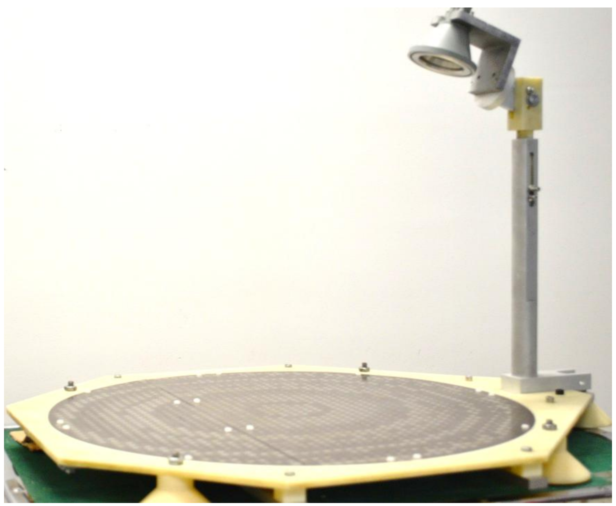
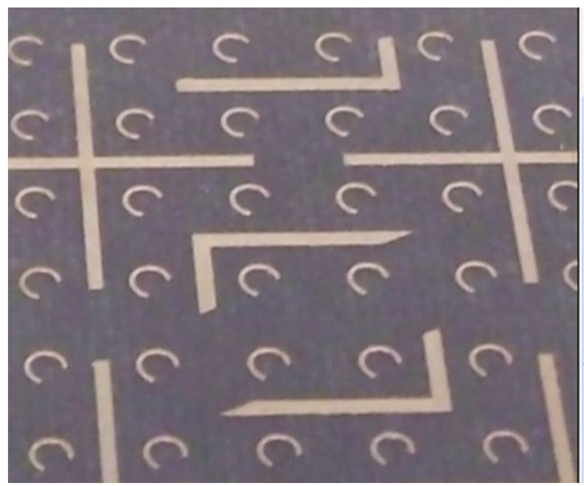
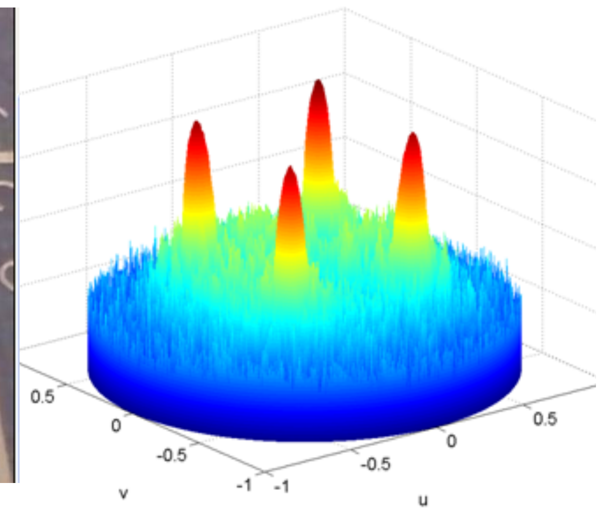
Progress in Reflectarray Antenna Research: From Enhanced Frequency Features to Advanced Radiation Capabilities







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OUTLINE

- Introduction of reflectarray antennas
- Reflectarray analysis and synthesis methods
- RA with enhanced frequency features
- RA with advanced radiation capabilities
- Conclusions

Antenna Classifications

Low gain antenna

1. Gain < 10 dBi
2. Examples:
   * Dipole and loop
   * Microstrip and slot
3. Applications: cell phone, laptop, PDA, WLAN, etc.

Middle gain antenna

1. 10 < Gain < 20 dBi
2. Examples:
   * Horn antenna
   * Spiral antenna
3. Applications: base stations, antenna & EMC measurement

High gain antenna

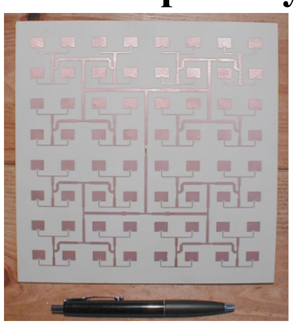
1. Gain > 20 dBi
2. Examples:
   * Reflector, lens
   * Antenna array
3. Applications: space and satellite comm.

High Gain Antenna Development

Parabolic Reflector

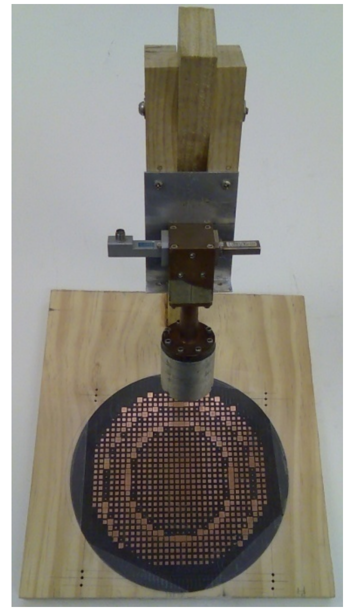
- ○ **Simple, well developed**
- ➢ **Bulky, limited beam scan**

Microstrip Array



- ○ **Low profile, flexible beams**
- ➢ **Power loss in the feed network**

New high-gain antennas



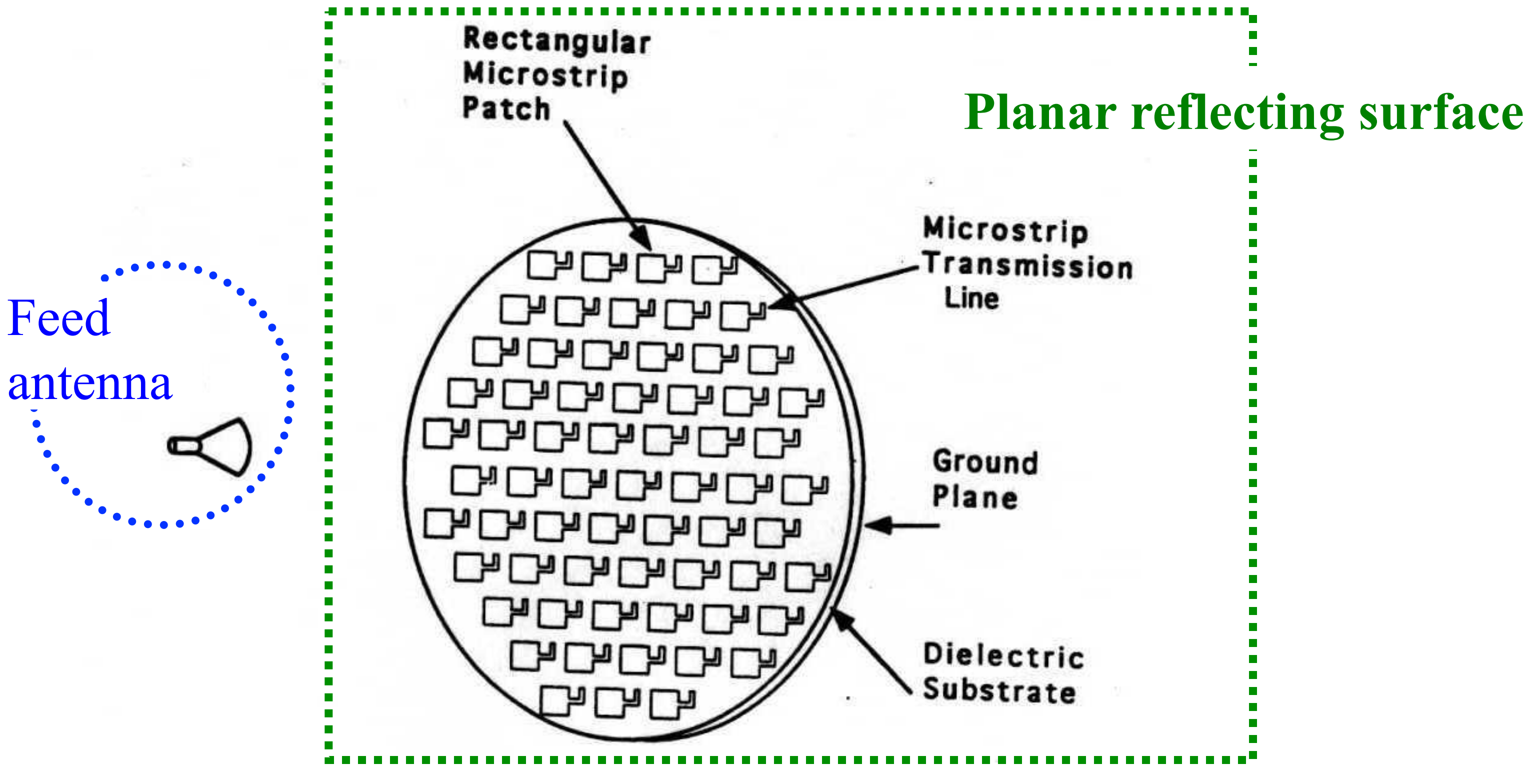
Reflectarray

- ○ Low profile
- ○ Low mass
- ○ Easy to fabricate
- ○ Easy for circuitry integration
- ○ **Element phase: individual control**

- ○ Beam-scanning reflectarrays
- ○ Amplifying reflectarrays
- ○ Multi-beam reflectarrays
- ○ Contour-beam reflectarrays

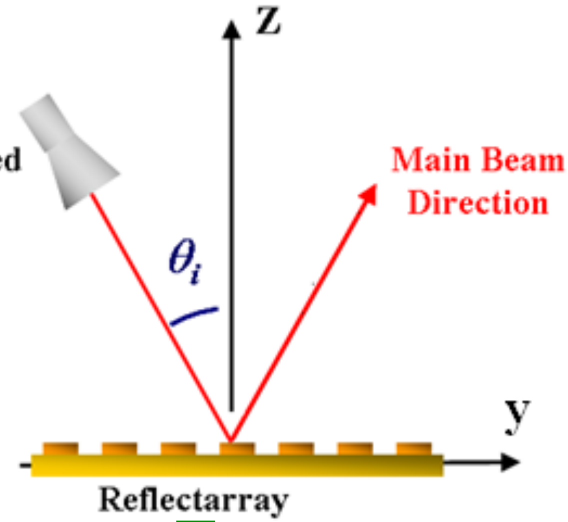
Images are from www.deepspace.jpl.nasa.gov and www.activefrance.com/Antennas

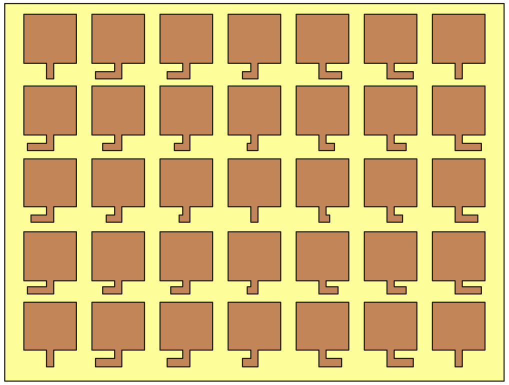
Reflectarray Antennas



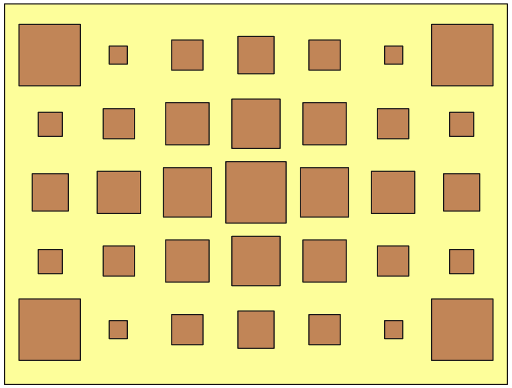
1. R. E. Munson and H. Haddad, "Microstrip reflectarray for satellite communication and RCS enhancement and reduction", U.S. patent 4,684,952, August 1987.
2. J. Huang, "Microstrip reflectarray antenna for the SCANSCAT radar application", JPLPublication No. 90-45, Nov. 15, 1990.
3. D. M. Pozar and T. A. Metzler, "Analysis of a reflectarray antenna using microstrip patches of variable size", Electronics Letters, April 1993.

