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PENCIL BEAM PATTERNS OBTAINED BY PLANAR ARRAYS OF PARASITIC DIPOLES FED BY ONLY ONE ACTIVE ELEMENT

M. Álvarez-Folgueiras, J. A. Rodríguez-González and F. Ares-Pena

Department of Applied Physics, Faculty of Physics
University of Santiago de Compostela
Santiago de Compostela 15782, Spain

Abstract—In this paper, an innovative method for obtaining a pencil beam pattern is presented. Planar arrays of parasitic dipoles are used to modify the pattern of an active dipole above a ground plane, in order to obtain a pencil beam of moderate gain and bandwidth. Only one feed point and one active element provide a very simple feeding network that reduces the complexity of the antenna. The correct configuration of the elements of the parasitic arrays allows to obtain the desired pencil beam pattern. Three designs that use parasitic arrays fed by a $\lambda/2$-dipole and synthesize pencil beam patterns are shown: 1) an antenna designed at 1.645 GHz and composed by one layer of 49 parasitic elements; 2) an antenna designed at the same frequency but composed by two layers of 49 parasitic elements; 3) an antenna designed at 5 GHz, composed by one layer of 49 parasitic elements, and taking into account the dielectric substrate and teflon screws.

1. INTRODUCTION

It is well known that array antennas are the solution of choice for many radar and communications applications in space and on Earth. Their advantages include the possibility of fast scanning and precise control at the radiation pattern [1–4]. The drawbacks of the arrays are mainly related to their weight, DC-to-RF efficiency and the complexity, relatively high losses in the power distribution system and expensiveness of the network (which may be active or passive). Therefore, considerable interest is focused on designing

Corresponding author: F. Ares-Pena (francisco.ares@usc.es).

a planar array with a simple feeding network [1–5]. Recently, the use of parasitic arrays [6–8] illuminated by smaller active arrays has received some attention because they introduce degrees of freedom that allow patterns to be synthesized without modification of the active array feed, which can be quite simple [9]. Pattern reconfigurability is achieved by appropriately switching on or off the array elements [10, 11]. Planar arrays of Yagi-Uda elements have been considered by Skobelev [12]. In addition, the use of Genetic Algorithms for the optimization of arrays of Yagi-Uda antennas is presented in [13, 14]. Modified Yagi-Uda antennas have been proposed in [15–17]. In [18], the design of a source that uses a Fabry-Perot resonance with a cavity made of a ground plane is presented. However, the obtained directivity in this antenna has a small bandwidth. Active and parasitic arrays can also be combined on printed circuit boards [19].

In this paper, an innovative and very simple method for the design of planar arrays with only one feed point is shown. Three examples of planar arrays made of parasitic dipoles illuminated by an active dipole above a ground plane are presented. The antennas, whose geometries have been optimized by a Particle Swarm Optimization algorithm (PSO) [20–24] and by a Downhill Simplex algorithm using the method of moments program FEKO [25], radiate a pencil beam of moderate gain and bandwidth (BW).

2. METHOD

The antenna system is composed by two parts: i) the feeding part comprising a $\lambda/2$-dipole placed $\lambda/4$ in front of a ground plane, and ii) a planar array composed by parasitic dipoles (see Fig. 1). This radiating

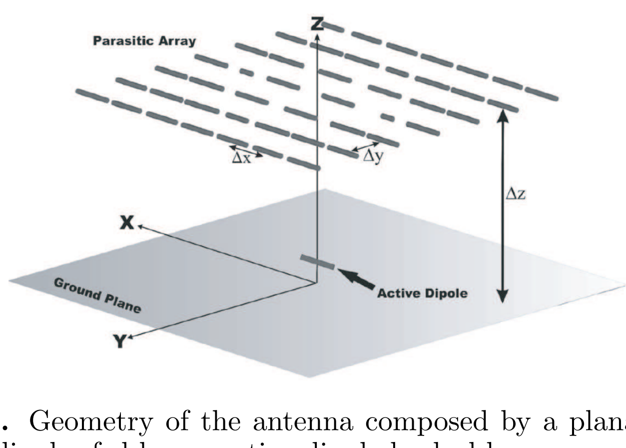

Figure 1. Geometry of the antenna composed by a planar array of parasitic dipoles fed by an active dipole backed by a ground plane.

system works as a set of scattering elements in a mutual coupling environment localized in a plane. Each element in the presence of others has a trans-scattering capability, which shall be phased up.

The proposed method is based on the optimization of the array geometry in order to obtain a high directivity pattern. The feeding part of the antenna is previously fixed and it remains unaltered during the PSO optimization.

A uniformly spaced planar array of parasitic dipoles of length $\lambda/2$ is considered as a starting point in the optimization process. In this procedure, the length of each parasitic dipole, the distance between the planar array and the ground plane (Δz), and the interspacing in the Y-axis direction (Δy) of the parasitic array (see Fig. 1) are modified. Note that the interspacing in the X-axis (Δx) is not taken into account in the optimization process: we found that the optimal value was always the smallest as possible. The aim is to find the optimal array geometry that fulfil the requirements of a given design problem. In order to speed up the optimization process, we consider quadrantal symmetry for the parasitic array that reduces the number of unknowns. In addition, the ground plane is assumed to be infinite in order to simplify the simulations performed in the optimization.

