Evaluation of the Phase Discretization Effect in Transmitarrays Formed by Sub-Wavelength Patches

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***Abstract*— Most of the transmitarray phase shifting cell designs assume a periodic repetition of the same cell to account for the coupling effects of the neighboring cells. However the behavior in terms of magnitude and phase of the transmission coefficient calculated in this way may change when the neighboring cells have different phase, as normally happens in transmitarrays due to phase discretization. This paper characterizes this effect using a family of sub-wavelength patch cells covering the entire 360º phase shift interval, all with transmission coefficient better than -0.2 dB in the periodic structure. A stepped-phase structure is analysed considering different phase step values from 5º up to 90º. It is shown that the magnitude of the cells transmission factor changes considerably at the transition between different elements, with the unit cells with higher phase shift showing increased transmission while the lower phase shift cells in the transition tend to block the transmission more.**

***Index Terms*—Transmitarray, flat lens, unit cell, frequency selective surface (FSS), transmission coeficient, elements transition.**

I. Introduction

The development of antennas for satellite communication systems, which require high gain and low weight antennas has boosted the potential of transmitarray antennas as promising alternatives to reflectors and dielectric lenses. Transmitarray antennas are characterized by presenting a discrete phase shift, unlike the more common options. Each element ideally presents a high transmission coefficient magnitude and a different phase shift. The transition between two different elements can be problematic in terms of magnitude and phase response. In [1] is presented a transmitarray with double square rings that solved the transition issue between the 0º and the 360º unit cells, nevertheless, the cells' period is considerably large and for the intermedia phase shift cells the problem remains.

In this work we focused on the study of the sub-wavelength ($\lambda/4$) cells already developed in [2] in terms of discretization and cells transitions (frequency = 30 GHz and period = 2.5mm). The cells were based on the previous work of [3] and [4]. In Section II are evaluated different discretization steps and in Section III is made a more detailed observation over specific phase shift elements transitions and its influence.

II. Transmitarray Discretization

The sub-wavelength patch unit cells being studied are formed by 5 metallic square patches, interleaved by 4 layers of Rogers 5880 dielectric ($\varepsilon_r = 2.2$ and $tan\delta = 0.0009$) with 0.787 mm thickness. The total height is 3.35mm and the in-plane width of each cell is 2.5mm corresponding to $\lambda/4$ at the operating frequency of 30 GHz.

The evaluated structure corresponds to 4 equal elements along y dimension (only 1 would be needed since it is periodic but for better 2D visualization of the field a larger structure along y was used) and a row of different elements along x dimension. The transmitarray, see Fig. 1, is periodic along x and y dimensions. To avoid reflections at x_{min} and x_{max} borders the transmitarray is symmetric in x-axis. This way the elements at x_{min} are repeated at x_{max}.

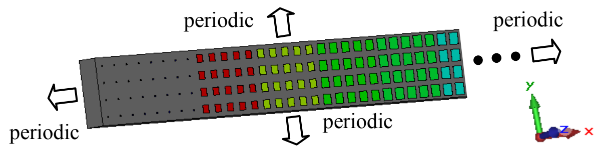

Fig. 1. Example of a transmitarray configuration to be evaluated (discretization step is 30º).

A plane wave with right hand circular polarization is normally incident on the transmitarray surface ($|E_x| = |E_y| = 1$). E_x and E_y were considered individually because it allows to evaluate the transmitarray for perpendicular and parallel orientation of the field in relation to the cells transition plane. The transmitarray is defined from x = -150mm to x = 150mm, corresponding to 120×4 elements. The phase is changing from 0º to 360º and back to 0º. In Fig. 2 the field representation in front of the transmitarray illustrates the intended 360º phase shift. The transmitarray performance is evaluated at $5mm$ ($\lambda/2$) in front of it. All simulations were done with CST Microwave Studio [5].

Four discretization steps were considered: s = 5º, s = 30º, s = 45º and s = 90º. It is important to note that the cells do not have a constant phase interval and so the mentioned steps are just a reference. Since the field is approximately constant along y-axis, from now on the near-field is presented for a line at y = 0 mm. The near-field magnitude and phase is shown in Fig. 3 and Fig. 4 for x- and y-components. The phase response is well behaved for large discretization steps; however, for s = 45º, the phase already shows some strong ripple. Only at s = 90º the phase response is severely affected at both planes.

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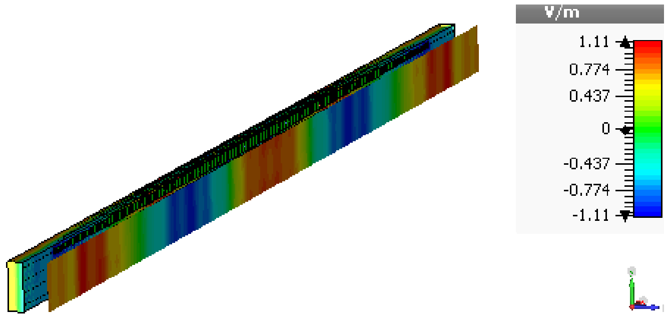

Fig. 2. Near-field evaluation $5mm\ (\lambda/2)$ in front of the transmitarray (discretization step is 30º).

