Agile Beam Radiating Surfaces

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Abstract: *This paper deals with a new agile beam low profile antenna generating an agile radiating surface to obtain multiple types of radiation patterns for beam forming and beam steering applications. Surface agility, and consequently radiation pattern diversity, are obtained by dividing the radiating surface into small areas called pixels, where each one is able to generate an uniform surface field varying in amplitude and phase. This approach was already presented in the ARMA (Agile Radiating Matrix Antenna) concept [1] and this paper presents a generalization of this technique by introducing any shaped pixels.*

I. INTRODUCTION

Active Beam Antennas are able to generate different radiation patterns to perform Beam Forming or Beam Steering.

There is a well-known approach to perform this beam agility called AESA (Agile Electronically Scanned Array). This technique replaces the radiating surface by an array of periodically spaced radiating antennas (Dirac Comb Sampling [1]) fed by a BFN (Beam Forming Network). Unfortunately, this technique presents some limitations like electromagnetic coupling effects, side lobe levels, frequency bandwidth limitation, and high number of elements which increase the BFN cost [1].

Recently, a new approach, called ARMA (Agile Radiating Matrix Antenna), was introduced using a periodic rectangular function sampling procedure to reduce these limitations [2], [3], [4].

This paper generalizes this new technique by suppressing the periodicity problem, introducing any shaped samples called "pixels", and also by designing conformal agile surfaces.

II. PRINCIPLE

For any antenna, far electromagnetic fields (E(P), H(P)) are obtained from the radiating surface fields ($E_S(x,y)$, $H_S(x,y)$) generated on or around the antenna (equivalent principle) using the following relationship :

$$\vec{E}(P) = \frac{jk}{4\pi}\Psi(R)(1+cos\theta)\left(cos\phi\overrightarrow{e_\theta} - sin\phi\overrightarrow{e_\phi}\right)SFT. \quad (1)$$

$$SFT = \oiint E_S(x,y)e^{j(k_x\, x\, Sin\theta\, Cos\phi\, +\, k_y\, y\, Sin\theta\, Sin\phi)}\, ds. \qquad (2)$$

With $\Psi(R) = e^{jkR}/R$.

To perform the agility, the whole surface S (planar or non-planar) is divided into small joined surfaces and the far fields is given by the superposition (summation) of the electromagnetic field radiated by each sampling element (pixel) and multiplied by a weighting function [1]. In the first ARMA concept [1] the pixel shape was square or rectangle [2]. In this paper, there is no restriction on the shape of the joined sampling elements. This paper presents two kinds of generalizations of the ARMA concept:

- In the first case scenario:

A planar ARMA with any shaped pixels building a planar radiating surface; the shape of one pixel, inside the matrix, can differ from that of any other pixels. However, all the pixels must be still joined together to correctly build the whole radiating surface.

- Second case scenario:

Conformal ARMA and conformal pixels are designed, for example, to be placed on cylindrical or spherical targets (planes, rockets, missiles…). The conformation can also be used to increase some radiating performances of the antenna.

III. PLANAR LOW PROFILE STRUCTURES

III.1 - Any shaped Planar Pixel design.

The technique used to design square planar pixels [2] is based on introducing walls in a high gain low profile EBG antenna [5], [6]. This approach can be easily generalized to the design of any shaped pixel, since the pixel cavity is working on EBG modes which presents an evanescent law in the radial direction [5] .Thus, it is possible to generate a quasi-uniform radiating surface field on the top of any shaped pixel (fig 1).

The technique used to feed the pixel cavity in linear or circular polarization [9] can be performed, as for the square pixel, using a dipole, a slot, a patch or a waveguide. For example, let us consider a rotational-symmetric circularly polarized pixel, fed by a circular patch as shown on the fig 1 (a). The E field generated on the upper surface has, as expected, a uniform amplitude shown on fig 1 (b).

