Two-Dimensional Transmitarray Beamsteering Using Stacked Tunable Metamaterials

João Reis[1,2], Zaid Al-Daher[1], Nigel Copner[1], Akram Hammoudeh[1], Rafael Caldeirinha[1,2], Telmo Fernandes[1,2]
[1]Faculty of Computing, Science and Engineering, University of South Wales, United Kingdom
[2]Instituto de Telecomunicações (DL-IT), ESTG, Polytechnic Institute of Leiria, Leiria, Portugal
joao.reis@southwales.ac.uk

***Abstract*—A new 2D-beamsteering antenna technique using an electronically controlled transmitarray is presented in this paper. When coupled to a conventional horn or an array patch antenna, the proposed transmitarray has the ability to steer the main lobe of the original antenna radiation pattern in both elevation and azimuth planes, with ranges up to 30^o and 30^o, respectively. The transmitarray is implemented using varactor-diode controlled unit-cells with bandpass filtering characteristics around 5.35GHz. Electromagnetic simulations are presented to prove the concept.**

***Index Terms*—beamsteering, transmitarray, varactor-diode, unit-cell.**

I. Introduction

Antenna phased arrays are one of the most common techniques to perform electronic control of beam direction, without the use of any mechanical components [1], [2]. Each radiating element of the array is usually connected to a phase shifter which allow one to modify the phase of the signal between 0º and 360º, with a specific phase step. The phase progression between adjacent elements leads to the directional beam to be steered to a desired angle. If the elements of the array are uniformly positioned along a single line, the array is considered to be linear and can only steer the main beam in one direction (elevation or azimuth – 1D beam steering). When the elements are uniformly distributed and the phase is progressive along two directions on the same plane, the array is considered to be planar and the main beam can scan two directions (elevation and azimuth – 2D beam steering) [1], [2]. Nevertheless, the use of one phase shifters for each element of an array, quickly becomes a limitation of this technology resulting in bulky, electronically complex and expensive systems [2].

Over the last years, transmitarrays (also known as microwave lenses) [3]–[8] have been seen as a feasible alternative to phased arrays especially with the recent development in frequency selective surfaces (FSS) [9] and metamaterials (MM), which are engineered materials able to produce electromagnetic properties unusual or non existent in nature [10].

In [3] and [4], [5], 1D steering antennas were realized using transmitarrays of FSS and MM, respectively. The steering is achieved by applying an electronically controlled progressive phase, between adjacent elements of the structure, acting as phase shifters in a linear phased array. In [3], the phase is controlled by tuning varactor diodes capacitance in unit-cells and consequently the resonant behaviour of the FSS, whereas in [4], [5] the phase control is achieved through the variation of the refractive index in each MM unit-cell, also employing varactor diodes.

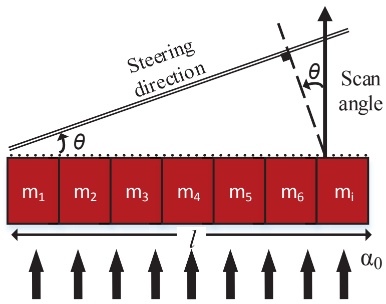

Figure 1: Model of a transmitarray topology for 1D beamsteering analysis.

In this paper, a new beam steering technique is proposed using an electronically controlled MM/FSS transmitarray with capability to steer the main beam in two directions simultaneously (elevation-θ and azimuth-ϕ). The novelty of this work lies in electronically controlling each element of the planar array individually rather than control an entire row or column as in some examples in literature. The control of the phase in each element of the array allows one to introduce a phase distribution along the two directions of the structure leading to the possibility of the main lobe being steered in two directions, by increasing the complexity hardware controller only.

II. Transmitarray operation

The principle of beamsteering using a transmitarray compared to a linear phased array [1], is shown in Fig. 1. The linear transmitarray is composed by N elements with a periodicity of $p=l/N$ where l represents the total length of the structure.

The incident Electromagnetic (EM) wave propagated through the structure experience different phase shifting γ_i after penetrating each N element of the array in the steering direction θ. This can be calculated using,

$$\gamma_i = 2\pi.p.i.sin\theta/\lambda \quad (1)$$

Thus, the transmission phase α_i in each element can be expressed as,

$$\alpha_0 + 2k\pi = \alpha_i + \gamma_i \Leftrightarrow \alpha_i = -\gamma_i + \alpha_0 + 2k\pi, \quad (2)$$

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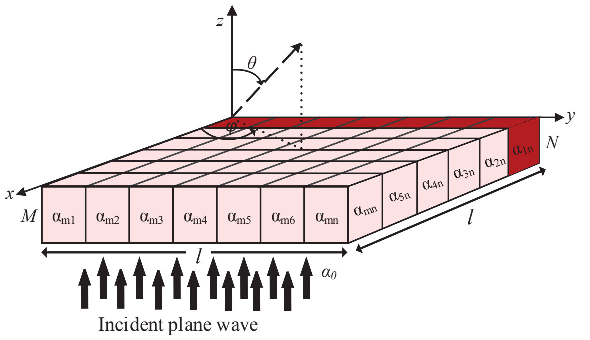


Figure 2: Proposed model of analysis for a 2D transmitarray topology.

