Research Progress on Printed Air-fed Array Antennas

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HIGH-GAIN ANTENNAS

Mirror Ant.
- High efficiency & wideband with simple feeding
- Curvature structure less flexibility

Traditional Ant.
- Planar (printed) structure with reconfigurable beam
- Complex feed-network less efficiency & bandwidth

Array Ant.
- Towered feed with supporter
- Always

Simple feeding
Printed Air-fed Array Antenna
To perform co-phased aperture by individual compensation of separated elements
To directly excite all elements by a single-feed illumination without complex network

Planar structure
Existed Shortage
Middle
- Efficiency & bandwidth

Need to be improved!
Could be avoid?
**Introduction**

Full forward reflecting with very less backward overflow

Feed-blockage in the front results in aperture efficiency drop

*Besides Off-Set*

*To avoid blockage effect*

Decrease feed cross-section

Utilize polarization isolation

*Polar-twisted TSA feed*

---

**Reflector Ant.**

*Both Mirror & Air-fed array*

**Lens Ant.**

Most forward transmitting with unavoidable backward reflection

No blockage existing since feed is behind the aperture

*To reuse backward reflection*

Place reflector behind feed

Flat the interface of lens

*Compound Air-fed Array*
FZP Antennas

Structural evolution

<table>
<thead>
<tr>
<th>simple lens</th>
<th>Fresnel lens</th>
<th>phase-reversing lens</th>
<th>planar lens</th>
</tr>
</thead>
</table>

Practical structure

<table>
<thead>
<tr>
<th>FZP Lens</th>
<th>Transparent center</th>
<th>FZP Reflector</th>
<th>Opaque center</th>
</tr>
</thead>
</table>

Conceptual design

Stepped ray-length $r_n = (F+n\lambda/2)$ from focus to ring-edges

Transparent & Opaque zones alternatively arranging

Diffracted-field contribution

$$\propto \text{Fresnel Integration on each active-zones}$$

$$FI = \int_{\text{active zones}} \exp(-j\omega \tau^2 / 2) d\tau$$

$$= C(\omega) - jS(\omega)$$

$$\omega_n = 2\sqrt{(r_n - F) / \lambda}$$

Full-integrated four-layer FZP Lens Antenna

2 pairs of 2-layer
- 2 pairs for enhancing forward gain
- 2-layer for suppressing back-lobe

Fed by stacked circular-patch with parasitic-ring

Spectral-domain analysis with
- Vector Hankel-transform
- S-D Immittance method

4-ring sample
- X-band 15 % BW for $(G \geq 18 \text{ dBi} \& \ VSWR \leq 2:1)$
- $G_{\text{max}} = 21 \text{ dBi}$, $\text{SLL} \leq -18 \text{ dB}$, $F/B \geq 11 \text{ dB}$

Sizes:
- $F = 9.15\lambda$
- $D \approx 18\lambda$
Traditional Zoning Rule
by $\lambda/2$ stepping

Improved Zoning Rule
by co-phase summation

Practical Zoning Application

For 1-D (Strip) FZPR with Screen

More contribution from Screen:
Gain enhancement $= +2.11$ dB

For 2-D (Ring) FZPR with Screen

Based on complicated integration:
Gain enhancement $\leq +1$ dB

Gain enhancement $= +0.97$ dB

The contribution depends both Field strength & Ring-area of each zones, it lights the weightiness of the 1st zone as that in 1-D structure, and more obvious for longer focal-length with more rings.
**Basic Principle**

- **Ray-path phase** by \( k \Delta r_n \)
- **Reflection phase** \( \phi_{R,n} + \phi_{F,n} \)

**Characters**

- **Dynamic range** \( (\phi_R)_{\text{max}} \)
- **Frequency dependence** \( \phi_{R,n}(f) \)
- **Phase pattern of feed** \( \phi_{F,n} \approx \text{const.} \)

**Compensation**

- Element with phase compensation

**Structural Feature**

- **Structure**
  - Planar printed array
  - Focus-length \( \approx \) Aperture size
  - Towered feed with supporter

**Disadvantages**

- ★ Narrower Bandwidth
- ★ Lower Efficiency

**Topics for Developing**

**Improvement Schemes**

- Broadband-feed for Illuminative Pattern
- Broadband-element for Phase Compensation
- Avoiding \(+2\pi\) repeat by Phase Dynamic-range

- Aperture-distribution
  - Array optimization with Shaped feed
- Avoiding blockage
  - Normal illumination with Polar-transform