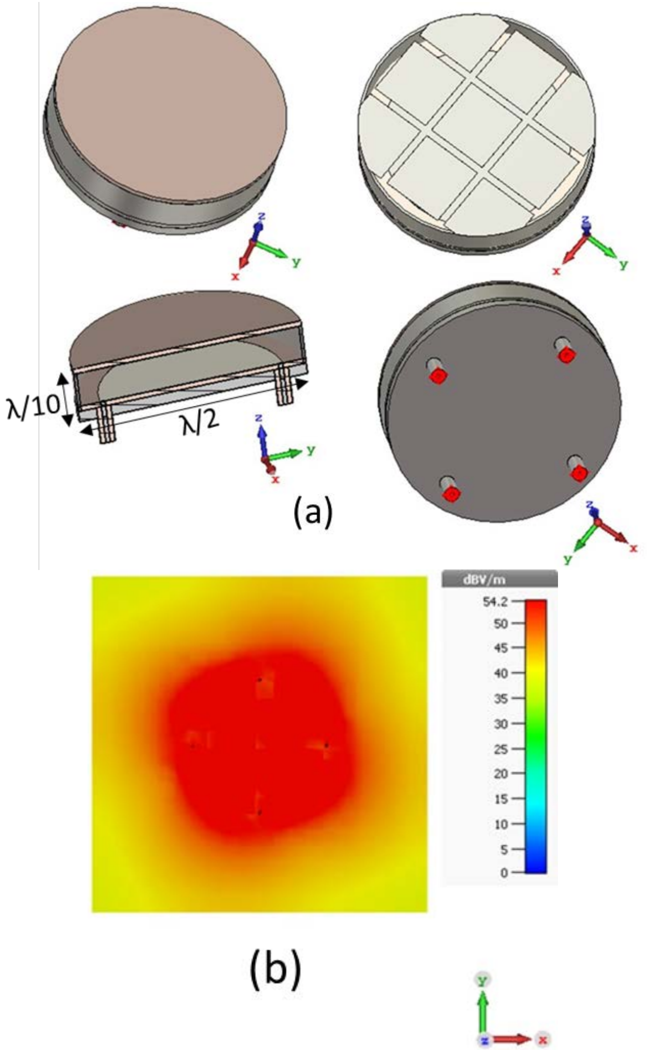

Fig 1: (a) Circular pixel fed by 4 ports: upper view with the radome, upper view without the radome, cut-view, bottom view with the 4 ports to build circular polarization. (b) Uniform radiating surface field on the pixel top.

Thanks to the low profile EBG technique [6], the ARMA height is very small (approximately λ/10) and the bandwidth can be very large (fig 2) like for the square ARMA solution [1].

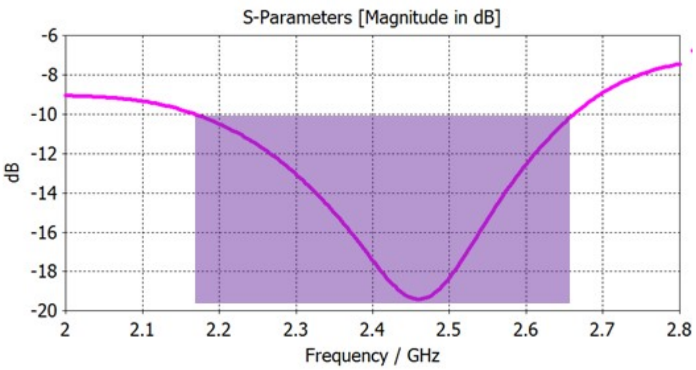

Fig 2: Sii (i=1 to 4) parameters evolution as a function of the frequency showing a wide frequency band: 18%.

This pixel can be used alone as a “pixel antenna” (for example to obtain a large coverage for indoor RFID applications), or it can be introduced in the following ARMA solutions.

III.2 - Whole planar antennas design:

Having pixels of any shape allows us to optimize the whole radiating surface of ARMA to satisfy some specifications: footprint constraints, particular beam shape, optimization of the number of elements, introduction of symmetries, limitations of edges effects. Some examples are given here for illustrating these very important properties:

III.2.a - The Butterfly antenna [7].

This antenna is built with pixels of different shapes: a circular pixel (like in §III-1) associated with 2 trapezoidal ones (fig 3a) to obtain the Butterfly Agile Antenna.