Phasing Elements in Reflectarrays

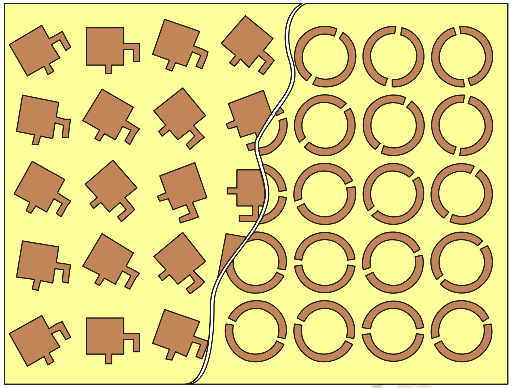




Phase/time delay lines



Variable element size

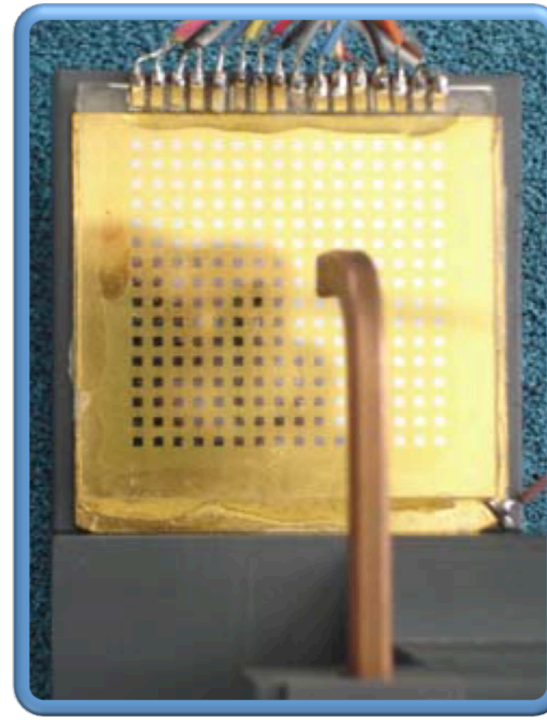


Element rotation

Reflectarray Applications

3m aperture dual-frequency RA

Integrative design of RA & solar panels



77GHz RA using LC material and LTCC technique

JPL, NASA

GAC, ESA

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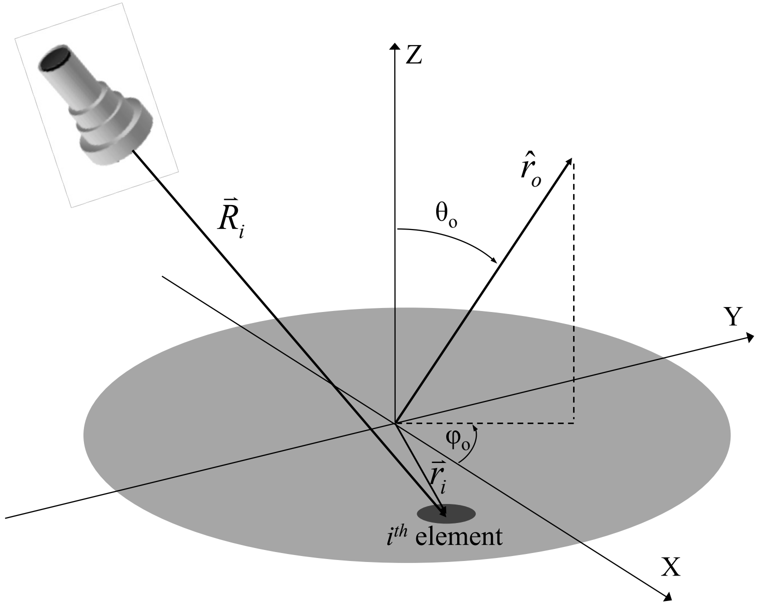
Reflectarrays Design Overview



- **Design goals:**
  - **Radiation patterns**
  - **Beam direction**
  - **Directivity**
  - **Gain and efficiency**
  - **Bandwidth**
  - **Axial ratio**

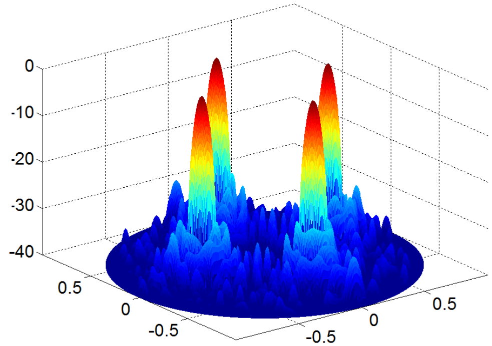
- **Design parameters:**
  - **Aperture size (D), feed location (f/D), and feed pattern (q value).**
  - **Phase elements: patch, ring, dipole; substrate thickness & permittivity.**
  - **Phasing approaches: variable size, element rotation, delay lines.**

Reflectarray Design Engine

Analysis Tools

Planar and Conformal Systems

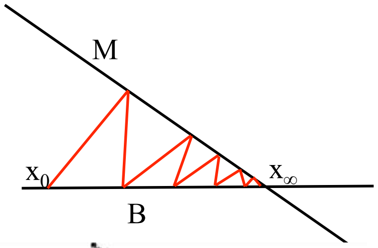
- **Radiation Analysis**
  Array Theory
  Aperture Field
  Full-wave
- **Efficiency Analysis**
  Illumination efficiency
  Spillover efficiency
- **Phase Error Analysis**

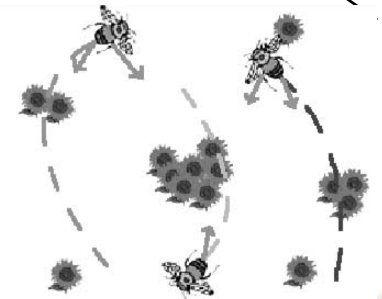


Optimization Tools

Phase-only Optimizations

- **Alternating Projection Method (APM)**
- **Particle Swarm Optimization (PSO)**

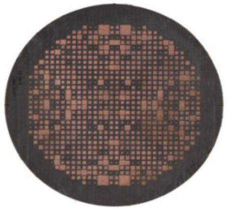


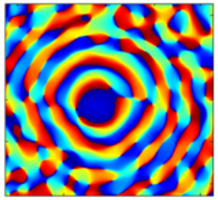


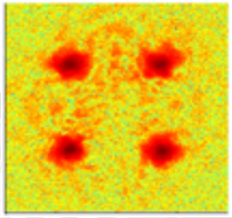
Measurement Tools

Near-Field Measurements

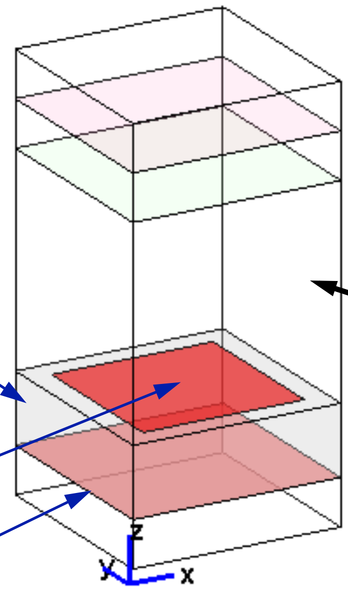
- **Spectral NTFF**
  Principal plane pattern cuts
- **Microwave Holography**
  Measured aperture fields for accurate simulations



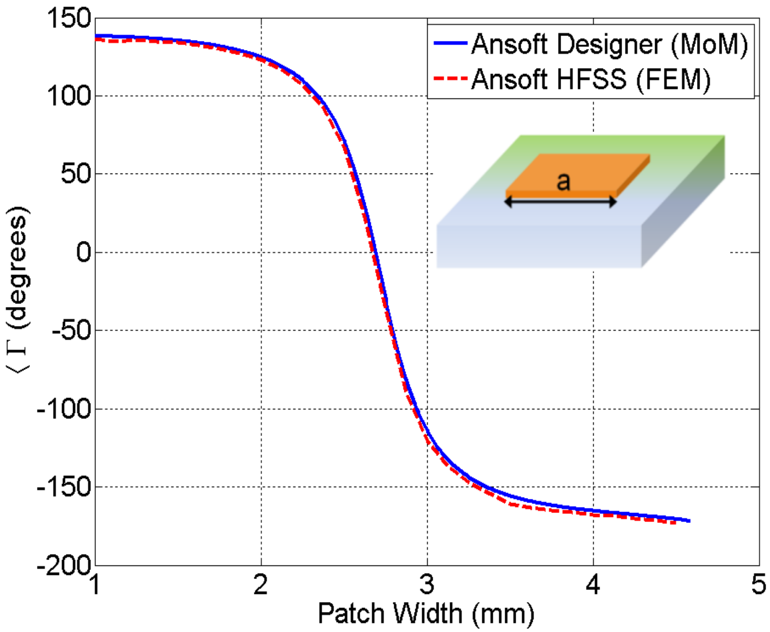




Element Analysis



FDTD model



Full-wave analysis of unit cell:

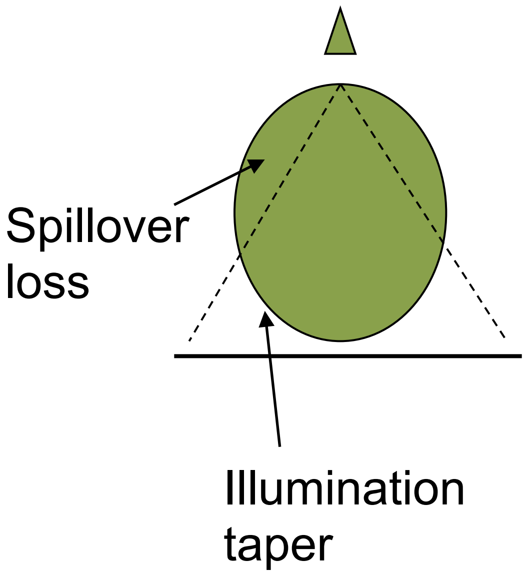
- **Infinite array approach: in-house FDTD program, Ansoft Designer, HFSS, CST, FEKO …**
- **Incident angle, phase range, phase quantization, quasi-periodic**

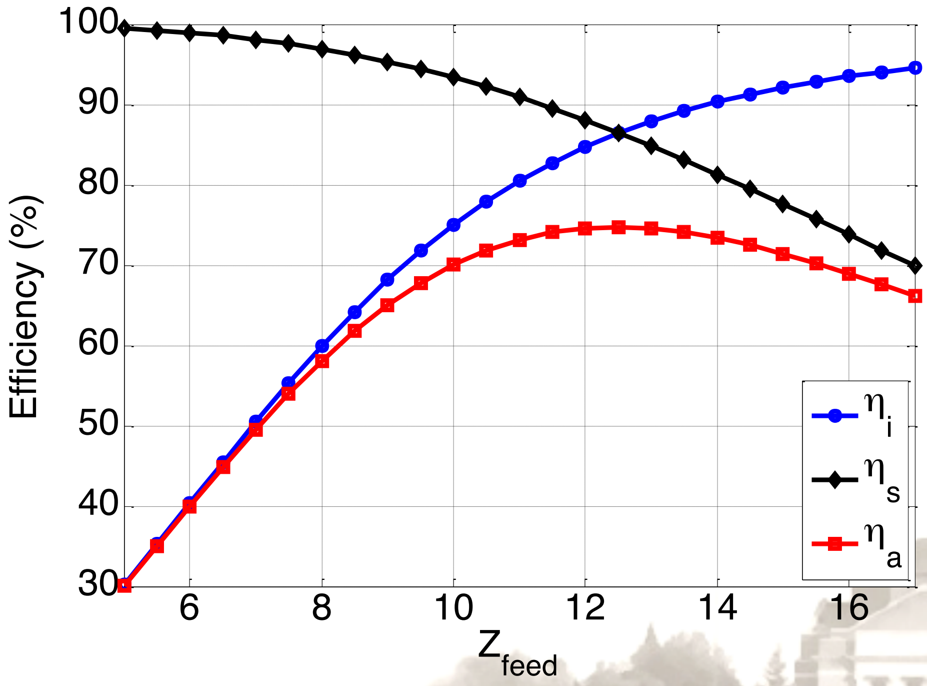
Efficiency Analysis

Aperture efficiency (η_A):

$$\eta_A = \eta_s \times \underbrace{\eta_t \times \eta_p}_{\eta_i} \times \eta_o$$

η_s - spill over
η_i - illumination
η_t - taper
η_p - *phase*





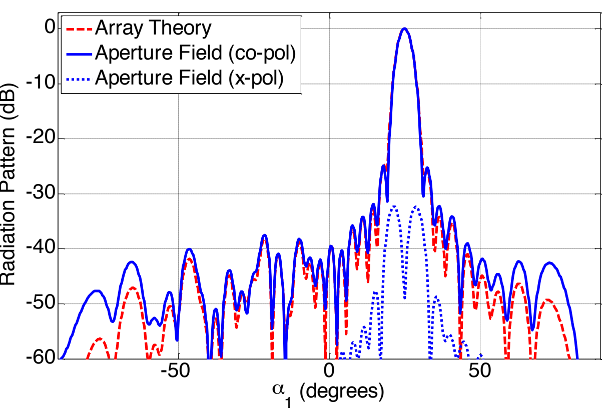
Radiation Pattern Analysis

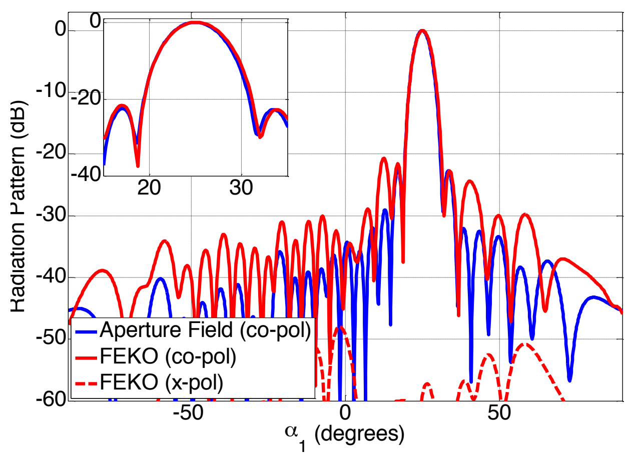
- Array theory approach
- Aperture field method
- Full wave simulation

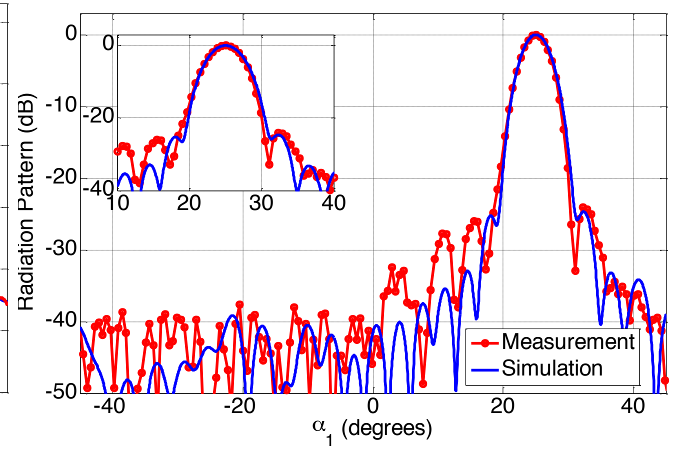
$$\vec{E}(\hat{u}) = \sum_{m=1}^{M}\sum_{n=1}^{N} \vec{A}_{mn}(\hat{u}) \cdot \vec{I}(\vec{r}_{mn}),$$

$$\hat{u} = \hat{x}\sin\theta\cos\varphi + \hat{y}\sin\theta\sin\varphi + \hat{z}\cos\theta$$