**Enhancing Efficiency**

- Extending Bandwidth
RA Antennas

Broadband TSA feed
Traveling wave radiator

Thin physical cross-section

VSWR ≤ 2:1
5.2~12.8 GHz

Feed pattern
f = 10 GHz

~ 74°

Bandwidth Broadening Technology

Stacked Patch element

Double-/ Triple-layer Square-/ Rectangular Patch

Square-patches

Rectangular Patch

A_a = A_y = 17 mm (= 0.57λ_0)
Aspect-ratio τ = s_y / s_x

The ϕ is almost independent on τ

Phase compensated by Patch’s size
(ϕ_{R,n})_{max} = 450° ~ 750°
Orthogonal Polar-Transform

Reflection Phase-difference

\[ \Delta \phi = \phi_y - \phi_x \]

- \( \frac{\pi}{2} \)
- 0
- \( \frac{\pi}{2} \)
- \( \pm \pi \)

Reflected

<table>
<thead>
<tr>
<th>Reflected</th>
<th>RHCP</th>
<th>Co-LP</th>
<th>LHCP</th>
<th>X-LP</th>
</tr>
</thead>
</table>

Avoiding feed-blockage

- \( \Delta G_{\text{OPT/non-OPT}} \) up to 3.9 dB
- for 37-element 3-layer RA
  - \( G_{\text{peak}} = 18 \text{ dBi} \)
- \( \Delta G \leq -1.6 \text{ dB} \) up to 26.8 %
- for 489-element 2-layer RA
  - \( G_{\text{peak}} = 27.6 \text{ dBi} \)

Arbitrary polarized-state may be performed!
Efficiency Enhancing Technology

Feed-Pattern Shaping

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

Take Phase-Pattern \( \phi_F(\theta_n) \) into the compensation account

Improves 1-D Aperture efficiency

- 100%
- 83.7%
- 70.6%

Simulated & Measured patterns

E-plane (10 GHz)

Coupled TSA

Choke to suppress side-lobes
**TA Antennas**

**Comparison of Schemes**

**TA based on multilayer interference**
- **with** forward summation - backward canceling as a Filter,
- **but** lower efficiency due to residual reflection, impossible to steer the beam orientation.

**TA 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 better performances!

**TA with Directly corner-fed**
- **Stacked square-patch**
- \( F/D = 0.5 \) TSA-feed

**TA with Proximity-fed**
- **U-slotted rectangle-patch**
- \( F/D = 0.5 \) TSA-feed

**Main performances**

<table>
<thead>
<tr>
<th>Data</th>
<th>Freq. range</th>
<th>( BW_{\Delta G-3dB} )</th>
<th>( G_{\text{max}} ) (dB)</th>
<th>XPL (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated</td>
<td>(8.2~10.2)GHz</td>
<td>21.6 %</td>
<td>16.3</td>
<td>(-12.5)</td>
</tr>
<tr>
<td>Measured</td>
<td>(8.6~11.0)GHz</td>
<td>24.3 %</td>
<td>15.4</td>
<td>(-10.9)</td>
</tr>
</tbody>
</table>

**Comparing to RA**
- Broader bandwidth & Lower SLL
- Lower Gain & Higher cost
- Same Towering structure

**How to coordinate the merits of RA & TA?** How to avoid the towered structure?
Principle & Schemes

Consists of

- **a cover** with high-reflectivity in the front
- **a base** with full-reflection in the back
- **a feed** with forward radiation embedded into a resonant spacing

Performances:

- **High Gain**
  
  - As high as required by increasing Reflectivity $\gamma$ & Spacing; $G \approx (1 + \gamma) / (1 - \gamma)$
  
  - 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.

- **Low Profile**
  
  - Comparing to the RA & TA with towering feed structure.

Improvements:

- **Cover**
  
  Broadband single-/double-layer FSS of printed patches

- **Base**
  
  PEC or broadband AMC (artificial magnetic conductor) as Grounded FSS

- **Feed**
  
  Broadband wide-slotted plate (MS-fed) or U-slotted patch (Coaxial fed) in cavity environment

**FSS cover**

- Inversely printed on superstrate
- For high reflectivity

**Wide-slot radiator**

- Ground plate without substrate
- For broad band-width & broad-beamwidth

**U-slotted patch**

- Ground plate with substrate
- For low $f$ ~sensitivity

**AMC surrounding feed**

- 11.7 mm (0.55 $\lambda$) Height
**Design & Comparison**

Optimized sizes for different combination of Cover/ Radiator/ Base

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

\[ f_r = 14 \text{ GHz}, \quad \lambda_r = 21.43 \text{ mm} \]

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

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**
Principle of CAFA

The short focus-length of thin FPR antenna results in serious phase difference on aperture!