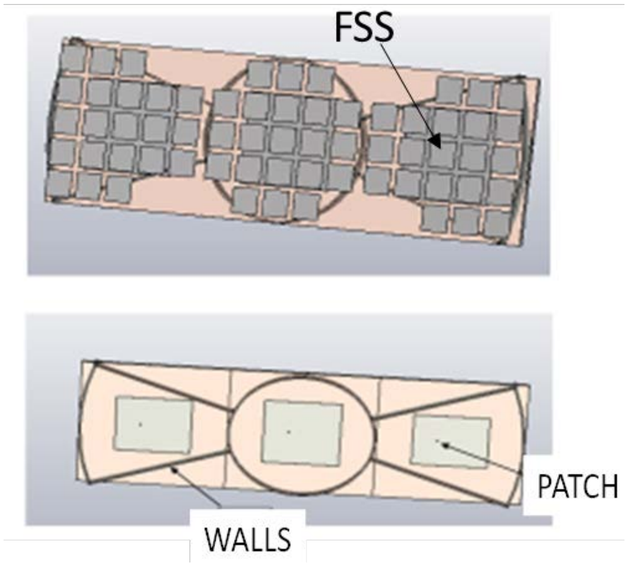

Fig 3 a: The Butterfly antenna with and without the FSS.

Such agile beam antenna is able to steer a beam in the symmetrical plane of the antenna (fig 3b).

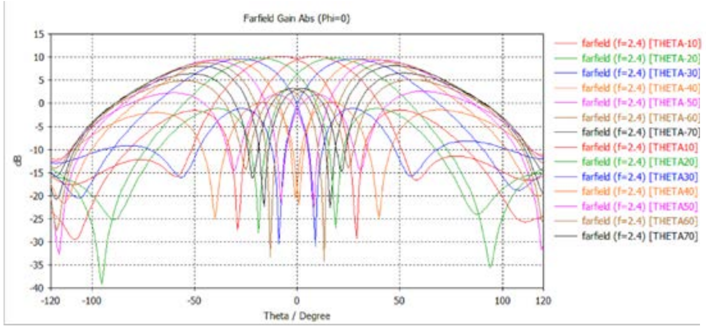

Fig 3 b: Steered beam patterns obtained at 2.4 GHz with a Butterfly Antenna with only 3 pixels.

Butterfly antennas are usually used together in a circular symmetrical arrangement to cover a large circular area (fig 3c), involving a switching process.

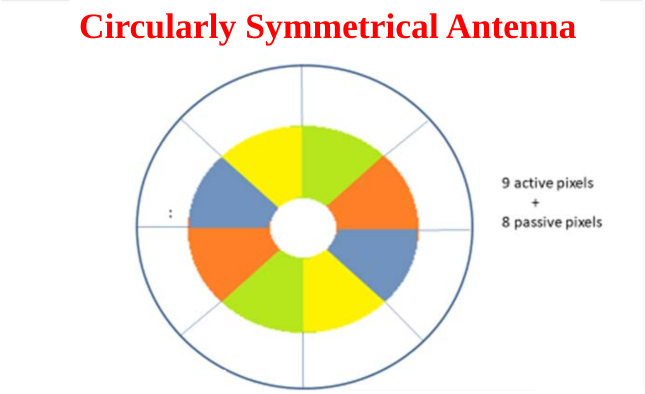

Fig 3 c: Rotational-symmetric antenna with a large coverage, built with 4 Butterfly antennas of 5 pixels.

III.2.b - Rotational-symmetric patterns.

To obtain patterns with a very good symmetry of revolution it is better to design a rotational-symmetric antenna: For axial Gaussian beam antennas, which radiate the maximum of the energy in the axial direction, the square shape of the antenna and the square shape of the pixel (ARMA [1]) are not very disturbing because the edges of the structure are not strongly illuminated. That is not the case for antennas with no axial patterns (Isoflux [8], [9], [10] for example), for which rotational-symmetric patterns are ideally obtained from a rotational- symmetric antenna and suitably shaped pixels (fig 4).