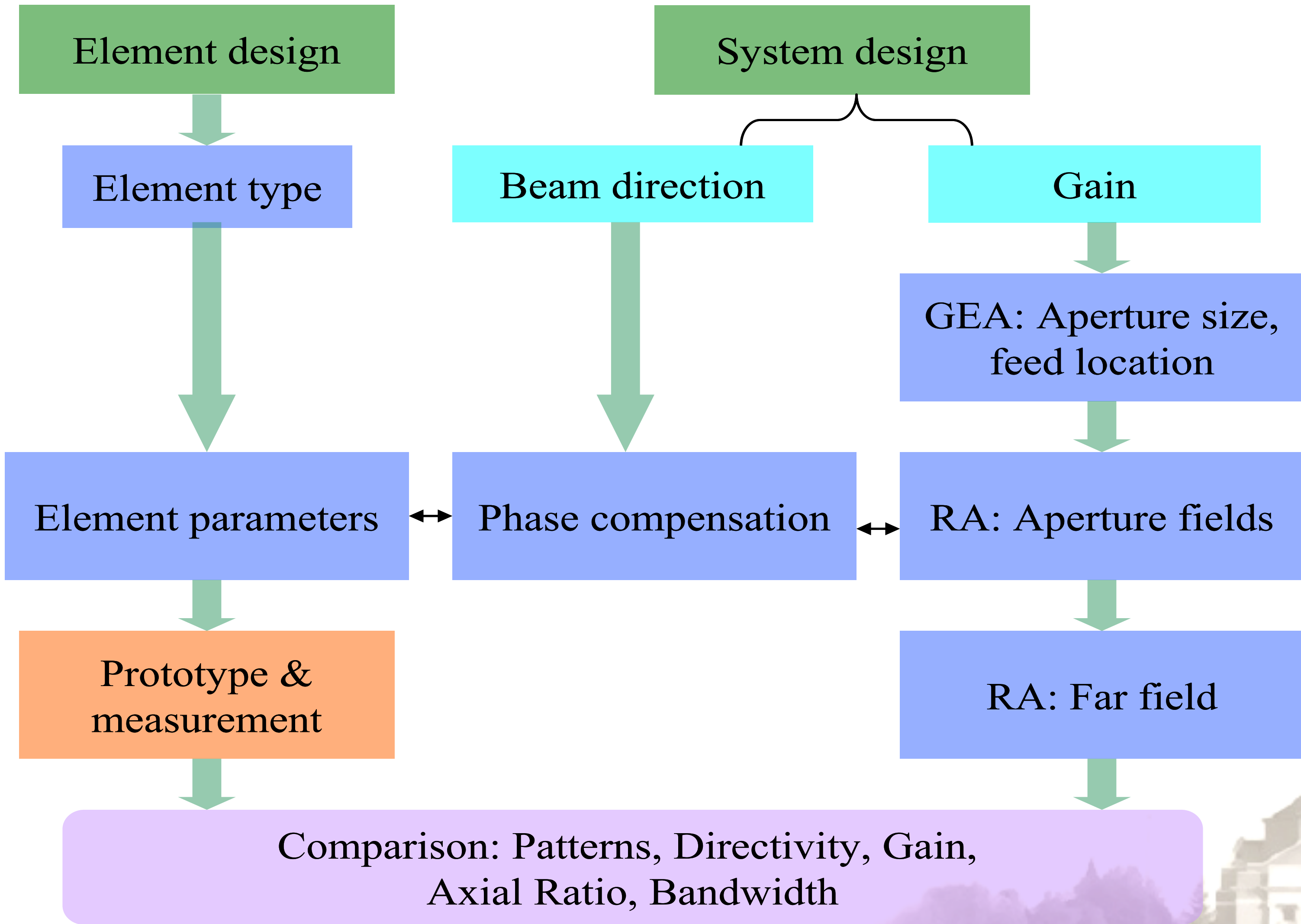
$$\begin{bmatrix} E_x^{ref}(m,n) \\ E_y^{ref}(m,n) \end{bmatrix} = \begin{bmatrix} \Gamma_{xx} & \Gamma_{xy} \\ \Gamma_{yx} & \Gamma_{yy} \end{bmatrix} \begin{bmatrix} E_x^{inc}(m,n) \\ E_y^{inc}(m,n) \end{bmatrix}.$$







Reflectarray Design Roadmap



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  - Broadband reflectarrays
  - Multi-band reflectarrays
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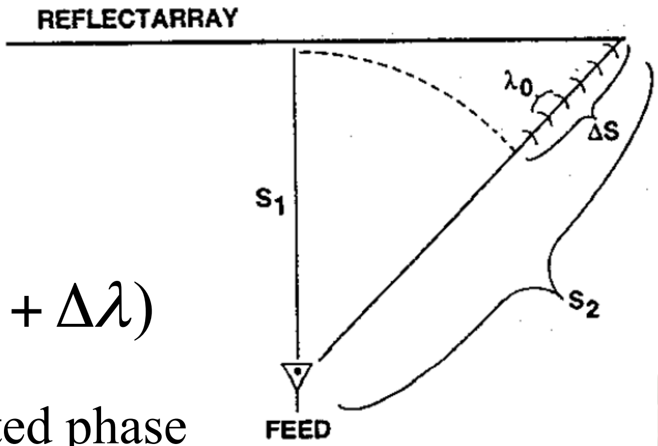
Bandwidth of Reflectarrays

- Printed reflectarray has an inherent **narrow bandwidth**.
- Bandwidth of a microstrip reflectarray is limited primarily by two factors.

1) Bandwidth of Elements

- A micorstrip patch element generally has a bandwidth of about 3 to 5 %.

2) Differential Spatial Phase Delay



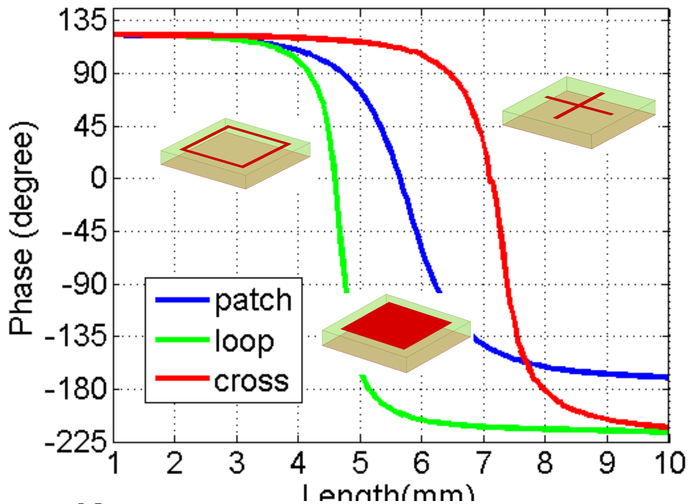
at the design frequency $\Delta s = (N + d)\lambda$

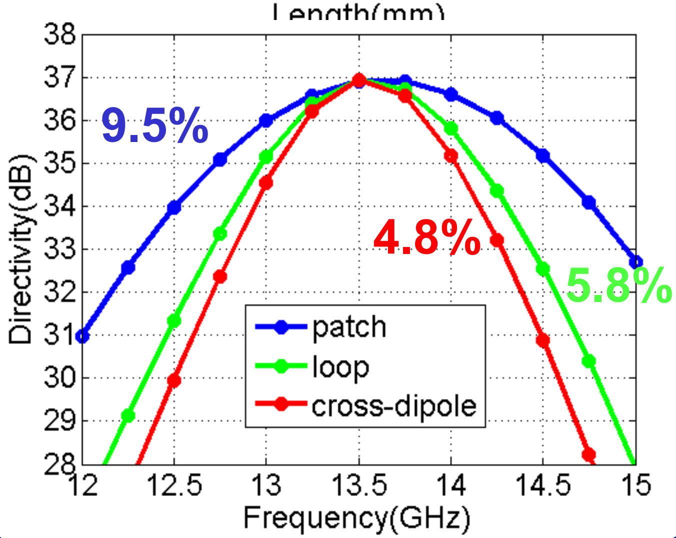
as frequency changes $\Delta s = (N + d)(\lambda + \Delta\lambda)$