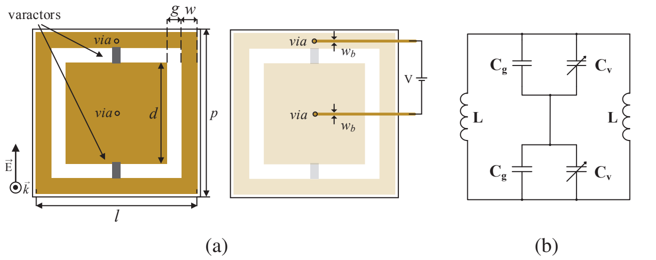


Figure 3: (a) Top and bottom view and (b) Equivalent circuit of unit-cell.

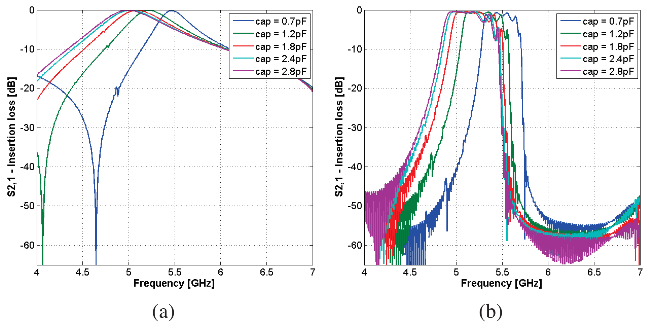


Figure 4: $S_{2,1}$ insertion loss (dB) for (a) 1 layer and (b) 5 layers stacked separated λ/16 by an air gap.

where α_0 is the phase of the incident EM wave and k=1,2,3... The direction of the re-transmitted wave θ is calculated by the phase difference ψ (progressive phase) between adjacent elements using,

$$\psi = \alpha_i - \alpha_{i-1} = -\frac{2\pi}{\lambda}.p.sin\theta \Leftrightarrow \theta = -sin^{-1}(\psi.\frac{\lambda}{2\pi}.\frac{1}{p}) \quad (3)$$

By varying the phase α_i of each array element in an progressive way ψ , the incident wave can be steered with a desired direction θ relative to the normal.

To extend the analysis for 2D beam steering, the principle of analysis can be compared to a planar phased array as illustrated in Fig. 2. A progressive phase between adjacent elements should occur along the X and Y direction of the MxN array. As in (3), the relation between the two dimensional output directions (θ,ϕ) and the progressive phase delay is given by

$$\begin{cases} \psi_x = -\frac{2\pi}{\lambda}.p.sin(\theta).cos(\phi) \\ \psi_y = -\frac{2\pi}{\lambda}.p.sin(\theta).sin(\phi), \end{cases} \quad (4)$$

where ψ_x and ψ_y are the progressive phases along X and Y axis, respectively, and p the periodicity of the elements of the array.

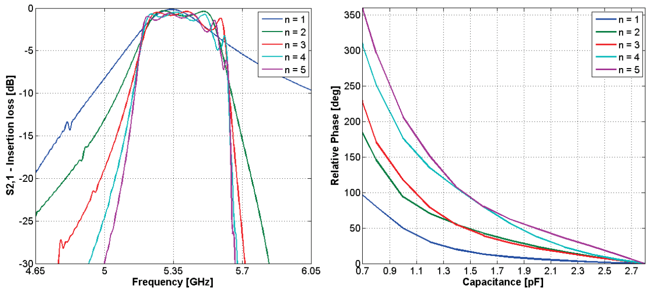
III. Array Elements Design

In order to electronically control the phase in each element of the array, it is proposed to use a square slot unit-cell with band-pass filtering capability [9], [11], loaded with varactor diodes (voltage controlled capacitance) [3]. The unit-cell and its equivalent circuit is depicted in Fig. 3. For a Transverse Electrical (TE) excitation, L represents the inductance effect of the vertical wire with thickness w and length l, C_g represents the capacitance introduced by the gap g and length d and C_v represents the varactor. Operating as a spatial filter with a estimated resonant frequency $f_o = 1/2\pi.\sqrt{L_s.C_s} = 1/\pi.\sqrt{L.(C_g + C_v)}$ obtained from circuit analysis of the equivalent circuit [11], the EM wave passes through the structure with almost no variation in transmission magnitude, but experiencing a controlled phase shift by applying a bias to the terminals of the varactors.