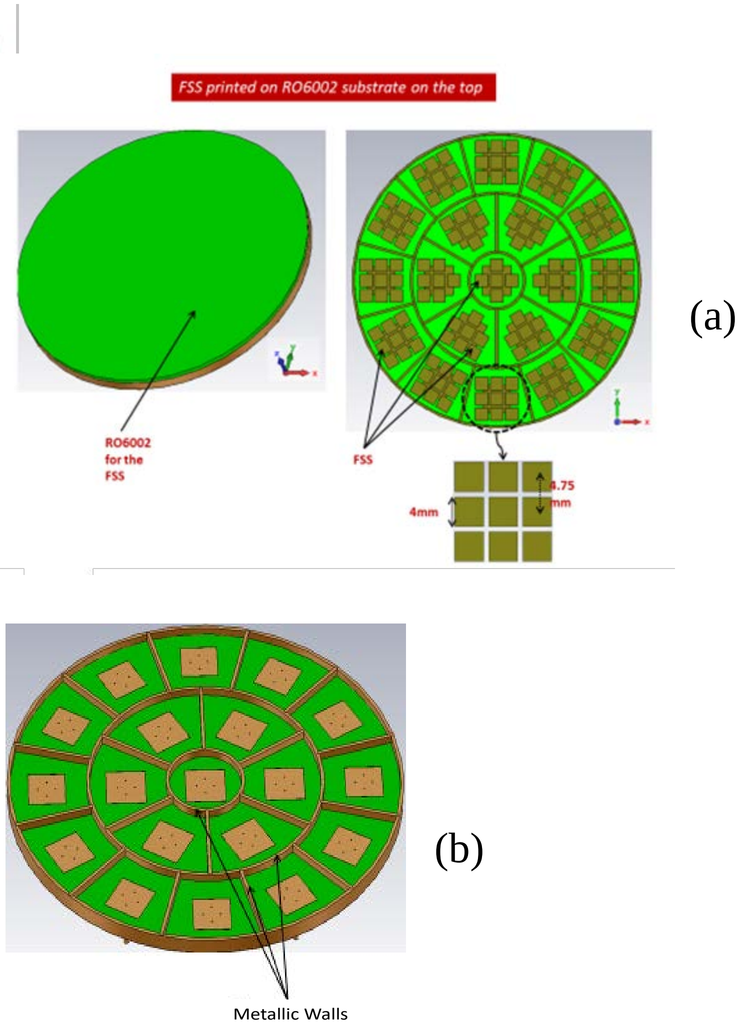

Fig 4: Rotational-symmetric low profile antenna fed by four ports patches (circular polarization): (a) Global views with and without the radome, (b) Without the FSS.

To illustrate this behavior, the circularly polarized radiation pattern and the axial ratio, obtained from this kind of antenna (fig 4) are presented in fig 5 and compared with one obtained from a square ARMA solution [9]. The square shaped low profile antenna ARMA with 5X5 pixels [9], [10] shows (fig 5a) a strong non uniformity of the gain of about 2.75 dB. The axial ratio is less than -3 dB for high values of Ѳ till 60° (fig 5 b) and bad around the axial direction due to the diffraction by the edges.

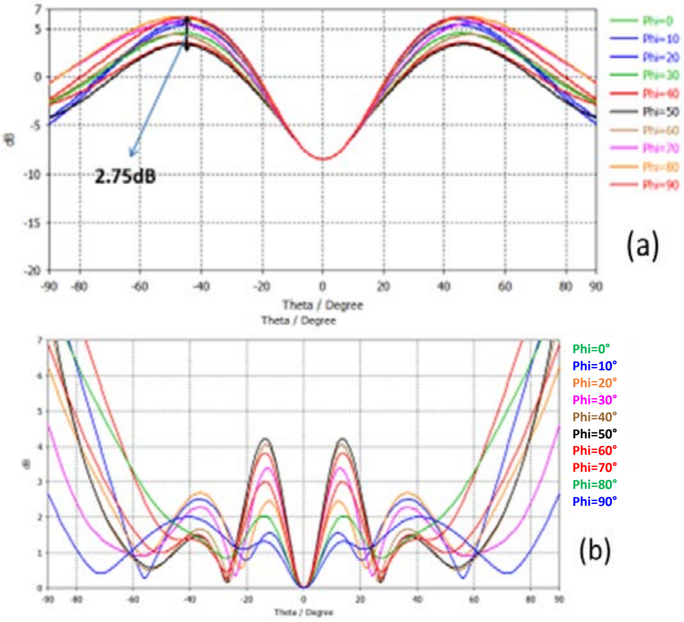

Fig 5: Isoflux radiation pattern (a) and axial ratio (b) as a function of Θ for the 5X5 square ARMA solution [9].

