Printed Air-fed Array Antennas

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INTRODUCTION - 1

TITLE

Printed Air-fed Array Antennas

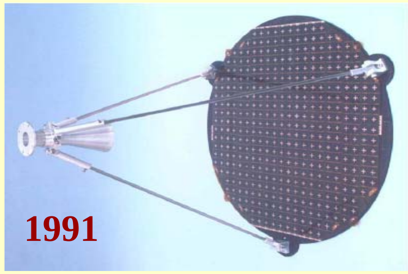
Adopt **Printing Technology**
for a planar aperture with thin structure

Illuminated by a **Separated Feed**
through **ray** *rather than transmission-line*

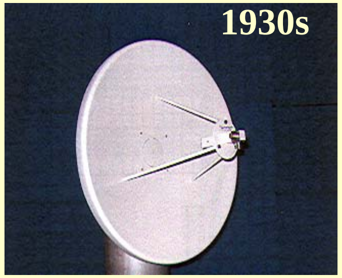
Provide a Radiation **Aperture**

Illuminating onto a
Discrete Aperture

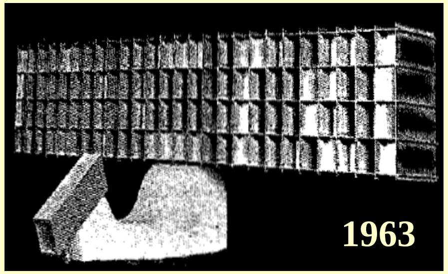
Printed Reflect-array Ant.



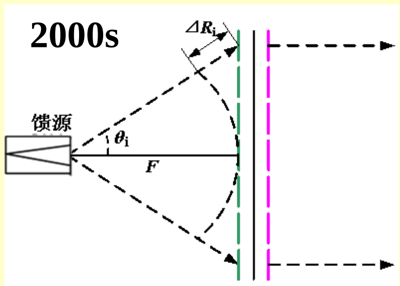
Reflector Ant.



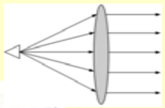
Reflect-array Ant.

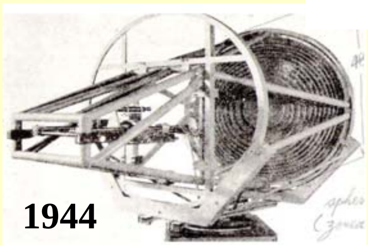


Printed Transmit-array Ant.

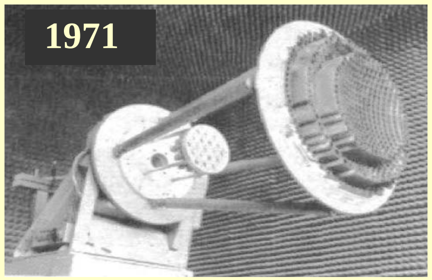


Lens Ant.





Transmit-array Ant.



HIGH-GAIN

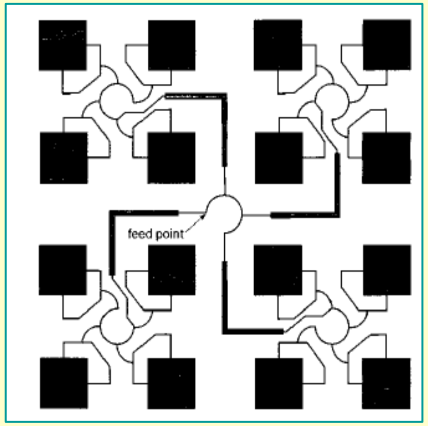
Reflector Antenna

♦ High efficiency & wideband with simple feeding

♦ Curvature structure less flexibility

Traditional Antenna

Array Antenna



♦ Planar (printed) structure with reconfigurable beam

♦ Complex feeding less efficiency & bandwidth

Printed Air-fed Array Antenna

Simple feeding

middle {efficiency, bandwidth}

Planar structure

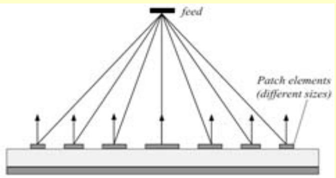
FAMILY

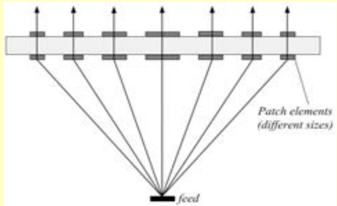
Feed + Mirror

(1963/1991)
Reflect-array
as a reflector
(RA)

(1986/2000)
Transmit-array
as a lens
(TA)

with phase-correction





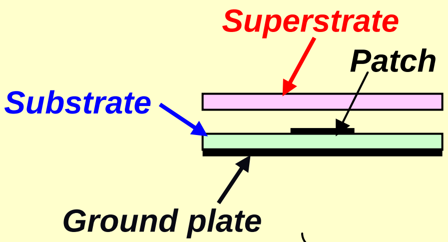
Towering structures occupy larger volume

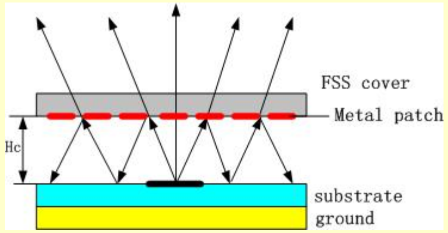
Combination of RA+TA

Cover + Base

(1983/2004)
Microstrip-patch
with a superstrate as cover
(MP+C)

(1999/2006)
Fabry-Perot
as a resonator with cover/base
(FPR)





Resonant structures result in narrow bandwidth

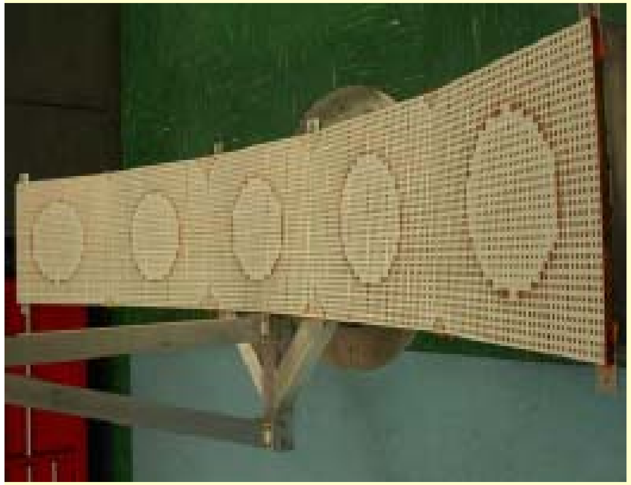
Phase-correction for elements

Compound Printed Air-fed Array

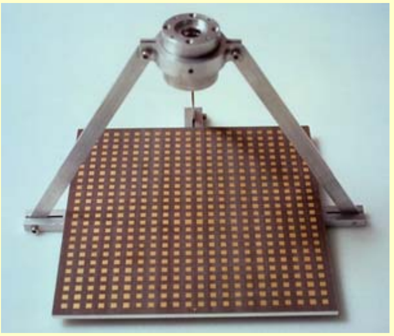
Printed Reflectarray

REFLECTARRAY - 1

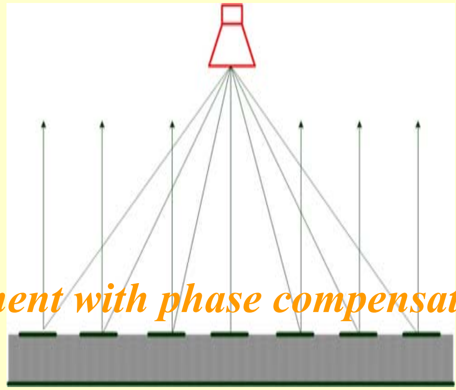
Antennas Samples



Principle



Reflect-array



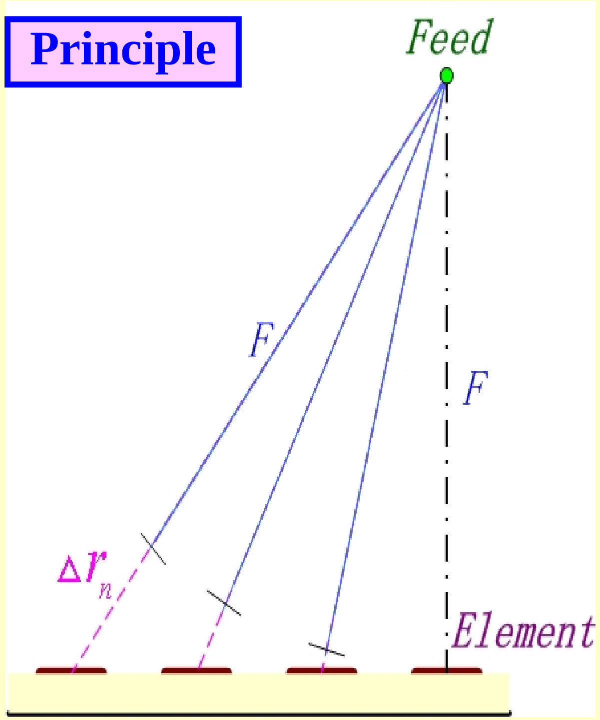
Advantages

- ★ *Design Flexibility*
- ★ *Diversified Types*
- ★ *Conformable Structure*
- ★ *Deployable and Foldable*
- ★ *Simply Air-fed*

Disadvantages

- ★ *Narrower Bandwidth*
- ★ *Lower Efficiency*

Need to be improved !



Compensation

Ray-path phase $k\Delta r_n$

by $\parallel$

Reflection phase $\phi_{R,n}$

Characters

Dynamic range $(\phi_R)_{\max}$

Frequency dependence $\phi_{R,n}(f)$

Improvement Schemes

Extending Bandwidth

Broadband-feed
for
Illuminative Pattern

Avoiding $\varphi + 2\pi$ repeat
by
Extending φ Dynamic-range

Broadband-element
for
Phase Compensation

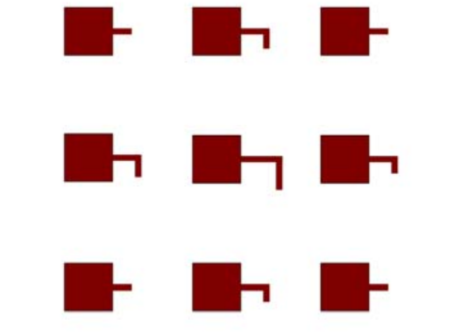
Enhancing Efficiency

Avoiding Feed-blockage
⇩
Normal illumination with
Polarization Transform

Improving Aperture-distribution
⇩
Array optimization with
Pattern Shaped feed

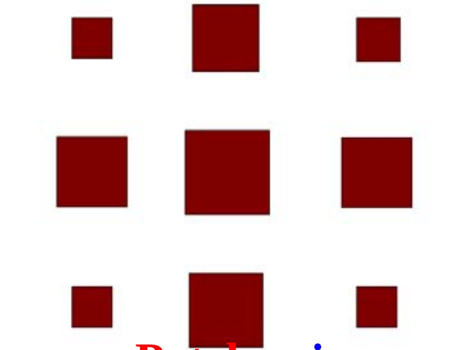
Patch Elements

John Huang (1991)



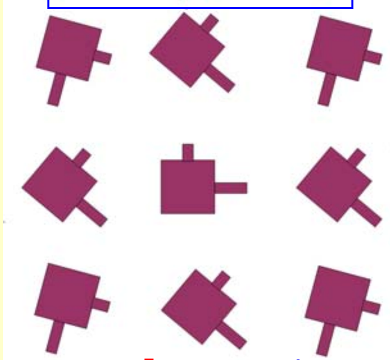
Patch loaded *stub*
(LP) $\phi_{R,n}$ ~*length*

D. M. Pozar *et al* (1993)



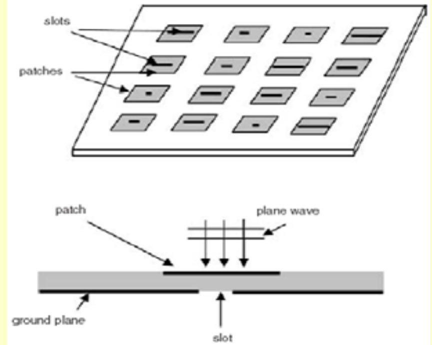
Patch *size*
(LP) $\phi_{R,n}$ ~ *area*

John Huang (1998)



Patch *rotation*
(CP) $\phi_{R,n}$ ~ *angle*

M. R. Chaharmir *et al* (2003)

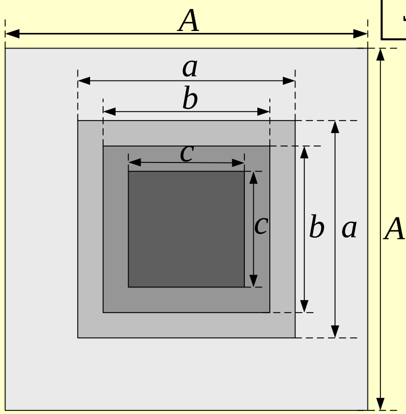


Patch loaded *slot*
(LP) $\phi_{R,n}$ ~*length*

Band-broadening Schemes 1 --- *Simulating patch-antenna*

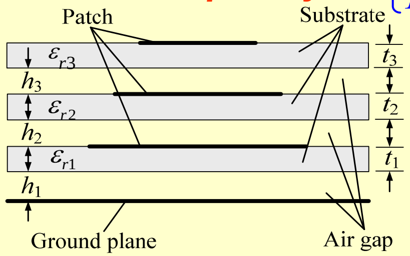
Multi-layered Patches

J.A. Encinar, *et al* (2001, 2003)



double-/ triple-layer

$BW_{-1.5\ dB}$ =16.7 %
$BW_{-0.5\ dB}$ =10.0 %



$(\phi_{R,n})_{max}$=450°/750°

Phase compensated by Patch's *size*

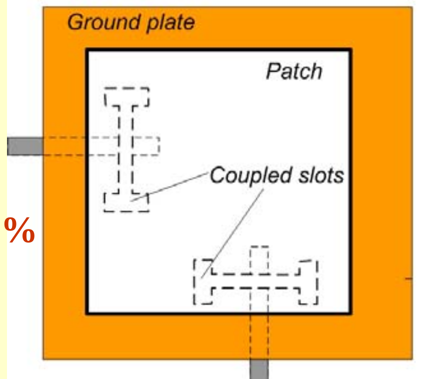
Square Patches

for { *Single LP* / *Dual (Cross) LP* }

Aperture-coupled Patch

M. E. Bialkowski *et al* (2002)

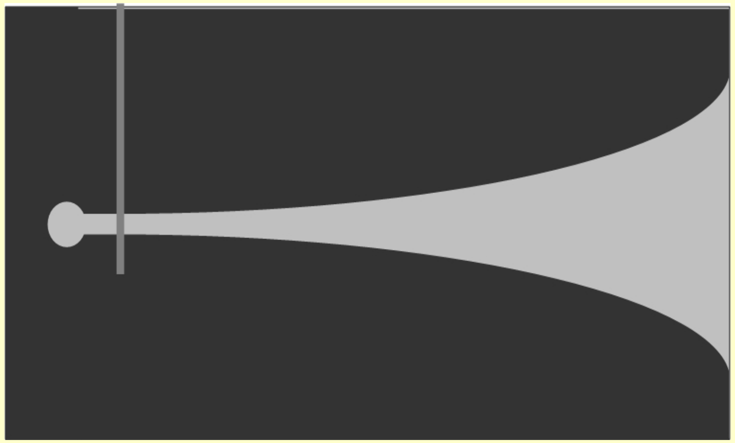
$BW_{-3\ dB}$ =21.2%



Phase compensated by Stub's *length*

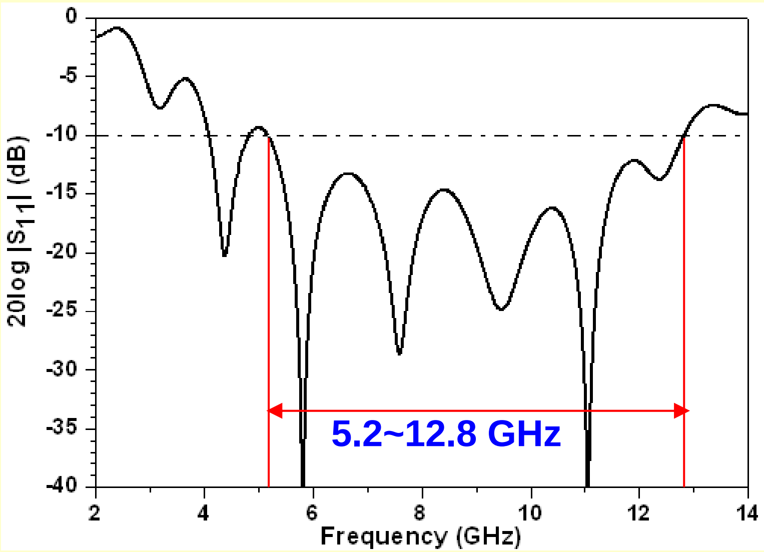
Feed

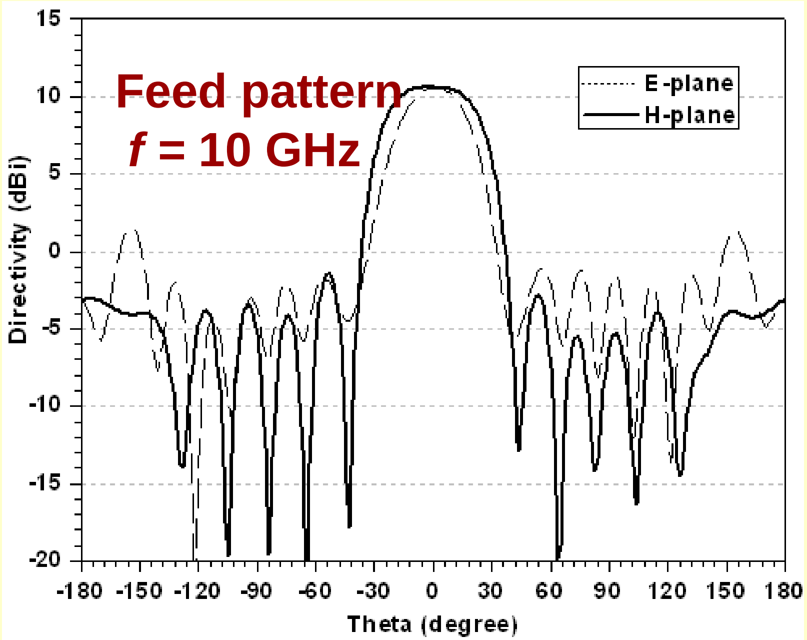
Band-broadening Schemes 2 --- *Broadband TSA as feed*



Merits

- *Broadband traveling wave radiation*
- *Almost equal beamwidth as* $\Theta^{E}_{-10\text{dB}} \approx \Theta^{H}_{-10\text{dB}} \approx 74^{\circ}$
- *Thin sheet with small physical cross-section*
- *Potential for beam-shaping or polar-transform*





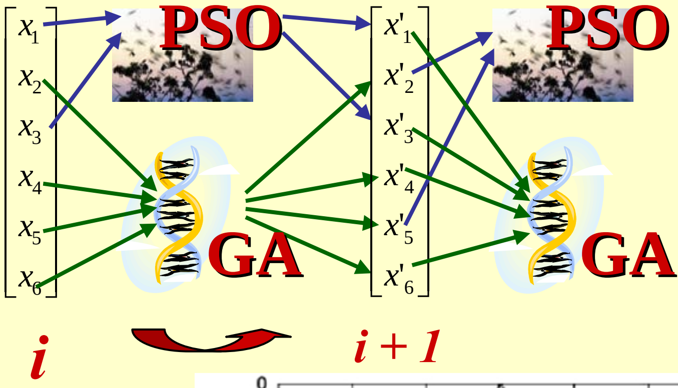
Band-broadening Schemes 3 --- *Optimizing array architecture*

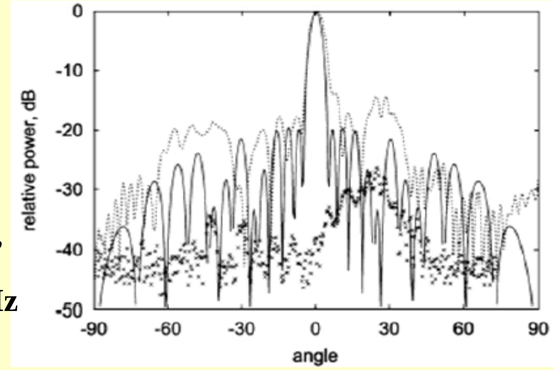
Given:
- *Array sizes with constant period*
- *Element structure & substrates Feed structure with complex pattern*
- *Frequency range & permitted SLL*

Target: ***Possible Maximal Gain***

Parameters: *Sizes & position of each element*

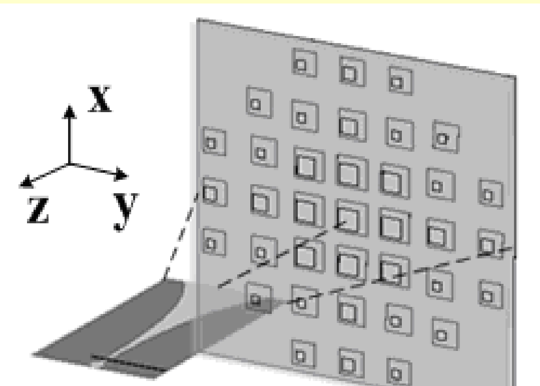
Algorithm:
- *Genetic Swarm Optimization* **(GSO)**
- **CST** *Microwave Studio*



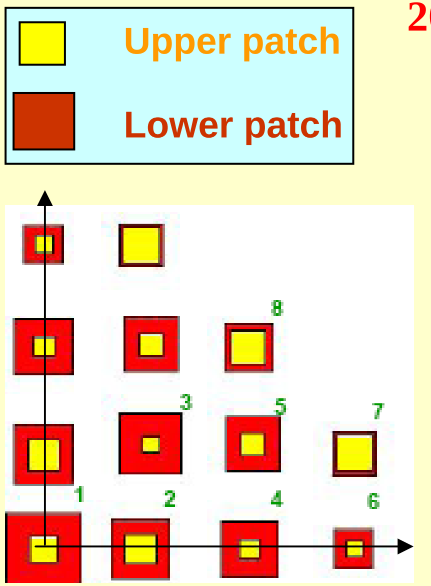


Pre-condition

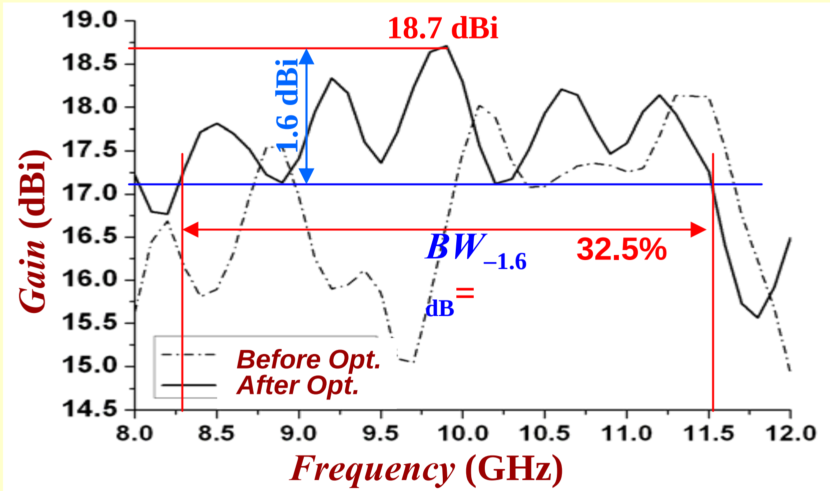
SLL≤ –15 dB ***over***
20 % BW **(9~11) GHz**



