Bandwidth Enhancement Techniques for Printed Compound Air-fed Array Antennas

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1. Introduction

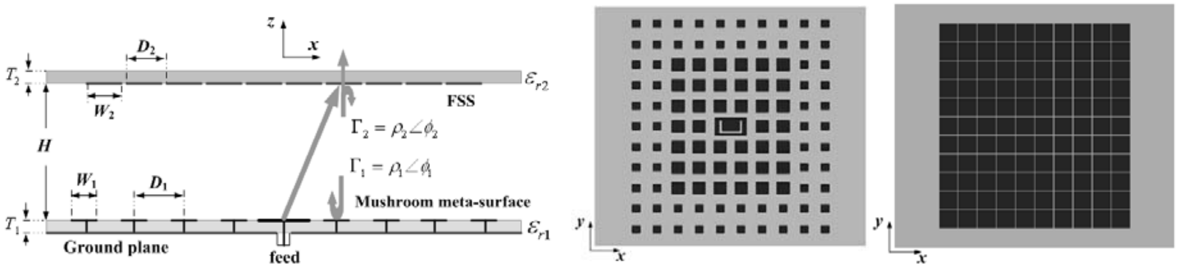
Over the last decade, a class of high-gain printed antennas: the reflectarray (RA) [1-2], transmitarray (TA) [3-4], and Fabry-Perot resonator (FPR) [5-8], summarized as air-fed array [9] were developed, which avoid the serious loss due to feeding network. The traditional RA or TA consists of the printed radiator array illuminated by a feed apart from the array approximately the aperture size of array, which has high profile in structure. The traditional FPR antenna has much lower profile as half wavelength [5-7] but usually owning very narrow bandwidth due to the high quality factor of resonant cavity, and lower efficiency due to the non-uniformity of aperture distribution. In order to enhance the bandwidth and efficiency, but keep its low-profile structure, an improved antenna named as printed compound air-fed array (PCAFA) as shown in Figure 1 was developed [9-10] successively. The original design of PCAFA consists of three components: a tapered FSS as cover for phase compensation of illuminated rays, an inversely tapered HIS as base for phase compensation of multiple reflection rays, and an embedded broadband radiator as printed feed. Alternatively, in this paper the cover is a uniform FSS with partial reflectivity; the base is a mixed HIS with prescribed reflection phase. It can further improve the gain bandwidth of PCAFA by proper designing.

Let us briefly review the ever existed techniques in advance, as well known that the main cause of narrow bandwidth to PCAFA is the mechanism of high-Q resonance, similar as so-called EBG resonator antennas [11-17]. A simplest method is to decrease the Q-factor by decreasing the reflectivity of cover [11-13], however such approaching benefits its bandwidth with the scarification of gain and aperture efficiency. The second method is to combine double layers of FSS for getting an increasing slope of reflection phase-frequency response rather than decreasing response [14-15], however the cost is the rising spacing between FSS layers and then the volume of antenna. The third method to greatly enlarge the bandwidth of gain-drop is fed by a radiator array [16-17], but it needs a complex feeding network again.

The technique for enlarging the gain-bandwidth product proposed in this paper is to perform a flat gain-frequency response with small ripple inside, and with abrupt slope-down outside the band, by means of combined techniques. Firstly, choose a proper FSS as cover with stable frequency response of reflectivity and reflected phase to minimize gain deterioration caused by reflectivity and phase variation. Secondly, adopt mushroom-patch HIS rather than patch-HIS as base to suppress the lateral waves including surface wave and parallel guide wave. Thirdly, properly arrange two or more kinds of size of HIS elements to get a flat gain-frequency response. These steps provide the possibility to approach maximal gain-bandwidth product based on a low profile structure with the height less than half-wavelength and single feed only. The detailed principle and design procedure will be presented, and then a designed example of PCAFA antenna is simulated, which exhibits 9.9 % (14.1 %) relative bandwidth of –1dB (–3 dB) gain-drop from peak gain (19.1 dBi) corresponding to 71 % aperture efficiency.