where N is an integer, dλ is the compensated phase

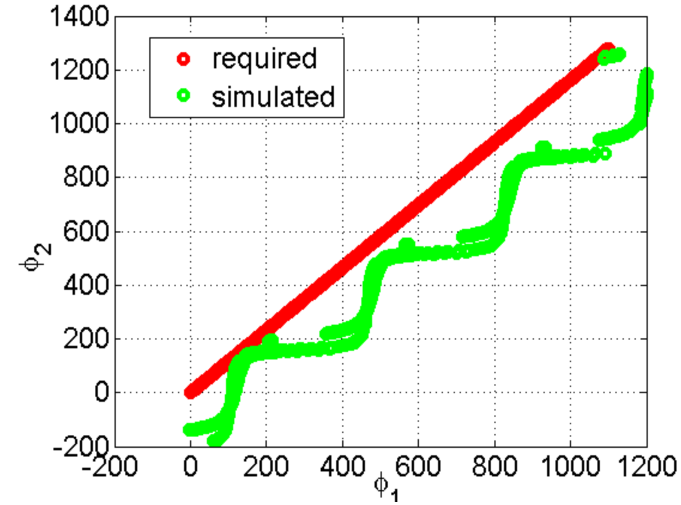
Bandwidth Enhancement Methods

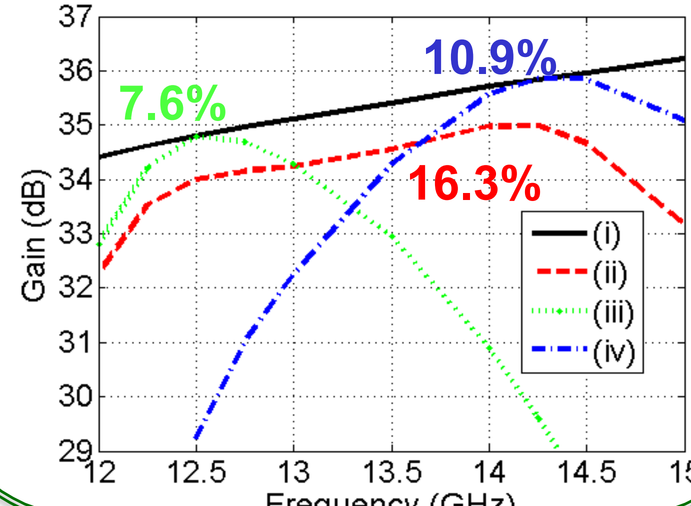
Element bandwidth



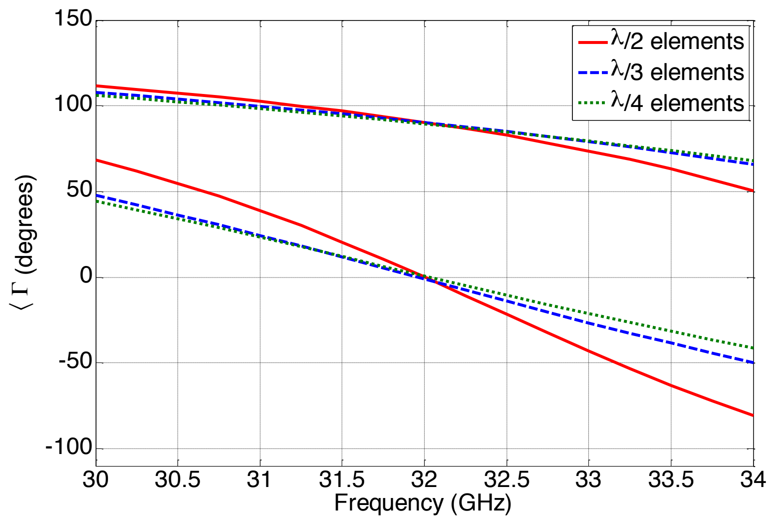


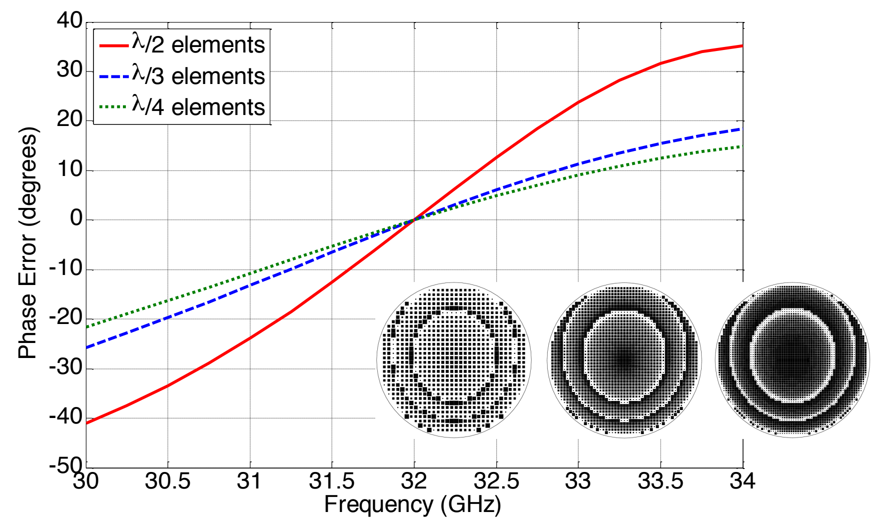
Wideband phase synthesis

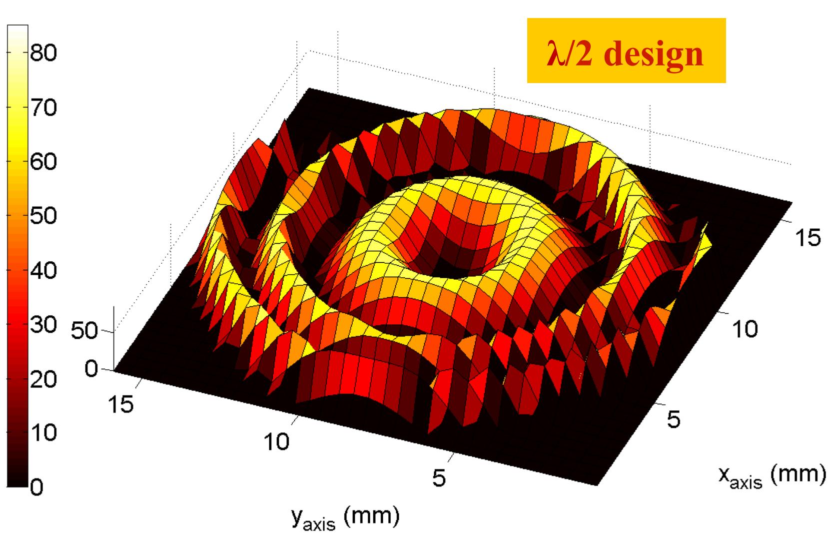


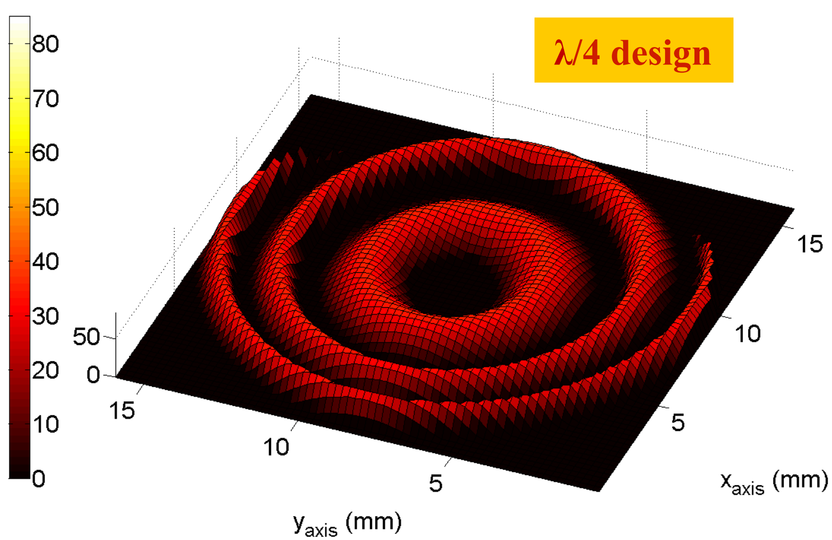


Broadband Sub-λ RA: Freq. Behavior





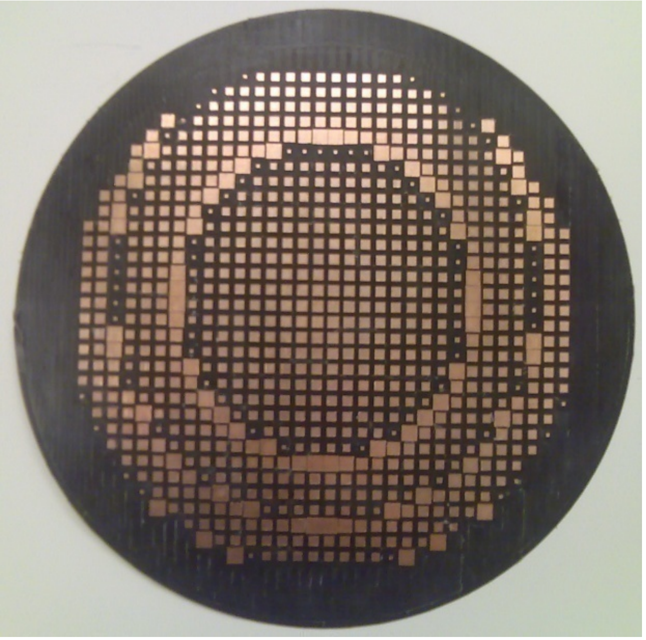




Broadband Sub-λ RA: Prototypes

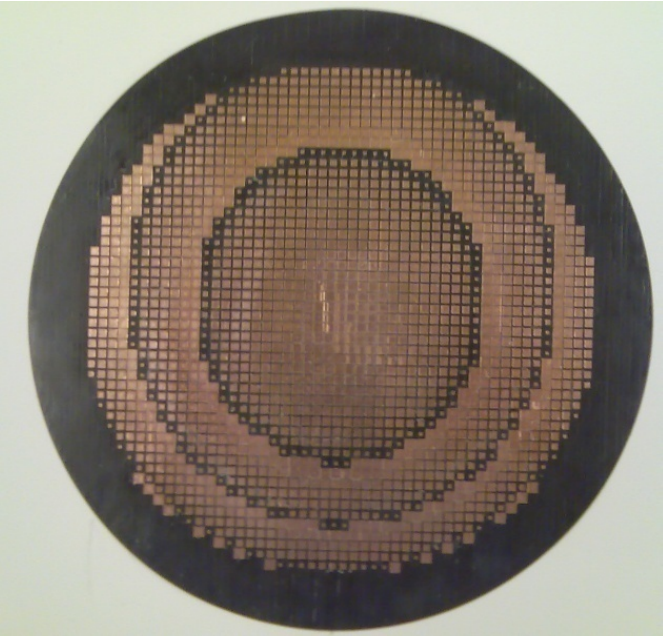
λ/2 element spacing array

(848 patches)



λ/3 element spacing array

(1941 patches)



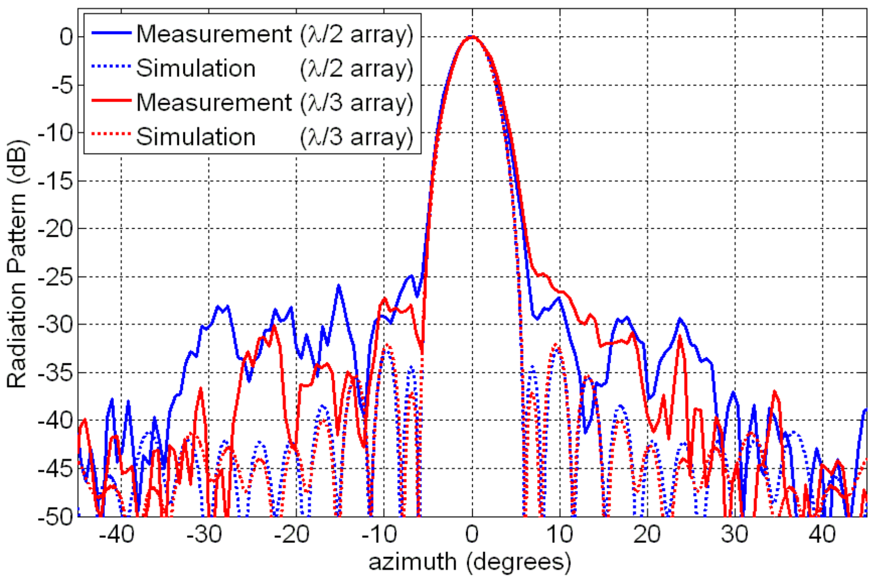
Circular aperture (D = 6.275 inch = 17λ @ 32 GHz)

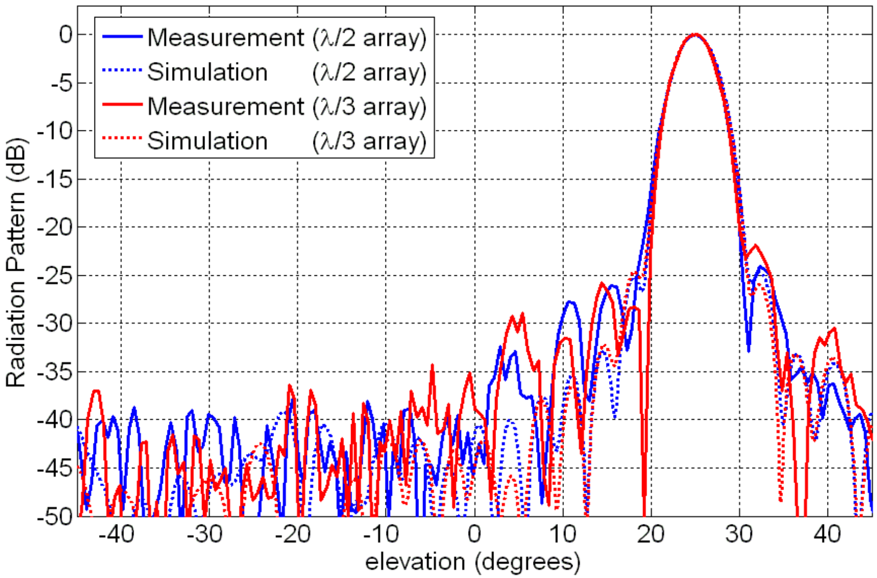
Material

20 mil Rogers 5880 (ε_r=2.2) substrate with 0.5 ounce cladding

Broadband Sub-λ RA: Patterns

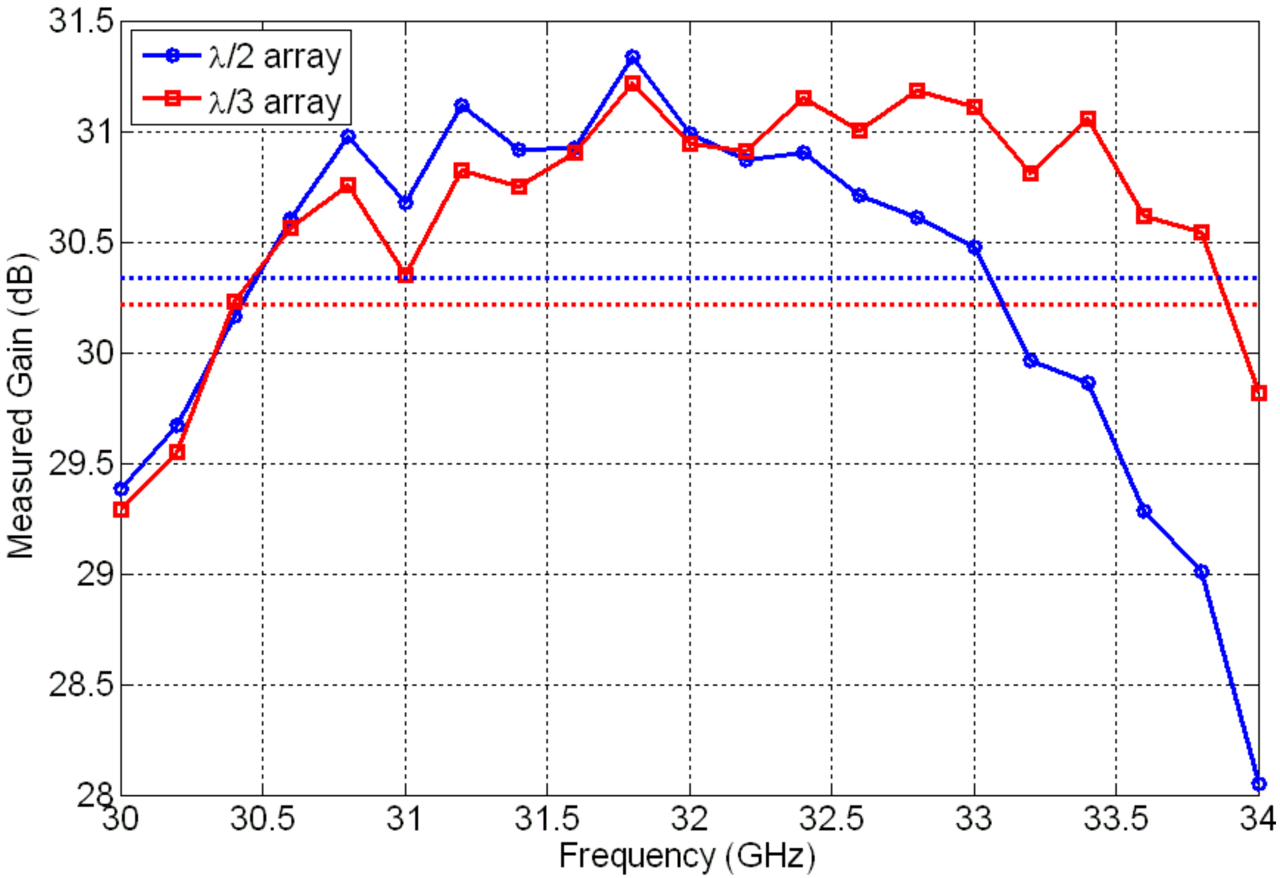
32 GHz





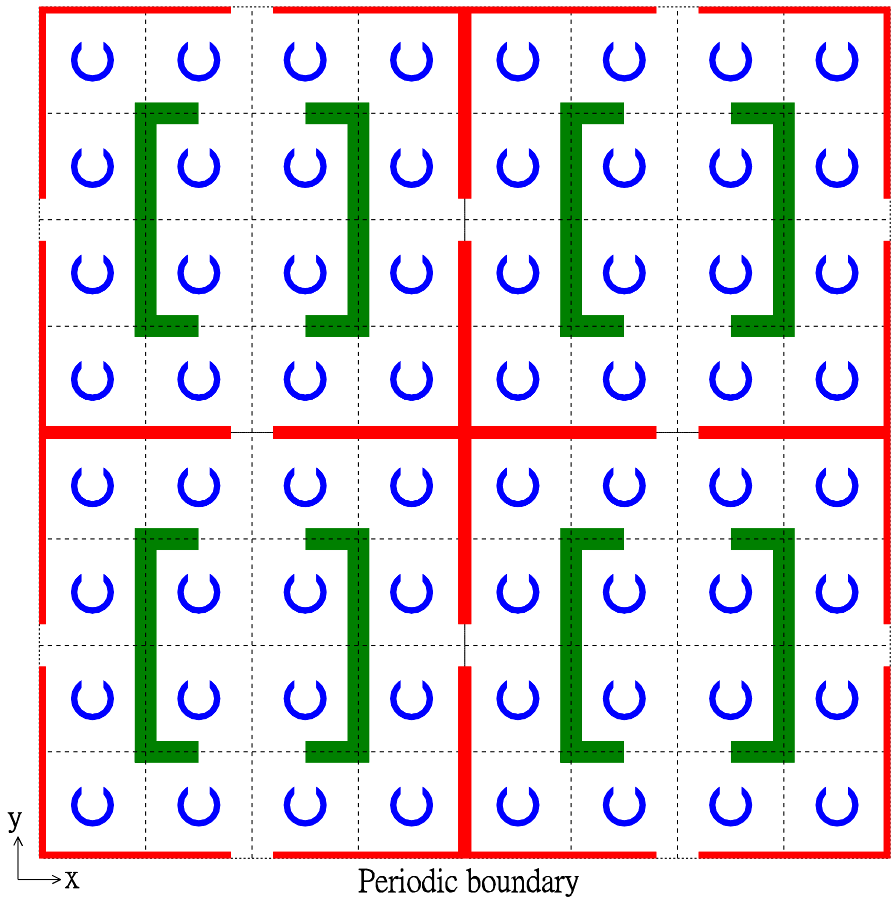
Gain (dB)	λ/2 array	λ/3 array
Simulation	32.805	32.8355
Measurement	31.4080	31.3670

