Innovative Antenna Solutions for Satellite Telecommunications

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Abstract

The paper deals with high performance scanning antennas for satellite applications. By referring to array antennas, we propose an optimal synthesis approach able to determine the excitations of the array elements that can be reconfigured with tunable metamaterials for the realization of beam scanning. The achieved results are satisfactory and show improvements with respect to benchmark state of the art. Then, slot array antennas have been identified as possible realization technology in conjunction with electrically tunable nanomaterials. A preliminary characterization of the loaded-slot in terms of radiated power is presented.

1. Introduction

The interest in satellite communications is continuously growing. In particular, nanosatellites are becoming more and more popular due to their relatively low cost and fast development, and satellite network application capabilities [1]. In this respect, a vital component of a mobile satellite communication terminal is a low-profile high gain antenna with beam steering capabilities [2].
In the last years, the emerging concept of metasurface has been investigated as a possibility to design beam forming networks for satellite communications without resorting to phase shifters. In [3] Smith et al. have presented a waveguide-fed metasurface realizing an efficient extended beam steering. To reach such an extended scanning angle without loss performance, the basic idea was to design the single radiating elements excitations in such a way the maximum radiation peaks (but for one) fall in the invisible part of the spectrum [3]. In particular, they exploited real and positive, as well as complex excitations, whose distribution has been analytically derived to accomplish the above properties for the radiated field.
Unlike the *analysis* approach developed in [3], we propose herein an optimal synthesis approach for the array excitations obeying assigned field constraints. The optimal synthesis of array antennas plays a key role in many fields of applied electromagnetics including satellite [4], radar [5], and cellular [6] telecommunications. Amongst the different possible approaches to the problem, the ones guaranteeing the best exploitation of the available degrees of freedom (and hence the most effective use of the antenna resources) are those aiming at a 'mask-constrained' power synthesis [7]-[10]. The latter consists in looking for square-amplitude distributions of the field lying between two arbitrary upper-bound and lower-bound functions. In the case of fixed-geometry arrays (wherein the antenna layout is a-priori assigned while the elements' excitations are the available degrees of freedom), the problem has been solved in a globally-optimal fashion in both cases of pencil [11] and difference [12] beams. By starting from [11], we present a synthesis algorithm dealing with real and positive excitations.
Stimulated from the encouraging results, we tried also to sketch a possible way of realization of this kind of scanning antennas. In [13], the new concept of inverse design has been used to realize a multibeam lens antenna [14] whose symmetric electromagnetic properties allow to accommodate multiple beams all having the same performance (i.e., with no deterioration with the pointing angle). However, a smart practical way of reconfigurability of that kind of inclusions-made devices has not been yet proposed.
As a further possibility, slot antenna arrays are largely used in radar and telecommunication applications since they can be compact and low-cost. As it is well known, a powerful synthesis method has been introduced by Elliott [15],[16] for the determination of the lengths and offsets of every longitudinal slot in waveguide-fed linear or planar arrays, including the effects of mutual coupling. The Elliott's method makes use of an equivalent circuit representation for the isolated slot and for the whole array and it has been demonstrated to be fast and accurate also in case of design of large arrays with hundreds or thousands of slots. However, in order to realize a scanning or even reconfigurable antenna without using phase shifters it is necessary to tune somehow the single radiating elements. In this respect, we investigate herein the possibility of covering the resonant slots with ad hoc (possibly nanostructured) materials whose electromagnetic characteristics change with the applied voltage, thus allowing for a tunable response. In the paper, we present the characterization of a single loaded slot from a radiative point of view. More in detail, we analysed the radiated power of the slot by varying thickness, permittivity and losses of the covering nanomaterial, as well as the offset of the slot with respect to the centreline of the waveguide. The

results shown that, by fixing the offset of the slot and the thickness of the material, there is a significant variation in the radiated power by increasing the permittivity value. Such a result demonstrates that if an equivalent admittance for the loaded slot is derived [1], the corresponding slot excitation can be possibly adjusted towards the desired behaviour.
On the basis of the above, the final aim of the work is to consider such an additional constraint on excitations within the optimal synthesis approach. While this last activity is ongoing, in the following we present and assess the synthesis approach in Section 2, while the loaded slot characterization is shown in Section 3.