37-element RA illuminated by TSA



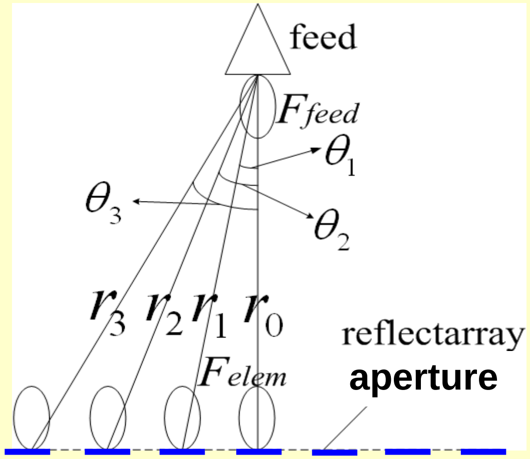
8 kinds of element by symmetry



Efficiency-enhancement Schemes 1 --- *Feed Shaping*

Principle

$$\textit{Aperture distribution} \propto \begin{cases} F_{feed}^{E} \cdot \cos\theta \cdot F_{elem}^{E} / r \\ F_{feed}^{H} \cdot F_{elem}^{H} / r \end{cases}$$



Requires quasi–uniform aperture distribution

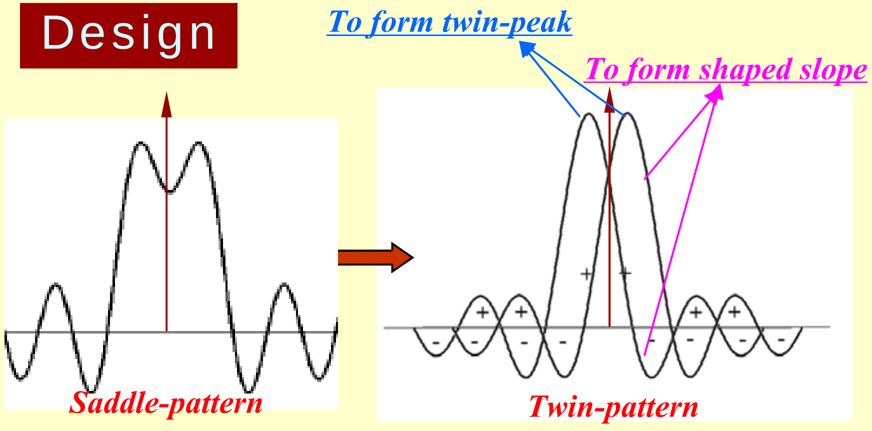
↓

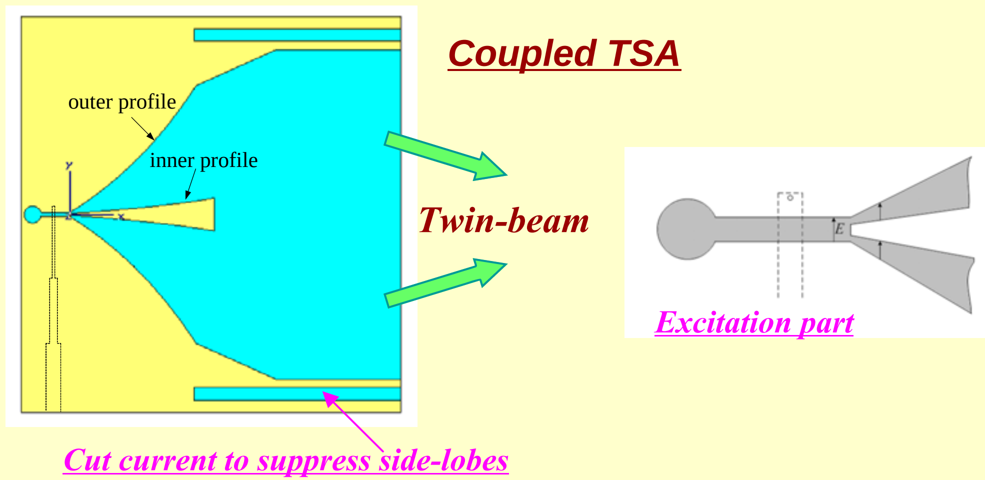
Enhance oblique illumination
Restrict normal illumination
Suppress over-flow leaking

↓

Expects a saddle-pattern with low leakage loss by *Structural Synthesis*

Design





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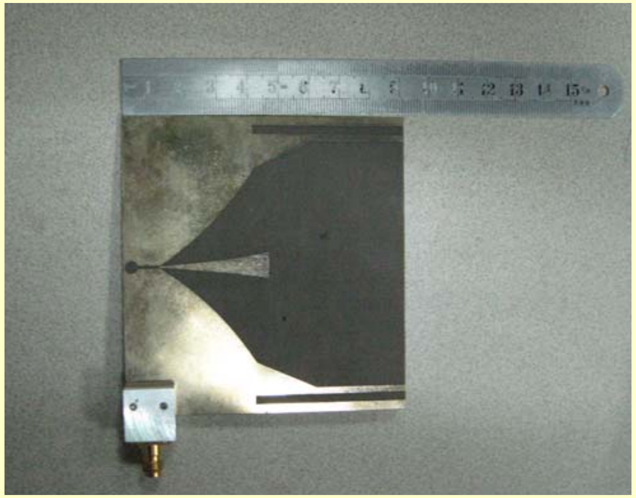
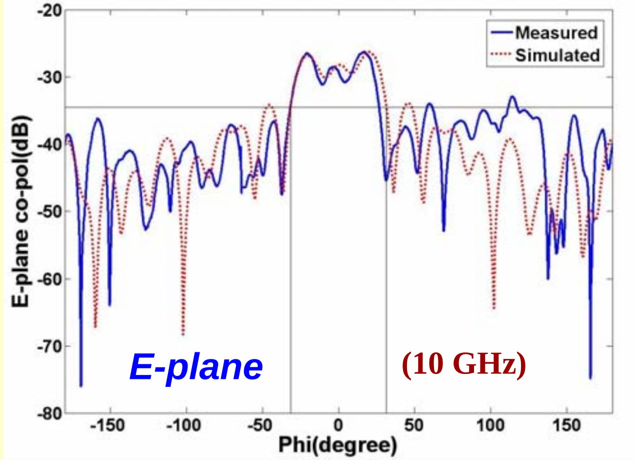
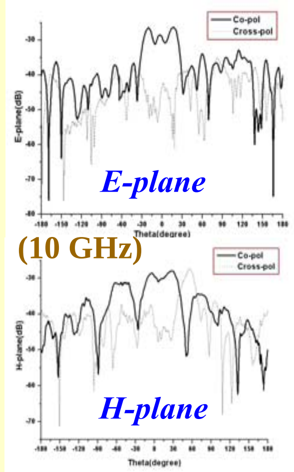
Prototype



Patterns





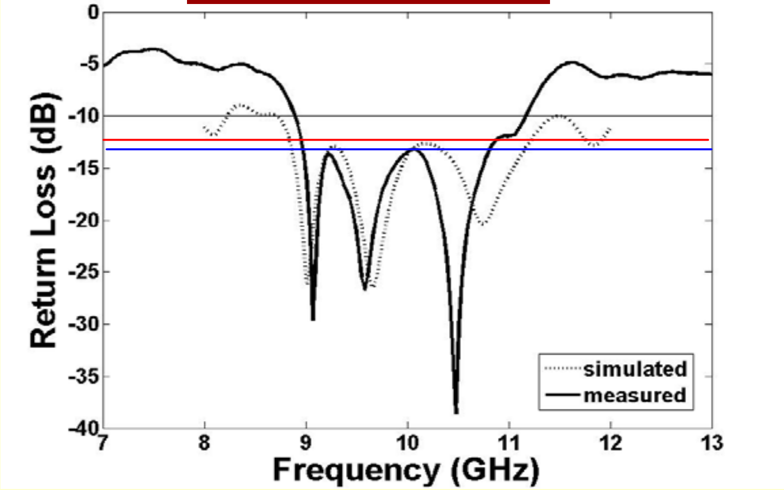
Simulated & **Measured** patterns

- *Good agreement each other*
- *Edge illumination & SLL≤ −10 dB*

Measured patterns

- *Cross-polar level ≤ −10 dB*
- *H-plane pattern is unsatisfied*

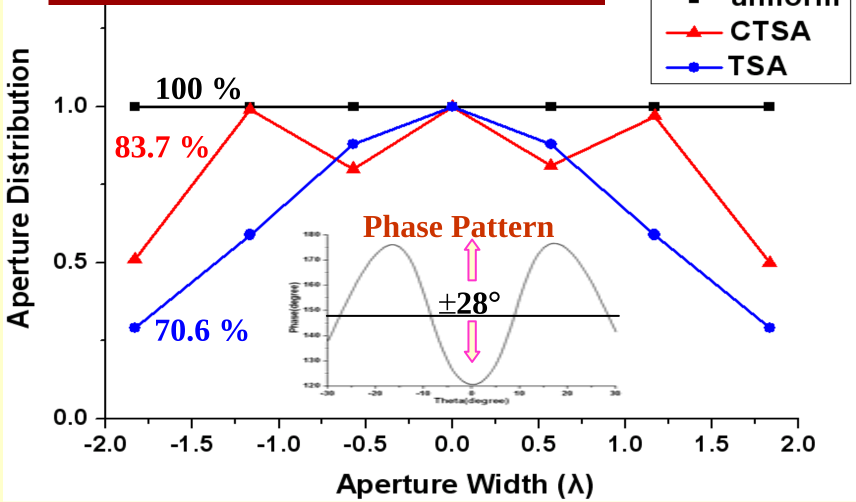
Return Loss



Simulated: 8.9-11.2 GHz (22.8%) VSWR<1.6

Measured: 9.0-10.8GHz (18.2%) VSWR<1.4

Aperture Efficiency



***Improves* 1-D Aperture efficiency 70.6% → 83.7%**

***corresponding to* 1-D Total antenna efficiency → 66.4%**

Take* Phase-Pattern *into the compensation account

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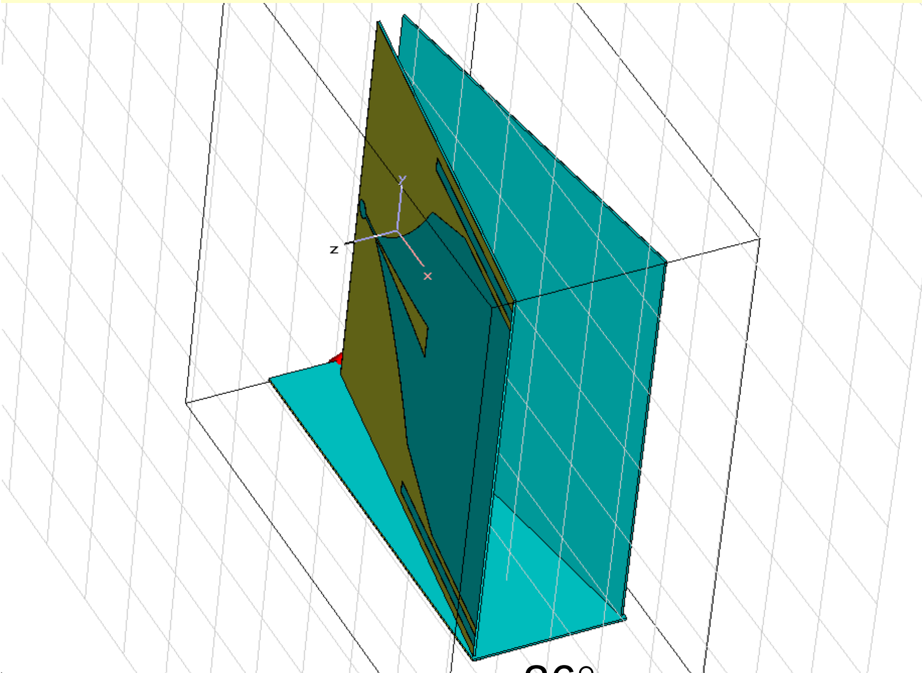
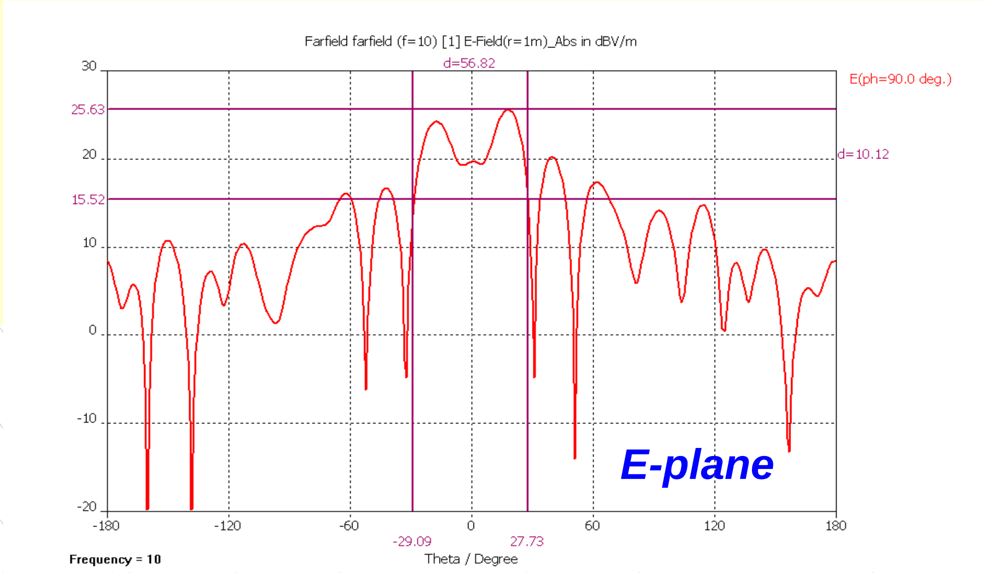
2-D Shaping Principle

A pair of 1-D plates
crossed with 36° angle

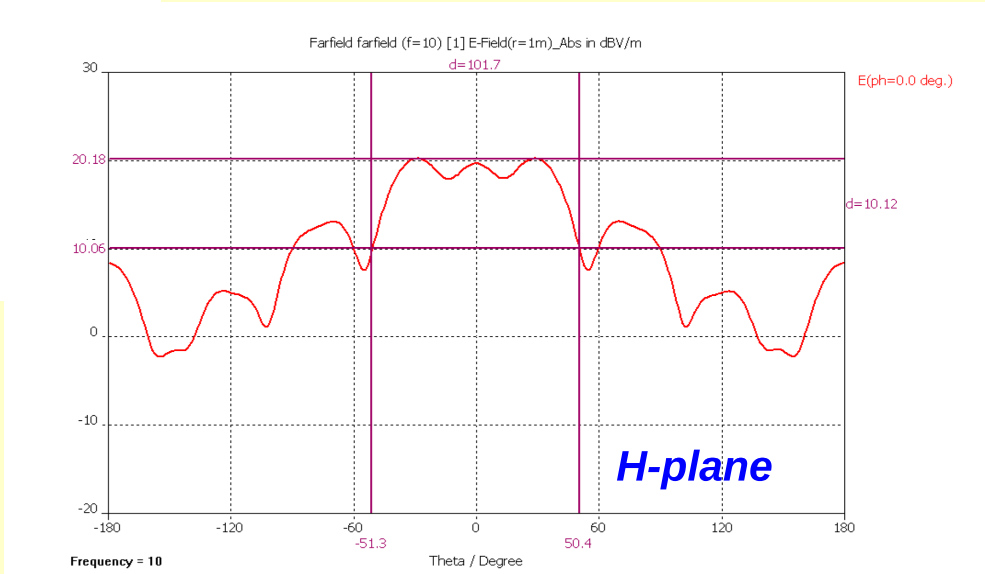


36°
angle

Saddle-beam in H-plane needs to be narrowed by using bended CTSA pair



Almost keep the pattern in E-plane as 1-D plate

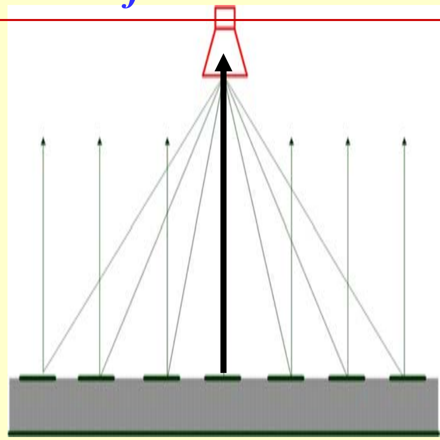


Saddle-beam in H-plane needs to be narrowed by using bended CTSA pair

Efficiency-enhancement Schemes 2 --- *Avoiding feed-blockage*

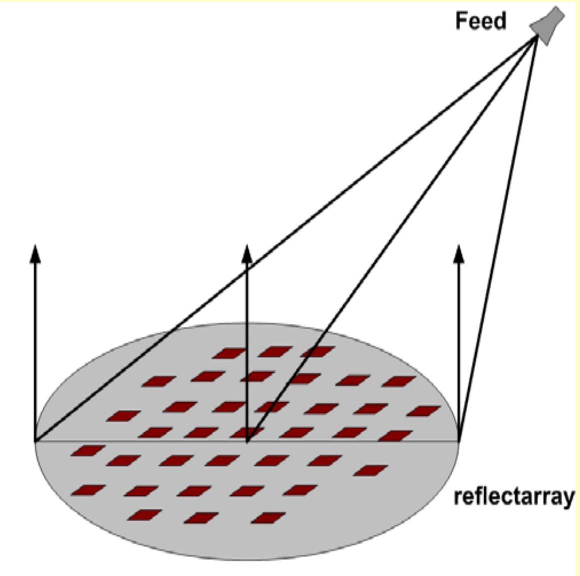
Blockage effects

Feed intersects reflected wave – blockage loss
Wave reflects into feed – interior mismatching



Traditional

By off-set feed
with elliptic aperture



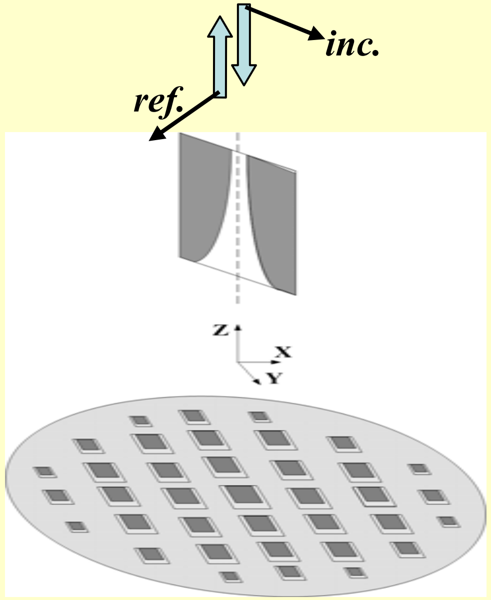
Results in:
- *Unsymmetric pattern*
- *Imaging side-lobe*
- *Twice phase difference*

Polarization Transform Types

- LP ⟹ x-LP
- LP ⟹ CP
- CP ⟹ LP
- CP ⟹ x-CP

New scheme

By polarization twist
with sheet-type feed



Merits:
- *Minimized blockage*
- *Polarized isolation*

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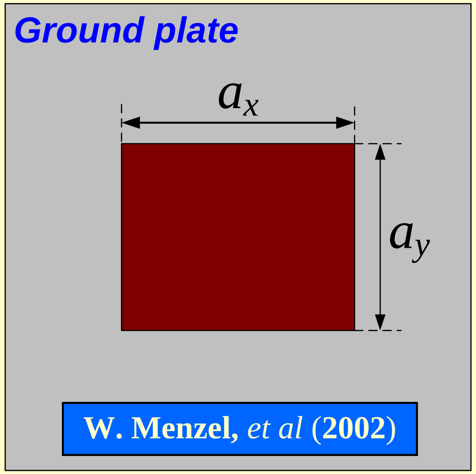
Polar -Transform

Square Patches

for { *Single LP*, *Dual (Cross) LP* }

Rectangular Patch

for { *Cross P-T*, *Arbitrary P-T* }

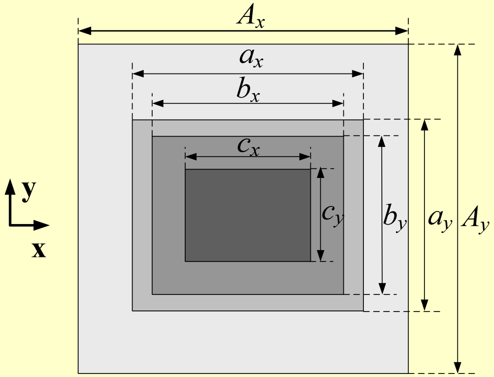


$a_x > a_y$

$\lambda_{Rx} > \lambda_{Ry}$

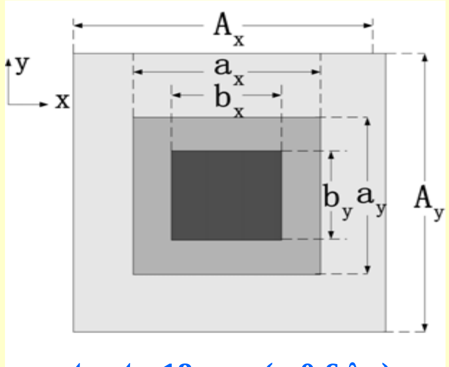
$f_{Rx} < f_{Ry}$

$\phi_x < \phi_y$



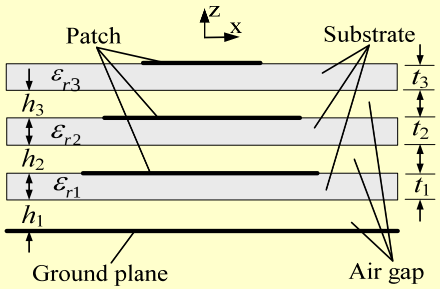
$A_x = A_y = 17mm (= 0.57\lambda_0)$

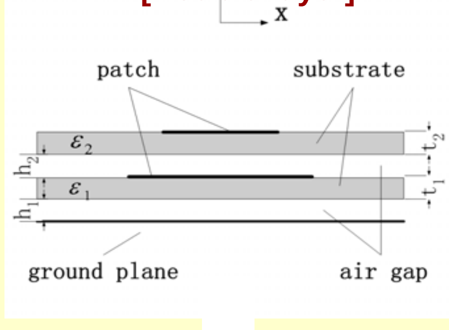
[Triple-layer]