Broadband Sub-λ RA: Gain & BW



λ/2 array: The **1 dB gain bandwidth is 8.03%.** (30.48 GHz to 33.05 GHz)
λ/3 array: The **1 dB gain bandwidth is 10.94%.** (30.39 GHz to 33.89 GHz)

Single-Layer Tri-Band RA: Geometry



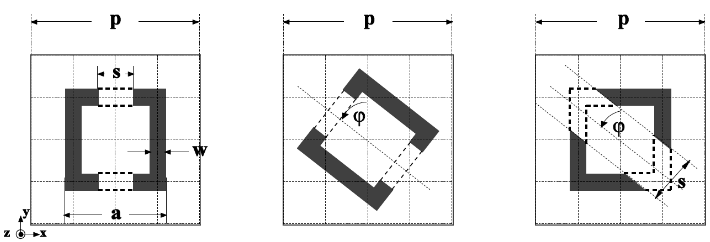
Printed on a single layer
h = 62 mil, ε_r=2.33.

Element geometry:

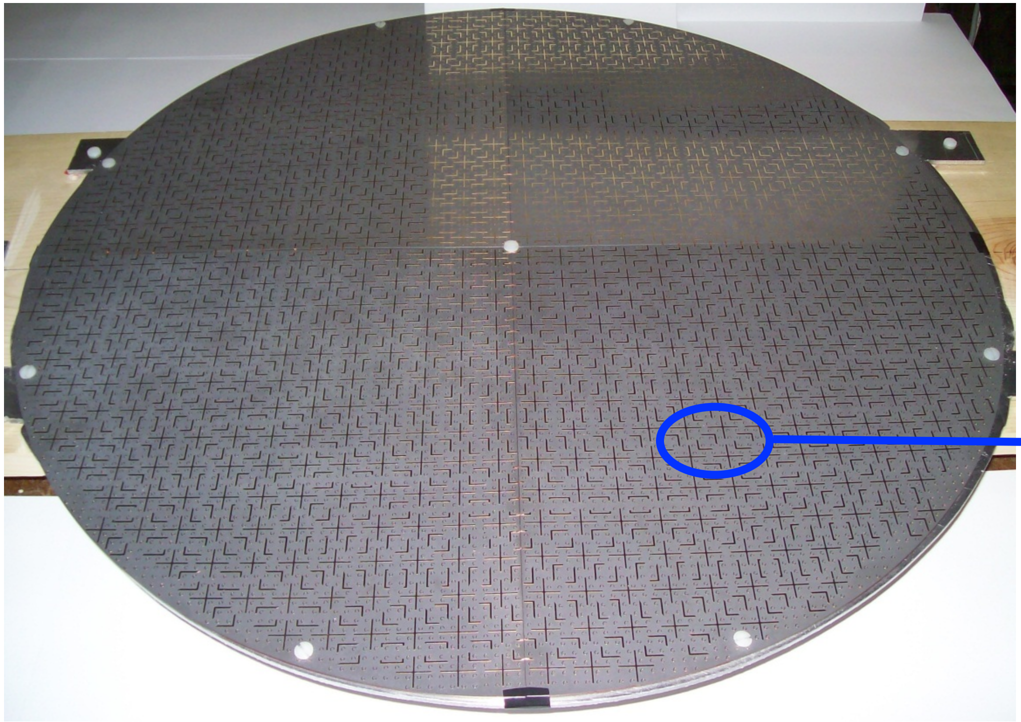
1. Ka band (32 GHz):
- ❖ Circular ring for CP
- ❖ Use angular rotation technique for phase compensation

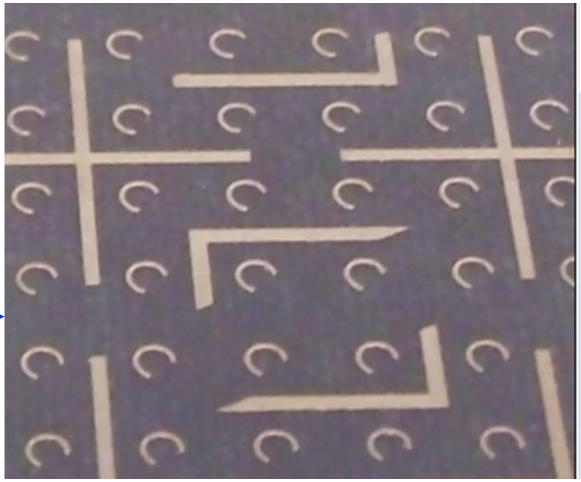
2. C band (7.1 GHz):
- ❖ Cross dipole for reversed CP
- ❖ Adjust the dipole size for phase compensation

3. X band (8.4 GHz):
- ❖ Split square loop for CP
- ❖ Change slot positions for phase compensation



Single-Layer Tri-Band RA: Prototype

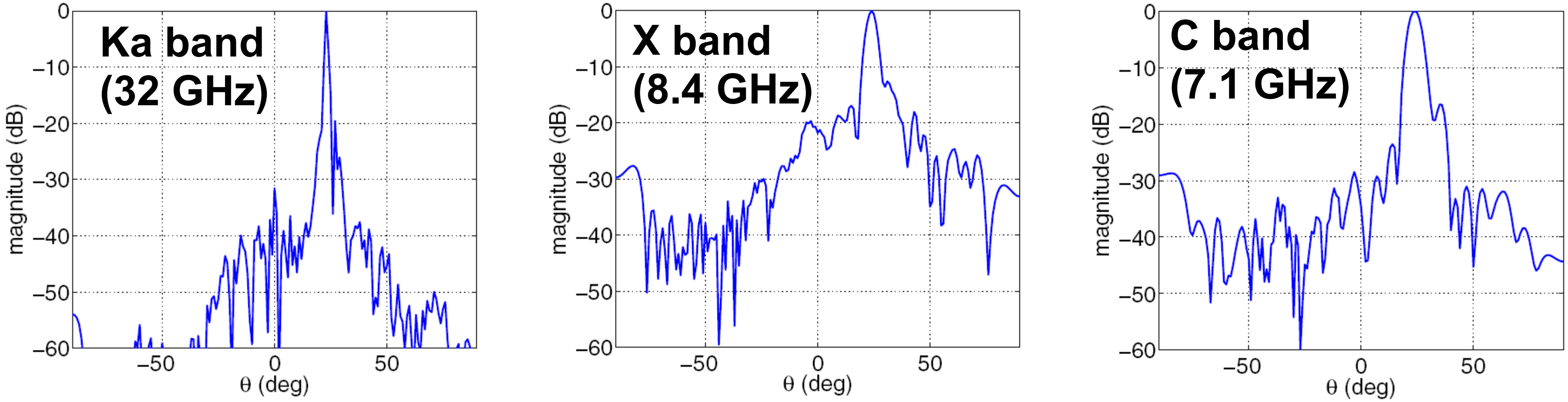




A circular reflectarray with a diameter of 0.566 meter, including:

- 692 cross dipoles at C band (7.1 GHz)
- 685 square rings at X band (8.4 GHz)
- 10,760 circular rings at Ka band (32 GHz)

Single Layer Tri-Band RA: Results



	Peak Gain (dB)	Center Frequency (f_c)	-1 dB Bandwidth (%)	η_a @ f_c (%)
Ka	38.7	31.8	6.3	20.6
X	29.1	8.4	2.0	26.5
C	28.4	7.1	1.8	38.8

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  - **Multi-beam reflectarrays**
  - **Beam scanning reflectarrays**
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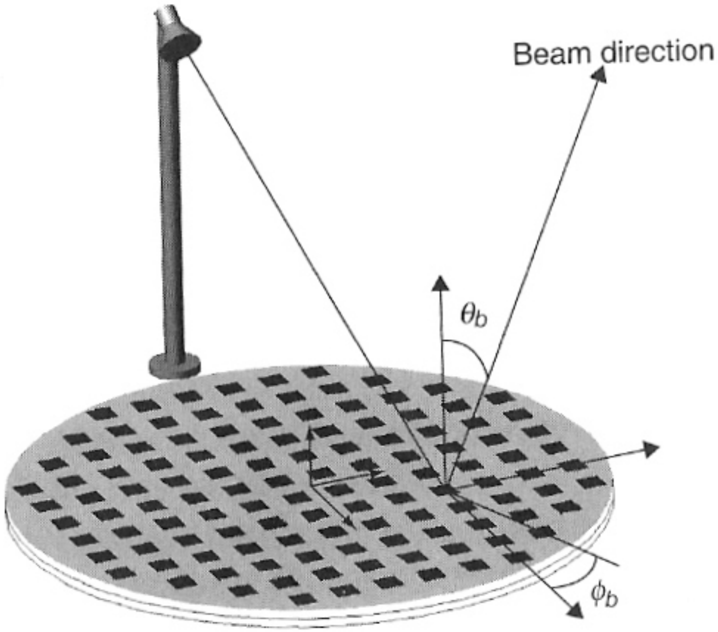
Advanced Radiation Performance of RA



An important feature of RA:

Reflection phase of each element can be individually adjusted ➔ abundance of design freedom.

➢ Advanced radiation properties:

- **Multiple beams from a single feed;**
- **Contoured beam pattern or shaped beam pattern;**
- **Wide beam scanning angles.**

Direct Methods for MBRA Design

Superposition Approach

The field on the reflectarray surface

Number of beams

$$E_R(x_i, y_i) = \sum_{n=1}^{N} A_{n,i}(x_i, y_i)\, e^{j\phi_{n,i}(x_i, y_i)}$$

$$E_R(x_i, y_i) = A_i^{Feed}(x_i, y_i) \cdot \sum_{n=1}^{N} e^{j\phi_{n,i}(x_i, y_i)}$$

$$\phi(x_i, y_i) = \angle \left\{ A_i^{Feed}(x_i, y_i) \cdot \sum_{n=1}^{N} e^{j\phi_{n,i}(x_i, y_i)} \right\}$$

Problem: Amplitude Error

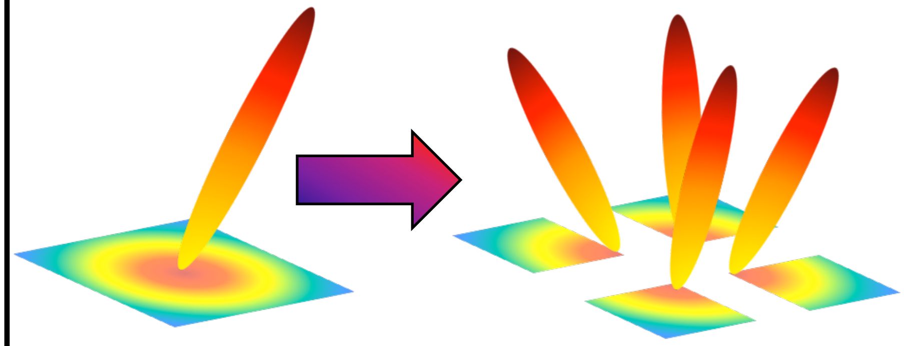
$$\left| \sum_{n=1}^{N} e^{j\phi_{n(i)}(x_i, y_i)} \right| \neq 1$$

Disadvantage:

- ❑ **Reduced gain** (due to side-lobes)
- ❑ **High side-lobe levels**

Geometrical Approach

The reflectarray surface is divided into N sub-arrays each radiating a beam in a given direction.