2. Principle and analysis

2.1 Resonant Condition



(a) Side view; (b) Stepped mushroom-HIS base; (c) Covered FSS

Figure 1: Configuration of PCAFA

The proposed antenna (Figure 1) consists of three parts: a broadband U-slotted patch radiator as a feed, surrounded by 11 rows × 10 columns mushroom HIS elements with square-cell (period D_1=4.8 mm) and square-patch (patch size W_1) shorted by via to a full-reflected plate as a base, and suspending 11 rows × 10 columns FSS elements with also square-cell (period D_2=5.4 mm) and square-patch (size W_2) as a partial-reflected cover. Both the superstrate of cover and substrate of base have the same relative permittivity (ε_{r1}=ε_{r2}=3.2) and thickness (T_1=T_2=1.6 mm), while H is the spacing between cover and base. The aperture of this PCAFA antenna is 60 mm in E-plane, 70 mm in H-plane, designed for central frequency of 14 GHz.

To denominate the reflection phase of cover and base as $\phi_1(f)$ and $\phi_2(f)$ respectively, and the reflectivity of cover as $r(f)$, then the resonant condition is:

$$\frac{4\pi H}{c} f - \phi_1(f) - \phi_2(f) = 2N\pi \quad (N = 0, 1, 2 \ldots) \tag{1}$$

where $\boldsymbol{c}$ is the light speed, and N is resonant mode number. Let

$$\Phi(f) = \phi_1(f) + \phi_2(f) \tag{2}$$

$$\Theta(f) = \frac{4\pi H}{c} f - 2N\pi \quad (N = 0, 1, 2 \ldots) \tag{3}$$

then the resonant condition (1) becomes:

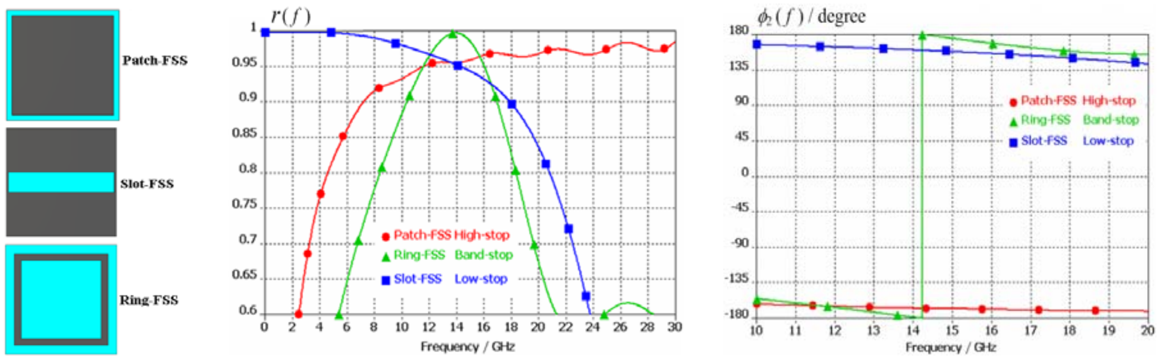
$$\Phi(f) = \Theta(f) \tag{4}$$

On the other side, the gain $\boldsymbol{G}$, as well as directivity $\boldsymbol{D}$ is determined by:

$$D = (1 + r(f)) / (1 - r(f)) \tag{5}$$

It has peak value at resonant frequency f_0, and drops down when off resonance. Hence the bandwidth of gain-drop depends on both the derivatives of the reflectivity $r(f)$ and the phase response $\delta(f) = |\Theta(f) - \Phi(f)|$ to frequency. Obviously, sharp variation of $r(f)$ and $\delta(f)$ will result in narrow bandwidth of gain-drop. In other words, to achieve broadband gain, it requires a cover as well as a base to provide stable reflectivity and reflection phase response over a wide band.

2.2 Design of FSS Cover



(a) Unit cell of three types of FSS; (b) reflectivity frequency response; (c) reflection phase response

Figure 2: Comparison of three types of FSS cover

To compare three kinds of FSS with the same period of unit cell (Figure 2a), all they exhibit high reflectivity at central frequency f_0=14 GHz, but different frequency responses of reflectivity (Figure 2b) and reflection phase (Figure 2c). Among them, the patch-type FSS features a high-stop filter, its $r(f)$ reaches about 0.95 at f_0 and keeps stable with small ripple over a wide band. On the contrary, the slot-type FSS exhibits a low-stop filter, its $r(f)$ reaches similar value at f_0 but over a narrower band. The ring-type FSS behaves a band-stop filter, its $r(f)$ has peak value 0.99 at f_0 but drops quickly apart from central frequency. Besides the reflectivity, the reflection phase also differs from each other, where the patch-type FSS has the flattest phase curve $\phi_2(f)$ around the value of -180^{o}, It is better than the other two types.