$A_x = A_y = 18$ mm ($= 0.6\ \lambda_0$)

[Double-layer]





$h_1 = 3$ mm, $h_2 = h_3 = 2$ mm

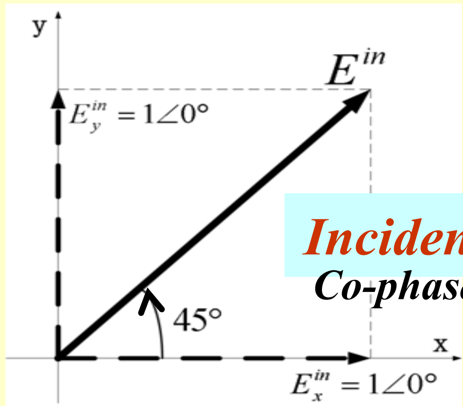
$\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 2.2$

$t_1 = t_2 = t_3 = 0.5$ mm

$h_1 = h_2 = 2$ mm

$\varepsilon_1 = \varepsilon_2 = 2.2$

$t_1 = t_2 = 0.5$ mm

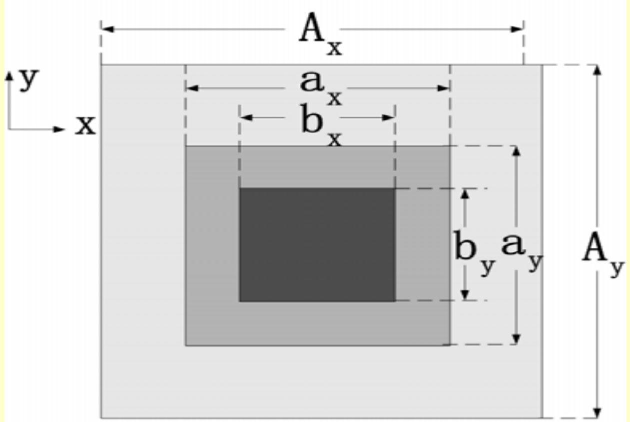


Reflection Phase-difference

$\Delta\phi = \phi_y - \phi_x$	$-\pi/2$	0	$\pi/2$	$\pm\ \pi$
Reflected	RHCP	Co-LP	LHCP	X-LP

Multi-layer structure with given parameters

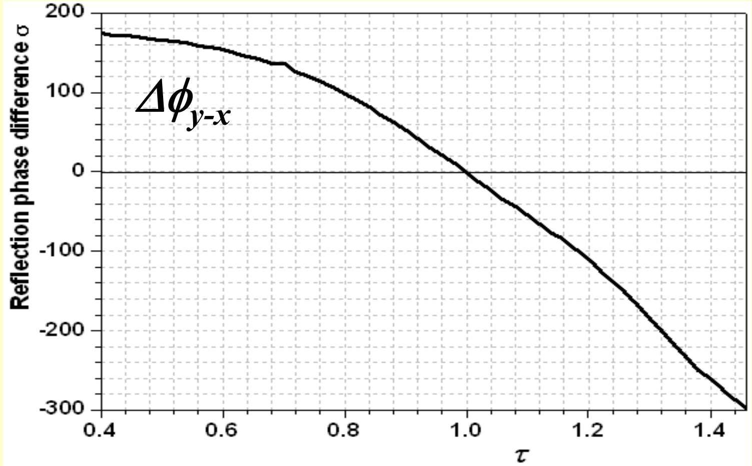
Double -Layer



$A_x = A_y = 18$ mm ($= 0.6\ \lambda_0$)

$t_1 = t_2 = 0.5$mm, $\varepsilon_1 = \varepsilon_2 = 2.2$,
$h_1 = h_2 = 2$mm, $A_x = A_y = 18$mm,
$s = b_x / a_x = b_y / a_y = 0.7$,
at $a_x = 11$ mm

$f = 10$ GHz
45º polar-twist



Two orthogonal components

- ***Almost same amplitude*** **due to** ***complete reflection***;
- ***Wide range*** **(480º)** ***phase***

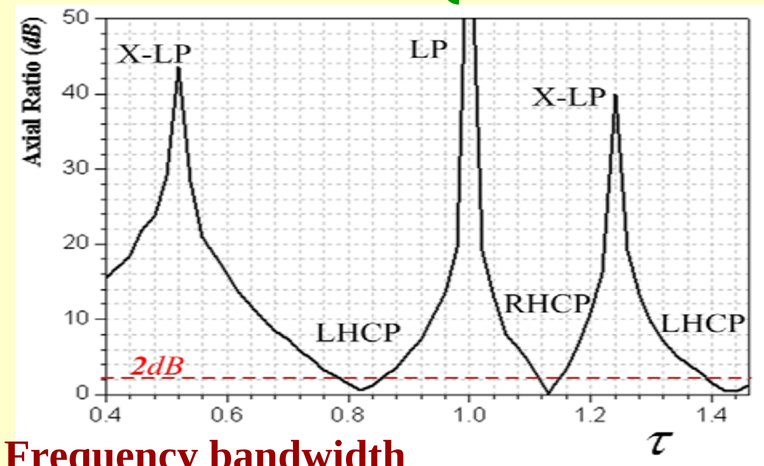
for both { ***phase compensation*** / ***polarization transform .*** }

Defined

- ***Similarity ratio*** $s = b_x / a_x = b_y / a_y$
- ***Aspect ratio*** $\tau = a_y / a_x = b_y / b_x$
- ***Patch side*** a_x ***~ lower patch, in x- side***

Adjusted

- $s = 0.7$ ***within*** **(0.6~0.8)**
- τ ***for polarization transform***
- a_x ***for phase compensation***



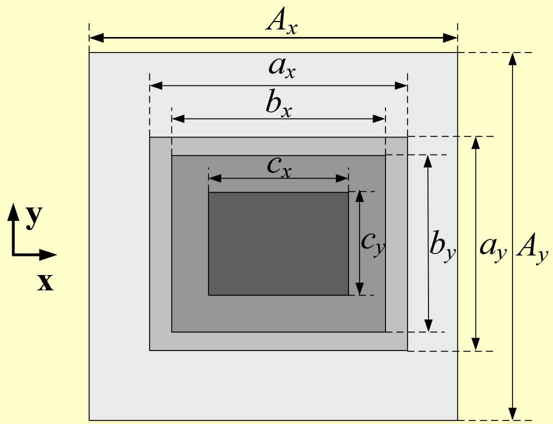
Frequency bandwidth

4 %	***for***	**X-LP (*axial ratio* > 30 dB)**
10 %		**LHCP (*axial ratio* < 2 dB)**

REFLECTARRAY - 13

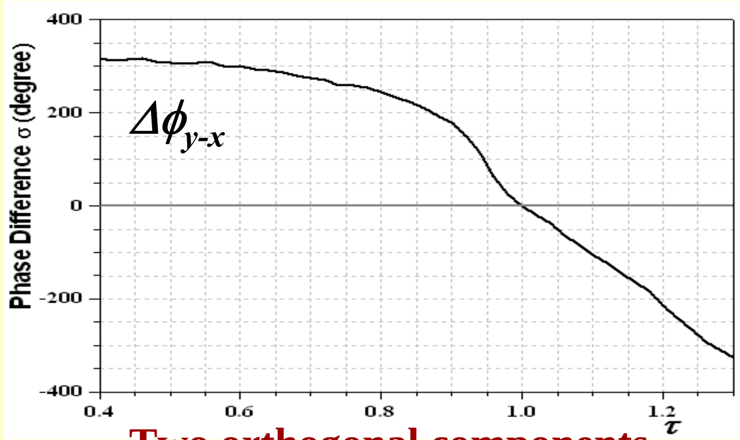
Triple -Layer

***f* = 10 GHz**
45º polar-twist



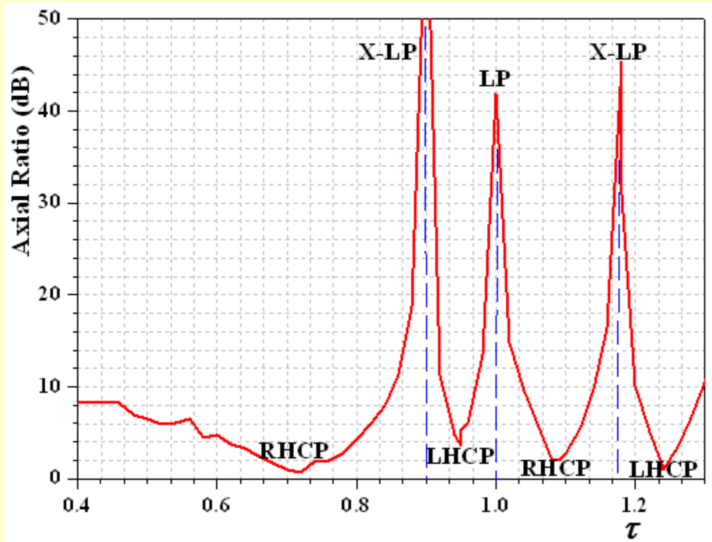
$A_x = A_y = 17mm (= 0.57\lambda_0)$

$t_1 = t_2 = t_3 = 0.5$ mm, $\varepsilon_{r1} = \varepsilon_{r2} = \varepsilon_{r3} = 2.2$
$h_1 = 3$ mm, $h_2 = h_3 = 2$ mm, $A_x = A_y = 17$ mm,
$S_1 = c_x / a_x = c_y / a_y = 0.7$,
$S_2 = b_x / a_x = b_y / a_y = 0.9$, at a_x=12 mm



Two orthogonal components

Wide range* (640º) *phase for both
- *polar transformation*
- *phase compensation*



τ =0.90 / 1.18 ⇨ X-LP, τ =1 ⇨ Co-LP
τ =0.72 / 1.08 ⇨ RHCP, τ =1.24 ⇨ LHCP

Defined

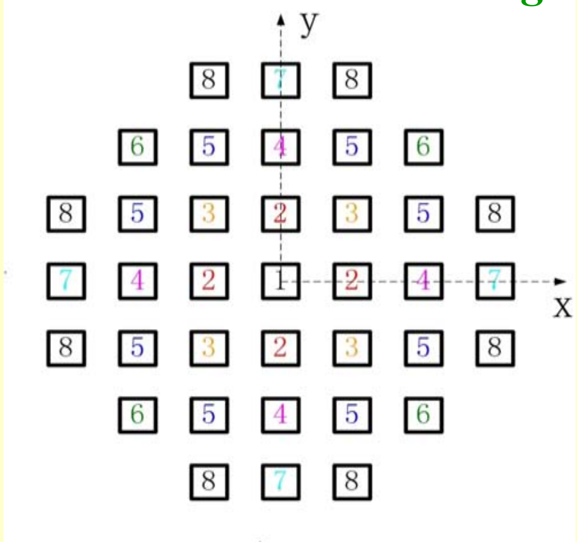
- ***Similarity ratio*** $S_1 = c_x / a_x = c_y / a_y$
  $S_2 = b_x / a_x = b_y / a_y$
- ***Aspect ratio*** $\tau = a_y / a_x = b_y / b_x = c_y / c_x$
- ***Patch side*** a_x *~ lower patch, in x- side*

Adjusted

- S_1 **= 0.7,** S_2 **= 0.9 *within* (0.6~0.9)**
- τ ***for transform polarization***
- a_x ***for phase compensation***

Array Architecture

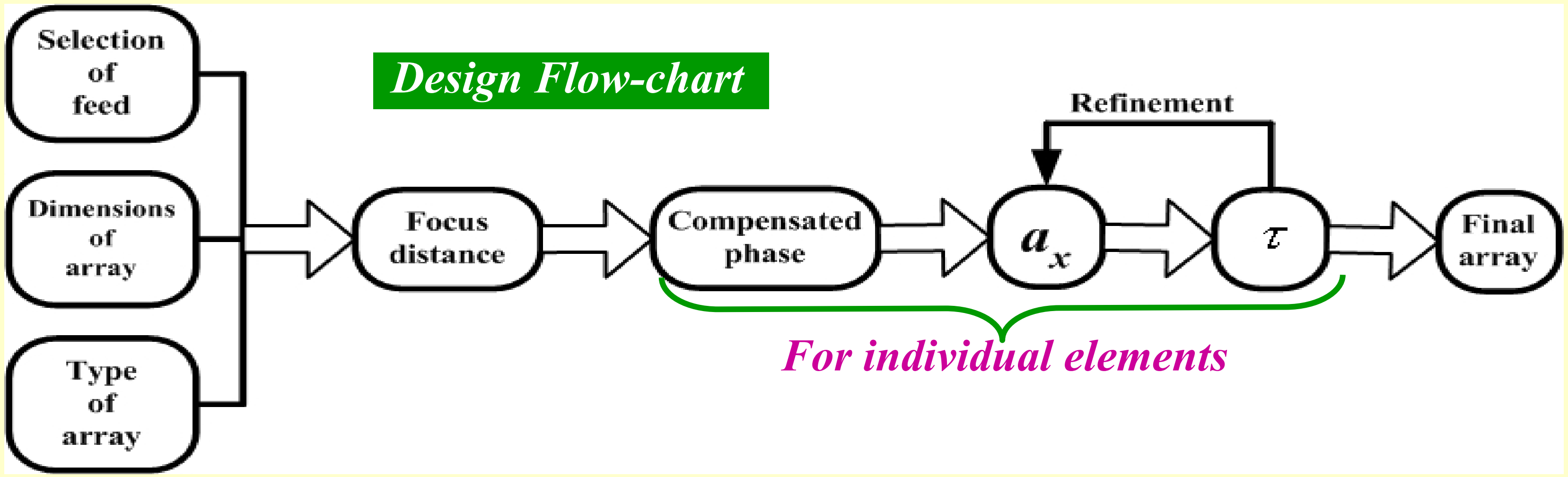
Elements with numbering



37-element array

8 kinds of element

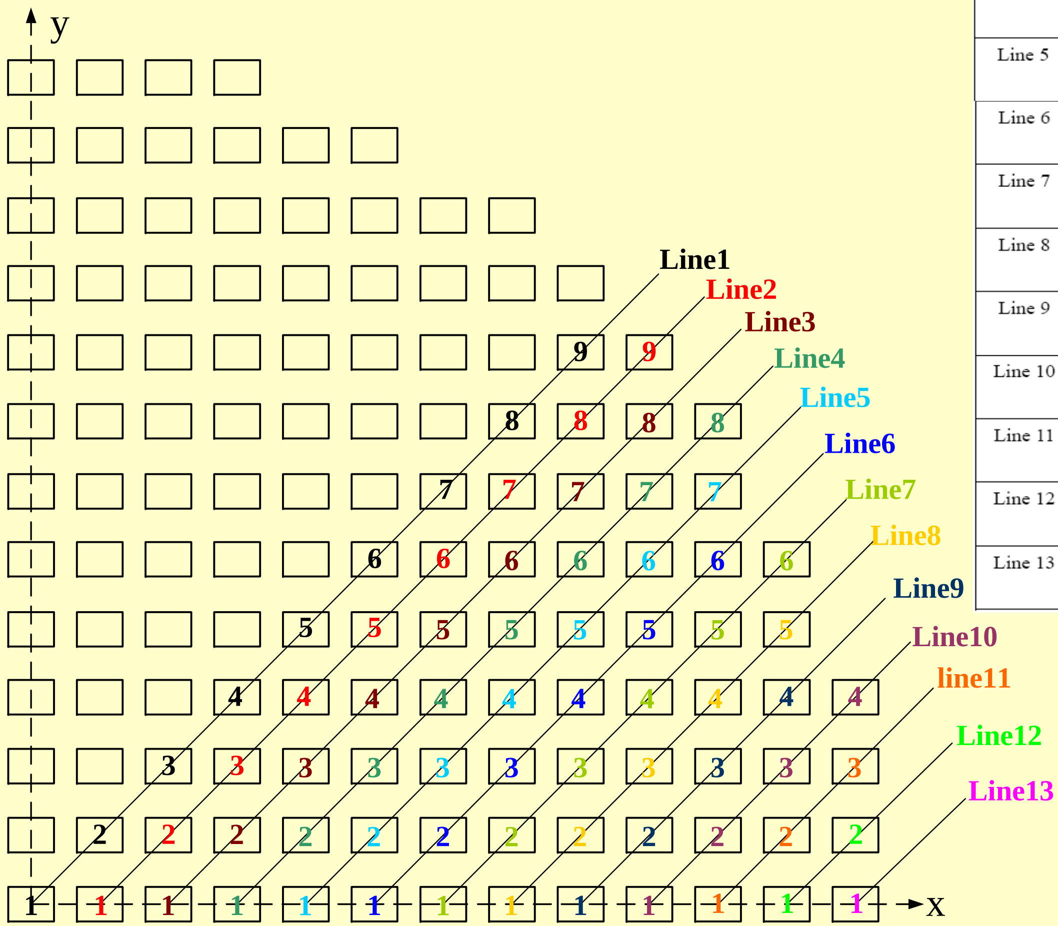
Kind of	1st	2nd	3rd	4th	5th	6th	7th	8th
Numbers	1	4	4	4	8	4	4	8



REFLECTARRAY - 15

馈源的相位方向性图 → 各单元的补偿相位 → 各单元的尺寸

No. / Line	1	2	3	4	5	6	7	8	9
Line 1	(16, 0.828)	(15.7, 0.835)	(15.08, 0.827)	(14.34, 0.78)	(13.2, 0.715)	(11.25, 0.51)	(8.55, 1.46)	(13.44, 0.725)	(10.5, 1.33)
Line 2	(15.84, 0.83)	(15.36, 0.832)	(14.7, 0.81)	(13.85, 0.745)	(12.18, 0.672)	(9.92, 1.37)	(14.34, 0.78)	(11.95, 0.66)	(8.55, 1.46)
Line 3	(15.46, 0.835)	(14.92, 0.82)	(14.2, 0.77)	(13, 0.705)	(11.02, 1.29)	(8.35, 1.47)	(13.3, 0.715)	(10.26, 1.345)	
Line 4	(15.03, 0.825)	(14.45, 0.785)	(13.5, 0.725)	(11.75, 0.635)	(9.5, 1.395)	(14.12, 0.76)	(11.6, 0.615)	(8.05, 1.5)	
Line 5	(14.52, 0.795)	(13.78, 0.742)	(12.32, 0.676)	(10.3, 1.347)	(7.25, 1.61)	(12.72, 0.695)	(9.62, 1.385)		
Line 6	(13.9, 0.75)	(12.72, 0.695)	(10.95, 1.3)	(8.53, 1.46)	(13.55, 0.728)	(10.83, 1.305)			
Line 7	(12.88, 0.7)	(11.35, 0.545)	(9.22, 1.415)	(14.06, 0.76)	(11.7, 0.62)	(8.53, 1.46)			
Line 8	(11.45, 0.575)	(9.62, 1.385)	(14.41, 0.785)	(12.5, 0.68)	(9.62, 1.385)				
Line 9	(9.76, 1.38)	(7, 1.655)	(13, 0.705)	(10.35, 1.34)					
Line 10	(7.36, 1.592)	(13.36, 0.72)	(10.95, 1.3)	(7.6, 1.56)					
Line 11	(13.44, 0.725)	(11.35, 0.545)	(8.45, 1.465)						
Line 12	(11.45, 0.575)	(8.9, 1.435)							
Line 13	(9.1, 1.422)								



