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# BROADBAND DESIGN OF PRINTED COMPOUND AIR-FED ARRAY WITH HEXAGONAL CONFIGURATION

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**Abstract**—A printed compound air-fed array antenna with hexagonal configuration is developed, which consists of a stacked-patch radiator, an FSS-cover and an AMC-base both with square elements arranged as a hexagonal grid respectively. By means of optimal option for all the structural parameters individually, a broadband prototype is designed at 10 GHz, the peak-gain of 17.11 dBi is performed by hexagonal aperture with side-length of 45 mm (1.5 wavelength); a common frequency bandwidth of 8.20% for VSWR $\leq 2.0:1$ and gain-drop $\leq 2$ dB and SLL $\leq -15$ dB is obtained by simulation. They are verified by measured results as 16.59 dBi peak-gain and 7.54% common bandwidth.

## 1. INTRODUCTION

The compound air-fed array (CAFA) proposed by Zhang et al. [1] is a new member of printed antennas family, it can be considered as a Fabry-Perot resonator (F-PR) antenna [2, 3] with phase compensation for the reflection phase from the elements of FSS-cover and/or AMC-base, as well as adopted in reflectarray (RA) and transmitarray (TA) design. The obvious merit of CAFA is quite low profile with thickness in wavelength even sub-wavelength, especially comparing to the conventional air-fed RA and TA with a towering feed. However, there is an unavoidable weakness of quite narrow bandwidth as a few percentages, due to the resonance mechanism, especially for a high-gain antenna since the behavior of contradiction between bandwidth and gain. On the other side, because the feed is embedded in the antenna and the spacing between cover and base is quite small, the illuminated angle of the feed can be very narrow. As a consequence, the effective

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aperture size is restricted which means the gain can hardly be quite high. Hence, to broaden bandwidth but keeping relative high gain becomes a challenging project. Most previous papers on F-PR antenna follow the criterion in optics, they focus to the high-gain and neglect the nature of narrow bandwidth. Some paper [4–7] have paid efforts to extend the common bandwidth of F-PR or CAFA, the bandwidth up to 7.9% for both VSWR $\leq 2.0:1$ and gain-drop $\leq 3\,\text{dB}$ has achieved, however, all they adopted square elements arranged in a square grid for the cover and/or base, thus resulted in relative higher side-lobe in 45° diagonal-plane and the invalidation of four corner-zones. For further improvement, a CAFA with hexagonal grid is utilized, and specifies the common bandwidth for VSWR and gain-drop and also SLL. Then the simulated analysis, comparison and optimal option, prototype design and fabrication, test and verification are performed in sequence, the final results are described below.

## 2. STRUCTURE DESCRIPTION

A stacked-patch radiator (Fig. 1) with broad impedance bandwidth and almost axial-symmetric pattern is employed as the feed of CAFA. Where a narrow slot with sizes ($l_S \times w_S$) crossed to the polarization was cut in a lower-layer rectangular patch with sizes ($l_f \times w_f$) placed on the central part of base for extending bandwidth toward the lower bound. An upper-layer parasitical patch with sizes ($l_p \times w_p$) having the center offset $d_{offset}$ along the polarization from the center of lower-layer was used for improving the symmetry in pattern. The substrate

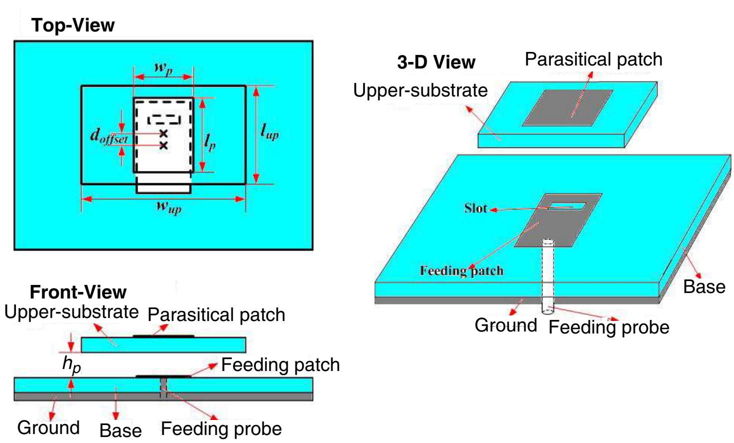
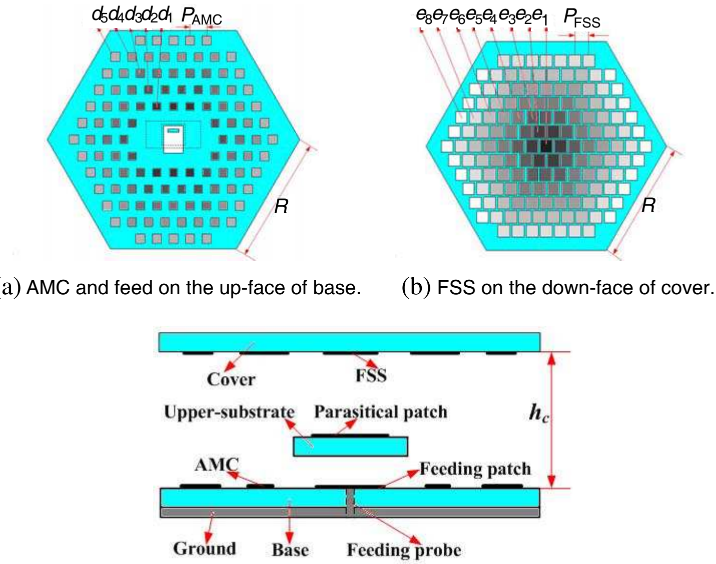