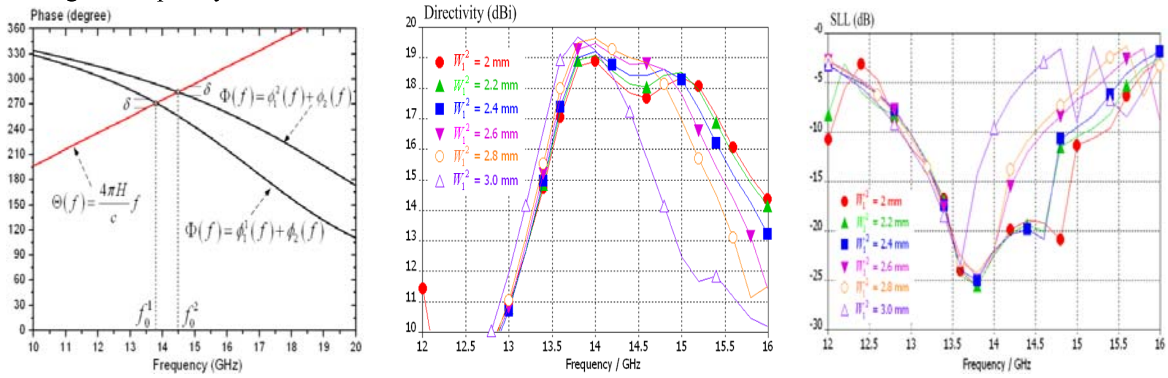
Therefore, the patch-FSS is chosen to be periodical element of the cover. It is also an evident reason that the EBG-type cover exhibiting band-stop character always results in narrow bandwidth due to narrowband response of reflectivity and reflection phase.

2.3 Design of HIS Base

When the FSS-cover is designed, its reflection phase $\phi_2(f)$ is also determined. The next step is design of the HIS-base with proper reflection phase response $\phi_1(f)$, which is much more sensitive to frequency and patch size than $\phi_2(f)$, thus is a key factor on gain-frequency response of the PCAFA antenna. The traditional HIS-type base constructed by a uniform array of patches, the uniform reflection phase $\phi_1(f)$ over the whole base results in single resonant frequency with a narrow bandwidth.

The authors had employed inversely tapered patch-type HIS-bases to suit a tapered FSS-cover [10-11], however had not yet reach the optimal design based on quantitative analysis. In this paper, a uniform FSS-cover corresponds to a tapered mushroom-type HIS-base. Figure 1b shows a stepped base with two kinds of HIS element size to provide two sub-areas with different $\phi_1^1(f)$ and $\phi_1^2(f)$, which own different but close resonant frequencies, and form a resultant broader frequency response of total $\phi_1(f)$, and then extends the gain-bandwidth. For instance, a stepped base constructed by two kinds of HIS element size arranged as rectangular rings surrounding the U-slotted patch as (Figure 1b). The patch sizes are stepped from W_1^1 to W_1^2, which corresponds to the reflection phase of ϕ_1^1 and ϕ_1^2, and then resonates at f_0^1 and f_0^2, respectively, as described in Figure 3a. Furthermore, Figure 3b show the full-wave simulated curves of gain-frequency response by using CST-2006, where $W_1^1 \equiv 3.0$ mm but W_1^2 decreasing from 3.0 mm to 2.0 mm. Correspondingly, the difference between f_0^1 and f_0^2 extended even two peaks appear in the gain curve; however, the gain-drop bandwidth might be broadened obviously with a little loss in peak gain; fortunately, the bandwidth of side-lobe level (*SLL*) is also enhanced with bandwidth of gain as shown in Figure 3c.