阵列单元口径面分布（1/4阵面 ）

焦距 $F = 310$ mm

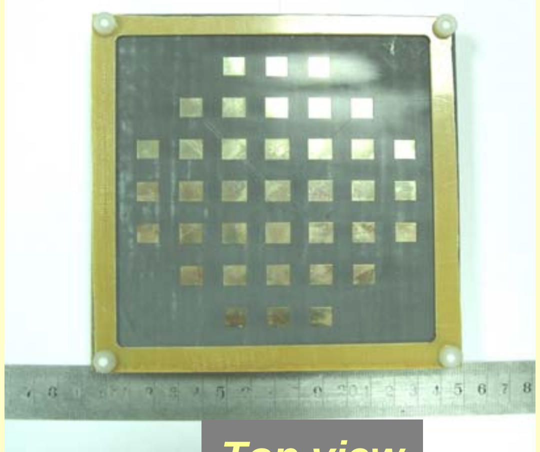
口径 $D = 450$ mm

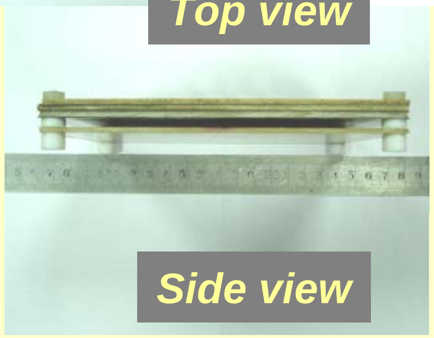
72 种单元

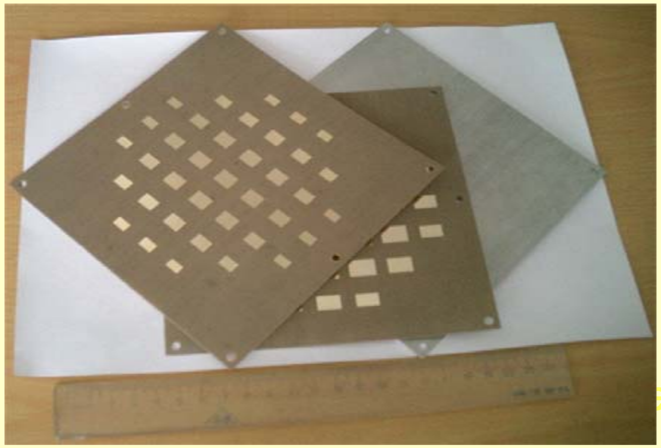
$\phi_{max} = 793°$

Prototypes

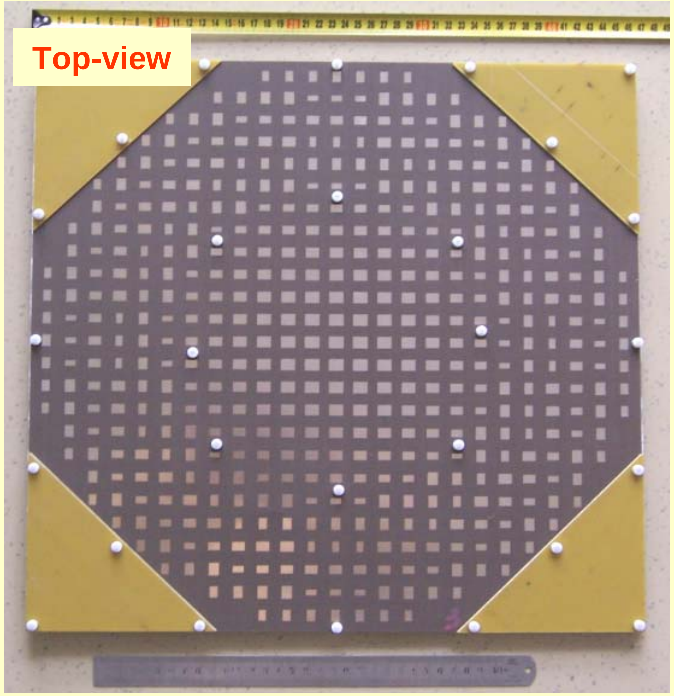
37-element 2-/3-Layer Sample

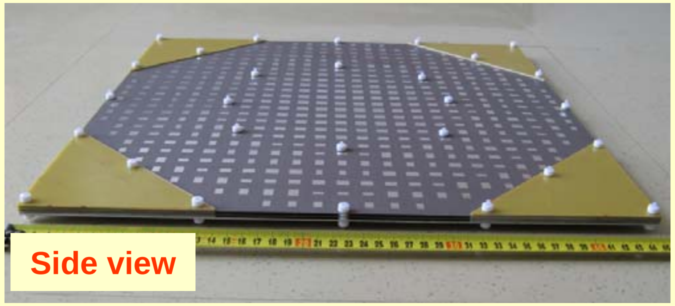

Top view


Side view



489-element 2-Layer Sample

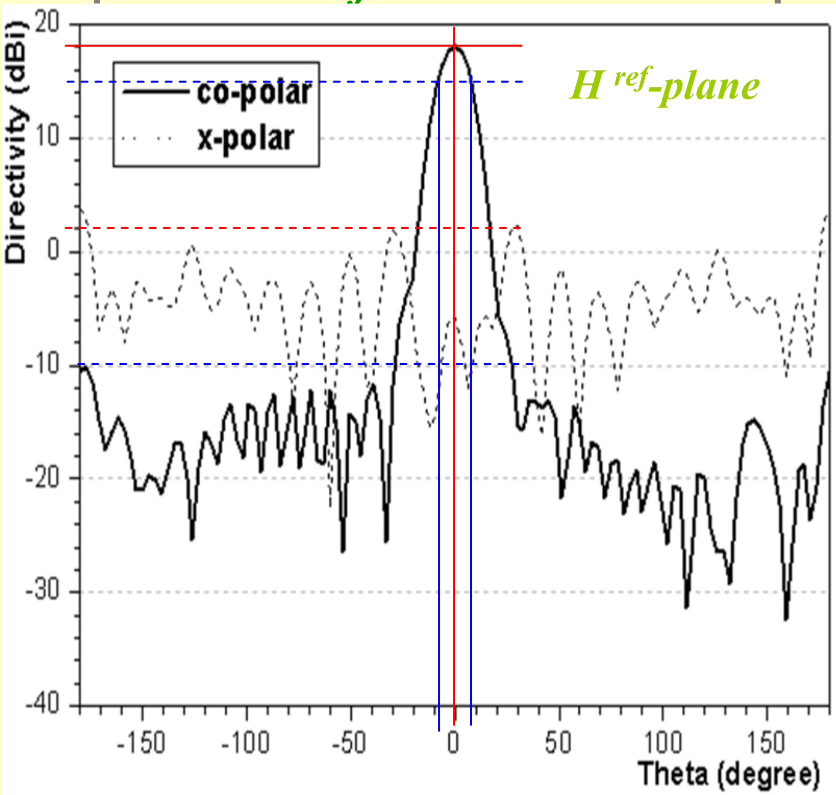

Top-view


Side view

37-element LP→ X-LP reflectarray

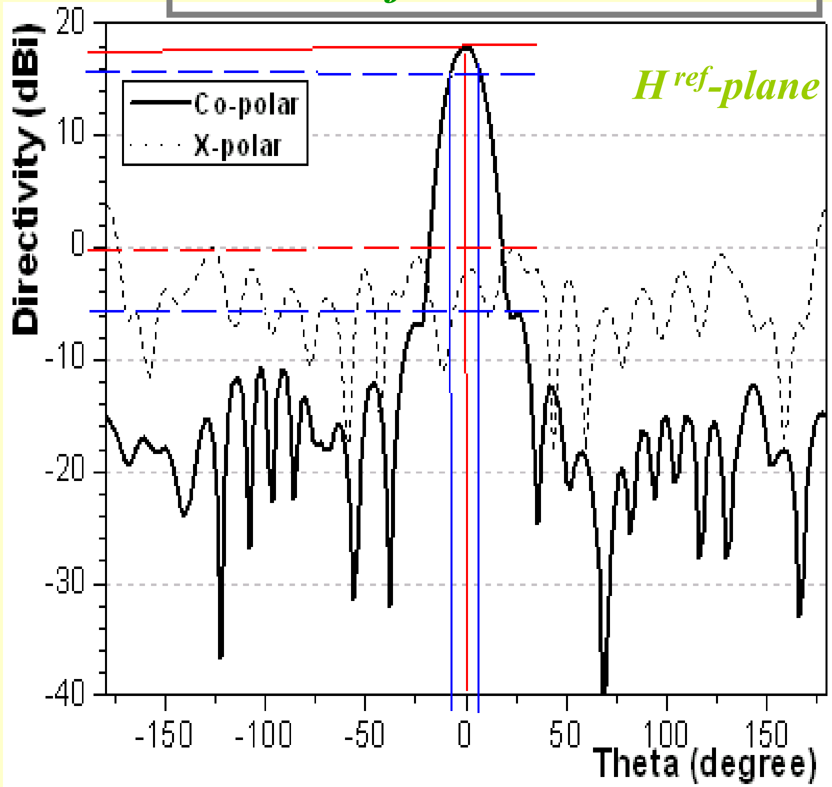
Pattern

Double-layer reflectarray at f=10 GHz



Gain ~ 18 dB
η_{Aper} ~ 47.1 (37.7) %
HPBW ~ 16°
SLL ~ –28 dB
X-Polar ~ –16 dB

Triple-layer reflectarray at f=10.1 GHz



Gain ~ 17.9 dB
η_{Aper} ~ 50.6 (40.5) %
HPBW ~ 16°
SLL ~ –24 dB
X-Polar ~ –17.9 dB

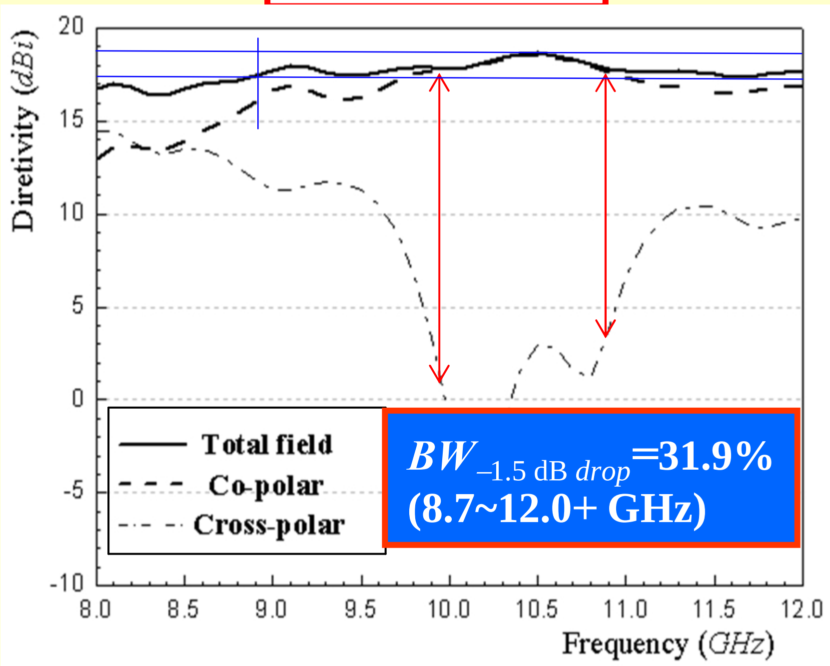
Enhancing
Aperture efficiency

37-element LP → X-LP reflectarray

Directivity & Polarity *vs. Frequency*

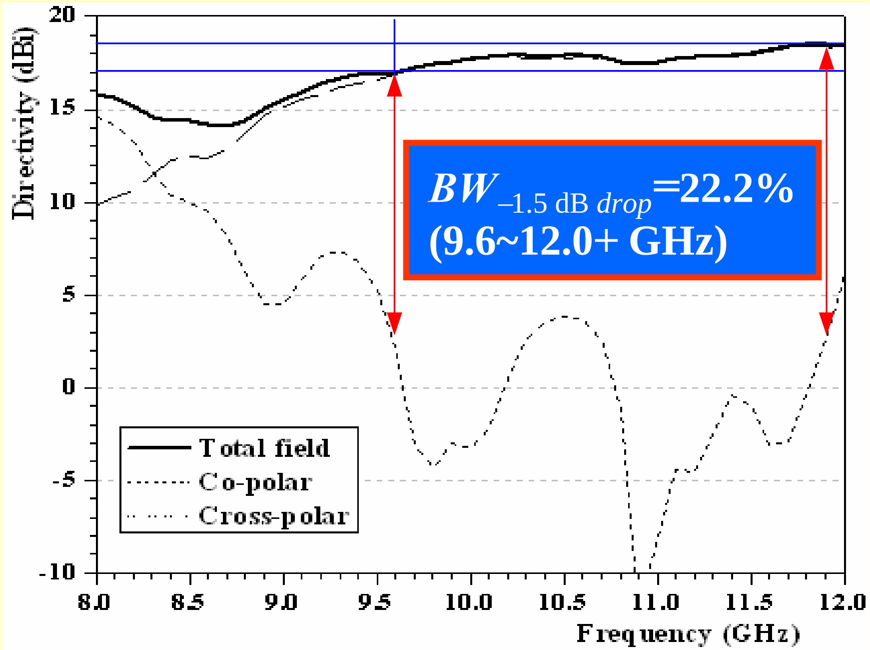
Double-layer reflectarray

Z. H. Wu, *et al* (2004)



Triple-layer reflectarray

H. H. Chen, *et al* (2006)



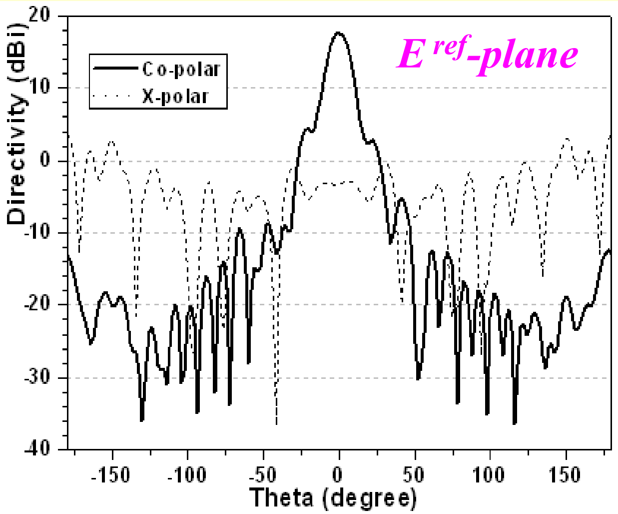
X-Polar ≤ –14 dB
within (9.9~10.9) GHz ~9.6%

Extending → *Bandwidth*

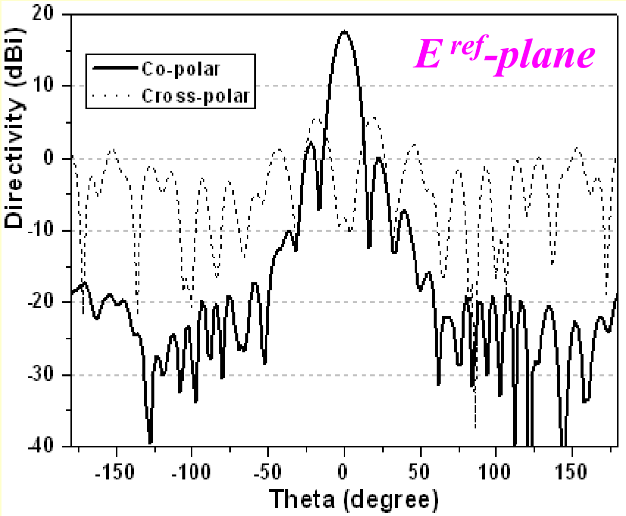
X-Polar ≤ –14 dB
within (9.6~11.9)GHz ~21.4%

37-element LP → X-LP reflectarray

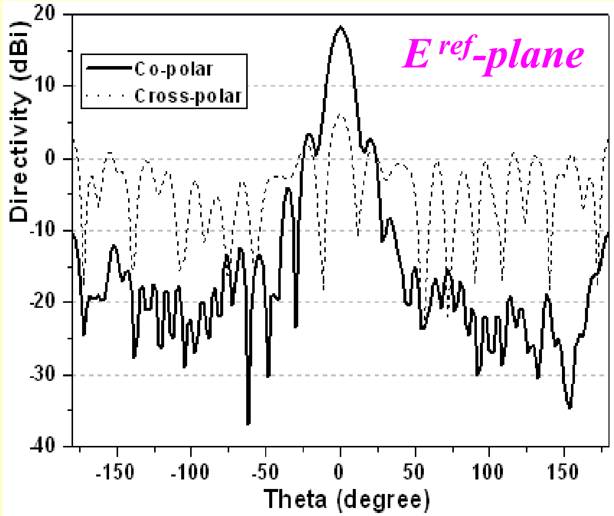
Pattern *vs. frequency*



f = 10 GHz



f = 11 GHz



f = 12 GHz

Directivity ~ 17.7 dBi
HPBW ~ 14°
SLL ~ –13 dB
X-Polar ~ –21 dB

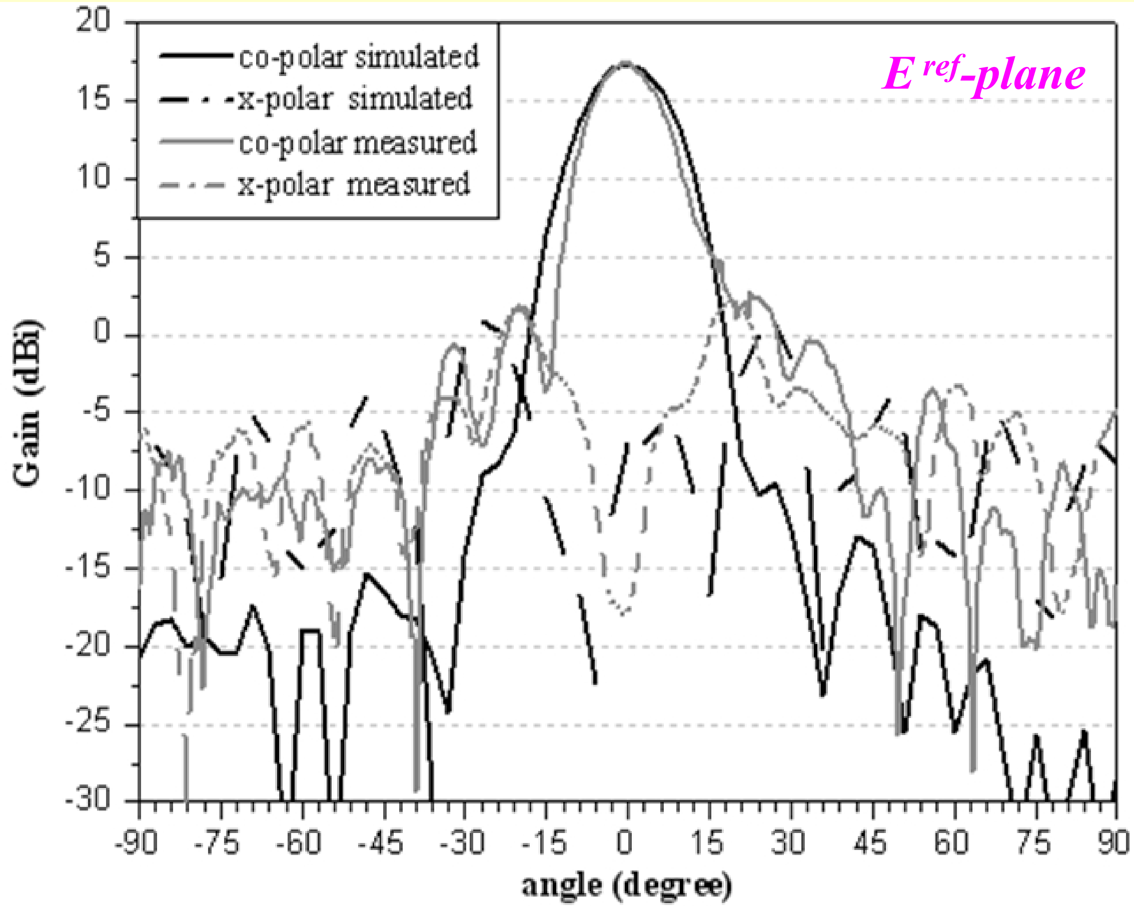
Directivity ~ 17.5 dBi
HPBW ~ 14°
SLL ~ –15.3 dB
X-Polar ~ –25.7 dB

Directivity ~ 18.2 dBi
HPBW ~ 12°
SLL ~ –14.7 dB
X-Polar ~ –12 dB

37-element LP → X-LP reflectarray

Pattern & Polarization

Double-layer at Frequency 10.2 GHz



Simulated

Directivity ~17.4 dB
HPBW ~ 12.5°
SLL ~ –15 dB
X-Polar ~ –24 dB

using Microwave Studio CST 5.0

Good agreement with

Measured

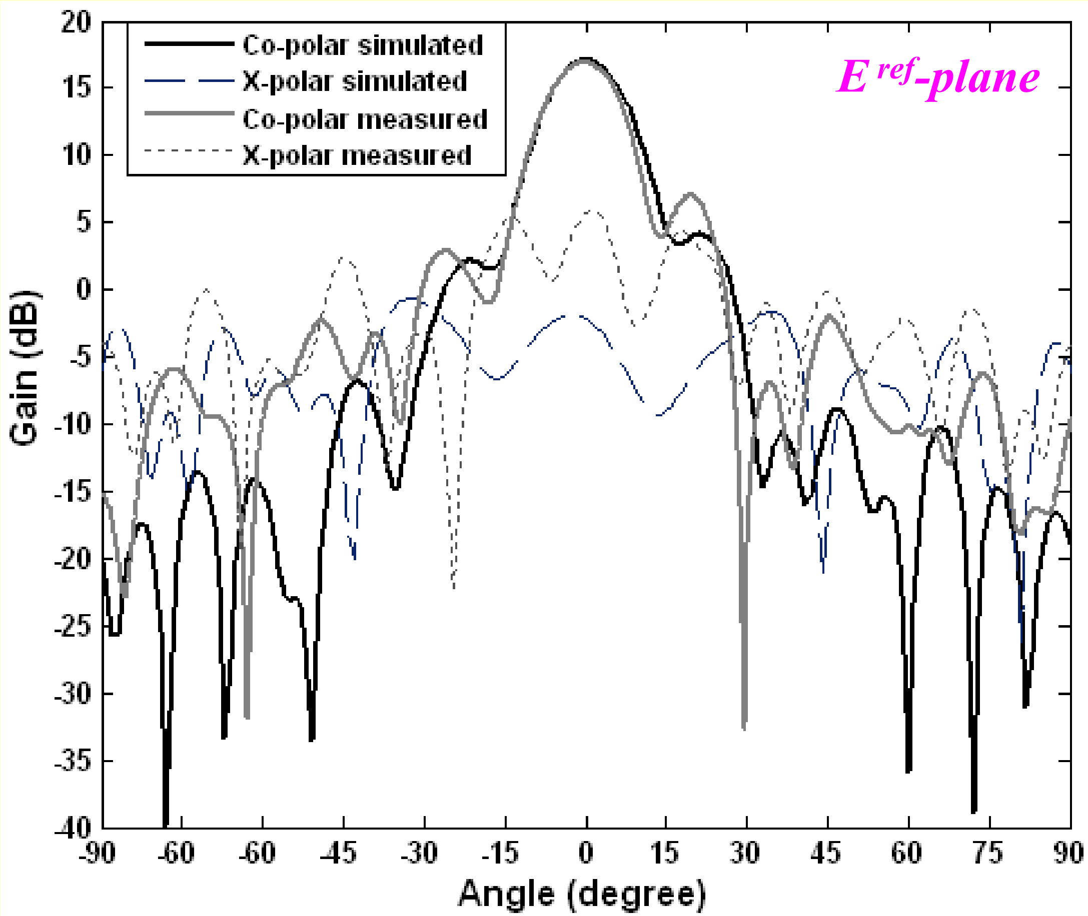
Gain ~ 17.4 dB
HPBW ~ 12°
SLL ~ –14 dB
X-Polar ~ –32 dB

at Ant. & Microwave Tech. Lab.