**Figure 1.** Structure of the feed.




(a) AMC and feed on the up-face of base. (b) FSS on the down-face of cover.

(c) Front-view of CAFA assembly.

**Figure 2.** Structure of the printed CAFA antenna.

of upper-layer has sizes ($l_{up} \times w_{up}$), and the spacing $h_p$ apart from the lower-layers, it is supported by rectangular plastic cushion under the two edges of upper-layer substrate. The position of feeding point is $f_y$ apart from the patch edge.

An assembly of CAFA (Fig. 2) consists of feed, base and cover. Where the central part of base occupied by feed is surrounded by the AMC elements with same period $P_{\mathrm{AMC}}$ involving square-patches arranged as 5 loops in hexagonal grid, the patch sizes are identical in the same loop, but inversely tapered from inner to outer in order as $\{d_j\}$. On the down-face of the cover, the FSS elements with same period $P_{\mathrm{FSS}}$ square-patches are arranged as 8 loops in hexagonal grid too, the patch sizes are identical in the same loop, but tapered from inner to outer in order as $\{e_i\}$. Both the cover and base with ground are in hexagonal shape with same side-length $R$ and thickness $h$, the spacing between cover and base is $h_c$, the dielectric constant of all material used are the same as $\varepsilon_r$=2.2.

By running a routine of design in principle, then simulation with parametric adjustment, and then performances optimization, a best set of parameters are finally designed and listed in Table 1.

**Table 1.** Structural sizes of antenna prototype (mm).

| Antenna Profile | AMC on Base | FSS on Cover | Feeding Patch | Parasitical Patch |
|---|---|---|---|---|
| $R$ =45.0 | $P_{\mathrm{AMC}}$=5.9 | $P_{\mathrm{FSS}}$=5.3 | $l_f$ =9.7 | $l_p$ =9.1 |
| $h$ =1 | $d_{1,2,3}$=2.8 | $e_{1,2}$ =4.8 | $w_f$ =7.0 | $w_p$ =8.0 |
| $h_c$=16.3 | $d_4$ =3.0 | $e_3$=4.7 | $f_y$=8.7 | $l_{\mathrm{up}}$ =11.1 |
| $h_p$ =0.8 | $d_5$ =3.2 | $e_{4,5,6}$ =4.6 | $d_{\mathrm{slot}}$=3.2 | $w_{\mathrm{up}}$ =18.0 |
| | | $e_7$ =4.5 | $l_s$=1.1 | $d_{\mathrm{offset}}$=1.4 |
| | | $e_8$ =4.3 | $w_s$=4.0 | |