2. Synthesis approach

Thereinafter, we consider the kind of antenna used in [3] as benchmark. Hence, let us consider the following expression for the radiated far field as defined in [3]:

$$AF(\phi,\theta) = cos\theta \sum_{n=1}^{N} I_n e^{-j\beta x_n} e^{-jkx_n sin\phi} \qquad (1)$$

wherein: k and β are the free-space and guide mode wavenumbers, respectively; x_n is the position of the n-th radiating element of the array (which is supposed to be fixed); ϕ and θ are the elevation and azimuth angles, respectively. For more details, see [3]. In the following, we consider $\theta = 0°$ and ϕ_0 as the target direction of the beam to be scanned.
By following the general approach developed in [9], the proposed constrained optimization problem reads:

Find I_n such that:

$$\max_{I_n} Real\{AF(\phi_0)\} \qquad (2.1)$$

Subject to:

$$Imag\{AF(\phi_0)\} = 0 \qquad (2.2)$$

$$|AF(\phi)|^2 \leq UB(\phi) \qquad (2.3)$$

$$Real\{I_n\} \geq 0 \qquad (2.4)$$

$$Imag\{I_n\} = 0 \qquad (2.5)$$

Thanks to the optimization function (2.1) the maximum field intensity is reached in the target direction, while constraint (2.3) allows to keep bounded the side lobes level elsewhere. Finally, constraints (2.4)-(2.5) enforce real and positive excitations which is the case considered herein.
Note that (2.1)-(2.2), (2.4)-(2.5) are linear functions of unknowns, while the constraint (2.3) is a positive semi-definite quadratic form, so their intersection is a convex set in the space of the unknowns. Consequently, the problem is formulated as a Convex Programming one and it can reach the global optimum solution in a very efficient and fast manner.

Moreover, in order to avoid superdirective sources, the following constraint has been also considered within the optimization problem (2):

$$Q \leq Q_{max} \qquad (2.6)$$

with:

$$Q = \frac{P(\underline{k}_{inv})}{P(\underline{k}_v)} \qquad (3)$$

wherein $P(\underline{k}_{inv})$ and $P(\underline{k}_{inv})$ stand for radiated power in the invisible and visible part of the spectrum, respectively. Accordingly, the constraint (2.6) set an upper bound for admissible values of Q [18]. Note that it is an important point because high energy content in the invisible part of the spectrum translates into narrow bandwidth, low gain and low fabrication tolerance antennas [19].

2.1. Assessment of the synthesis approach

In order to compare our results with those achieved in [3], we considered the same input parameters. Accordingly, the working frequency is 10GHz, the target direction $\phi_0 = 20°$ and the physical size of the antenna is 48cm. The optimization problem aims at maximizing the array factor (1) in the target direction by keeping it bounded elsewhere. We solved the optimization problem (2) by varying the spacing amongst array elements, hence their number. The performance have been evaluated in terms of Half-Power Bandwidth (HPBW) and Side Lobes Level (SLL). These parameters are summarized in Tables 1 e 2 for an inter-element spacing of $\lambda/4$ (65 elements) and $\lambda/8$ (129 elements), respectively. The green text indicates an improvement of performance with respect to [3]. Finally, encouraged from initial results, we solved the optimization problem for a higher scanning angle, that it $\phi_0 = 60°$, see Table 3. It is worth to underline that for the considered source, theoretical values are HPBW=6° with SLL=-13.8dB [20]. Hence, we were able to improve SLL by 0.6dB, while the HPBW is slightly reduced. Results are also shown in Figure 1 in terms of power pattern and synthesized excitations.

HPBW (deg)	SLL (dB)	Q (dB)
3.89	-9.1	0
3.77	-10.7	1
3.64	-12.6	2
3.54	**-14.5**	**3**
3.43	**-16.4**	**5**
3.40	**-16.5**	**10**
3.39	**-16.9**	**12**

Table 1. Radiation performance in terms of HPHW, SLL and Q for an array of 65 elements with an inter-element spacing of $\lambda/4$, $\phi_0 = 20°$.

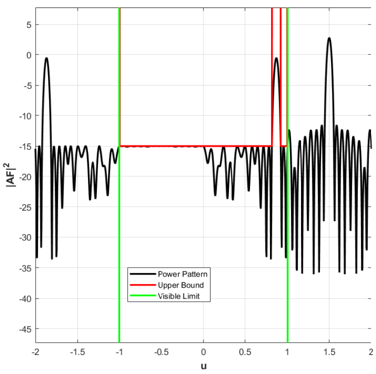
[1] As it is well known, equivalent input admittance curves have been derived by Elliott [17] for a standard slot on waveguide. However, as far as we know, no studies have been carried out for loaded slot, at least for high permittivity dielectric sheets.

HPBW (deg)	SLL (dB)	Q (dB)
Unfeasible	Unfeasible	4
3.53	-17.3	10
3.51	-20.2	15

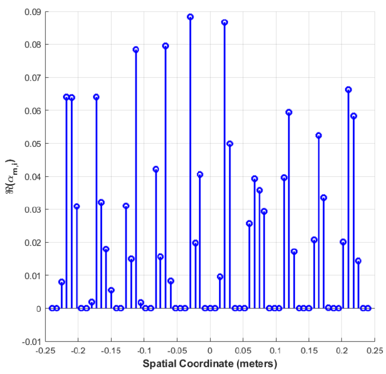
Table 2. Radiation performance in terms of HPHW, SLL and Q for an array of 129 elements with an inter-element spacing of $\lambda/8$, $\phi_0 = 20°$.