Simulations of the squared unit-cell were performed in CST Microwave Studio using periodic boundary conditions, waveguide port excitation and lumped elements to represent the varactors. The unit-cell of Fig. 3, with dimensions p=33mm , l =32.8mm, d=24mm, g=1.5mm, w=3mm and w_b=0.2mm, printed on double side Nelco NX9250 substrate with thickness t=1.5mm, $\varepsilon_r = 2.50$, $tan\delta = 0.0017$, and copper thickness $35\mu m$, has a band-pass filtering characteristic shifted from 5GHz to 5.45GHz when the capacitance is tuned from 2.8pF to 0.7pF as illustrated in Fig. 4a.

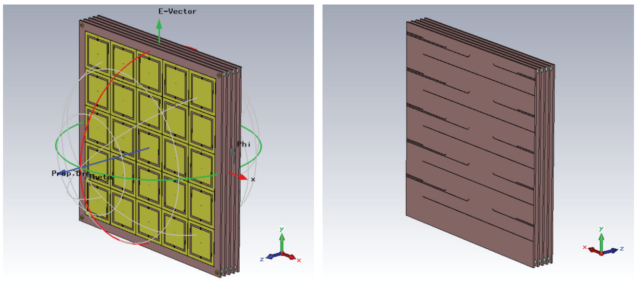
According to [6] and [9], in order to increase the bandwidth and phase up to 360^o, unit-cells can be stacked separated by an air gap to perform a λ/4 impedance match and expect maximum transmitted power. However, to reduce the overall thickness of the structure, layers were only separated by λ/16 (multiple of λ/4) with no significant impact in transmission losses or phase response. As illustrated in Fig. 5a, an increase in the number of layers, lead to an increase of the bandwidth of the unit cell, expecting less than 5dB attenuation in the transmitted power. Moreover, from Fig. 5b it can be noticed that to achieve 360^o of phase variation, in the tuning range of the varactor from 0.7 to 2.8pF, the number of stacked layers should be n=5 and thus confirming the base value of $n \geq 4$, given by [6].

Each element of the transmitarray is then composed by 5 stacked unit-cells separated 3.5mm with a tunable phase range of 360^o when the capacitance is tuned from 0.7pF to 2.8pF, as depicted in Fig. 5b. The bandwidth of the element,



(a) (b)

Figure 5: (a) $S_{2,1}$ insertion loss (dB) and (b) $S_{2,1}$ relative phase (degrees) at 5.35GHz, for n-layers spaced $\lambda/16$.



(a) (b)

Figure 6: (a) Front plane and (b) Back plane of transmitarray model in CST Microwave Studio.

is approximately 150MHz for a central frequency of 5.35GHz, yielding to a maximum insertion loss of 5dB in the pass-band, as illustrated in Fig. 4b.

IV. Transmitarray simulation

The proof of concept of a 2D beamsteering was achieved using a 5x5 transmitarray. Fig. 6 presents the simulation geometry excited by a plane wave in CST microwave studio using open space boundaries. The array is centred in XY plane with the TE wave being radiated in the positive direction of Z axis.

A MATLAB script was developed to extract the phase distribution along X and Y direction of the array for the desired output angle according to (4), and to extract the capacitance values from Fig. 5b for n=5 layers. The structure was optimized by simulations and it was found that a distance between layers of 5mm decrease the output angle error resolution to $\pm 2.5^o$. For the following example, in which the direction of the main lobe was intended to shift to elevation θ=25^o and azimuth ϕ=25^o relative to direction of propagation, the phase and the respective capacitance values given by the script, are detailed in matrices (5) and (6), respectively,

$$P_{x,y}(deg) = \begin{bmatrix} 324.6 & 243.4 & 162.3 & 81.1 & 0 \\ 2.4 & 281.3 & 200.1 & 118.9 & 37.8 \\ 40.3 & 319.1 & 237.9 & 156.8 & 75.7 \\ 17.1 & 356.9 & 275.8 & 194.7 & 113.5 \\ 115.9 & 37.8 & 313.6 & 232.5 & 151.4 \end{bmatrix} \quad (5)$$

