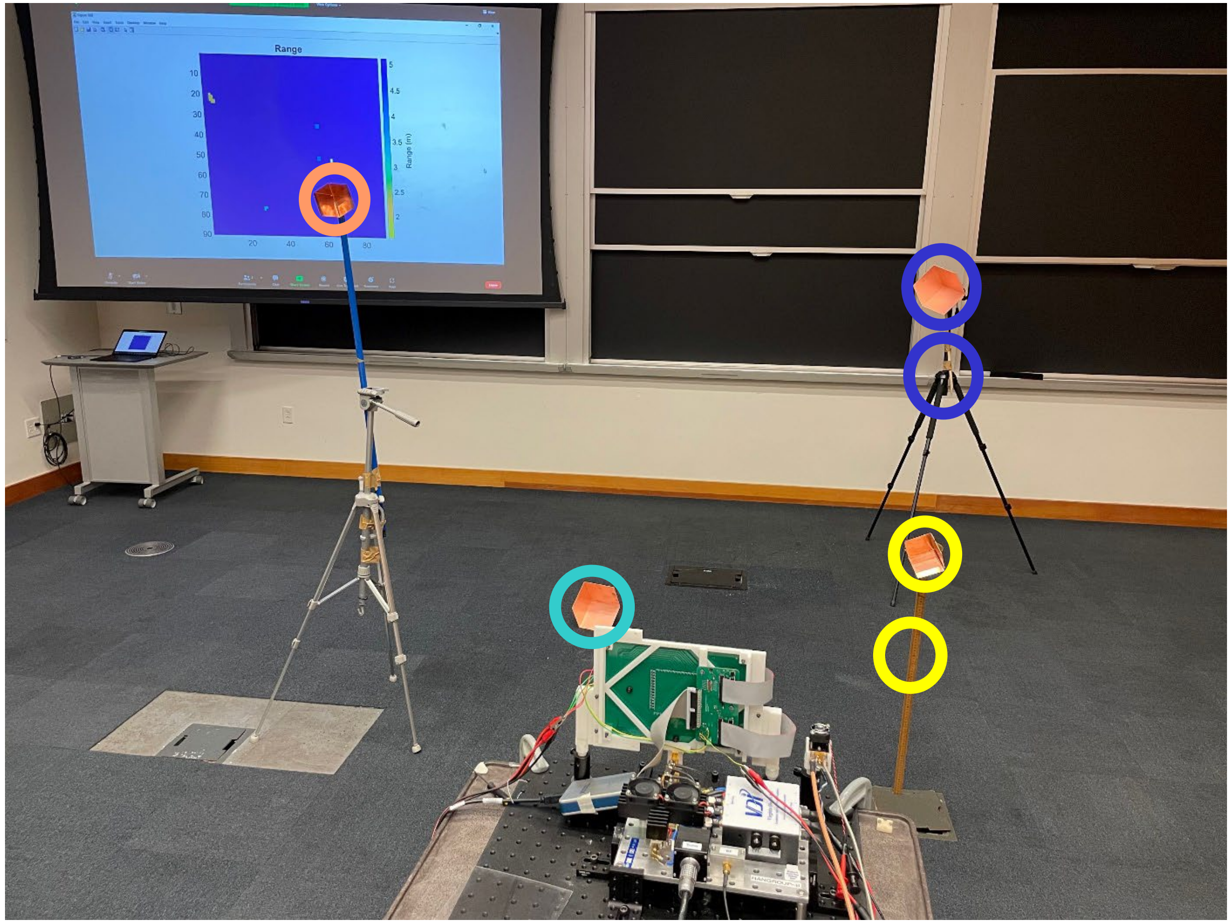


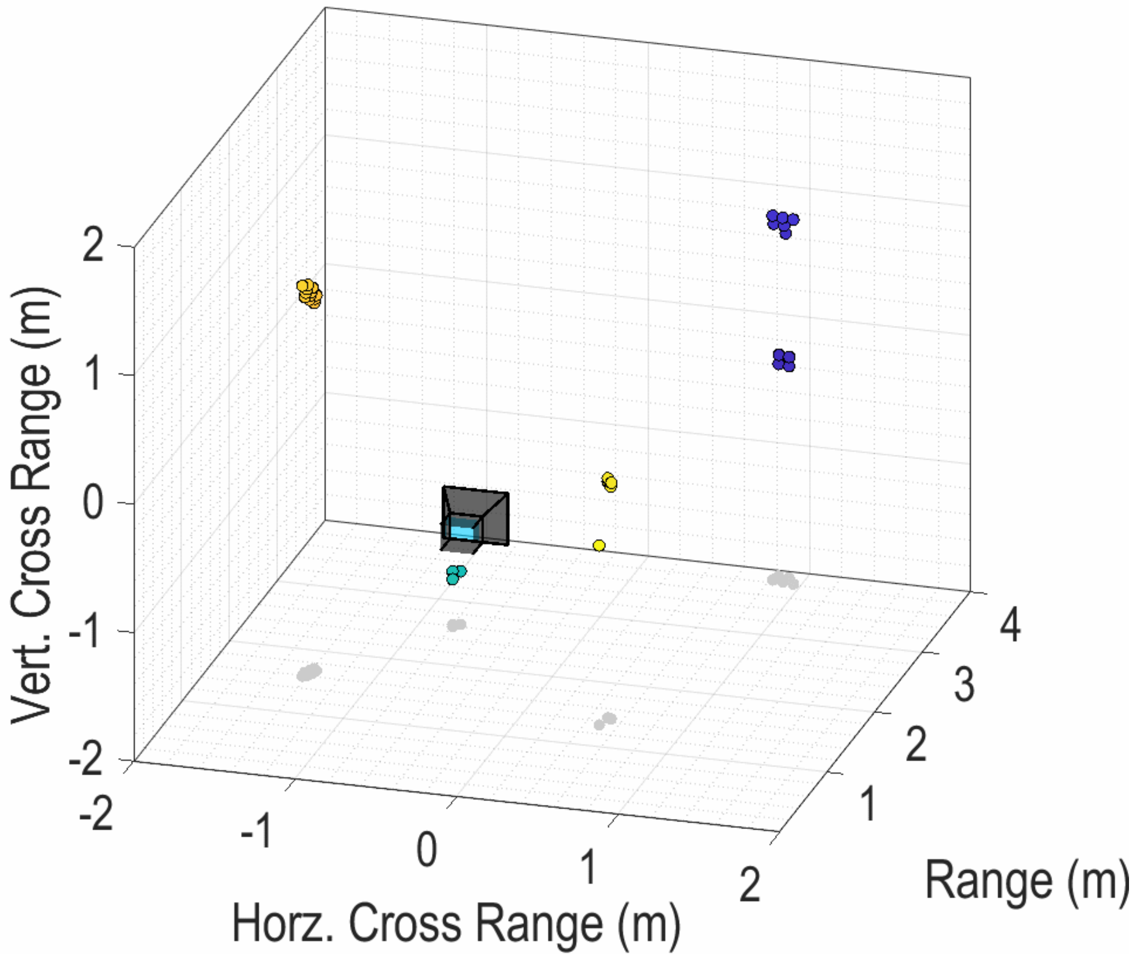
*1 degree step per dot

3D Radar Imaging



3D Radar Imaging





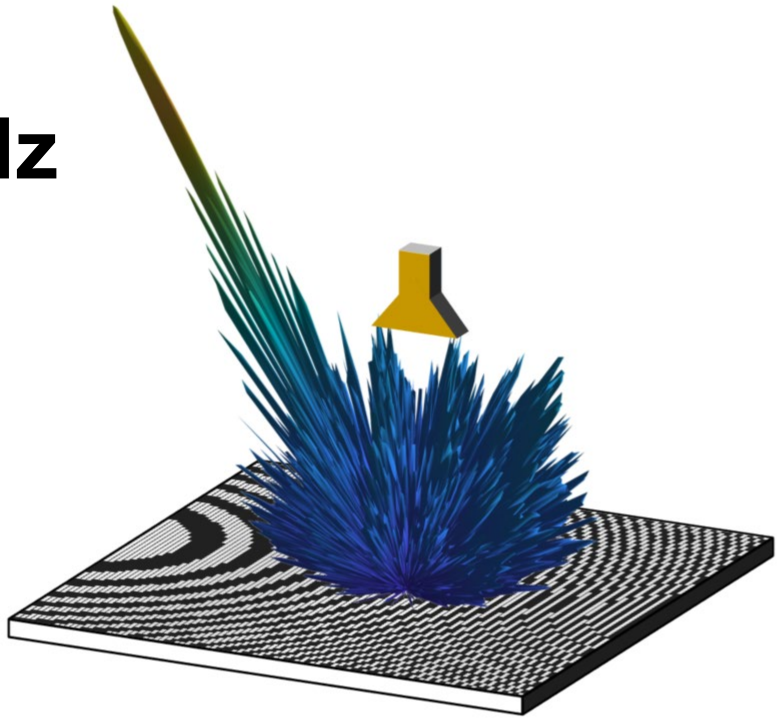
Performance Comparison

	Freq. (GHz)	Beam Forming Approach	Array Size	3dB Beam-width	Steering Range	Automatic Beam Profile Correction?	Technology	Area	Power Consumption	3D Sensing Demo?
ISSCC 2021 [1]	380	Active-Driven Beam Squint Antenna	2x1	~15° (1)	±40°	No	65nm CMOS	3mm^2	0.14W (TX) 0.16 (RX)	NA
ISSCC 2021 [2]	450	Active Reconfigurable Array+Si Lens	3x7	~7° (2)	±28° & ±8°	No	65nm CMOS	4mm^2	0.051~0.095W	
SPIE 2019 [3]	235	Reflect Array (Tiled GaN Chips)	32x32 (3)	~3°	> ±40°	No	GaN + Silicon Micromachining	31mm^2 (Chip) 500mm^2 (Array)	NA	
Nat. E. 2020 [4]	300	Transmit Array (Tiled CMOS Chips)	24x24	~10° (4)	±30°	No	65nm CMOS	4mm^2 (Chip) 16mm^2 (Array)	0.025W (5) (f_{clk}=5GHz)	
This Work	260	Reflect Array (6) (Tiled CMOS Chips)	98x98	1°	> ±60°	Yes	22nm CMOS	16mm^2 (Chip) 3100mm^2 (Array)	0.85W (7) (f_{clk}=100kHz)	Yes

(1) Achieved only in one dimension.
(2) Achieved through a Si lens (R=5mm).
(3) ~50% of array units not functioning
(4) Estimated from the simulated value
(5) Dynamic power driving phase shifter switches.
(6) The only all-inclusive solution requiring no external data control during beam scanning
(7) Dynamic power driving 98x98x2 phase shifter switches and 780Mb built-in cyclic memory

Conclusion

- **Towards high angular resolution THz antenna arrays**
  - Reflectarray architecture
  - 1 bit passive phase shifter design
  - Scalable architecture
  - Local memory
- **Demonstrated electronically steered 1° beam over 120° window in 2D**
- **Digital Beam Shaping via local memory**
- **Solid state 3D THz radar imaging**



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- **Thomas Keating**
  - THz absorbing materials

Thank You

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