HPBW (deg)	SLL (dB)	Q (dB)
6.4	-14.4	3

Table 3. Radiation performance in terms of HPHW, SLL and Q for an array of 64 elements with an inter-element spacing of $\lambda/4$, $\phi_0 = 60°$.



(a)



(b)

Figure 1. Results for 65 elements array (spacing $\lambda/4$) and $\phi_0 = 60°$. (a) Power pattern. (b) Real part of synthesized excitations (the imaginary part has been omitted since it is zero).

3. Characterization of a nanomaterial-loaded longitudinal slot on a rectangular waveguide

The goal of the characterization is to derive a hopefully systemized behavior for the radiation of a longitudinal slot in presence of an ad hoc material cover. The antenna, whose sketch is shown in Figure 2, has been modeled and simulated with CST Microwave Studio, while data have been processed in Matlab. The slot (length:10.7mm; width: 2.1mm) has been realized on a rectangular WR62 waveguide operating at 14GHz. In Fig. 2 it can be seen also the dielectric cover on the slot. It extends $\lambda/15$ from the slot's edges.

The campaign of simulations by varying the offset of the slot (from 0 to 5.5mm), the permittivity (from 50 to 550), the tangent loss (0.1, 0.2) and the thickness (from 2 to 10 μm) of the cover, concerned the evaluation of the radiated power as follow:

$$P_{RAD} = P_{IN} - P_b - P_f - P_{loss-diel} \qquad (4)$$

where P_{IN}, P_b, P_f, $P_{loss-diel}$ are the input, backward, forward and loss within the dielectric powers, respectively. In Fig. 3 are reported curves of the percentage of radiated power with respect to the input power by varying the offset of the slot, for a fixed thickness of the dielectric to 10μm, for six different permittivity values within the range defined above and for tangent loss equal to 0.1 (Fig.3(a)) and 0.2 (Fig.3(b)).

As it can be seen, the loaded slot significantly changes its radiative performance with permittivity. Such a result represents good news for applications we are interested in, because such a radiative behavior is linked to a change in the single element excitations. To this aim, the loaded-slot input admittance behavior is also needed and work is ongoing on that.

Further analyses and the final synthesis results taking into account the loaded slot characterization will be show at the Conference.

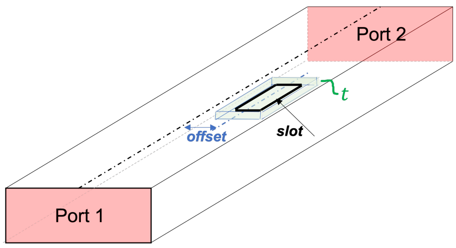
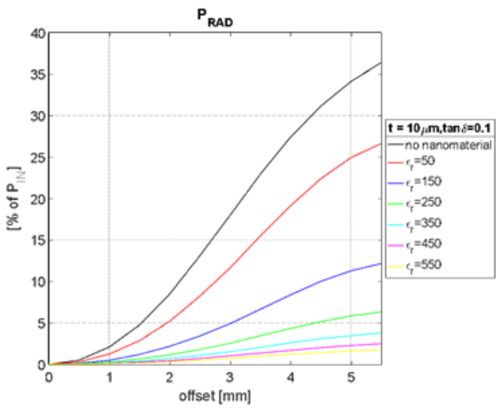
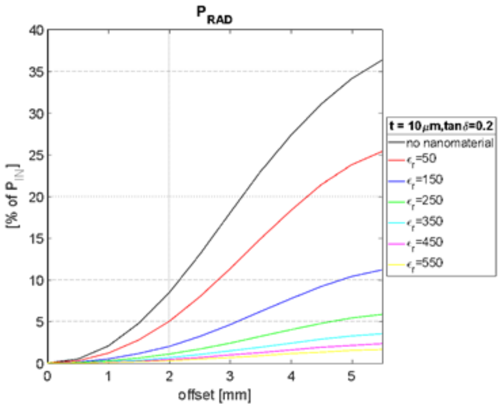


Figure 2. Sketch of the antenna modeled and simulated in CST Microwave Studio for the slot characterization.



(a)



(b)

Figure 3. Radiated power as percentage of input power by varying the offset, for tickness equal to 10μm, permittivity values [50,150,250,350,450,550] and tangent loss equal to (a) 0.1, (b) 0.2.

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