37-element LP → X-LP reflectarray

Pattern & Polarization

Triple-layer at Frequency 10 GHz



Simulated

Directivity~17.1 dB
HPBW ~ 14°
SLL ~ –13 dB
X-Polar ~ –19.3 dB

using CST Microwave Studio 5.0

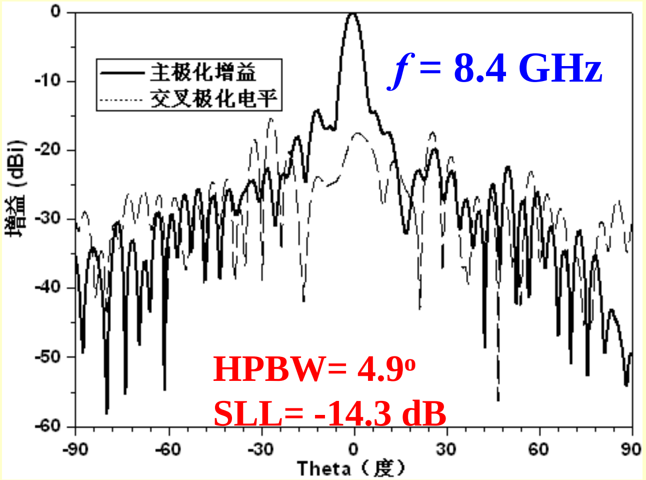
Measured

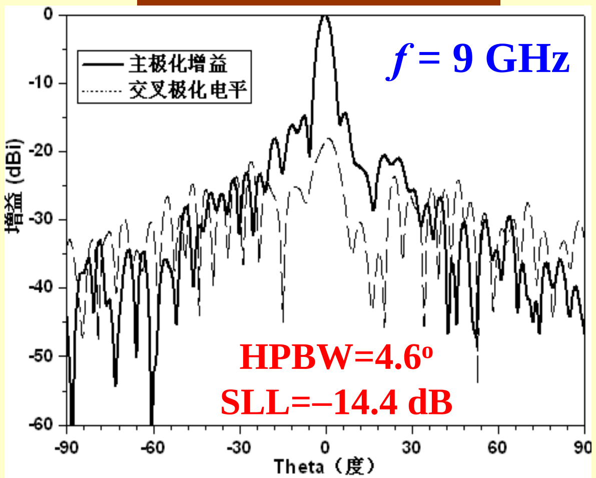
Gain ~ 16.9 dB
HPBW ~ 13.8°
SLL ~ –10 dB
X-Polar ~ –11.3 dB

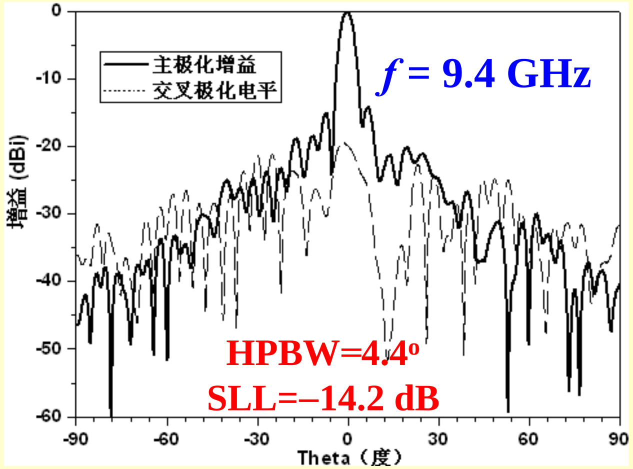
at Nat. Lab of Ant. & MW Tech.

489-element Double-Layer LP → X-LP reflectarray

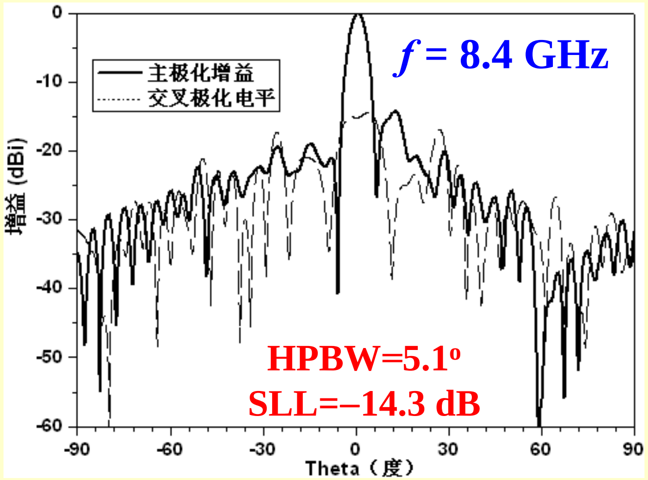
E-plane pattern

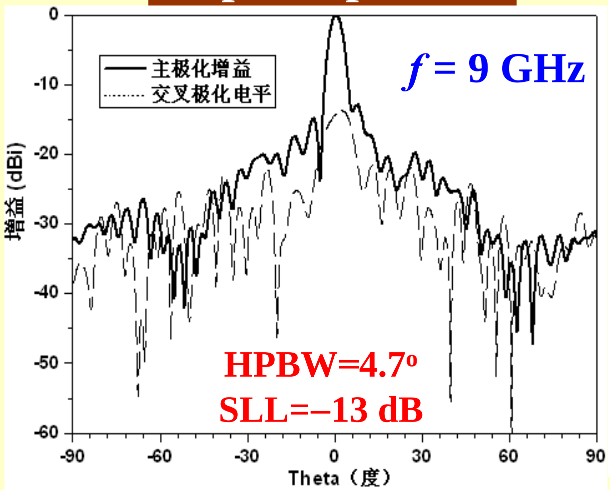


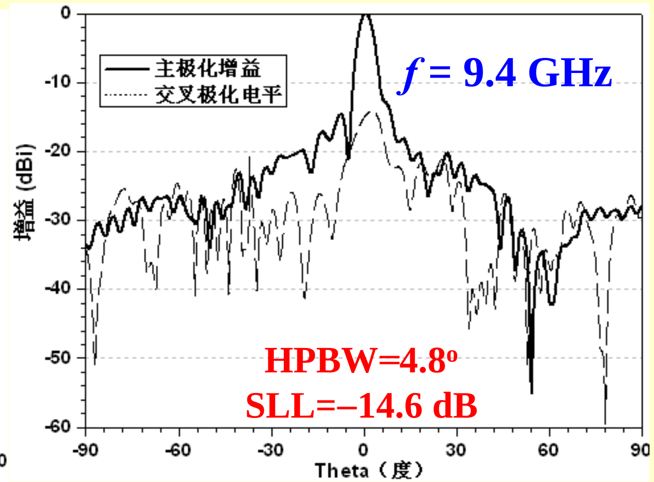




H-plane pattern

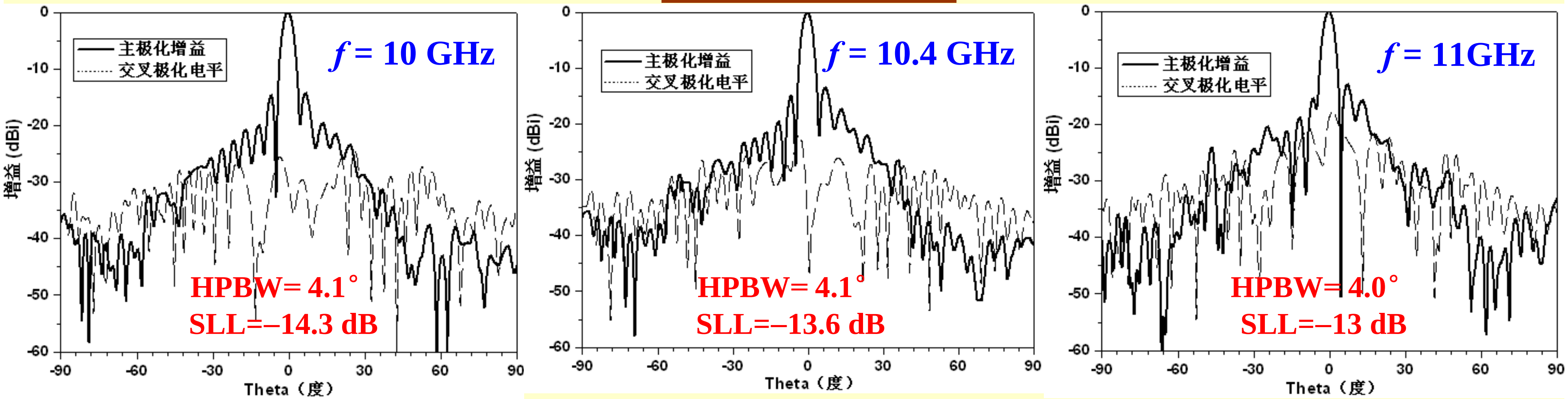




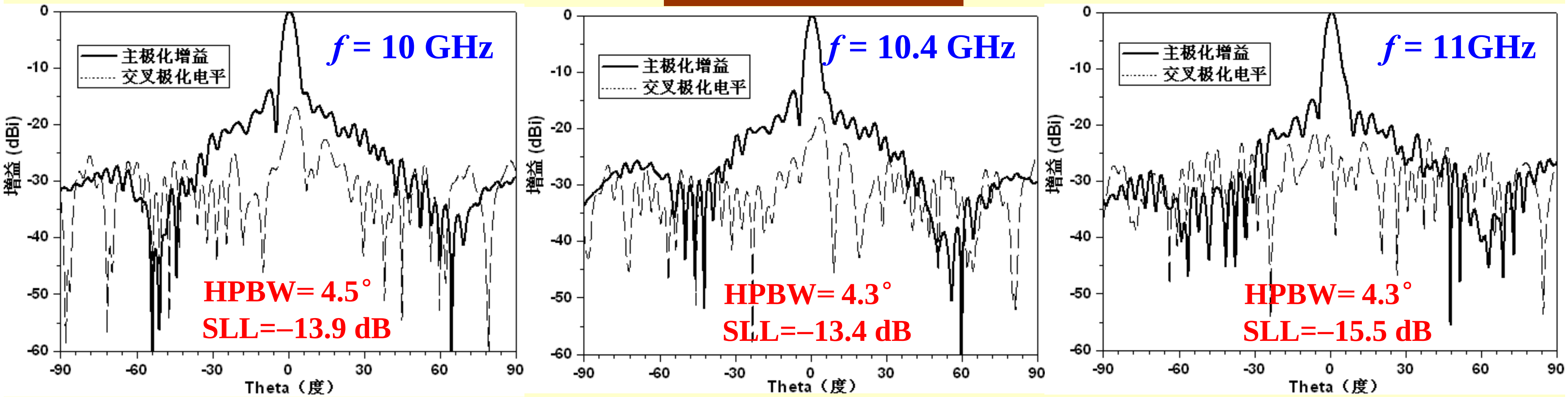


489-element Double-Layer LP → X-LP reflectarray

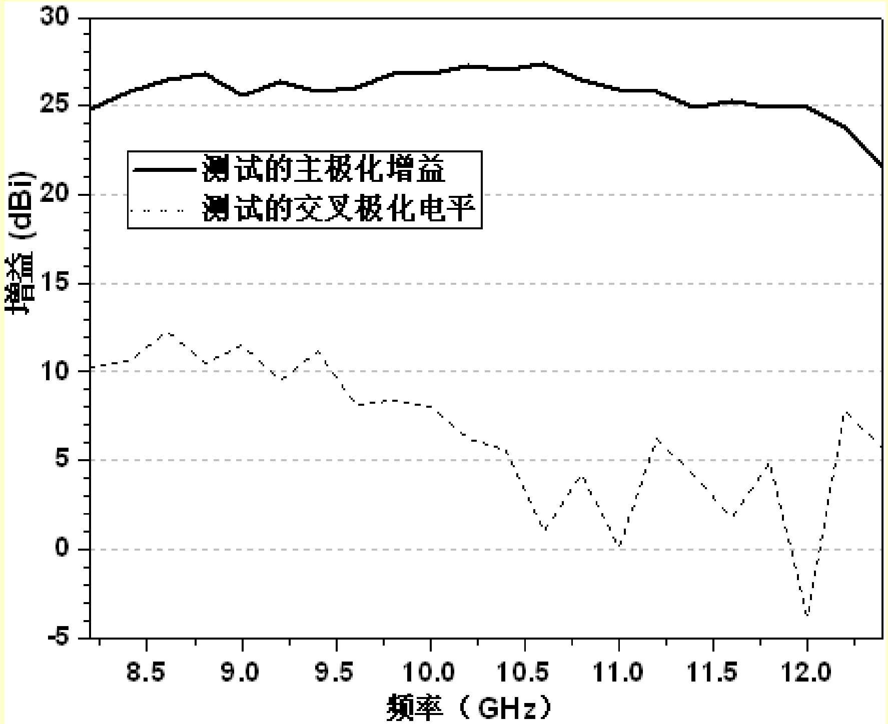
E-plane pattern



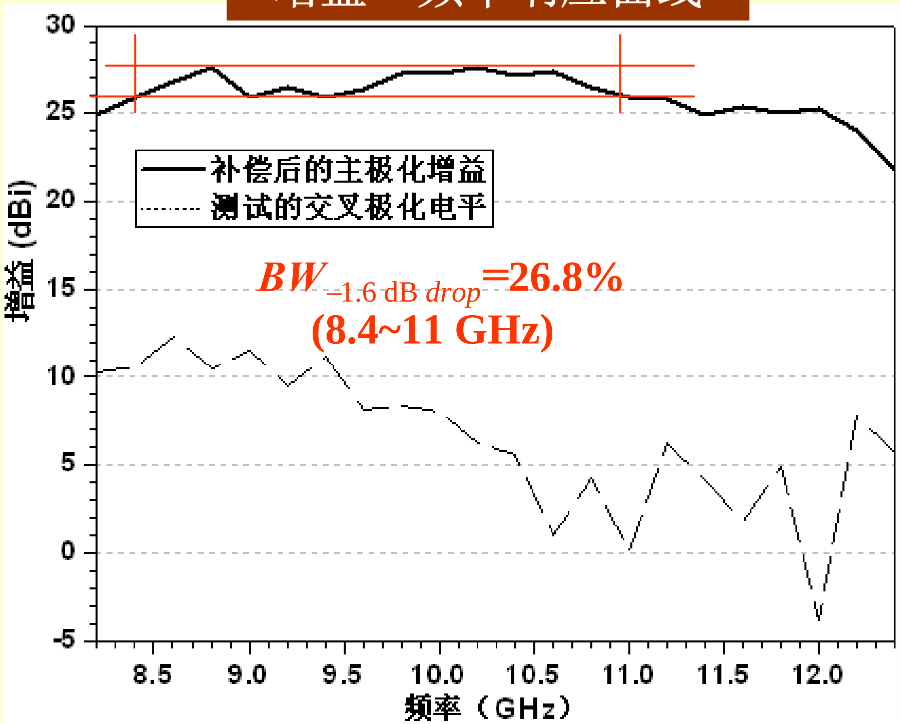
H-plane pattern



实测增益—频率响应曲线



按馈源回波损耗补偿后
增益—频率响应曲线



8.4～11 GHz
（26.8％）
G_{max} = 27.6 dBi
G / G_{max} <1.6dB
增益曲线平坦

8.2～12.4GHz
（40.8％）
XPL < -14dB
SLL < -13dB

Summary on Reflectarray

- *The Combined Techniques of sized, stacked, rectangular patch used as Elements of Reflectarray are available to improve its Bandwidth & Efficiency.*

- *The reflectarray with orthogonally polarization transform can reduce feed blockage and exhibit more stable frequency response due to polarized isolation between the feed and reflected wave.*

- *Three-layer reflectarray of microstrip patches exhibits wider bandwidth than two-layer reflectarray, but less aperture efficiency.*

- *The Polarization Transform in Reflectarray is a novel branch with respect to potential wider Applications.*

- *The reflectarray with improved & optimized performances needs to be further studied ;*

- *The mechanism analysis of non-periodic & non-axial-symmetric array is a serious challenge.*

Printed Transmitarray

Comparison

Contrast *to the* *shortcoming* *of a* Reflectarray *with* { ***Feed blockage &*** / ***Forward-towering*** } *as a* **Reflector** Ant.,

The *shortcoming* *of a* Transmitarray *are* { ***reflective loss &*** / ***backward-towering*** } *as a* **Lens** Ant.,

Both occupy a volume with larger thickness !

Transmitarray *based on* multilayer interference *with* { *forward summation* / *backward canceling* } *as a* **Filter**,

but { *lower efficiency due to incompletely canceling* / *& impossible to steer the beam orientation.* }

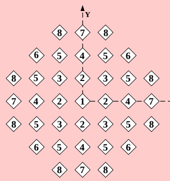
Transmitarray *based on* receiving-transmitting *with* *delay-line connection* *as a* **Repeater**,

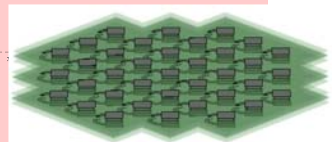
but *complicated transmission structure* *results in trouble for* { *design &* / *fabrication.* }

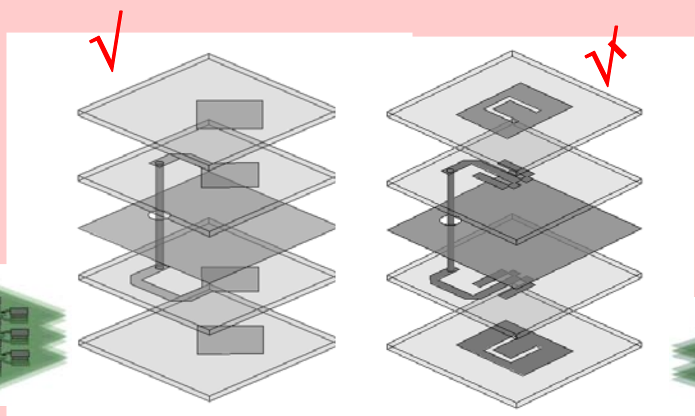
Select R-T type for improving performances !

37-element **TA** *with*
Directly corner-fed
stacked square-patch

F/D*=0.5 *TSA-feed

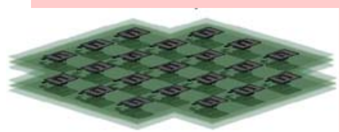


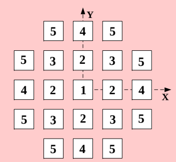




21-element **TA** *with*
Proximity-fed
U-slotted rectangle-patch

F/D*=0.5 *TSA-feed

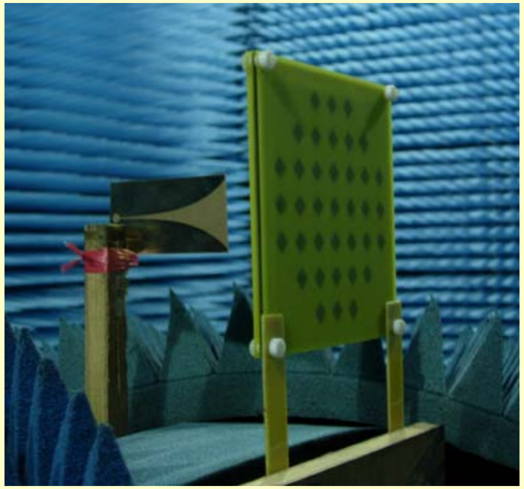




TRANSMITARRAY - 2

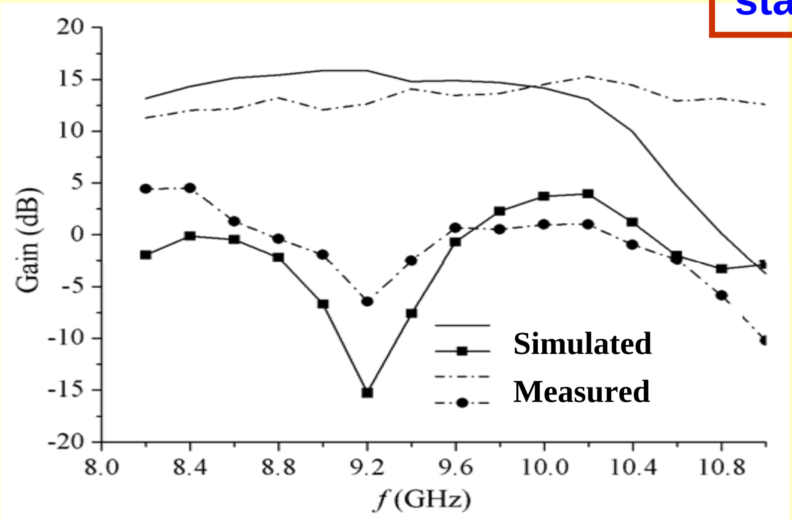
Prototype

37-element TA *with* Directly corner-fed stacked square-patch



F/D=0.5 *TSA-feed*

Gain *vs.* frequency

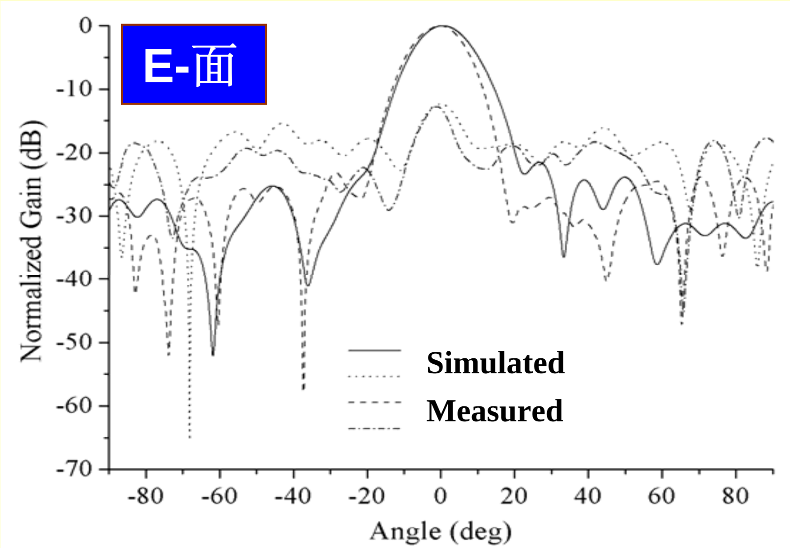


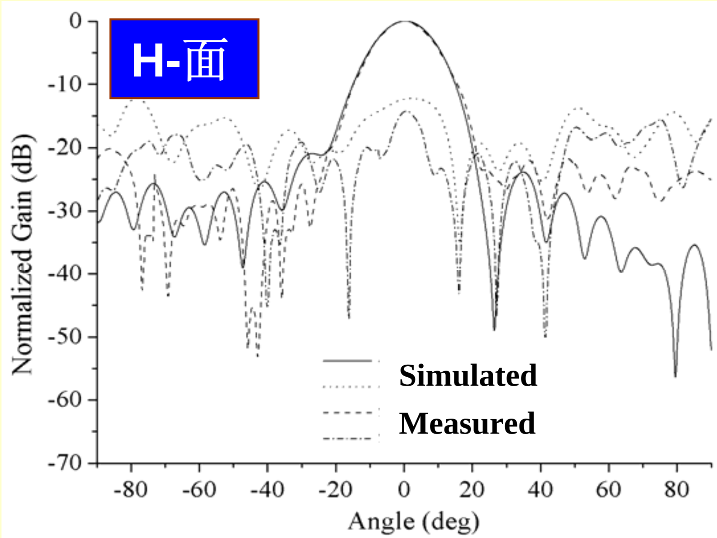
Main performances

Data	*Freq. range*	$BW_{\Delta G-3dB}$	G_{max} (dB)	*XPL*(dB)
Simulated	(8.2~10.2)GHz	21.6 %	16.3	–12.5
Measured	(8.6~11.0)GHz	24.3 %	15.4	–10.9

Pattern

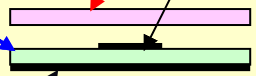
at f =10 GHz





Printed Fabry-Perot Resonator

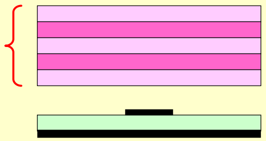
Review on Microstrip Patch Antenna with Cover

Superstrate (*cover*)
Patch
Substrate

Ground plate

--- with electrically-small thickness / spacing.