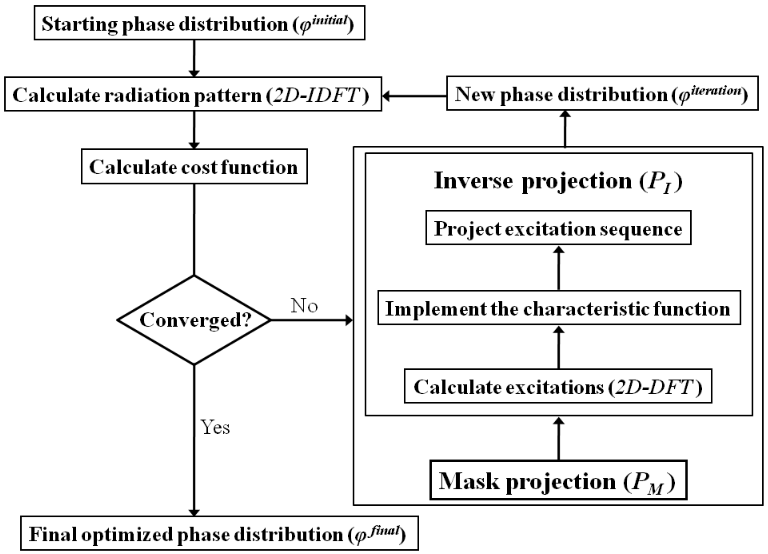
Problem:
Sub-Arrays with Smaller Apertures

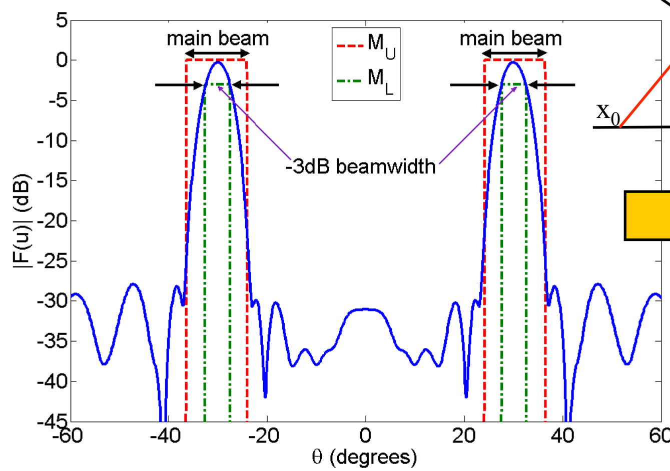
Disadvantage:

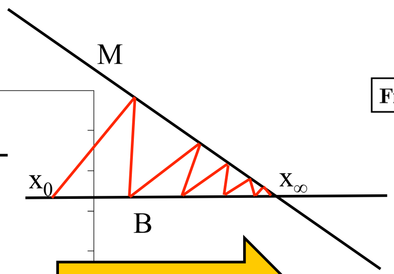
- ❑ **High side-lobe levels**
- ❑ **Gain reduction and beam widening**

Alternating Projection Method (APM)

- **APM**, or **intersection approach**, is a **robust local optimization search**, that is well suited for optimization of large array antennas.
- An **iterative process** that searches for the intersection between two sets.



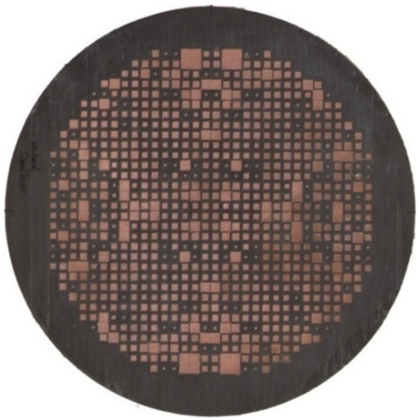


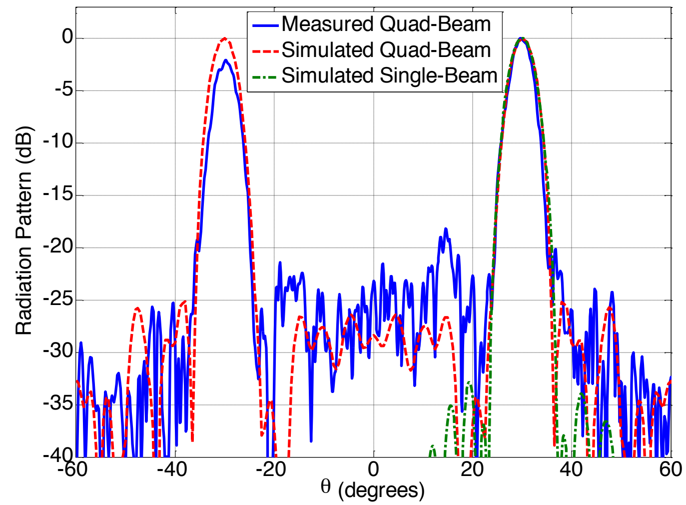


$$P_M F(u,v) = \begin{cases} M_U(u,v)\dfrac{F(u,v)}{|F(u,v)|} & |F(u,v)| > M_U(u,v) \\ F(u,v) & M_L(u,v) \le |F(u,v)| \le M_U(u,v) \\ M_L(u,v)\dfrac{F(u,v)}{|F(u,v)|} & |F(u,v)| < M_L(u,v) \end{cases}$$

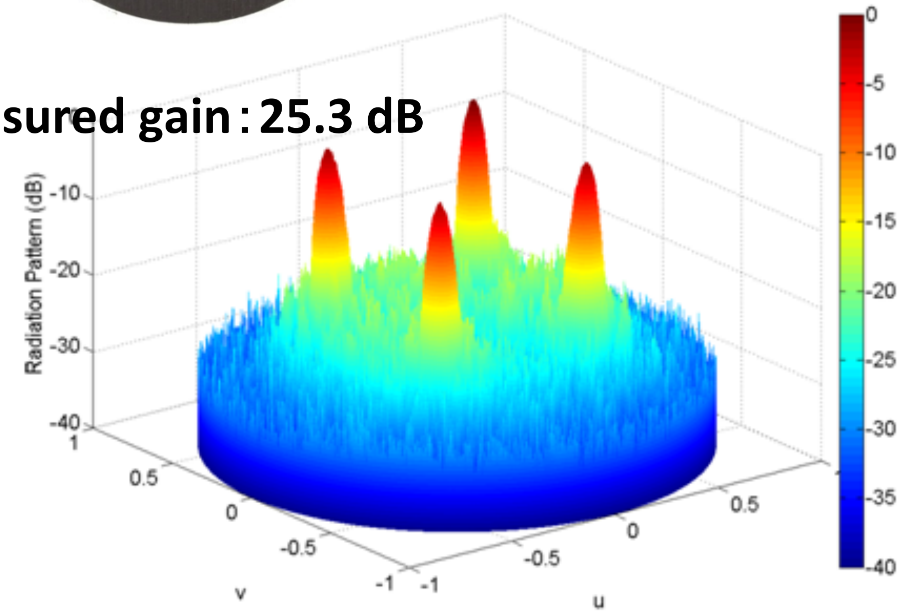
O.M. Bucci, G. Mazzarella, and G. Panariello, “Reconfigurable arrays by phase-only control”, *IEEE Trans. Antennas Propag.*, vol. 39, no. 7, pp. 919-925, July 1991.

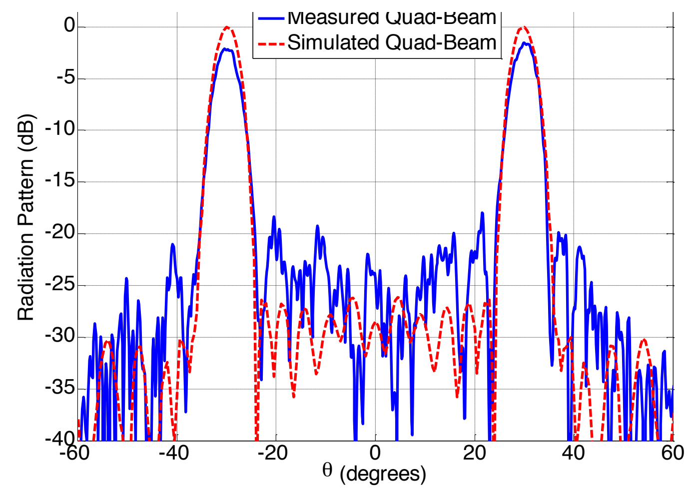
A Symmetric MBRA – APM Method





Measured gain：25.3 dB

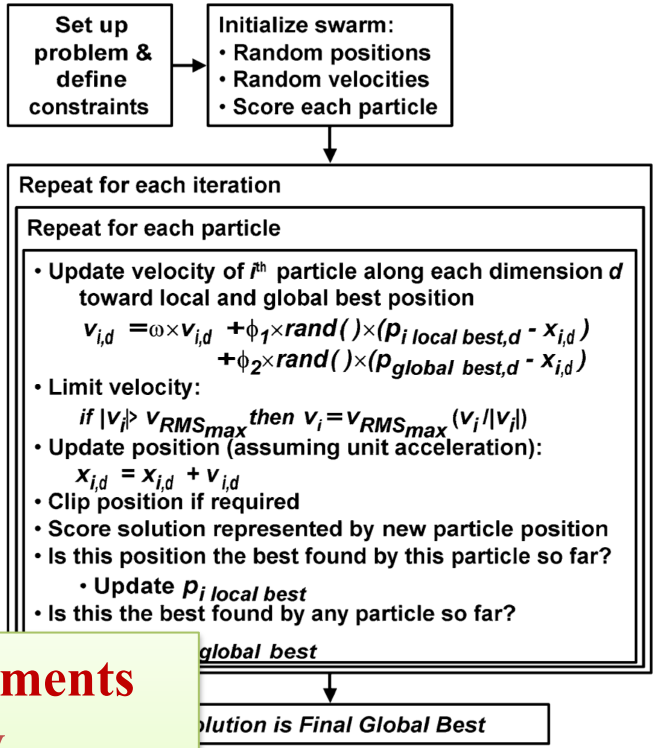




P. Nayeri, F. Yang, and A. Z. Elsherbeni, "Design of a single-feed quad-beam reflectarray antenna," *IEEE Trans. Antennas Propag.*, vol. 60, no. 2, pp. 1166 - 1171, Feb. 2012.

Particle Swarm Optimization (PSO)

- A **powerful global optimization** method, developed by Kennedy and Eberhart in 1995.
- A **stochastic evolutionary optimization** technique based on the movement and intelligence of swarms.
- It is comparable in performance with other stochastic optimizations such as **genetic algorithm (GA)**, with the added advantage that PSO is much **simpler** to implement.

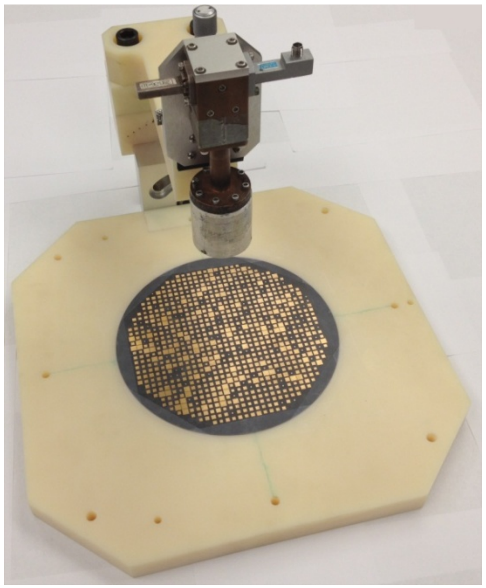


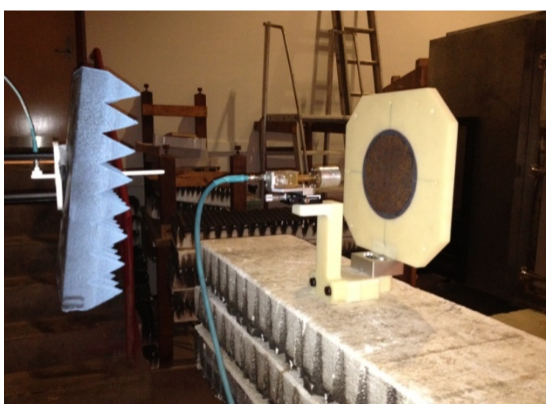
What's the challenge?

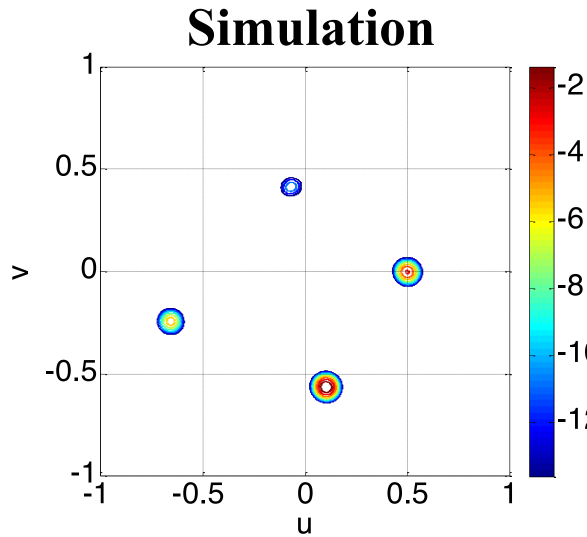
Very large number of elements
e.g. ~ 1000 element array
400 particles, 100,000 iterations
40 million fitness evaluations

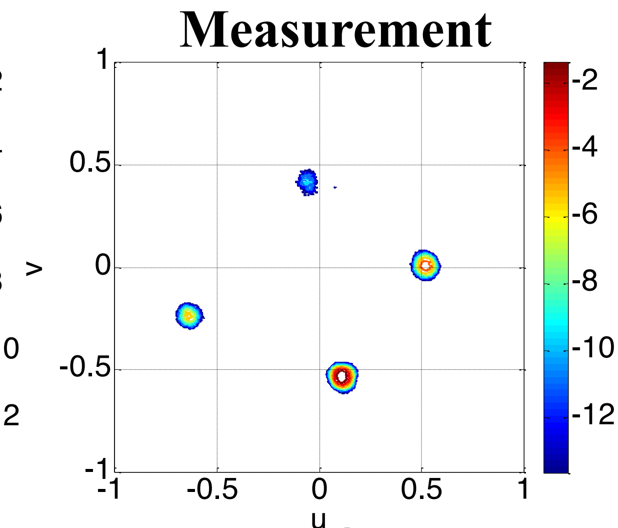
1. J. Kennedy and R. C. Eberhart, "P… *Networks IV*, Piscataway, NJ. 1995.
2. J. Robinson and Y. Rahmat-Sami… *IEEE Trans. Antennas Propag.*, vol. 52, no. 2, pp. 397–407, Feb. 2004.
3. D. W. Boeringer and D. H. Werner, "Particle swarm optimization versus genetic algorithms for phased array synthesis," *IEEE Trans. Antennas Propag.*, vol. 52, no. 3, pp. 771–779, Mar. 2004.