The magnitude variation of the field is also not very significant for small steps, Fig. 4, but especially when the field is parallel to the transition a strong variation is visible for larger steps, see Fig. 4(b). As the discretization step increases E_z also increases, as shown in Fig. 4(c), corresponding to an evanescent wave and representing losses. But what should be noted is the magnitude variation, which will be detailed in Section III. In order to fully evaluate the transmitted field, it was calculated its mean value for all x- y- and z-components at the plane presented in Fig. 2. Despite the field magnitude strong variation, its mean value is considerably stable for any discretization step, which means that the transmitted energy is reasonably constant. The unit cells transmission coefficient is above -0.2 dB (≈0.977), showing that discretization losses can be considered low.

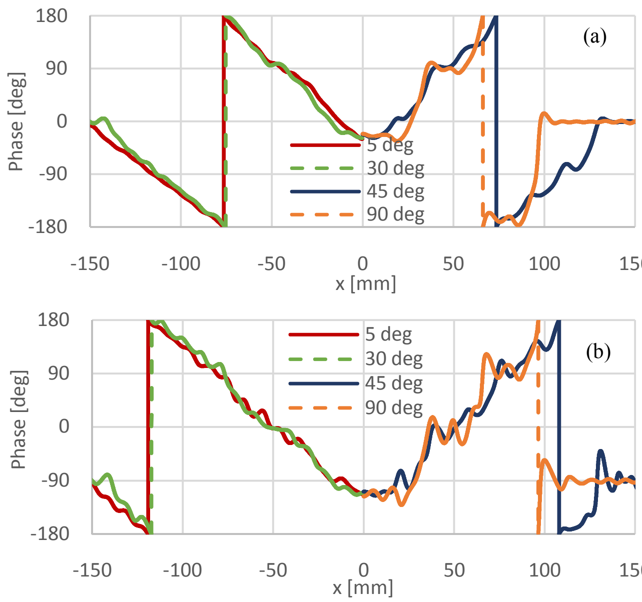

Fig. 3. E-field phase along a line positioned 5mm $(\lambda/2)$ in front of the transmitarray: (a) E_x; (b) E_y.

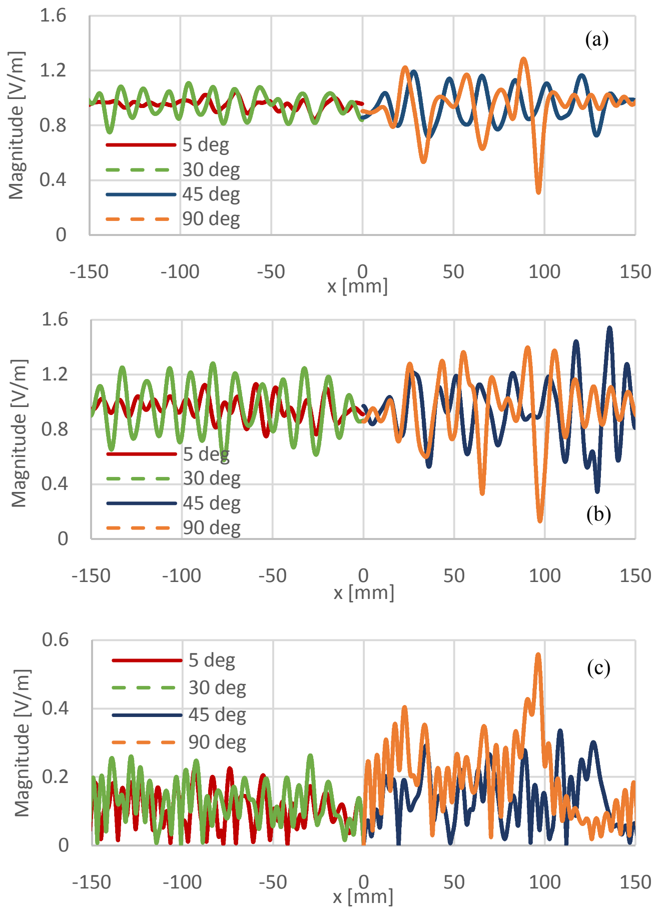

Fig. 4. E-field magnitude along a line positioned 5mm $(\lambda/2)$ in front of the transmitarray: (a) E_x; (b) E_y; (c) E_z.

TABLE I. E-FIELD MEAN VALUE AT $\lambda/2$ IN FRONT OF THE TRANSMITARRAY FOR DIFERENT DISCRETIZATION STEPS.