May enhance Directivity *with the cost of decreasing* Bandwidth;
or extend Bandwidth *with the cost of decreasing* Directivity.

N.G. Alexopoulos *et al.* (1983)

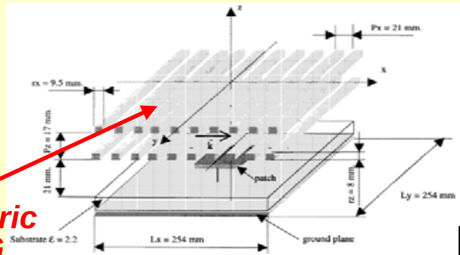
Multi-Superstrate


--- with thicker cover.

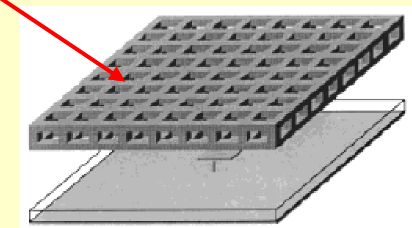
- *high* Directivity *but narrow* Bandwidth;
- *obvious side-lobe due to surface-wave*;
- *and too thick cover & high profile in structure.*

H.Y. Yang *et al* (1987)

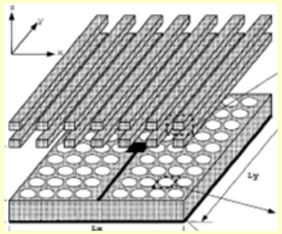
Dielectric EBG



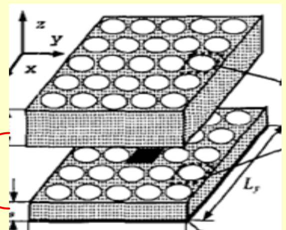
M. Thevenot *et al* (1999)



For both cover & base

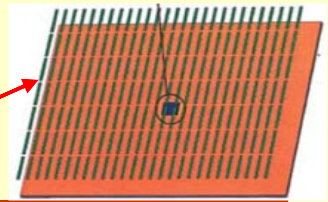


M. Qiu *et al* (2001)

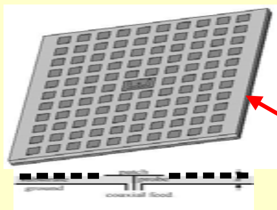


F.M. Zhu *et al* (2003)

Metal FSS cover



Y. J. Lee *et al* (2004)



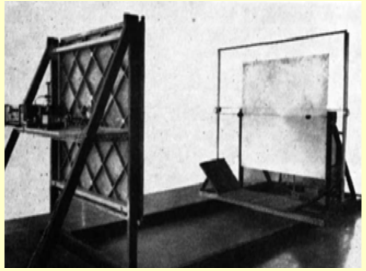
Z. C. Ge *et al* (2005)

Metal AMC base

F-P R

Review on Planar Fabry-Perot Resonator

Microwave Fabry-Perot Resonator (1966)



Components

- *A **Feed** with broad impedance-bandwidth is **Embedded** into a parallel-plates resonator*;
- *A **Base** with ground-plate provides full reflection of incidence for avoid **Backward** radiation*;
- *A **Cover** with high reflectivity & little transparency for **Forward** radiation*;
- *A proper **Spacing** between base & cover to meet the **Resonance** condition.*

Performances

$$G \approx (1+r)/(1-r)$$

- **High Gain** ~~~
  - *As high as required in Principle* by increasing *Reflectivity* r & *Spacing*;
  - *Is restricted in Practice* by *Conductivity* & *Leaking* due to finite plate-size.
- **Narrow BW** ~~~
  - *Narrow band for Gain-drop* due to the *Resonance*;
  - *Narrow band for Feed-matching* when employing *Simple-feed* (patch/dipole).

A common bandwidth must be specified ! ← *Usually, they does Not Coincide !*

- **Poor Efficiency** ~~~
  - *Poor uniformity of aperture-field distribution* for enlarging the plate size;
  - *Serious leakage of lateral-wave* for enlarging the spacing.
- **Thin Structure** ~~~ *Comparing to the RA & TA with towering feed.*

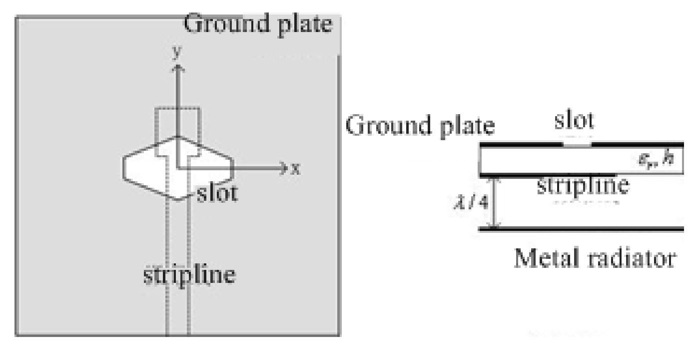
Schemes for Improvement

1. Improved **Cover** ~~~ *Broadband single- / double-layer FSS of printed patches*;
2. Improved **Feed** ~~~ *Broadband Wide-slotted plate (MS-fed) or U-slotted patch (Coaxial fed)* ;
3. Improved **base** ~~~ *PEC or broadband AMC (artificial magnetic conductor) as Grounded FSS.*

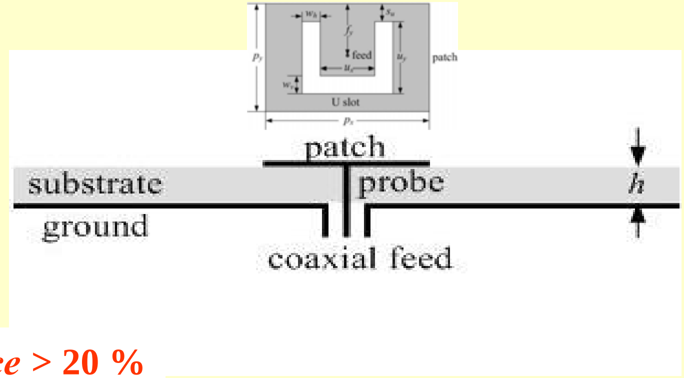
FABRY-PEROT RESONATOR - 3

Radiator structures

Using wide-slot radiator fed by microstrip line



Using U-slotted patch fed by coaxial probe



Bandwidth in free-space > 20 %

Broadband impedance matching
+
Appropriate beam-width for illumination

Initially designed sizes

EBG Cover effects *or* ***FSS Cover effects***

Integrated optimized design

With the cover together

FABRY-PEROT RESONATOR - 4

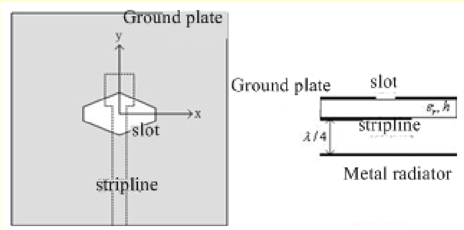
Base structures

(R ~ reflection coefficient)

PEC

$R \approx -1$

wide-slot radiator

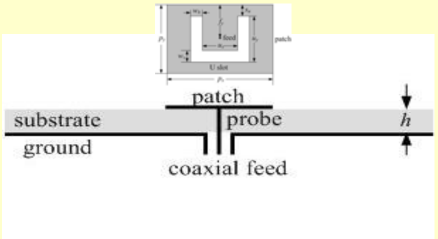


Ground plate

without substrate

zero impedance surface

U-slotted patch

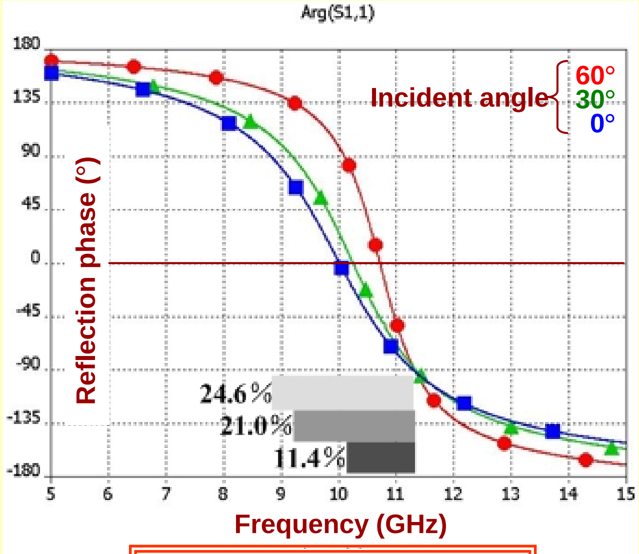


Ground plate

with substrate

low impedance surface

$f_0 \approx 10$ GHz
period ≈ 8 mm



Square-patch
Best performances
11.1% *for* ± 60°

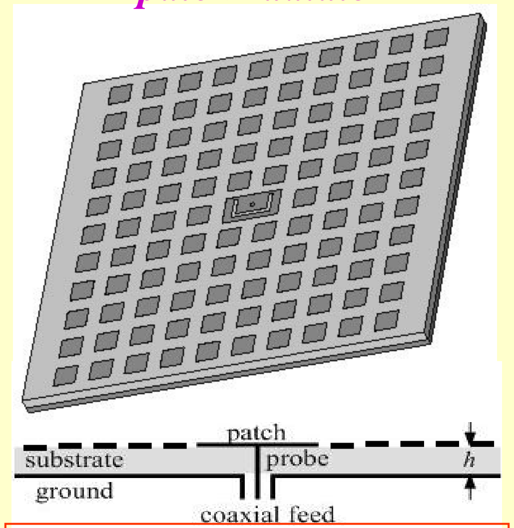
Mushroom
Complex structure
11.1% *for* ± 60°

UC-PBG
Narrow bandwidth
3.4% *for* ± 60°

AMC

$R \approx +1$

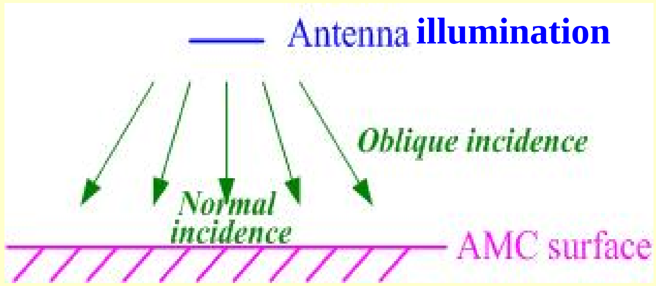
AMC surrounding patch radiator



High Impedance Surface

Sensitive to Frequency

Wide-range incidence



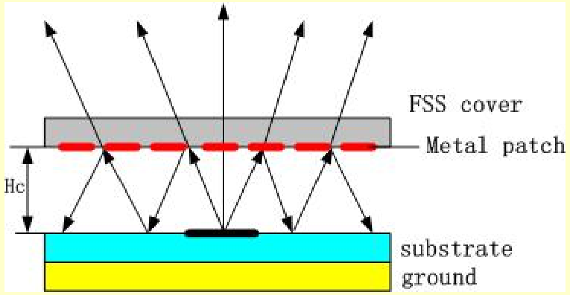
FABRY-PEROT RESONATOR - 5

Cover Structures

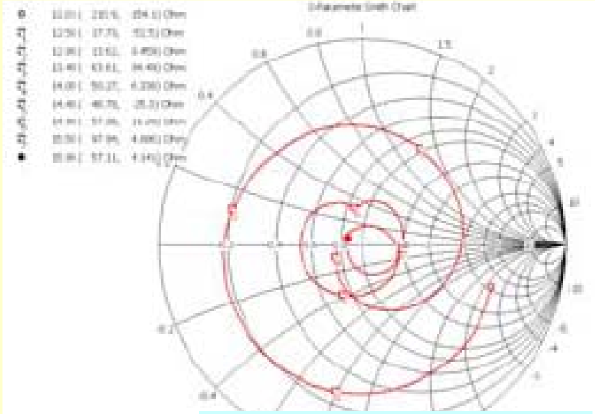
Lower-face FSS Cover

f_0=14 GHz *Area*=(62 mm)^2

ε_r=3.2, 7×7 cell *A* ≈8mm, *L* ≈7mm,



Total thickness 18.4 mm (0.86 λ_0)

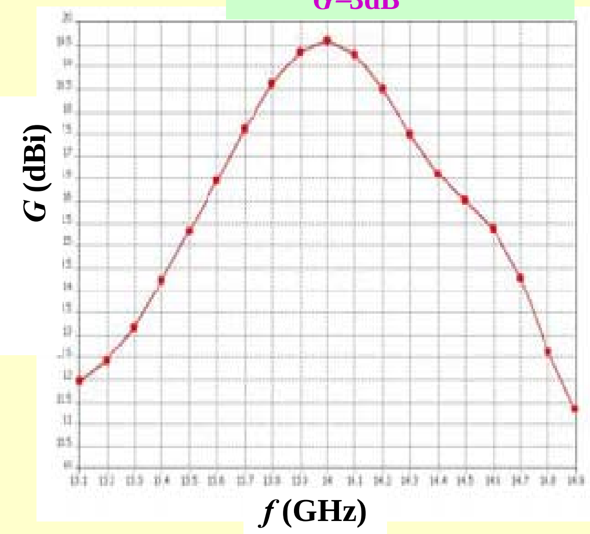


$BW_{VSWR \leq 2:1}$ =19.5 %

BW_{common} = 3.7 %

Unsatisfied

BW_{G-3dB}= 5.7 %



G_{max} = 19.6 dBi

η_{aper} = 87 %

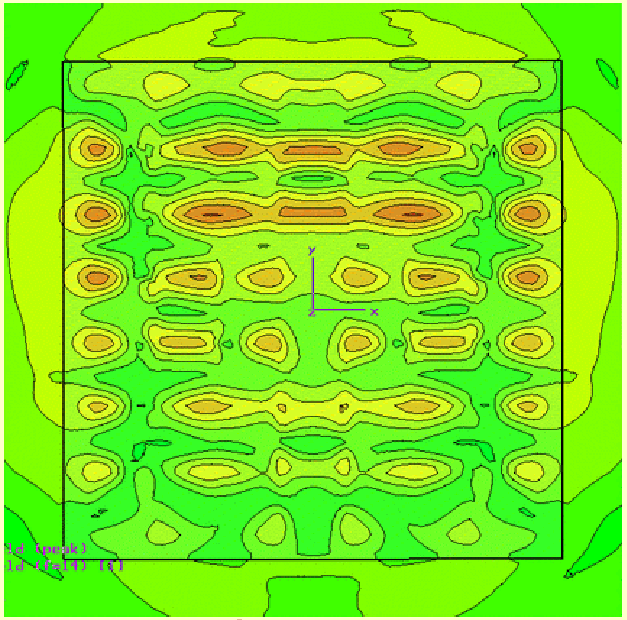
HPBW =19.0°×16.1°

SLL= –15.0 dB

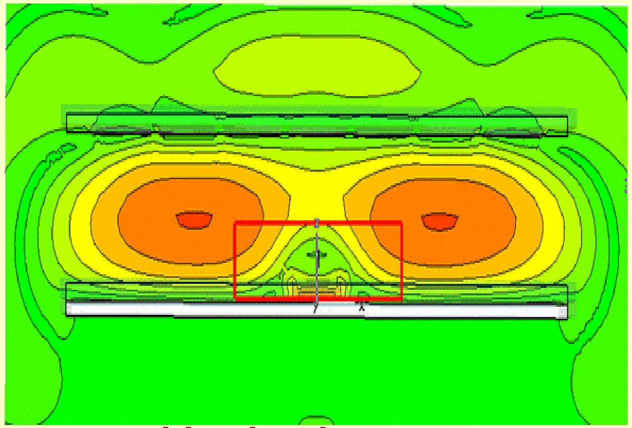
F/B = 21.2 dB

Quite good

Fields distribution



Top-view on aperture



Side-view in resonator

Design Samples

Optimized sizes for different combination of Cover-Radiator-Base

----- *Pay more attention to Coincide VSWR & Directivity bands with together*

f_r = 14 GHz, λ_r = 21.43 mm

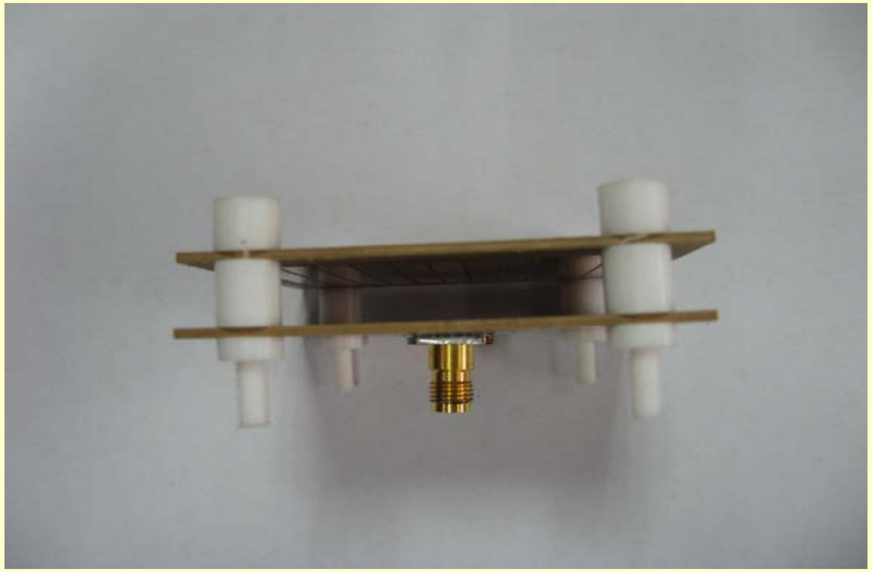
F-P Resonator Structure [*Aperture area* =(62 mm)^2]	*D* (dBi)	η_A (%)	Height (mm / λ)	Beamwidth (*E-/H-plane*)	*SLL* (dB) (*E-/H-plane*)	F/B (dB)	BW (%) *Common*
FSS//U-slotted patch//PEC	18.96	64.2	13.90/0.65	17.1°/16.1°	–17.0/–16.3	25.52	7.90
FSS//U-slotted patch//AMC	18.42	58.3	11.70/0.55	18.3°/18.9°	–18.0/–17.3	23.85	5.49
FSS//Wide-slot//PEC	19.60	87.0	20.04 0.94	15.5°/17.2°	–16.1/–18.3	21.20	3.75
EBG/Slab//U-slotted patch//PEC	17.83	57.7	20.24 / 0.94	18.1° / 18.6°	–15.1 / –16.1	23.14	7.69
EBG/Slab//U-slotted patch//AMC	17.75	56.6	18.24 / 0.85	18.8° / 19.6°	–15.5 / –17.3	23.50	5.64
Slab/EBG// Wide-slot//PEC	18.55	68.0	28.31 / 1.32	15.5° / 16.3°	–13.0 / –16.6	22.79	5.91
EBG/Slab// Wide-slot//PEC	18.50	68.0	27.01 / 1.26	15.4° / 17.0°	–12.8 / –16.7	26.69	6.84

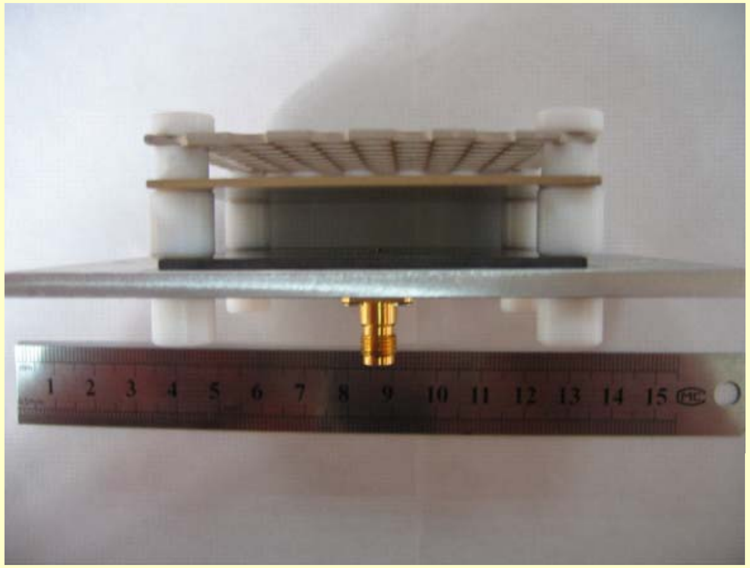
- Using FSS-cover always: *thinning structure*, *higher Gain*, & *broader common BW*;
- Using AMC-base always: *thinnest structure*, *lower Gain*, & *narrower common BW*;
- Comparing Wide-slot feed to U-slotted patch: *higher Gain* & *narrower common BW.*

Broadening common bandwidth of F-P R Ant is a major & essential challenge.