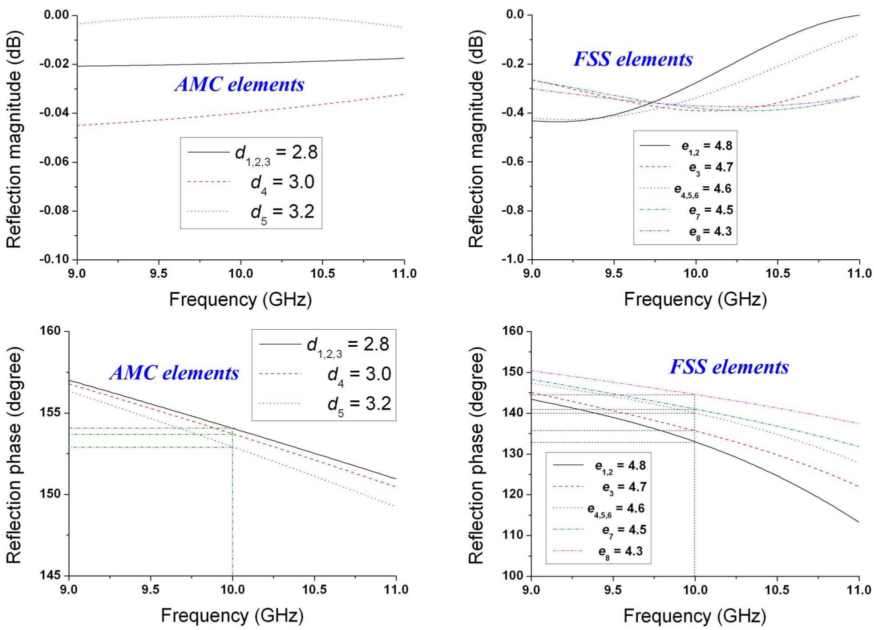



**Figure 3.** Frequency response of the reflection magnitude and phase on AMC and FSS.

## 3. SIMULATED AND MEASURED RESULTS

For compensating the phase difference resulted from the unequal length of rays directly radiated from the feed to different points on aperture, the FSS elements are designed of equal period but tapered size, while for re-compensating the phase difference resulted from the parallel rays reflected from cover to the base and then return to the cover with equal length, the AMC elements are designed of equal period but inversely tapered size, from inner to outer as shown in Fig. 2. The frequency response of the reflection magnitude and phase of AMC and FSS elements with different sizes are abstracted in Fig. 3 respectively. Where the reflection magnitude of AMC elements approaches 1 ($\sim$ 0 dB), and the reflection phase increases with decreasing elements' sizes; but that of FSS elements slight less than 1 ($>$ 0.4 dB) due to transmit out, and the reflection phase decreases with increasing element's size. Those tapered FSS and inversely tapered AMC provide approximate in-phase along the aperture or cover; However, the in-phase radiation from the aperture by multiple-reflected waves requires about $\lambda/2$ spacing between cover and base as a resonance condition, and results in restriction of bandwidth.

A CAFA antenna prototype was fabricated and measured for verifying the simulation; both the simulated/measured results are drawn in Figs. 4 & 5, and abstracted in Table 2. From Fig. 4, a peak-gain $G_{\text{peak}} = 17.11/16.59$ dBi which corresponds to an aperture-efficiency $\eta_{\text{peak}} = 70.0/62.1\%$; within the common bandwidth BW $= 8.20/7.54\%$, it satisfying $\{$VSWR $\leq 2.0:1$, Gain-drop $\leq -2$ dB, and SLL $\leq -15$ dB$\}$; the half-power-beam-width HPBW $= 26.4°/28.5°$ and side-lobe-level SLL $\leq -18.1/-19.7$ dB; and the cross-polar-level X-PL $< -30$ dB inside the main-beam are achieved. Fig. 5 abstracts

**Table 2.** Performances of antenna prototype.

| **Performance** | **Simulated** | **Measured** |
|---|---|---|
| $G_{\text{peak}}$ (dBi)<br>at frequency (GHz) | 17.11<br>10.1 | 16.59<br>9.8 |
| $\eta_{\text{peak}}$ (%) | 70.0 | 62.1 |
| HPBW (°) | 26.1 $\sim$ 26.4 | 28.1 $\sim$ 28.5 |
| SLL (dB) | $-(18.1 \sim 18.4)$ | $-(19.7 \sim 19.8)$ |
| X-PL (dB) | $< -30.0$ | $< -30.0$ |
| 20log<br>$(S_{11})_{\min}$ (dB) | $-14.25$ dB | $-16.42$ dB |
| BW (GHz) (%) | 9.59 $\sim$ 10.41<br>(8.20) | 9.57 $\sim$ 10.32<br>(7.54) |
| $\text{BW}_{\text{Gain-drop}}$<br>(GHz) (%) | 9.15 $\sim$ 10.74<br>(15.99) | 9.44 $\sim$ 10.33<br>(9.00) |
| $\text{BW}_{\text{VSWR}}$<br>(GHz) (%) | 9.59 $\sim$ 10.47<br>(8.77) | 9.57 $\sim$ 10.32<br>(7.54) |
| $\text{BW}_{\text{SLL}}$<br>(GHz) (%) | 8.69 $\sim$ 10.41<br>(18.01) | 8.61 $\sim$ 10.53<br>(20.06) |