Discretization step [deg]	**Near field**		
	Ex [V/m]	***Ey [V/m]***	***Ez [V/m]***
5	0.962	0.957	0.120
30	0.967	0.957	0.158
45	0.955	0.945	0.157
90	0.948	0.956	0.242
Δ max	0.019	0.012	0.122

III. TRANSITION BETWEEN DIFFERENT ELEMENTS

Transitions were previously evaluated in the context of discretization. In this section four raising transitions are studied individually: between 0º phase shift elements and 13º, 50º, 96º and 200º elements. Unlike the previous periodic structure, transitions are evaluated considering a non-symmetric transmitarray, with 0º elements for x<0 and higher phase shift elements for x>0. Simulated E_x phase is shown in Fig. 5 (Ey is not presented because it has a similar behavior). Phase transition is relatively smooth and as the distance to the transmitarray increases it gets continuous, unlike the discrete nature of the transmitarray.

The magnitude of E_x and E_y is presented in Fig. 6. A pattern is found for all tested element transitions; the amplitude is considerably smaller for x<0 in the vicinity of the transition, with increased intensity in x>0 or for larger phase shift angles.

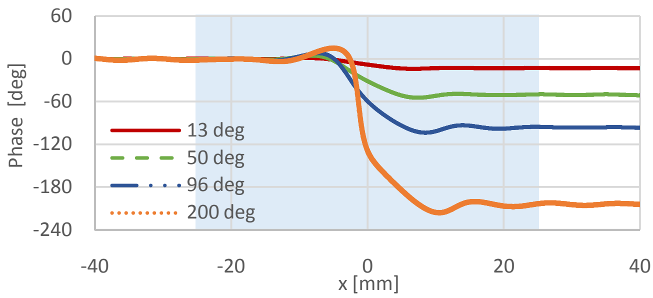

Fig. 5. E_x phase along a line positioned 5mm ($\lambda/2$) in front of the transmitarray with a transition at x = 0 mm.

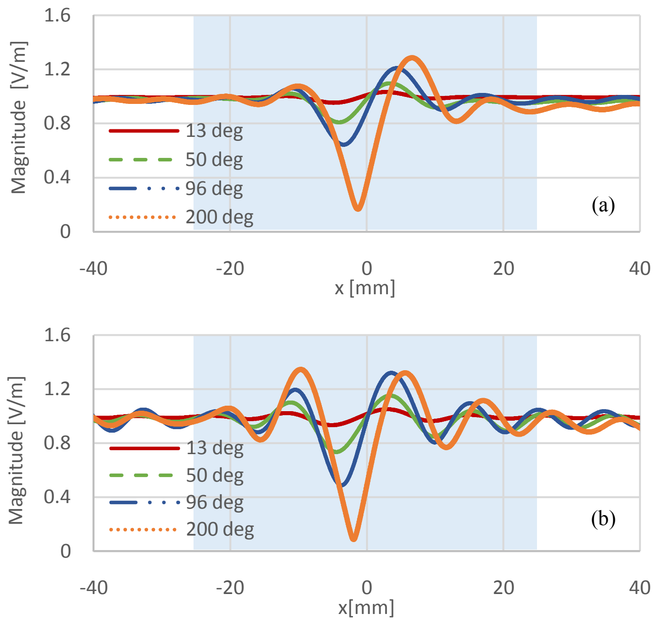

Fig. 6. E-field magnitude along a line positioned 5mm ($\lambda/2$) in front of the transmitarray with a transition at x = 0 mm: (a) E_x; (b) E_y.

In TABLE II. is represented the magnitude mean value of E-field components, for the plane defined by $x \in [-25,25]$ mm and $y \in [-5,5]$ mm, corresponding to the interval of magnitude disturbance due to the elements transition. The without transition columns represent an average between 0º elements and the higher phase shift elements. It is observed that E-field mean value is almost independent of the transitions, being more related with the transmission of the cells itself. As seen in Fig. 6, has the phase jump increases, a severe intensity amplitude reduction is observed for the lower phase shift elements in the vicinity of the transition, with an increase in the adjacent cells.

In terms of amplitude, the transmitted field is kept reasonably constant, although with fluctuations at the elements transitions. The phase response is the predicted one, but it must be noted that the incident field has constant phase and therefore any possible phase error due to a path change at the transition is not considered in the simulation, Fig. 5.

TABLE II. E-FIELD MEAN VALUE AT $\lambda/2$ IN FRONT OF THE TRANSMITARRAY FOR DIFFERENT TRANSITIONS.

Patch cell phase shift [deg]	**With transition**			**Without transition**		
	Ex [V/m]	***Ey [V/m]***	***Ez [V/m]***	***Ex [V/m]***	***Ey [V/m]***	***Ez [V/m]***
13	0.994	0.993	0.014	0.994	0.994	0.002
50	0.972	0.973	0.019	0.971	0.972	0.015
96	0.963	0.968	0.029	0.970	0.964	0.038
200	0.973	0.974	0.092	0.966	0.961	0.073

IV. CONCLUSIONS

In this paper it is shown that the discretization steps or intervals adopted in the transmitarray construction is not very relevant in terms of phase and amplitude response, when considering the integral of the E-field at the entire transmitarray surface. A more detailed observation of singular transitions showed that the energy flows to the elements with larger phase shift, deteriorating the desired phase response of the transmitarray.

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