The same results obtained with the new body of revolution antenna (fig 4) are presented on fig 6a and 6b.

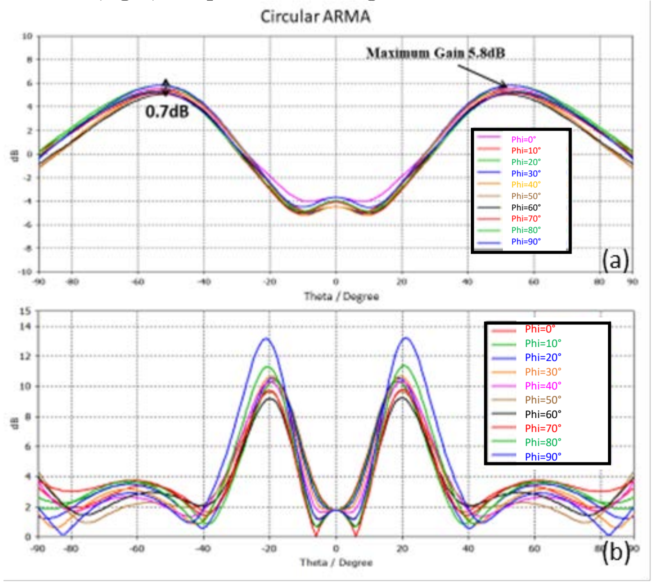

Fig 6: (a) Isoflux radiation pattern and (b) axial ratio; obtained with the rotational symmetrical ARMA.

The isoflux radiation pattern of the rotational symmetry ARMA is much more uniform (0.7 dB) than the one obtained with the square ARMA (2.75 dB); but the axial ratio is worse in the axial region. This behavior is due to the diffraction effect of the edges which occurs simultaneously in the axial direction in the rotational symmetrical case. It is not a problem for spatial bi-modes applications [9], [10] because the isoflux solution is used only for angles higher than 30°.

IV. CONFORMAL RADIATING SURFACES

The second part of this paper is devoted to conformal pixels used alone and called a “pixel antenna”. The conformal pixels building a conformal ARMA is also reported in this section.

The conformal elements can be used to match with conformal surfaces: particularly cylindrical or spherical ones, but the curvature can also be performed to increase some performances of the antenna patterns.

IV.1 - Conformal “pixel antenna”

As mentioned before, the pixel can be used alone as a “pixel antenna”. It can be bent on a cylindrical or a spherical surface in order to increase some performances, particularly the half-power beam-width in the bending plane. It is true that we will lose a bit of directivity, but the antenna coverage will be larger. This study aims at applications such as RFIDs, where the reader should have a wide beam-width in order to capture the signal from many tags located on a large surface. The increase in the surface coverage decreases the number of readers and hence the cost.

For example, the performance of a cylindrically bent antenna will be studied around the frequency of 2.5 GHz. The geometry of the planar antenna as well as the bent antenna are shown in Fig.7 with the most important parameters.

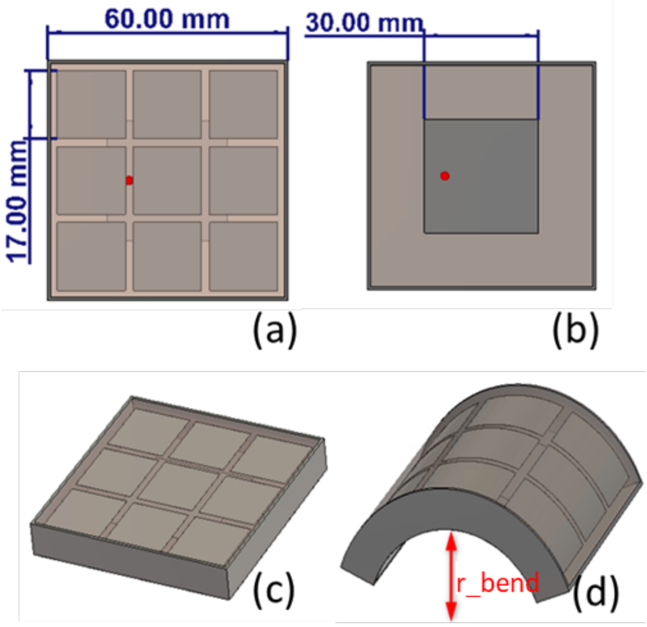

Fig 7: (a) top view of the used FSS, (b) Top view of the used patch, (c) 3D view of the planar pixel and (d) 3D view of the conformal pixel