FABRY-PEROT RESONATOR - 7

Prototypes





1-*layer FSS* Cover
U-*slotted patch* Feed
***AMC*-**Base
11.7 mm (0.55 λ) Height

2-*layer-slab EBG* Cover
U-*slotted patch* Feed
***PEC*-**Base
20.2 mm (0.94 λ) Height

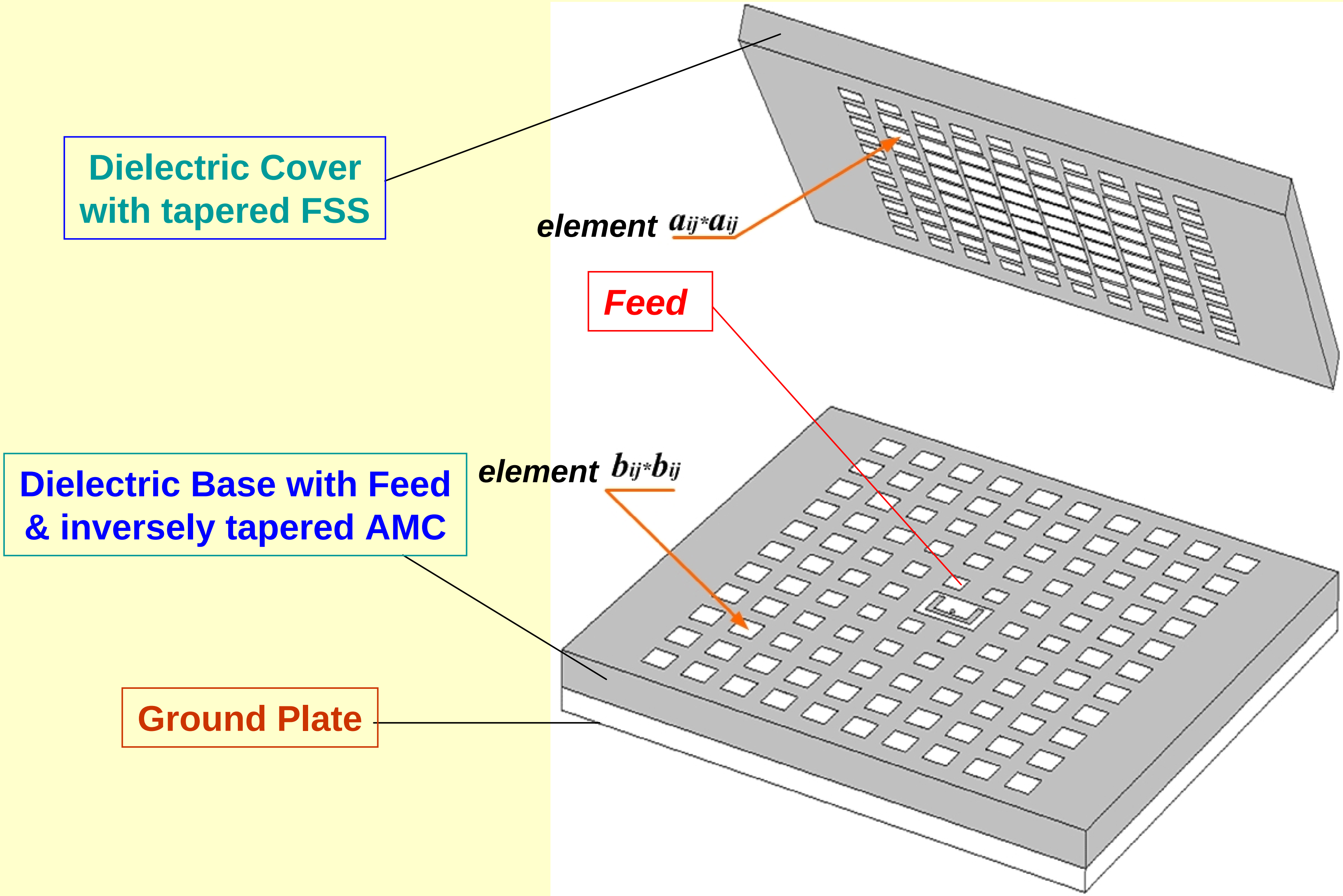
$< BW_{common}$

$Gain >$

Printed Compound Air-fed Array

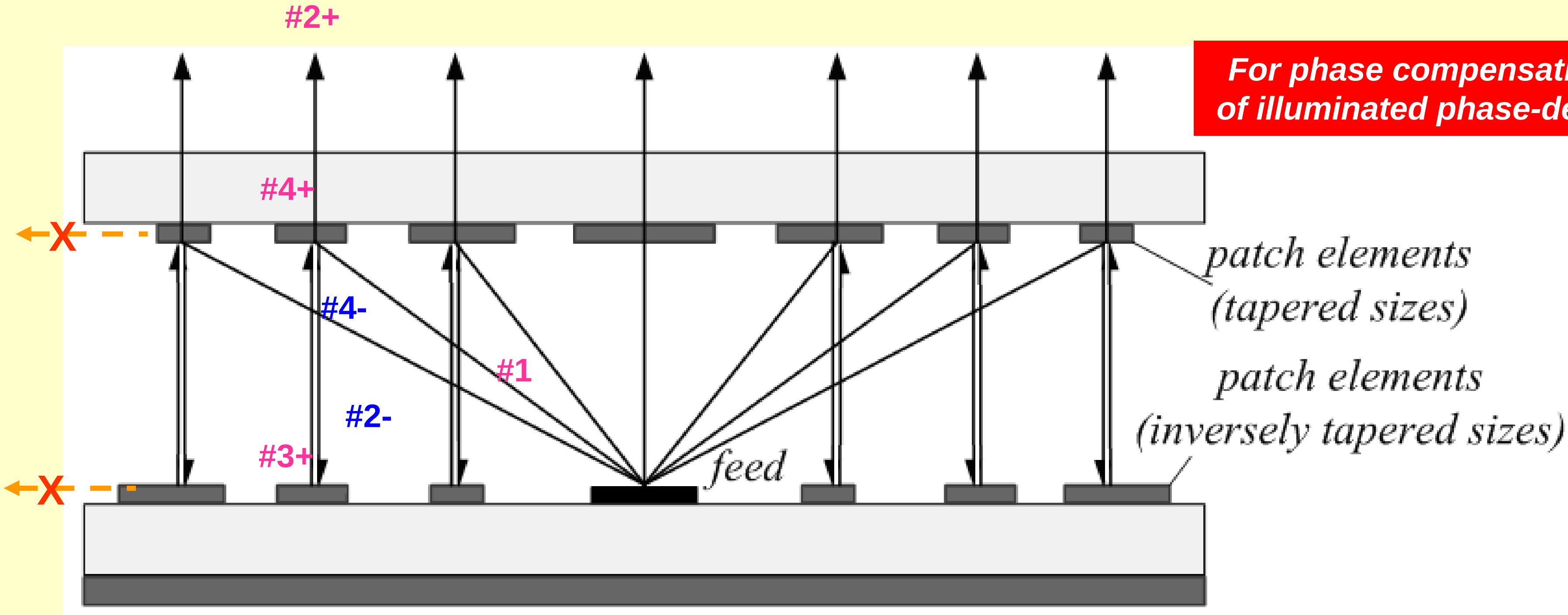
COMPOUND AIR-FED ARRAY - 1

Structure Sketch



COMPOUND AIR-FED ARRAY - 2

Improved Printed F-P Resonator Antenna



For phase compensation of illuminated phase-delay

Adjusting spacing for keeping radiation in co-phase superposition

For balance reflective phase between cover- & base- element

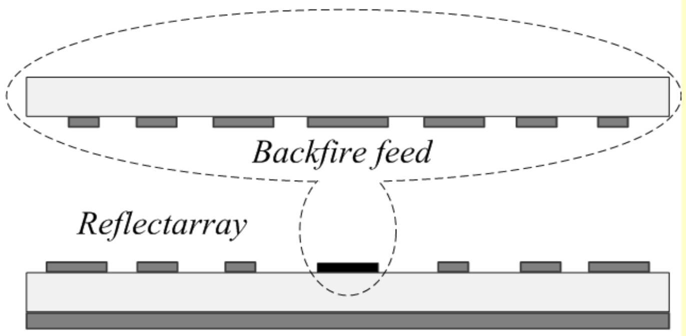
Comparing to the central ray

- #1 — delay
- #2 — lead
- #3 ···· — delay
- #4 ···· — lead

COMPOUND PRINTED AIR-FED ARRAY

COMPOUND AIR-FED ARRAY - 3

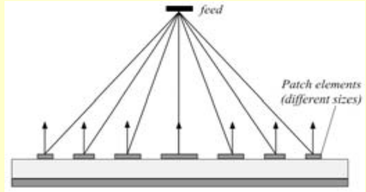
Understanding Compound Air-fed Array Antennas

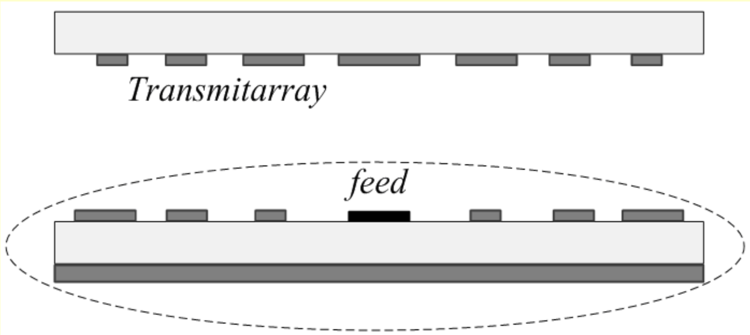


A modified reflectarray with a backfire feed

---- Near-field illumination and short focal length

Repeatedly utilizing the feed-blockage of RA

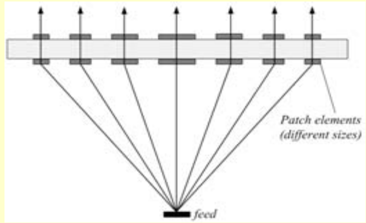


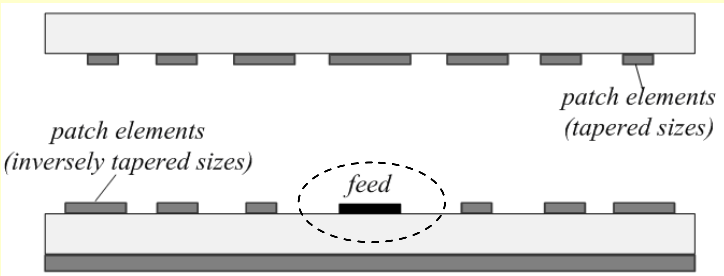


A modified transmitarray with an array feed

---- Near-field illumination and short focal length

Forming co-phase wave illuminating the TA

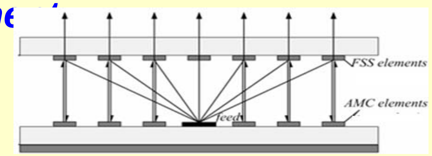




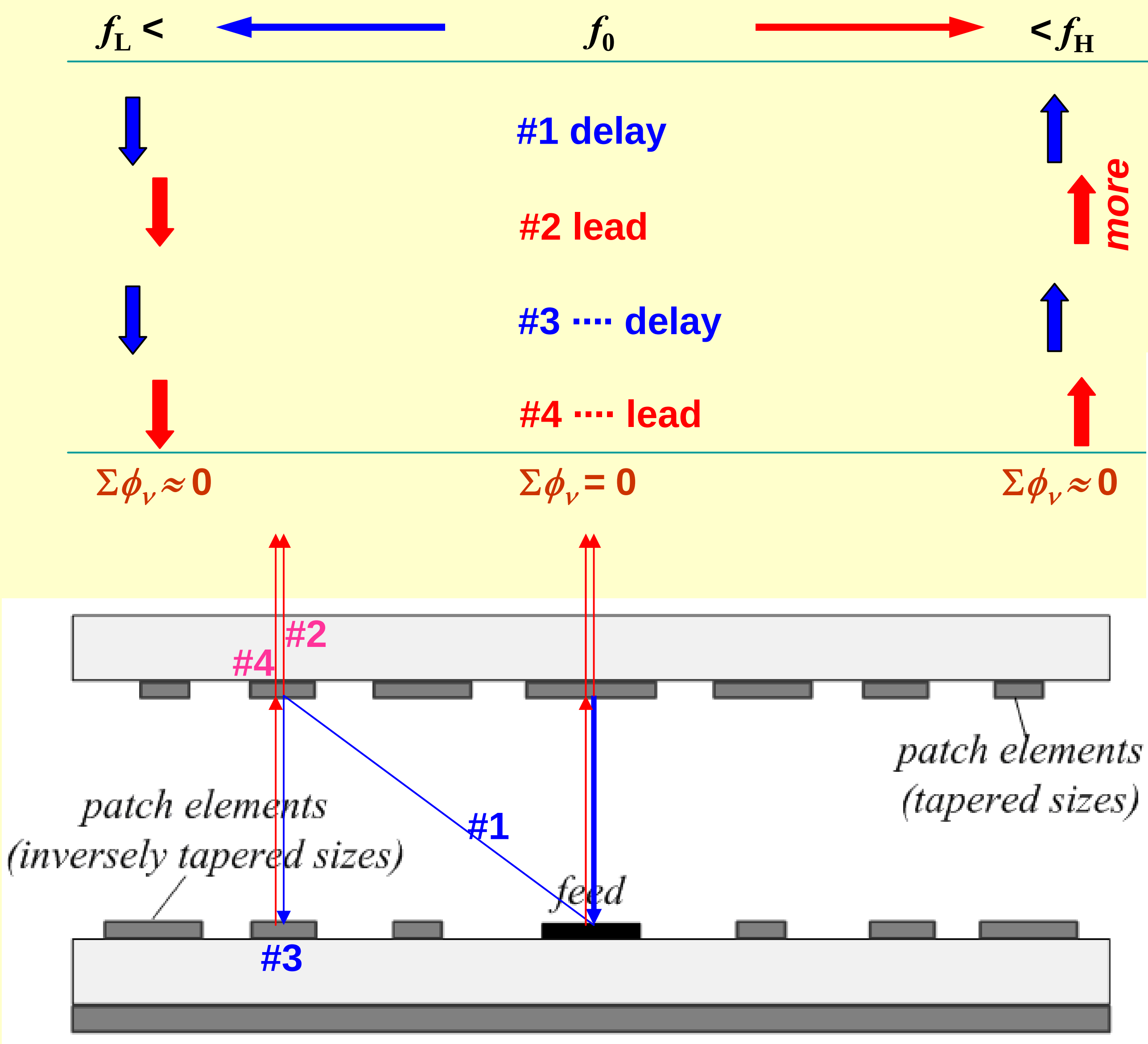
A modified Fabry-Perot array with an patch feed

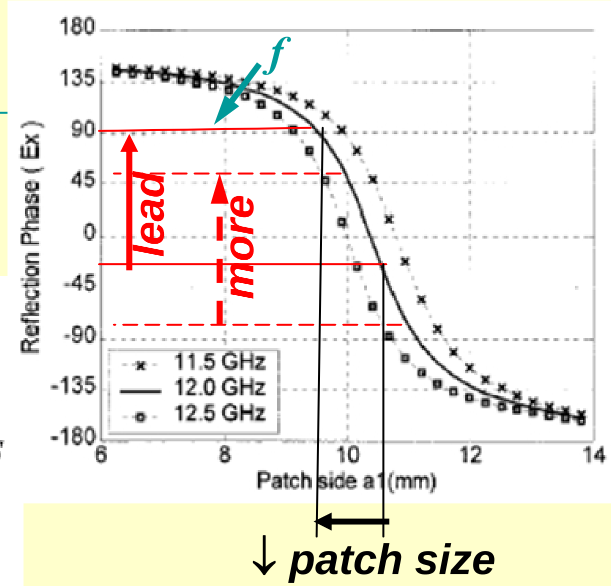
---- Quasi-period of tapered eleme
for bandwidth extending

Correcting phase for individual ray in F-P R



Phase Compensation in Frequency Band





COMPOUND AIR-FED ARRAY - 5

Let — Mis-resonant phase in Frequency Band

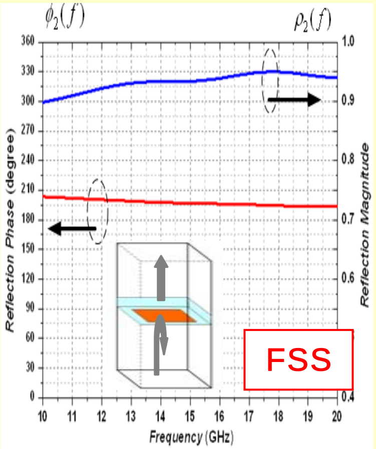
- $\phi_1(f)$: *Reflection phase of base;*
- $\phi_2(f)$: *Reflection phase of FSS;*
- H: *Cavity height;*
- c: *Light speed;*
- N: *Order of resonant mode* (= 0,1,2,…)

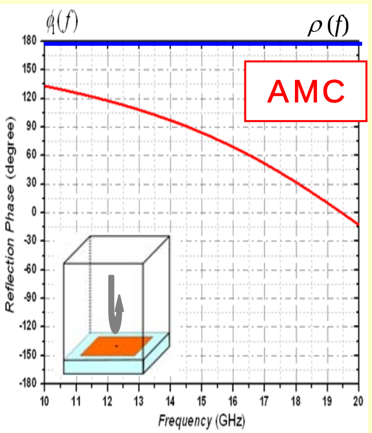
then

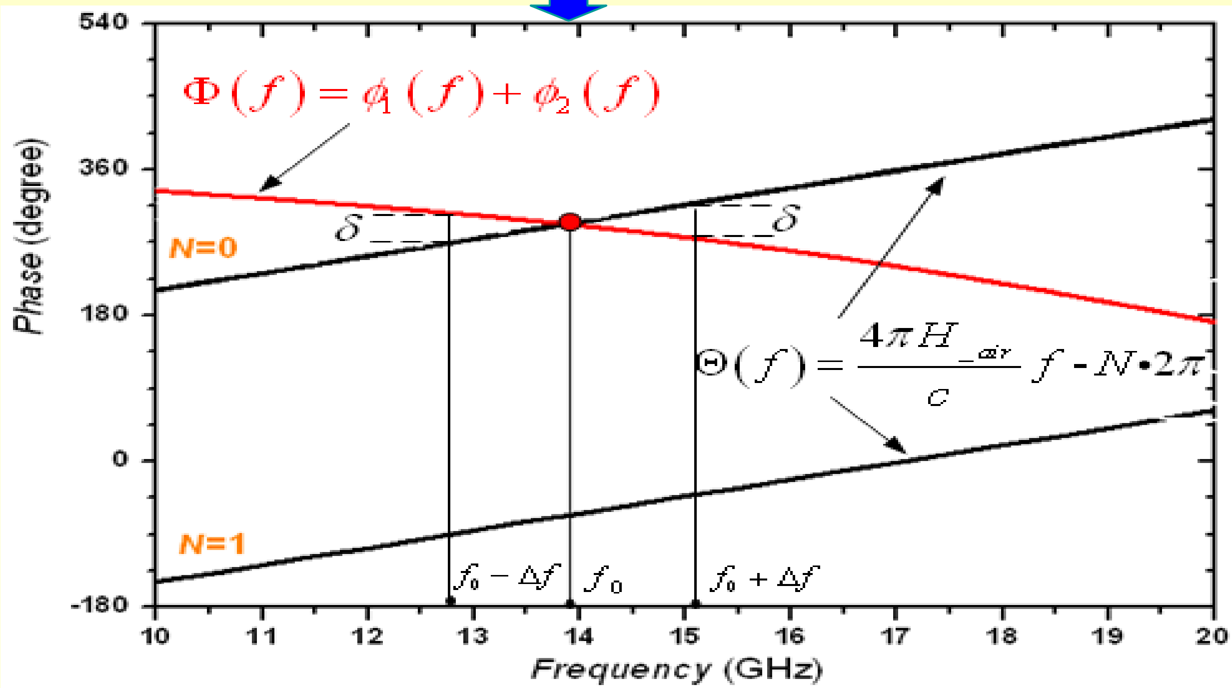
The resonance condition is

$$2\frac{2\pi f_0}{c}H - [\phi_1(f_0) + \phi_2(f_0)] = 2N\pi$$

where







At the bound of Bandwidth ***The mis-resonant phase***

$$2\frac{2\pi f_{H,L}}{c}H - [\phi_1(f_{H,L}) + \phi_2(f_{H,L})] - 2N\pi = \pm\delta$$

From required (f_H, f_L) to determine δ value !

Definition on gain-drop bandwidth

Reflectivity of cover : $\gamma = (G-1)/(G+1)$

Radiated field from aperture : $E(\gamma,\delta) = \dfrac{1-\gamma}{1-\gamma e^{-j\delta}} = \dfrac{1-\gamma}{(1-\gamma\cos\delta) + j\sin\delta}$

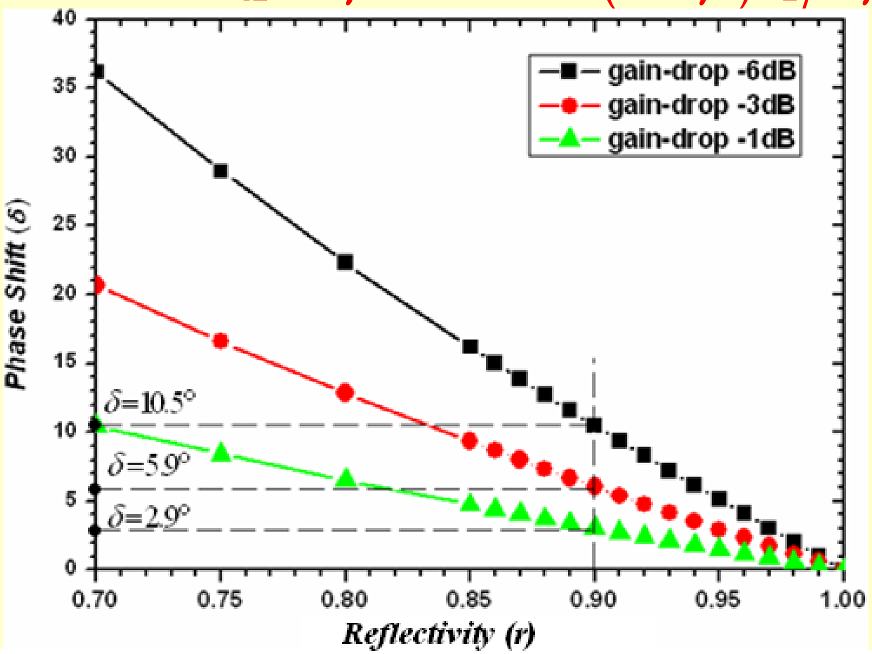
Gain : $G_{(\mathrm{dB})} = 10\log[(1+\gamma)/(1-\gamma)]$

Gain-drop $\Delta G_{-p(\mathrm{dB})}$:

$$p = 20\log\left|\frac{E(\gamma,0)}{E(\gamma,\delta)}\right| = 10\log\left[\frac{(1-\gamma)^2}{1-2\gamma\cos\delta+\gamma^2}\right]$$

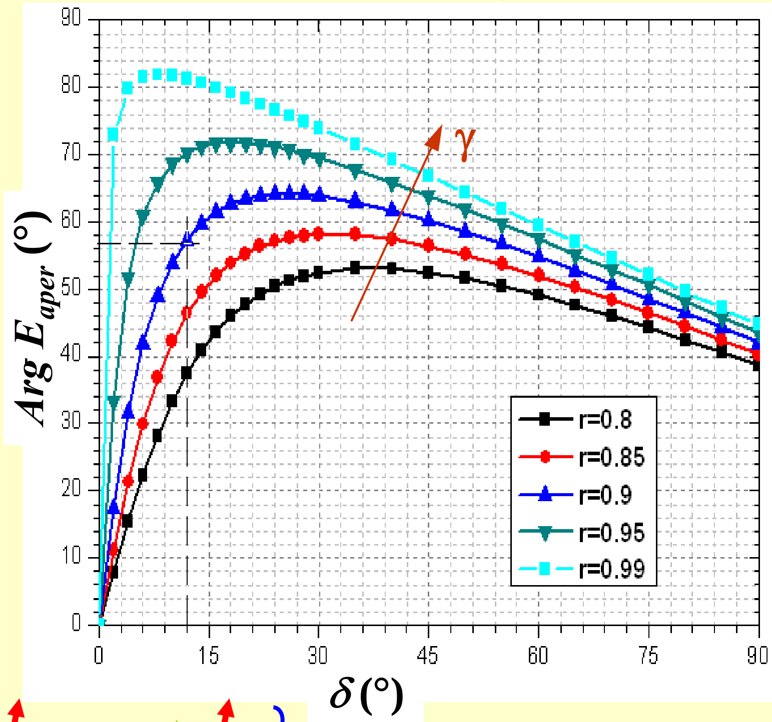
Gain-drop depends on δ & then bandwidth !