Essentially, bandwidth enhancement must be accompanied with decreasing the Q-factor of the resonant structure, but the improvements of the flatness on top of response curve and the sharpness of slopes outside bandwidth provide additional possibility to obviously broaden the bandwidth of gain with a little loss in peak gain. After proper selection of the sizes W_1^1 and W_1^2 to perform flat top of the gain-frequency curve, the reflection phase ϕ_1^1 and ϕ_1^2 are also determined. Then the spacing H may be designed for perform sharp slope of the gain-frequency curve.



(a) Resonant condition; (b) Gain-frequency response; (c) SLL-frequency response

Figure 3: Stepped base and its performance analysis (W_1^1=3.0 mm)

As well know that for a given antenna structure, its gain-bandwidth product has a limitation. The proposed technique provides a possibility to approach maximal gain-bandwidth product by means of optimal balance between gain and bandwidth. In additionally, by adopting mushroom-type HIS to fully suppress the lateral wave between the cove and base, the product of gain-bandwidth is enlarged, which means that with the same bandwidth, mushroom HIS provides higher gain and aperture efficiency.

3. DESIGN EXAMPLE AND PERFORMANCE

A design example of PCAFA antenna with two-step sized base is designed, and simulated by using CST-2006. The geometry parameters are chosen as: W_2=4.6 mm, H=8.8 mm, W_1^1=2.6 mm and W_1^2=2.0 mm. The performance on directivity *D*, *SLL* and return loss (*RL*) are shown in Figure 4. A flat gain response is observed with 19.1 dBi peak value corresponding to 71 % aperture efficiency, and −1 dB (−3 dB) gain-drop bandwidth covers 13.85~15.3 GHz (13.65~15.72 GHz), corresponding to 9.9 % (14.1 %) relative bandwidth. The common bandwidth of −1 dB gain-drop, *SLL* lower than −15 dB and *RL* less than −10 dB covers from 13.95~15.1 GHz, corresponding to 7.9 % relative bandwidth. The radiation patterns at 14 GHz shown in Figure 5 exhibit good cross-polarization ratio (*X-PL*) and front-back ratio (*F/B*). A little asymmetry on side lobe in E-plane appears because of the asymmetrical feeding in E-plane.

4. CONCLUSIONS

This paper proposes an essential technique to enhance the bandwidth of PCAFA antennas by enlarging the gain-bandwidth product and flatting the gain-frequency response. Three key techniques are combined: 1) employing a patch-FSS rather than slot-FSS or ring-FSS as cover to get a stable response of reflectivity and reflection phase; 2) using two or more kinds of element-size of HIS with proper arrangement as base, which benefits the flatness of gain-frequency response; 3) using mushroom-type HIS to suppress the lateral waves between the cover and base, which enlarges the gain-bandwidth product and supports enough aperture efficiency. A designed example of PCAFA antenna is simulated to validate this technique. The tested results of a prototype will be reported in the presentation.

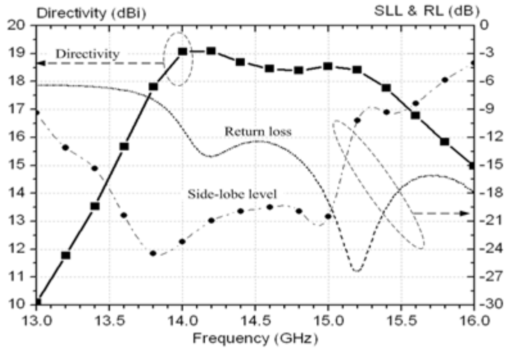


Figure 4: Simulated performance on *D*, *SLL* and *RL*

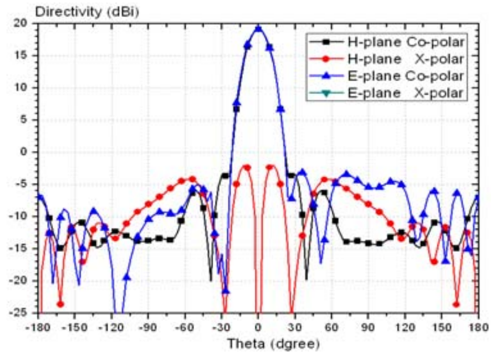


Figure 5: Radiation patterns at 14 GHz

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