The gain evolution as a function of ϴ in the bending plane (fig 8) shows that the maximum gain remains constant for r-bend higher than 50mm; consequently the bending procedure becomes efficient to increase the beam-width for r-bend lower than this value. Then a larger coverage is obtained in the bending plane.

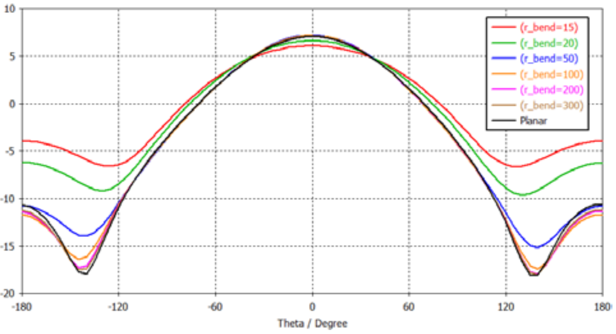

Fig 8: Radiation pattern (IEEE definition of the gain) evolution in the bending plane for different values of the bending radius.

IV.2 - Conformal ARMA :

Many applications need large ARMA high gain antennas located on cylindrical, spherical or conformal metallic surfaces. For example, let us consider bending a 1D ARMA of 17 pixels on a cylindrical concave or convex support (fig 9).

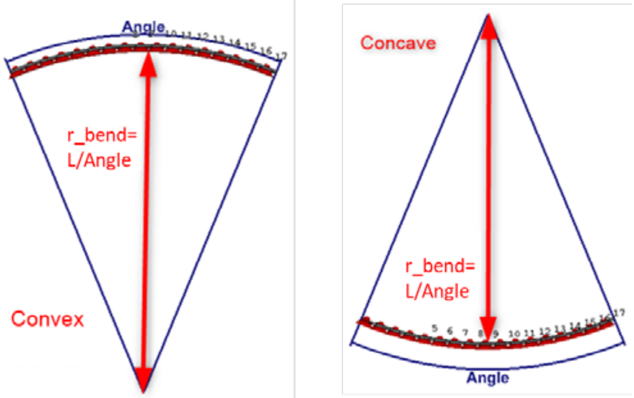

Fig 9: Convex and concave ARMA structures

The axial directivities evolution vs the frequency of the conformal ARMA (convex and concave) with several angles are compared to the one of the planar ARMA in (fig 10.)

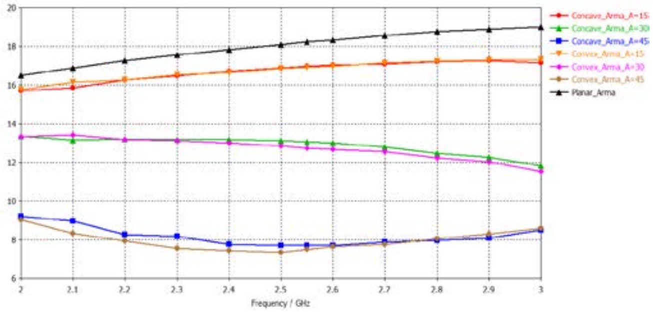

Fig 10: Axial directivity versus frequency for convex and concave ARMA compared to the planar ARMA.

We can notice when the bending angle increases (i.e., when the bending radius decreases), the directivity decreases. This is due to the phase delay between the elements which is seen in the far-field as we go farther from the center element. Another interesting conclusion which can be observed is that the axial directivity of the convex and concave ARMA are the same for an equal bending angle; this phenomenon is always due to the same delay contribution of the pixels in the 2 cases.