The phase compensation seems necessary!

Comparing to the central ray

- Adjusting spacing to keep co-phase superposition
- Self-compensation effect of frequency responses

For phase compensation of illuminated phase-delay

patch elements (tapered sizes)

patch elements (inversely tapered sizes)

For balance reflective phase between cover- & base- element

\[ \Sigma \phi_v \approx 0 \]

\[ \Sigma \phi_v = 0 \]

\[ \Sigma \phi_v \approx 0 \]
**Principle of Comparison**

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 element for bandwidth extending

Correcting phase for individual ray in F-P R

**COMPOUND PRINTED AIR-FED ARRAY**
### Performance comparison with Folded Reflectarray

**Southeast University**
- Proposer: Cover
- Proposer: Base
- Grid / Filter
- Tapered Reflectarray
- Cover
- Baseline
- Grid / Filter
- Tapered Reflectarray

<table>
<thead>
<tr>
<th>Profile Sizes</th>
<th>University of Ulm</th>
</tr>
</thead>
<tbody>
<tr>
<td>70×63×13 (mm)</td>
<td>150×150×25 (mm)</td>
</tr>
</tbody>
</table>

#### Simulated data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Southeast University</th>
<th>University of Ulm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0$</td>
<td>14.0 GHz</td>
<td>27.6 GHz</td>
</tr>
<tr>
<td>$D_{max}$</td>
<td>19.53 dBi</td>
<td></td>
</tr>
<tr>
<td>$G_{max}$</td>
<td>19.41 dBi</td>
<td>30.8 dBi / 29.5 dBi</td>
</tr>
<tr>
<td>$\eta_{aper}$</td>
<td>74.36 %</td>
<td></td>
</tr>
<tr>
<td>$\eta_{Ant}$</td>
<td>72.33 %</td>
<td>50.24 % / 37.24 %</td>
</tr>
<tr>
<td>SLL</td>
<td>$\leq -17.3$ dB</td>
<td>$\leq -20$ dB / $-21$ dB</td>
</tr>
<tr>
<td>BW$_G$</td>
<td>9.66 %</td>
<td>9.32 % / 2.90 %</td>
</tr>
<tr>
<td>BW$_{com.}$</td>
<td>7.99 %</td>
<td></td>
</tr>
</tbody>
</table>

#### Measured results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Southeast University</th>
<th>University of Ulm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{max}$</td>
<td>19.41 dBi</td>
<td></td>
</tr>
<tr>
<td>$G_{max}$</td>
<td>29.5 dBi</td>
<td></td>
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<td>SLL</td>
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<td>$\leq -20$ dB / $-21$ dB</td>
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<tr>
<td>BW$_G$</td>
<td>9.32 % / 2.90 %</td>
<td></td>
</tr>
<tr>
<td>BW$_{com.}$</td>
<td>?</td>
<td></td>
</tr>
</tbody>
</table>
Tapered FSS/AMC with U-slotted patch for 14 GHz

<table>
<thead>
<tr>
<th>FSS/AMC Array</th>
<th>12×13</th>
<th>15×16</th>
<th>18×19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Height (mm)</td>
<td>13.0</td>
<td>23.4</td>
<td>22.6</td>
</tr>
<tr>
<td>Resonant mode</td>
<td>Dominate</td>
<td>1st higher</td>
<td>1st higher</td>
</tr>
<tr>
<td>Peak Gain (dBi)</td>
<td>19.53</td>
<td>21.86</td>
<td>24.39</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>74.4</td>
<td>66.3</td>
<td>45.3</td>
</tr>
<tr>
<td>Common BW (%)</td>
<td>7.99</td>
<td>4.76</td>
<td>1.63</td>
</tr>
<tr>
<td>E-/H- Beam (°)</td>
<td>18.2 / 17.8</td>
<td>12.8 / 12.6</td>
<td>8.8 / 7.9</td>
</tr>
<tr>
<td>E-plane SLL (dB)</td>
<td>−17.3</td>
<td>19.7 / 18.7</td>
<td>16.5 / 12.9</td>
</tr>
</tbody>
</table>

* **Gain** enhanced due to Aperture enlargement
* **Height** increased for keep illuminated angle
* **Efficiency** dropped due to tapered distribution
* **Bandwidth** narrowed due to sharp mis-resonance
Recent progress – II Sub-wavelength Resonance Mechanism

Phase of: Reflection Ray-path
Resonant condition $\Phi(f) = \theta(f)$
from: Base Cover Spacing

$\phi_1(f) + \phi_2(f) = 4\pi H/\lambda \quad (N = 0)$

The location of intersected points correspond to each resonant spacing:

<table>
<thead>
<tr>
<th>Resonant points</th>
<th>P₁</th>
<th>P₂</th>
<th>P₃</th>
<th>P₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_1^{(o)}(p)$</td>
<td>112.6</td>
<td>74.9</td>
<td>-18.5</td>
<td>-82.8</td>
</tr>
<tr>
<td>$H/\lambda_0$</td>
<td>0.43</td>
<td>0.38</td>
<td>0.25</td>
<td>0.15</td>
</tr>
<tr>
<td>$H$ (mm)</td>
<td>9.3</td>
<td>8.1</td>
<td>5.5</td>
<td>3.2</td>
</tr>
</tbody>
</table>

$p \sim$ patch / period sizes

$\delta$ is more sensitive to $f$

Lower $H$

$\downarrow$ coupling between cover & base

$\downarrow$ feed illuminated area

Narrower Bandwidth

$\left\{\begin{array}{l}
-3$ dB gain-drop
VSWR$\leq2.0:1
\end{array}\right.$

$\downarrow$ Lower Gain/Efficiency

0.15$\lambda_0$

18.4 dBi
Recent progress – III

**Polygonal Array Architecture**

**Bandwidth Broadening**

**Octagonal aperture**
*as corner-cut & side-widen rectangle*

- Common BW: 7.99 %
- Peak Gain: 19.53 dBi
- \( \eta_{aper} = 74.4\% \)

**Hexagonal array**
*as honeycomb for sub-array element usage*

- Common BW: \( 8.20/7.54 \) %
- Peak Gain for \( \pm 3\)dB:
  - 19.53 dBi \( \eta_{aper} = 74.4\% \)
  - 19.31 dBi \( \eta_{aper} = 79.1\% \)
  - 19.44 dBi \( \eta_{aper} = 81.5\% \)
  - 20.08 dBi \( \eta_{aper} = 63.7\% \)

- Slightly extending 10.34 %
- Slightly extending 8.15 %
- Extending 9.38 %

**Sub-array Technique**

- VSWR \( \leq 2.0:1 \)
- Gain-drop \( \leq 2\) dB
- SLL \( \leq -15\) dB

- Simulated/Measured

- Peak Gain: 17.11/16.59 dBi
- Efficiency: 70.0/62.1 %

**Broadband Stacked-patch feed**
Recent progress – IV  Sub-Array Combination  (G*BW)  

7-subarray combination with tapered excitation  
(power ratio: 1: 6×1/6)  

Simulated/measured performances:  
\[
\begin{align*}
G_{\text{peak}} & = 22.87/22.51 \text{ dBi} \quad \text{Sub-array} \\
& \quad @ 9.6/9.7 \text{ GHz} \\
\eta_{\text{peak}} & = 37.7/34.7 \% \quad (17.11/16.59) \\
\text{BW}_{\text{common}} & = 9.63/8.28 \% \quad (70.0/62.1) \\
& \quad \text{for } \Delta G \leq -3 \text{ dB,} \\
& \quad \text{VSWR} \leq -10 \text{ dB,} \\
& \quad \text{SLL} \leq -15 \text{ dB}
\end{align*}
\]

If a 7-subarray combination with uniform excitation (power ratio: 7 ×2/7) then  
\[G_{\text{peak}} = 25.9 \text{ dBi, } \text{SLL} \leq -10.0 \text{ dB}\]

Alternative sub-array combination without network employed six parasitic-(stacked) patches in in developing.
Circular-Polarized Radiation

\[ E^x_{\text{out}} = E^y_{\text{out}} \]
\[ \theta^x - \theta^y = 90^\circ \]

Circularly Polarization

<table>
<thead>
<tr>
<th>Frequency (central)</th>
<th>Gain (Peak)</th>
<th>AR @ ( f_0 )</th>
<th>AR in HPBW</th>
<th>BW AR&gt;3 dB</th>
<th>RL</th>
<th>Efficiency (aperture)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.4 GHz</td>
<td>19.9 dBi</td>
<td>&lt; 1.0 dB</td>
<td>&lt; 2.0 dB</td>
<td>1.9 %</td>
<td>&lt;-10 dB</td>
<td>81 %</td>
</tr>
</tbody>
</table>
Printed Air-fed Array Antennas have constituted a flourishing family, almost every kinds had been concerned in SEU;

The CAFA antenna 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 BW in Gain-drop for high-gain antennas;

An Gain limitation of CAFA antenna with thin structure is to balance the size & efficiency, its solution is to act as a Sub-array.

The Circular-polarized radiation can be performed for CAFA by employing mushroom-type base with rectangular patches.

Thanks!