$$C_{x,y}(pF) = \begin{bmatrix} 0.75 & 0.89 & 1.16 & 1.59 & 2.8 \\ 2.76 & 0.83 & 1.02 & 1.35 & 2.17 \\ 2.13 & 0.76 & 0.91 & 1.18 & 1.64 \\ 1.62 & 0.7 & 0.84 & 1.04 & 1.37 \\ 1.36 & 2.22 & 0.77 & 0.92 & 1.20 \end{bmatrix} \quad (6)$$

where, each element (x,y) of the matrix as the same correspondence in the element positioning in the array, start counting from left to right, top to bottom. The 3D radiation pattern for the present example is given by Fig. 7, proving the main lobe being steered with components in two directions relative to the direction of propagation. Through the analysis of the respective 2D far-field plot (Fig. 8), one can observe that the main lobe has the maximum power direction in θ=26.8^o and ϕ=22.6^o, presenting an error of $\pm 2.5^o$ relative to the expected angle.

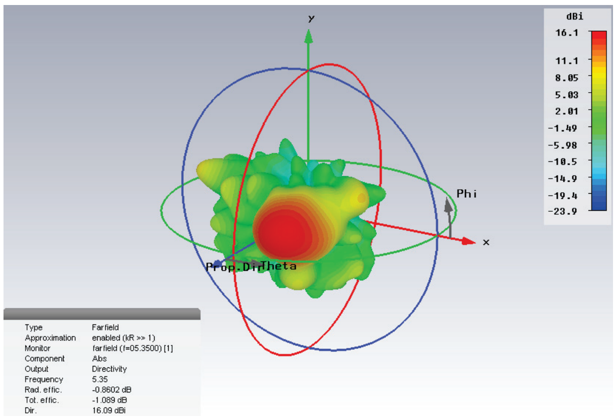


Figure 7: Radiation pattern for a 2 direction beam steering with main lobe direction shifted to θ=25^o and ϕ=25^o.

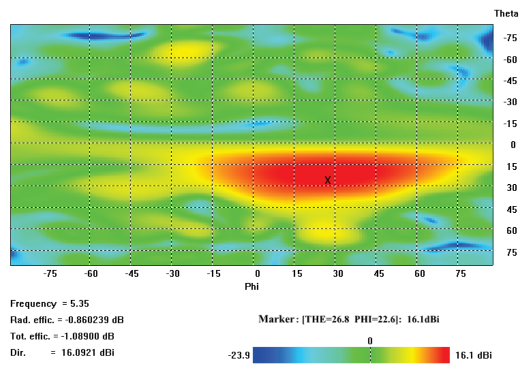


Figure 8: 2D far-field plot with marker at maximum power direction θ=26.8^o and ϕ=22.6^o.

As a second example, the main beam of the radiation pattern was intended to shift to θ=-18^o and ϕ=-10^o by applying the capacitance matrix (7). As in the previous example the phase matrix can be directly extracted from Fig. 5b for n=5 layers.

$$C_{x,y}(pF) = \begin{bmatrix} 1.93 & 1.55 & 1.23 & 1.02 & 0.88 \\ 2.04 & 1.61 & 1.30 & 1.05 & 0.90 \\ 2.20 & 1.67 & 1.35 & 1.09 & 0.92 \\ 2.42 & 1.73 & 1.41 & 1.13 & 0.95 \\ 2.8 & 1.79 & 1.46 & 1.16 & 0.97 \end{bmatrix} \quad (7)$$

In Fig. 9 and Fig. 10 is described the 3D radiation pattern and 2D far-field plot, respectively, illustrating the maximum power direction shifted to θ=-18.3^o and ϕ=-10.2^o.

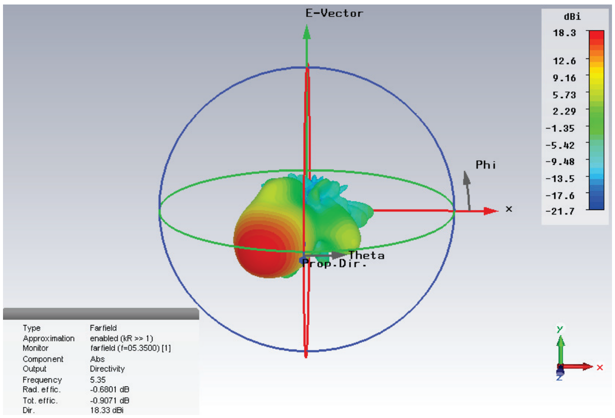


Figure 9: Radiation pattern for a 2 direction beam steering with main lobe direction shifted to θ=-18^o and ϕ=-10^o.