$$\delta = \cos^{-1}\{[1+\gamma^2 - 10^{p/10}(1-\gamma)^2]/2\gamma\}$$



Field-phase of aperture :

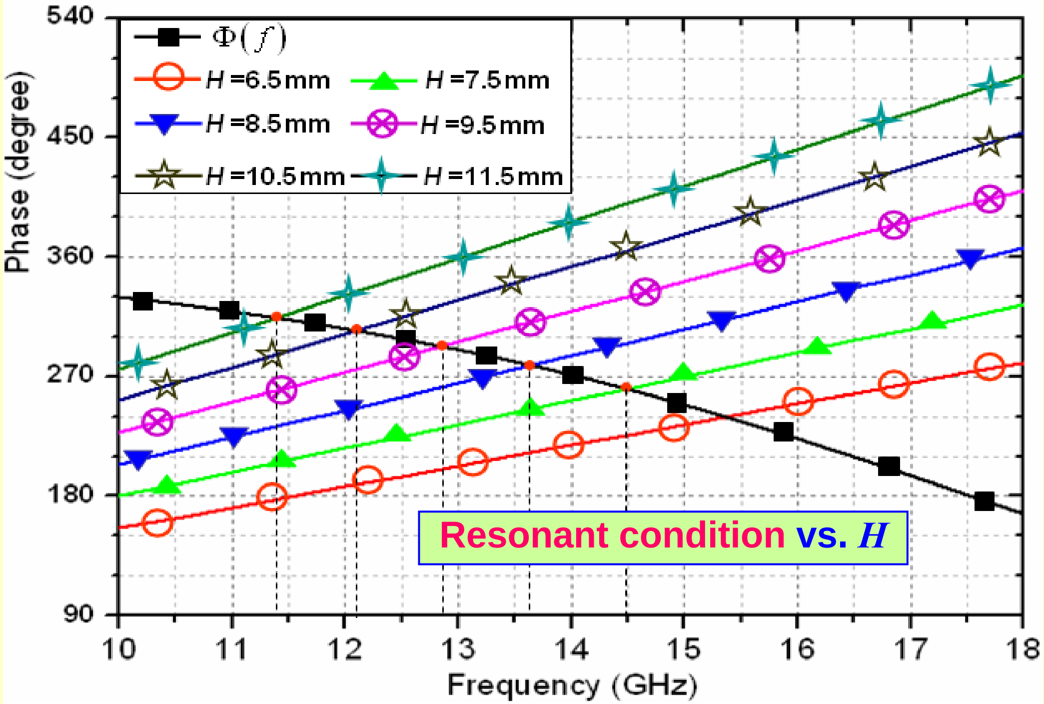
$$ArgE = \tan^{-1}\frac{\gamma\sin\delta}{1-\gamma\cos\delta}$$



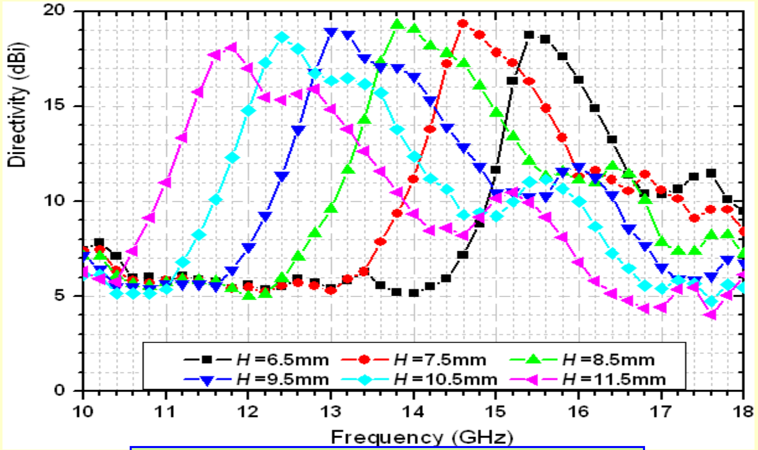
↑G ⇒ ↑γ
↓$ArgE$ ⇒ ↓p
} ⇒ ↓δ ⇒ ***Gain-drop BW***

COMPOUND AIR-FED ARRAY - 7

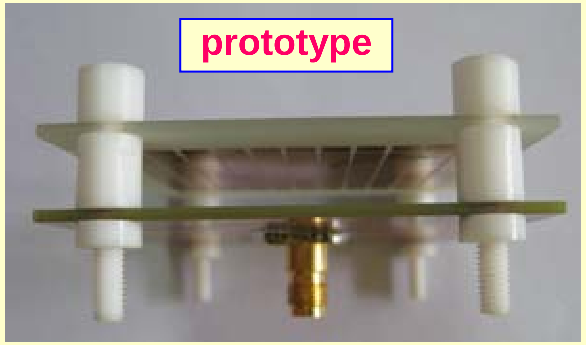
Validation of resonant condition



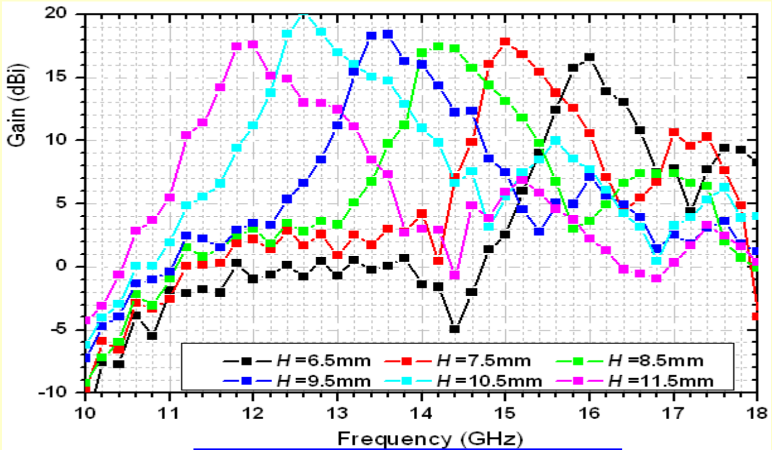
Resonant condition vs. H



Gain-frequency response vs. H
Simulated by CST 2008



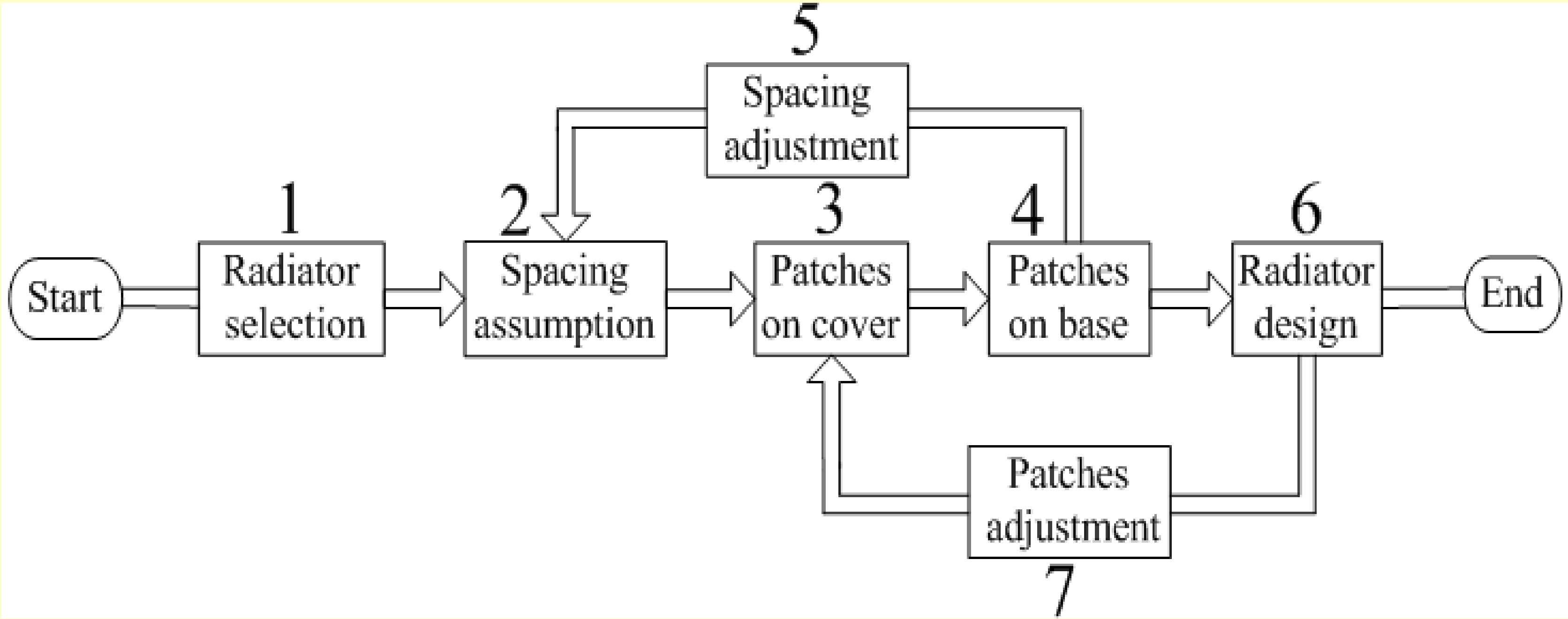
prototype



Gain-frequency response
Measured in SEU

1. The differences among calculated, simulated and measured f_0 are within **4%**
2. The difference between simulated and measured G_{max} is less than **2 dB**

Design Flow-chart



1. Choose a broadband feed in isolated case
2. Set the Spacing as about λ_0 /4
3. Illuminated phase-difference at aperture
4. Phase-compensation for cover elements
5. Phase-compensation for base elements [Iteration I]
6. Modify broadband feed under the effects of cover/base

(7. For changed radiator [Iteration II])

Full-structure Simulation

***----- by using* CST Microwave Studio 5.0**

Practical condition

and
- ***Ground plate with finite-size***
- ***Thin substrates with lower permittivity and loss***
- ***Equal square period with centered square patch-elements***
- ***A feed of array occupies centered two-period***

Design objective

or
- ***Maximizing the peak of Gain/Directivity***
- ***Maximizing the common Bandwidth for both VSWR & Gain-drop***
- ***Compromising the Gain/Directivity and Bandwidth***
- ***Minimizing the profile for acceptable Gain/Directivity & Bandwidth***

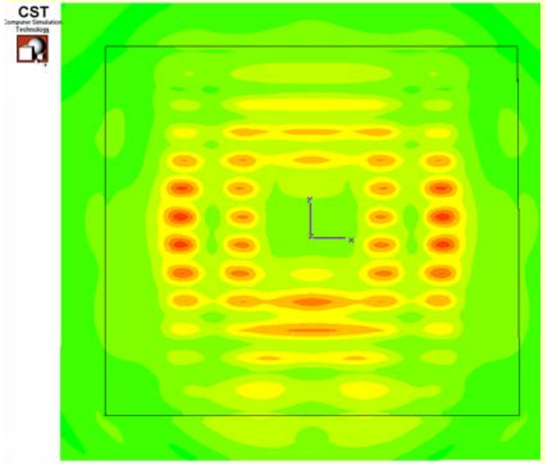
Simulated Performances

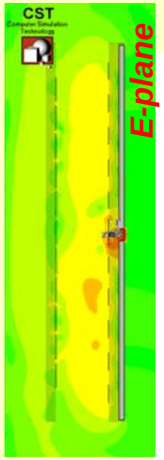
----- For different criteria at 14.0 GHz

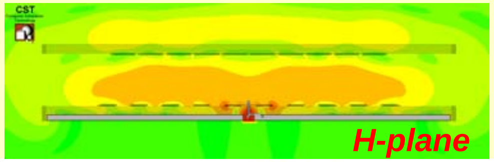
Structure *fed by U-slotted Patch*	*Square -period*	Tapered FSS/AMC	Tapered FSS only	Uniform FSS/AMC
Performances	**Unit**	for G_{max}	for $(BW_G)_{max}$	for h_{min}
Gain G	dBi	19.53	18.44	18.61
Aperture Efficiency η_{aper}	%	74.36	61.5	60.2
Common Bandwidth $\Delta f / f_0$	%	7.99	11.93	5.53
Profile Height h	mm	13.0	14.2	11.5
E-/H- plane Side-lobe *SLL*	–dB	17.3/18.7	18.0/19.2	19.5/16.9
Front-to-Back Ratio *F/B*	dB	36.36	25.05	31.54
E-/H-plane Beamwidth *HPBW*	°	18.2/17.8	18.7/18.9	20.0/18.6

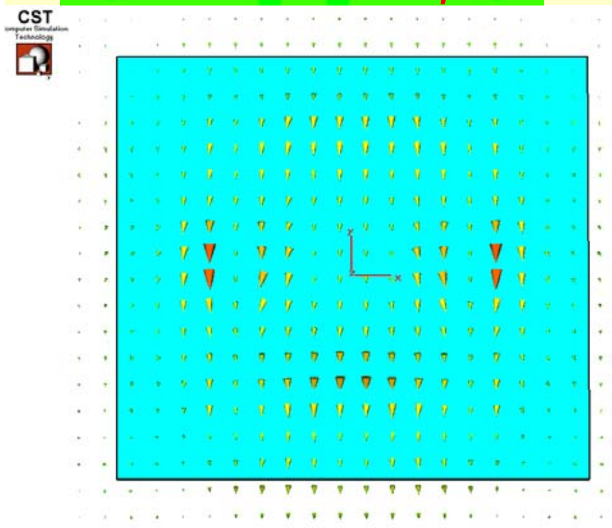
Example of D_{max} at 14.0 GHz

Power-density on aperture









Polarization on aperture

Aperture Distribution

Amplitude on aperture < (2.7:1) | Phase on aperture ∈ (±35°)

381	367	468	550	586	-12°	-14°	-18°	-29°	-20°
499	470	597	670	715	-13°	-15°	-19°	-34°	-21°
696	604	760	746	818	1°	-5°	-8°	-22°	-17°
871	699	866	730	796	15°	6°	3°	-7°	-10°
967	680	872	691	736	29°	18°	9°	1°	-6°
1000	638	859	696	739	35°	23°	9°	-3°	-5°
948	678	882	747	822	28°	15°	5°	-7°	-7°
853	691	861	809	930	12°	1°	-1°	-11°	-10°
705	578	716	798	915	-5°	-14°	-11°	-21°	-13°
542	468	559	688	720	-24°	-23°	-19°	-33°	-18°
434	443	529	599	551	-21°	-13°	-13°	-35°	-34°

Performance comparison

with Folded Reflectarray

W. Menzel, *et al*, (2002)
Proc. 32nd EuMC, 1–4

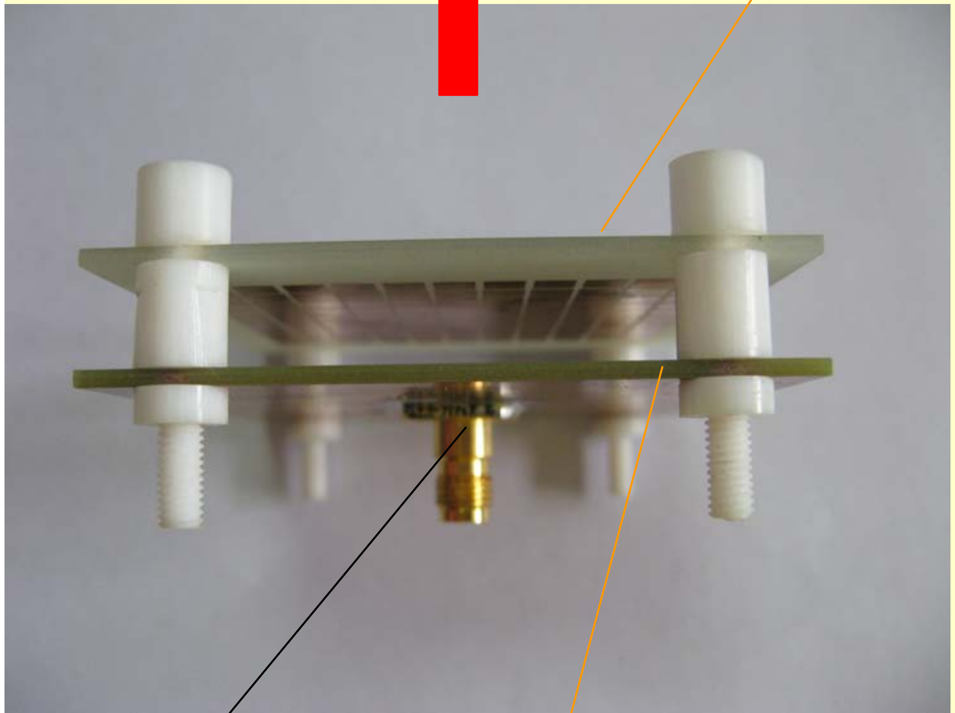
Southeast University	*Proposer*	University of Ulm
Tapered FSS Inversely tapered AMC	*Cover* *Base*	Grid / Filter Tapered RA
70×63×13 (mm)	*Profile Sizes*	150×150×25 (mm)
Simulated data	*Performance*	Measured results
f_0= 14.0 GHz	*Frequency*	f_0= 27.6 GHz
D_{max}= 19.53 dBi G_{max}= 19.41 dBi	*Directivity* *Gain*	G_{max}= 30.8 dBi / 29.5 dBi
η_{aper}= 74.36 % η_{Ant} = 72.33 %	*Aperture Efficiency* *Antenna Efficiency*	η_{Ant} = 50.24 % / 37.24 %
SLL ≤ –17.3 dB	Side-Lobe Level	SLL ≤ –20 dB / –21 dB
BW_G= 9.66 % $BW_{com.}$ = 7.99 %	*Gain BW for ΔG* $_{-3dB}$ *Common BW*	BW_G= 9.32 % / 2.90 %

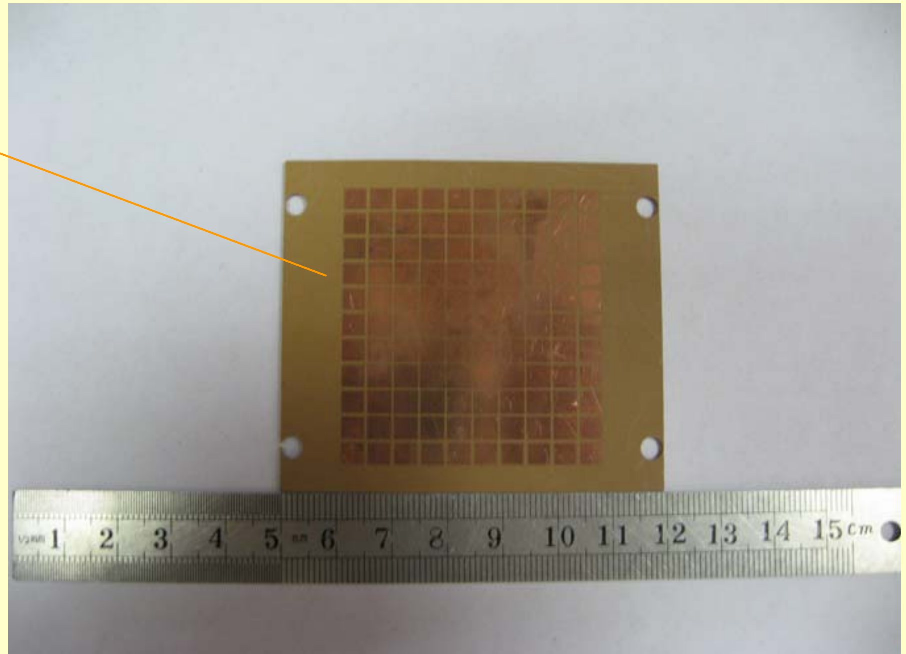
COMPOUND AIR-FED ARRAY - 13

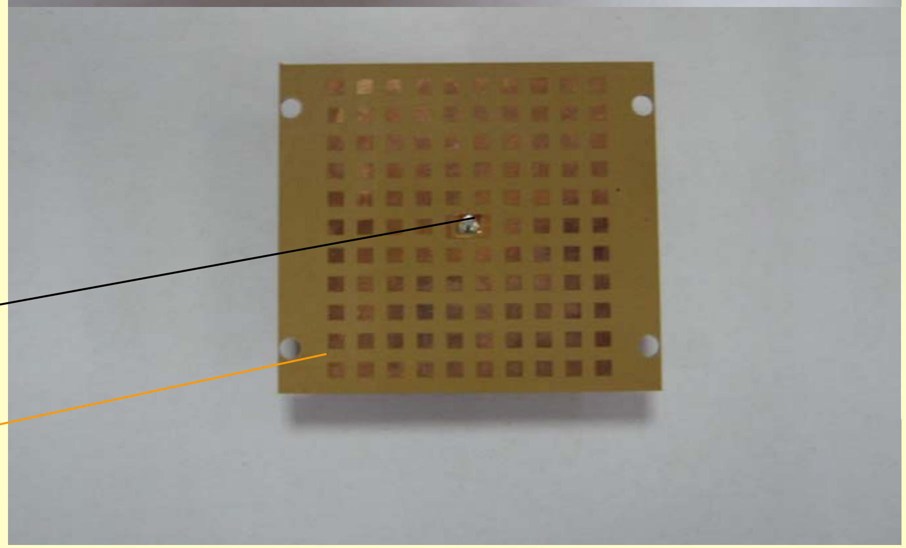
Structure Photos

Radiation

Cover with FSS







Coaxial connector

Feeding point

Base with AMC

Further approaches

There are three aims:

- *Enhancing Gain under defined Bandwidth*
- *Extending Bandwidth with enough Gain*
- *Thinning the profile with acceptable Gain*

There are three schemes:

- *Increasing both Spacing & aperture size*
- *Employing hexagon array & sub-array technique*
- *Utilizing sub-wavelength resonance mechanism*

There are three potentials:

- *For Sub-array elements of Phased Array*
- *For Base-station of Wireless Communications*
- *For Mobile Receiver of Satellite broadcasting*

The Research & Development are going on, it could not be concluded now !

Conclusion

Retrospect

Printed Air-fed Array Antennas have constituted a flourishing family, almost every kinds had been concerned in SEU;

The Compound Air-fed Array is a new member with good Performances, it is attractive in various Application aspects;

The contradiction of Gain with Bandwidth in impedance-matching has been extended to Bandwidth in Gain-drop for high-gain antennas;

An Gain limitation of compound Air-fed Array with thin structure is to balance aperture size & efficiency, the solution is used as Sub-array.

Thanks !