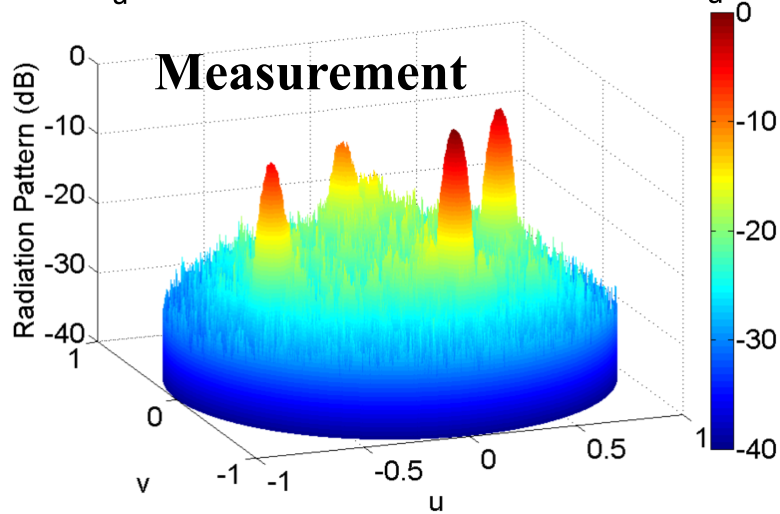
An Asymmetric MBRA – PSO Method







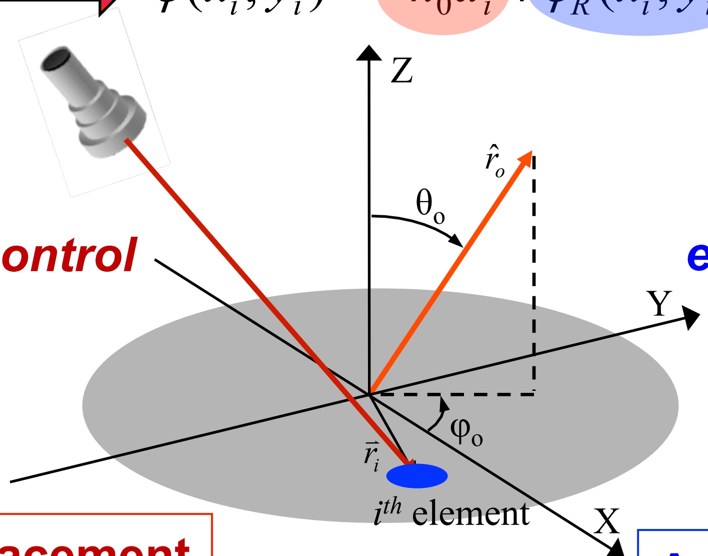




Beam Scanning Reflectarray Antenna

The phase on the reflectarray aperture can be changed to scan the beam

$$\phi(x_i, y_i) = -k_0 d_i + \phi_R(x_i, y_i)$$



spatial delay control

Feed Displacement

The phase center of the feed is moved to scan the beam

element phase control

Aperture Phase Tuning

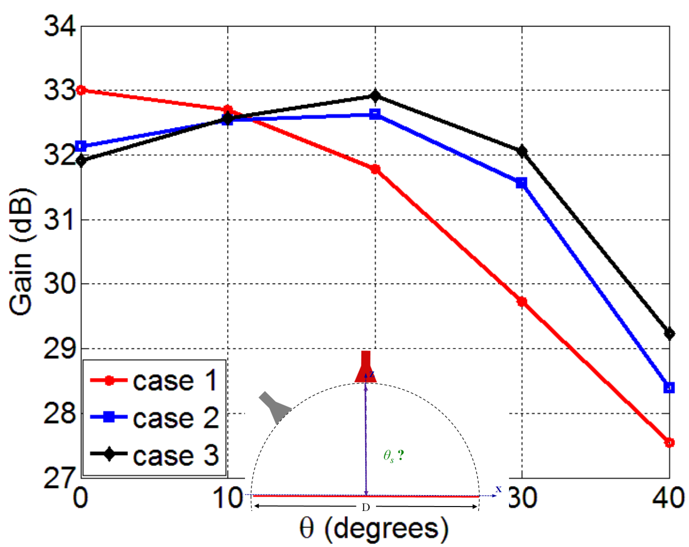
The phase of RA elements is changed to scan the beam

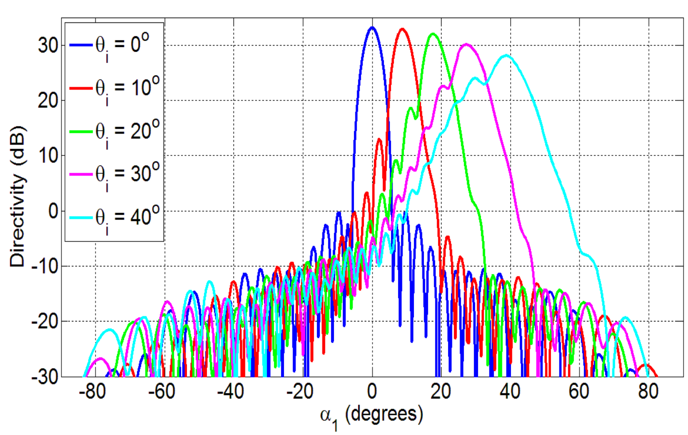
Hybrid Design

Improve system performance, Reduce system cost

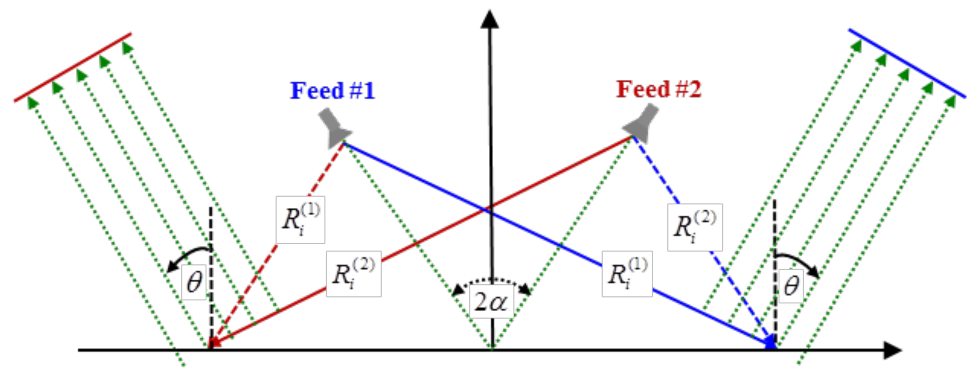
Bi-Focal Beam Scanning RA

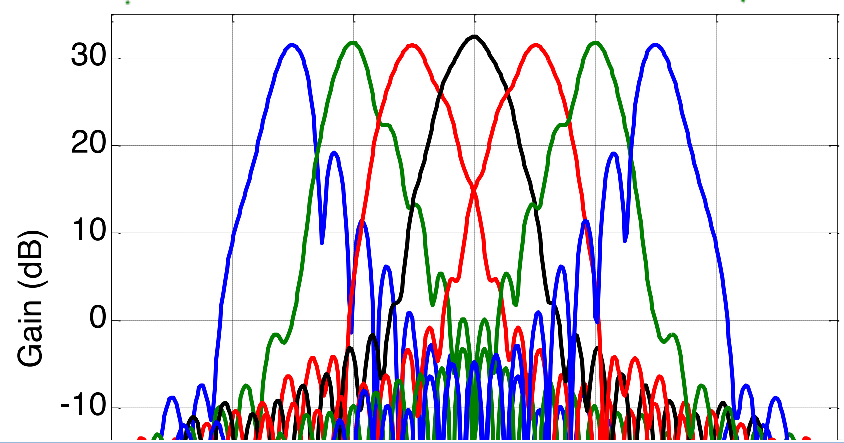
➢ Traditional parabolic RA:





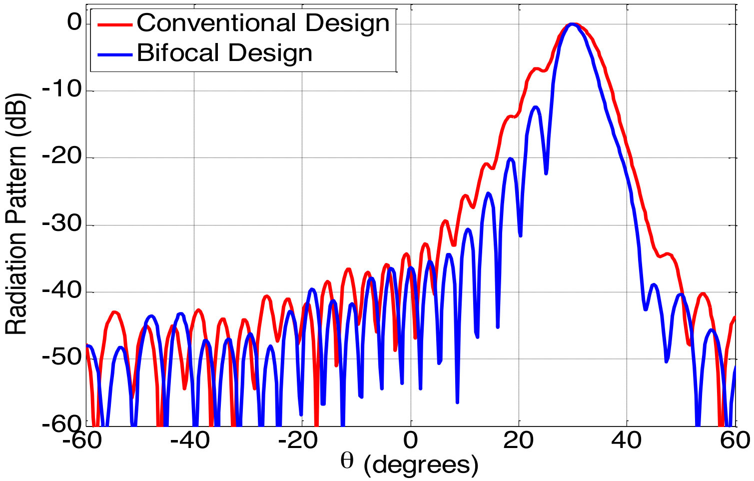
➢ Bi-focal design concept:



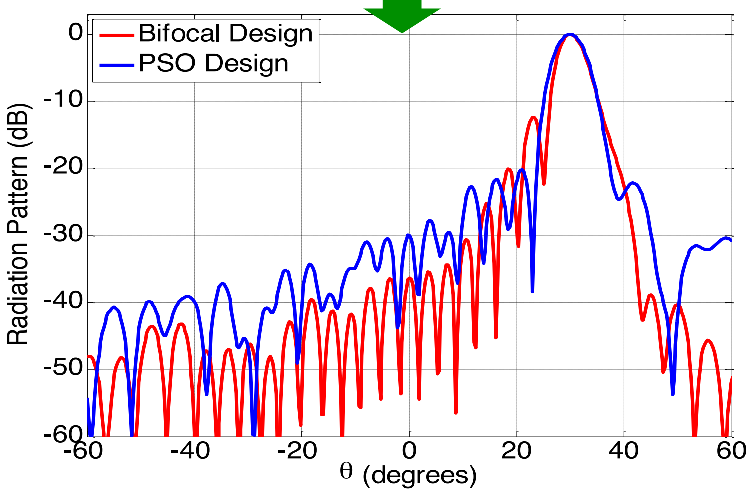


Scan Performance				
Angle	30	20	10	0
Gain（dB）	31.43	31.73	31.42	32.39

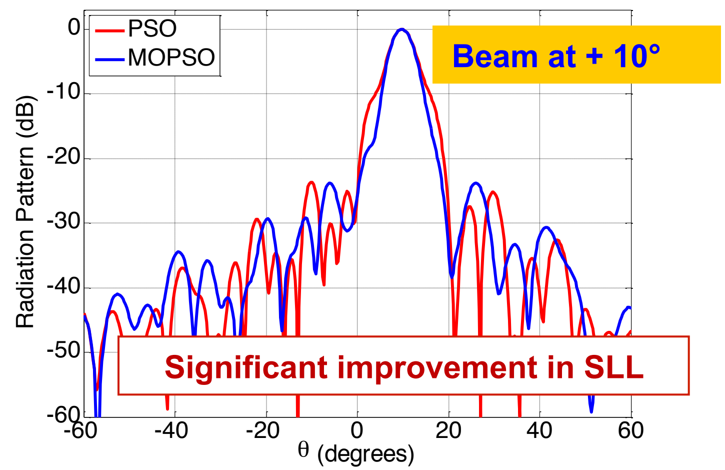
Reflectarray Optimizations

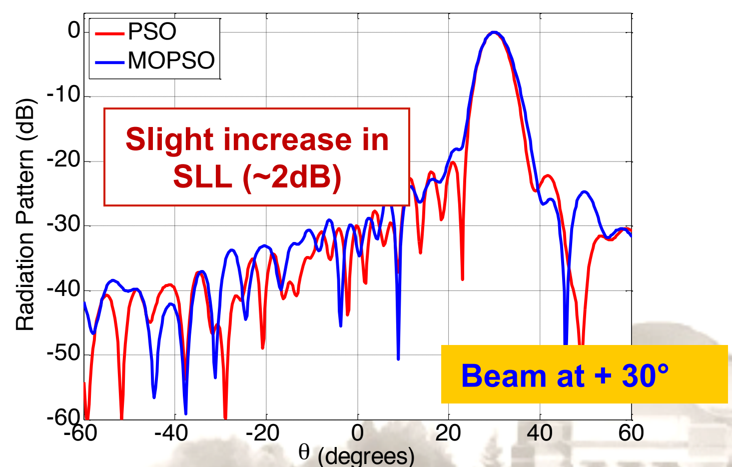


PSO



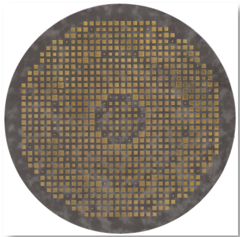
MOPSO



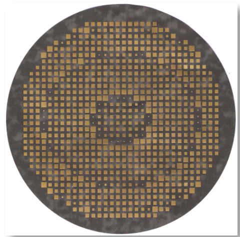


BSRA Prototypes & Measurements

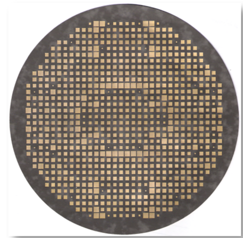
Parabolic



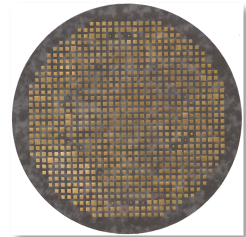
Bi-Focal

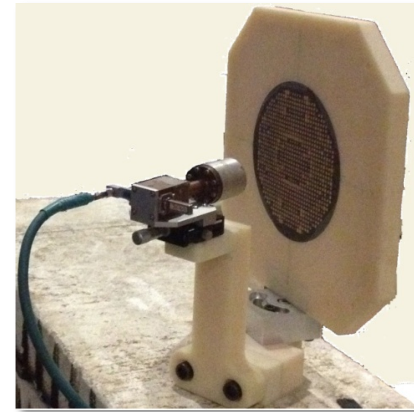


PSO



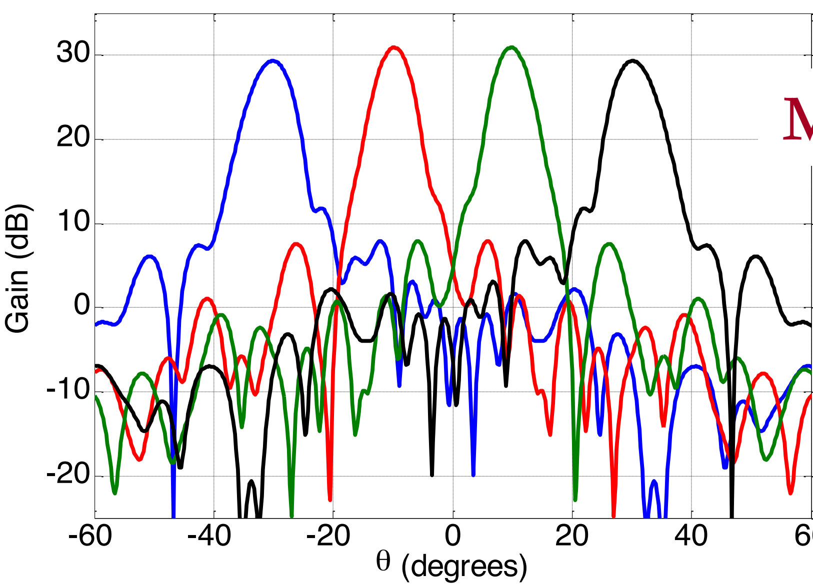
MOPSO





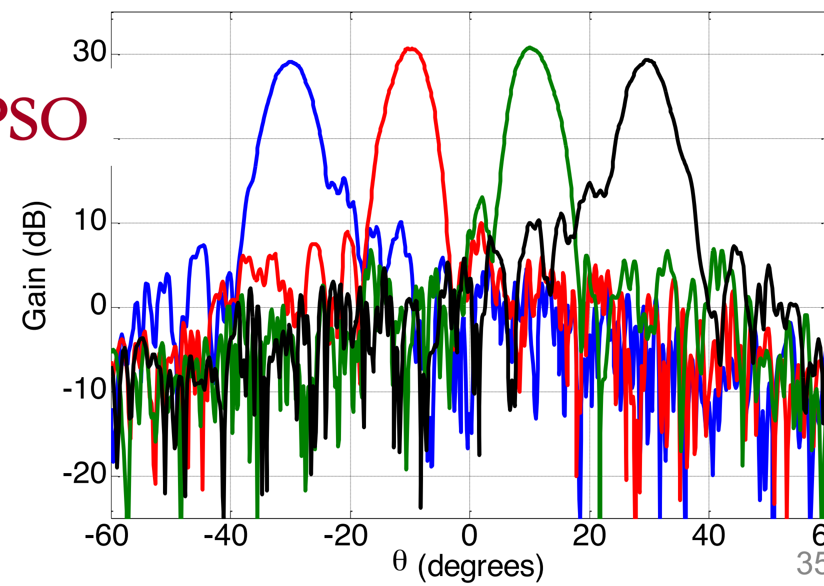
32GHz， D=160mm， 848 patch elements

Simulations



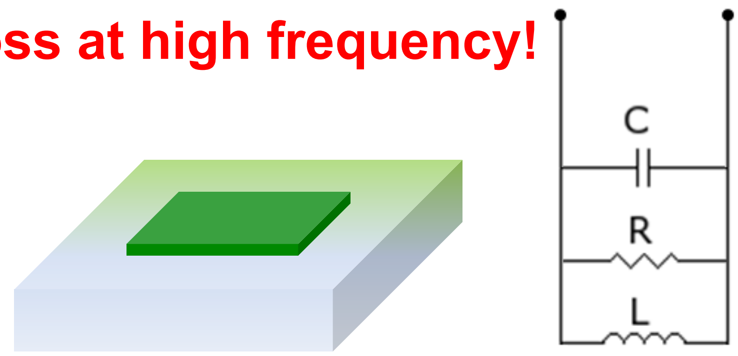
MOPSO

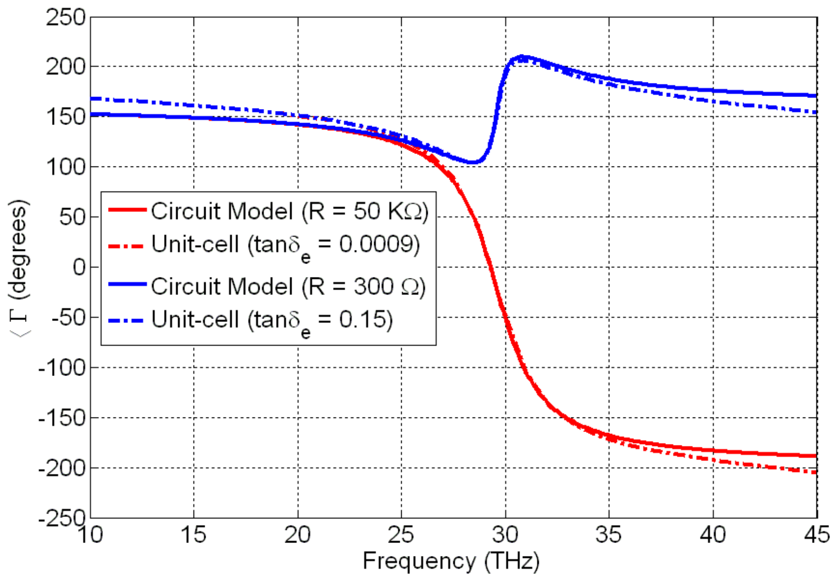
Measured



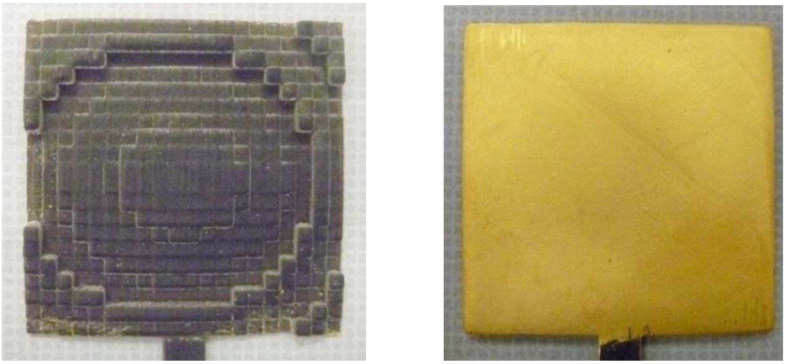
Infrared & THz Reflectarrays

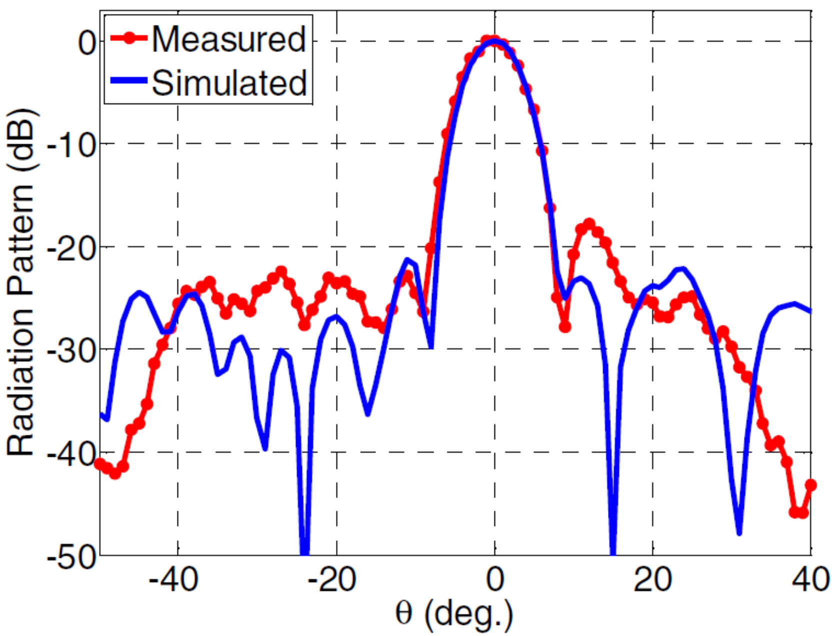
Loss at high frequency!



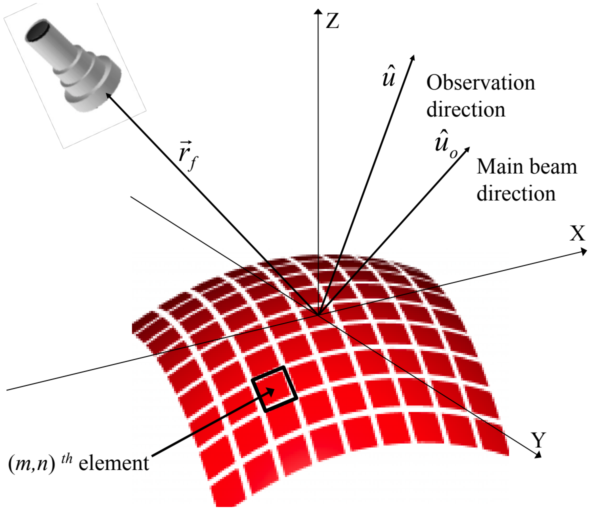


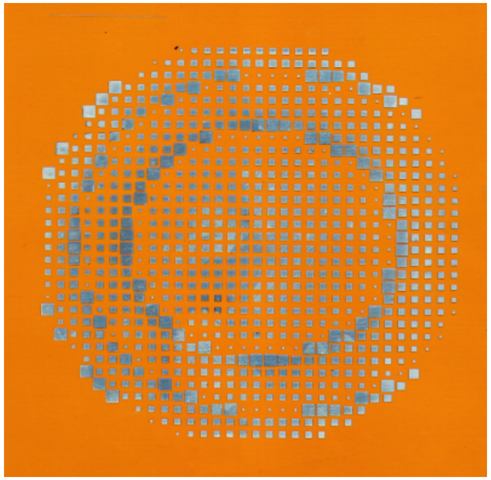
Dielectric reflectarray



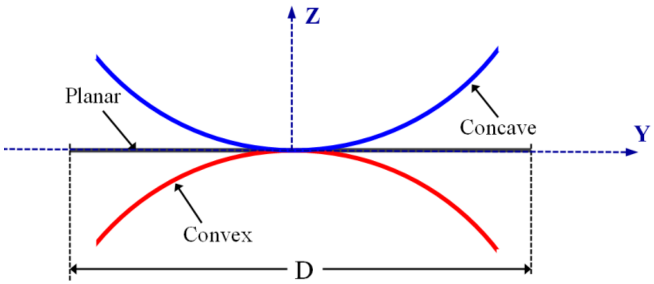


Conformal Reflectarray





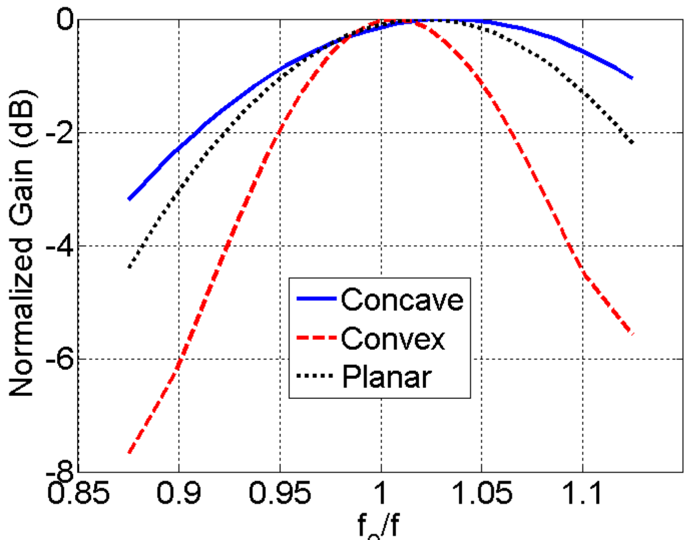
Inkjet silver printing on flexible material: Kapton



For D/R_c = 1, the gain loss in the conformal designs are:

Concave design ≈ 0.1 dB

Convex design ≈ 0.6 dB



OUTLINE

- ❖ Introduction of reflectarray antennas
- ❖ Reflectarray analysis and synthesis methods
- ❖ RA with enhanced frequency features
- ❖ RA with advanced radiation capabilities
- ❖ Conclusions

Conclusions

The printed reflectarray is a new generation of high gain antenna, and its multitude of capabilities will encourage continuous development and exciting applications in the future. **--- John Huang**

- **Analysis, design, and measurement techniques**
- **RA with wideband and multi-band features**
- **RA with multi-beam and beam-scanning operations**
- **New frontiers: infrared & THz RA, conformal RA, …**
- **Exciting applications in space exploration, satellite communications, radar, remote sensing …**

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- Thanks to the project collaborators:

Colleagues:	A. Elsherbeni	J. Huang	Y. Rahmat-Samii	G. Boreman
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	P. Nayeri	Y. Mao	A. Abdelrahman	F. Guo
	W. An	S. Cheng	X. Liu	

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  - National Science Foundation (NSF)
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Thanks!

Questions?