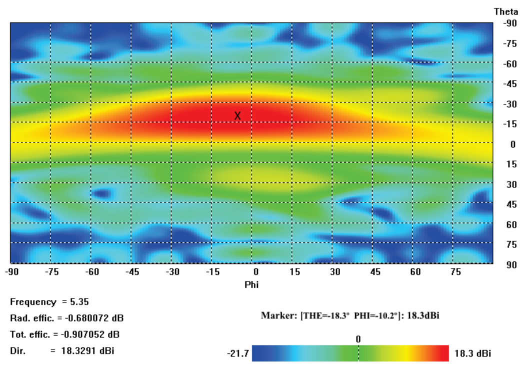


Figure 10: 2D far-field plot with marker at maximum power direction θ=-18.3^o and ϕ=-10.2^o.

To set the main lobe to the origin position θ=0^o and ϕ=0^o, all the varactors must be set to 0.9pF to apply the same phase in all array elements and consequently eliminating the progressive phase between them. When comparing Fig. 7 to Fig. 9, it is possible to see the degradation of the main lobe with the growth of secondary lobes. A maximum steer angle of 30^o in theta for all 360^o in phi can be achieved using the proposed framework, without major deformation of the radiation pattern.

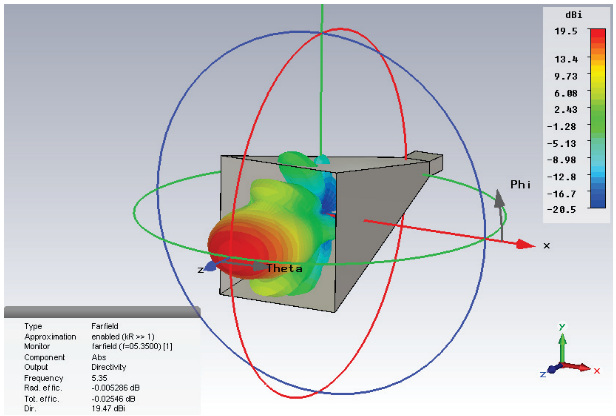


Figure 11: Radiation pattern of an horn antenna with aperture of 165x175mm and length 415mm at 5.35GHz.

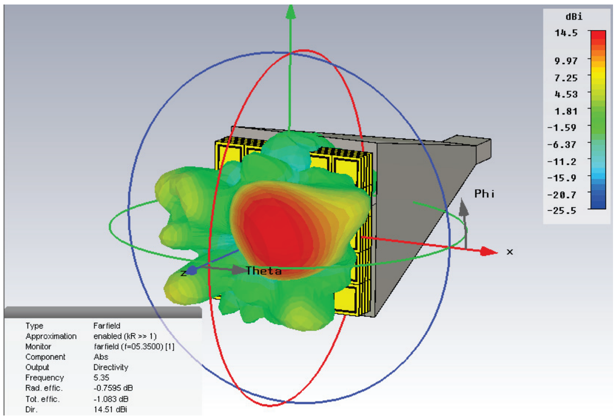


Figure 12: Radiation pattern with main lobe direction shifted to θ=25^o and ϕ=25^o using the transmitarray in front of an horn antenna.

To complete the proof of concept, the transmitarray was simulated in the near field of a horn antenna with aperture dimension 165x175mm and length 415mm. Without the structure, the antenna shown in Fig. 11 presented a relative good impedance matching at 5.35GHz with an $S_{1,1}$=-25dB and a maximum directivity of 19.5dBi when the main lobe was centred at θ=0^o and ϕ=0^o. When the transmitarray using (5) and (6) is applied in front of the horn antenna, the main lobe experiences a shift in direction to θ=24.7^o and ϕ=23.5^o with a maximum directivity of 14.6dBi as illustrated in Fig. 12. A parametric optimization of the entire system was performed and it was found that a distance between the structure and the antenna of 10mm present more accurate results in angle resolution.

V. Conclusions

The concept of a new transmitarray with 2D beam steering capability is presented and validated with EM simulations. The band-pass unit-cell is presented and its characteristics studied with an extended set of simulations performed using CST Microwave Studio. The impact of the number of stacked layers in the phase range are also presented in this paper.

Simulations of a transmitarray formed by 5 layers of 5x5 unit-cells separated by approximately $\lambda/16$ are performed. Two examples of beam steering are presented using plane wave excitation, in which the main lobe has the maximum power direction steered θ=26.8^o and ϕ=22.6^o and to θ=-18.3^o and ϕ=-10.2^o, proving the validation of the theoretical model and presenting an error lower than $\pm 2.5°$. A simulation of the full system is presented locating the structure 10mm in front of the aperture of a conventional horn antenna successfully completing the proof of concept.

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