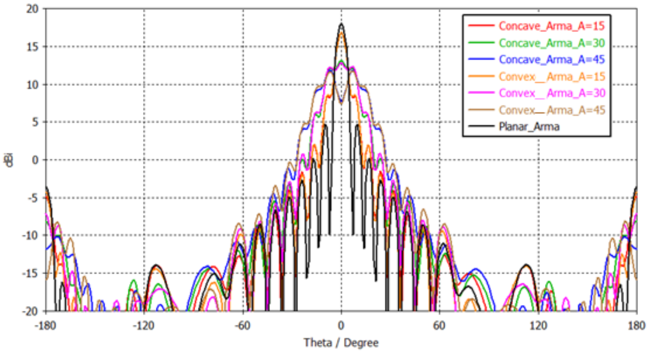

Fig 11: Radiation patterns in the bending plane at the central frequency for different A angles.

The gain evolution vs the bending angles (A) in the bending plane shows the same results: as shown in fig (11), when the bending angle increases, the gain decreases. The impact on the gain becomes very important for A = 30°; then a compensation process is proposed in the next section.

IV.3 - Axial Gain compensation of the conformal ARMA.

Even though the axial gain decreases strongly when we bend the ARMA structure, we can still apply a phase law in order to reconstruct properly and form the lobe in the broadside or any other scanned angle. The phase law is given by the following equation:

$$\psi_n = -k * rbend * cos\left(n * \Delta\varphi - \varphi_0\right) \qquad (3)$$

Where k is the wave vector, r-bend is the bending radius, $\Delta\varphi$ is the angle between two adjacent elements and φ_0 is the scanning angle.

Fig 12 shows the radiation patterns at 2.5 GHz in the bending plane for the planar ARMA (equiphase) and a convex ARMA structure with a bending angle of 30° with the adequate phase law applied on the elements to form the lobe in the broadside. We can see clearly that the radiation pattern of the planar ARMA is retrieved after applying the correct phases that compensate the curvature of the convex ARMA.

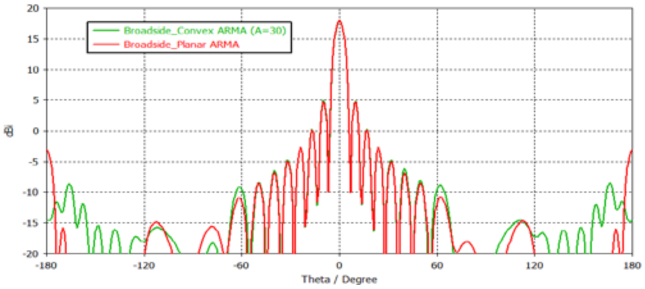

Fig 12: Broadside Radiation pattern comparison of the Planar ARMA and the Convex ARMA (bending angle = 30°)

For the same purpose, we also applied the correct phases on the convex ARMA structure in order to scan the main lobe to the direction of 60°. An interesting result is obtained: the backward radiation pixel lobe [1] is decreased by 4 dB (fig 13) while the side lobe levels are a little bit higher in the main directions.

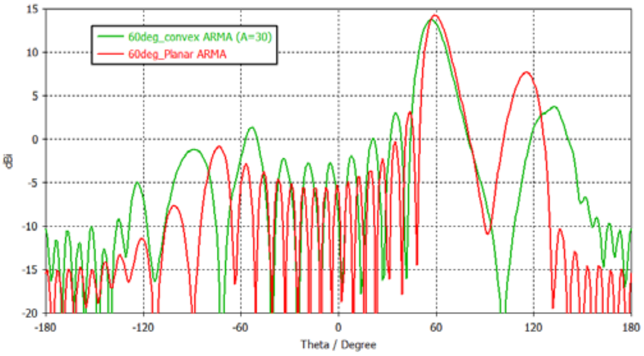

Fig 13: scanned Radiation pattern (60°) for the Planar ARMA and the convex ARMA (bending angle = 30°)

V. CONCLUSION

This paper generalizes the ARMA concept [1] based on the use of square pixels, by introducing any shaped pixels. The new pixel presents a homogeneous radiating surface of any shape allowing to build an ARMA with the suitable radiating surface for a desired radiation pattern. Furthermore, the pixel cavity can be modified to obtain an ARMA matching with conformal surfaces**.** This generalization, introducing the notion of "Agile beam radiating surfaces", keeps all the advantages of the square ARMA over the AESA arrays shown in the reference [1].

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