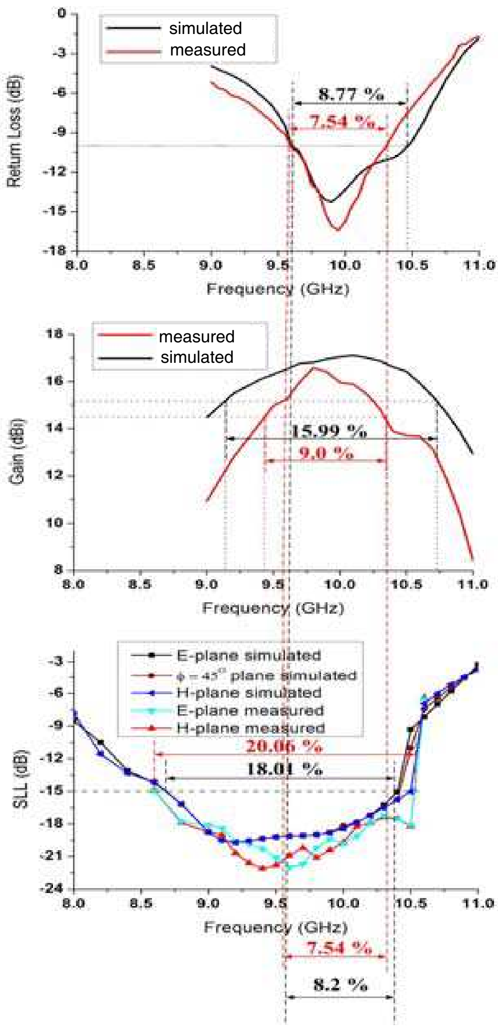



**Figure 4.** Frequency response of return loss, gain & SLL.

a set of typical pattern in $E$- and $H$- and also 45° diagonal-planes at 10 GHz. The difference between the simulated and measured peak-gain may be resulted from the inhomogeneous permittivity of dielectric material; the fabrication and assemblage error of CAFA; and also the collimation error between receiving CAFA and the transmitting horn in testing, etc. However, the difference is small and these results validate the design principle.

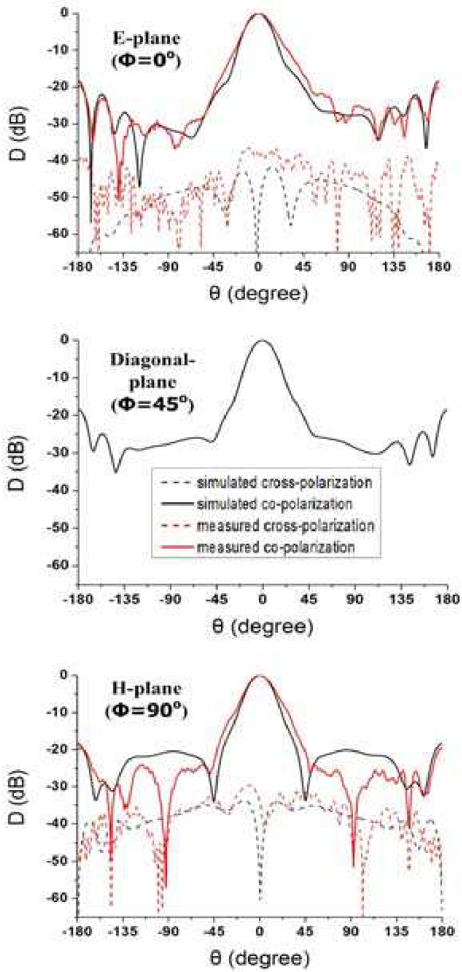



**Figure 5.** Radiation pattern of typical planes at 10 GHz.

The FSS (AMC) elements are arranged in square grid in reference [7], for briefness, the SLL and HPBW in $E$-/$H$-/diagonal-planes using both square grid and hexagonal gird are listed in Table 3. It is clearly seen that compared to the square gird, the differences of SLL and HPBW of different planes are smaller when using the hexagonal grid.

**Table 3.** Performance comparison for square-/hexagonal-grid used in the FSS (AMC).

| Gird | SLL (dB) | | | HPBW ($^{\circ}$) | | |
|---|---|---|---|---|---|---|
| | $E$-plane | $H$-plane | $45^{\circ}$-plane | $E$-plane | $H$-plane | $45^{\circ}$-plane |
| Square | – 21.8 | – 17.0 | – 17.5 | 21.3 | 24.0 | 22.5 |
| Hexagonal | – 18.4 | – 18.1 | – 18.2 | 26.1 | 26.4 | 26.3 |

## 4. CONCLUSION

The hexagonal CAFA using stacked patches as feed, combined with phase-compensated FSS-cover and AMC-base is a good scheme for designing a broadband antenna for both impedance and pattern performances with very low profile. However, its peak-gain is limited as a cost of broadband and profile, which does not satisfy the case of high-gain application. Fortunately, it is easy to arrange a larger hexagonal array by combining smaller hexagonal sub-arrays that will be studied in the next step.

## ACKNOWLEDGMENT

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