In this work, the variables above mentioned were optimized by means of PSO to minimize a cost function C consisting of a term to increase directivity in the broadside ($\theta = 0^\circ$, $\phi = 0^\circ$):

$$C = 1/directivity \tag{1}$$

All the optimization process were performed using the PSO tool of the program FEKO [25]. After the optimization process, the obtained antenna geometry is simulated for evaluating the induced currents in each parasitic element: those dipoles resulting with very low induced currents are removed from the array after checking that their elimination does not reduce the antenna performance. This array thinning allows the simplification of the antenna geometry. Finally, a finite ground plane that exceeds $\lambda/2$ of the antenna size in each direction is considered for obtaining a more realistic simulation with FEKO [25].

In order to improve the efficiency of the feeding network, the active impedance of the driven dipole, Z_A (the ratio between the voltage and the current in this dipole), must match to the characteristic impedance of the feeding main line (Z_0). This can be accomplished by performing a new optimization that uses the antenna geometry obtained in the PSO (global optimization method) which is slightly perturbed by means of a downhill simplex algorithm, a local optimization method (and thus faster than PSO) that is also included in the FEKO program. In the procedure, the length of the driven dipole is also perturbed in order to eliminate the reactance of Z_A easily, a design requirement since Z_0 is pure real. In this case, the cost function is defined as:

$$C = c_1/directivity + c_2\,|\mathrm{Im}(Z_A)| + c_3\,|\mathrm{Re}(Z_A) - Z_0| \qquad (2)$$

where the coefficients c_1, c_2, and c_3 adjust the relative weights of each term.

3. RESULTS

As an example of application, we consider an antenna designed at a frequency of 1.645 GHz and composed initially of 49 parasitic dipoles fed by a $\lambda/2$-dipole. All the dipoles are of radius 0.005λ. After the PSO-based optimization process that maximizes the antenna directivity (1), the array geometry shown in Fig. 2 is obtained. The total size of the planar array is $3.81\lambda \times 3.31\lambda$ with $\Delta y = 0.55\lambda$, $\Delta x = 0.55\lambda$ and it is located at $\Delta z = 0.6\lambda$ above the ground plane. These values have been calculated during the optimization process without imposing any kind of restriction to the antenna geometry. The radiation pattern obtained (see Fig. 2), has a directivity of 21.63 dB and a side lobe level, *SLL*, of -14.3 dB. Note that the maximum directivity of the uniform distribution aperture on a ground plane with the same size is 22 dB.

In order to study the influence of the parasitic array in the radiation pattern, the power pattern of a $\lambda/2$ dipole located at a distance of $\lambda/4$ above a ground plane is shown in Fig. 3. In this case, the directivity of the power pattern is 7.51 dB, so the parasitic array

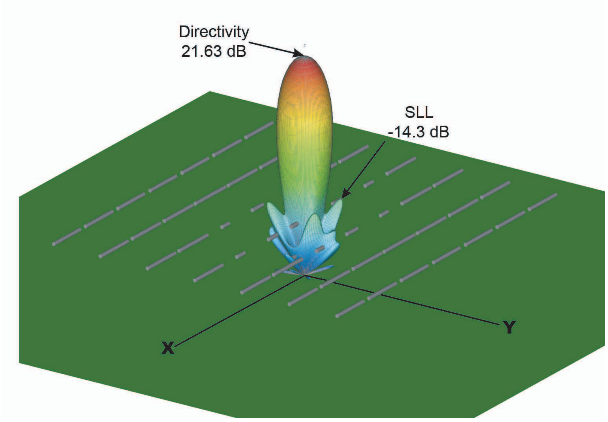

Figure 2. Geometry and power pattern radiated by the antenna of 49 parasitic elements placed 0.59λ in front of an infinite ground plane.

used in the proposed method achieves an improvement of 14.12 dB in terms of directivity.

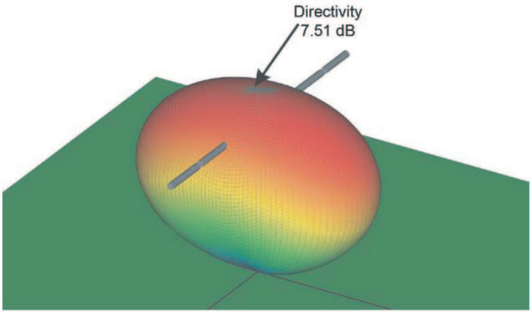

Figure 3. Power pattern radiated by a $\lambda/2$-dipole placed $\lambda/4$ in front of a ground plane.

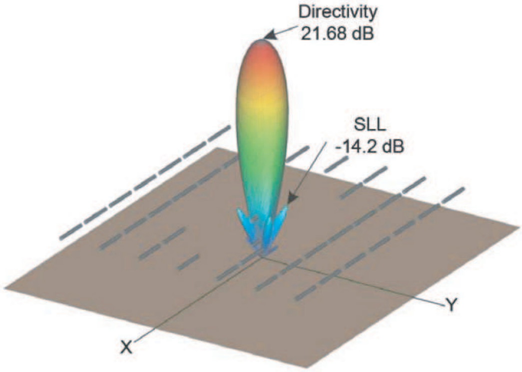

Figure 4. Geometry and power pattern radiated by the antenna of Fig. 2 after applying array thinning. A more realistic simulation has been performed by considering a finite ground plane and the electromagnetic characteristics of the copper.

After the optimization process, a simulation is done for analyzing the induced currents in each parasitic element. In this particular example 10 parasitic elements have practically null currents, so these elements are removed. A further simulation of the resulting antenna with this reduced geometry shows that the performance of the initial antenna is unaffected by this array thinning.

A more realistic simulation of the antenna that considers a finite ground plane sized $\lambda/2$ larger than the parasitic array in each direction, i.e., $4.81\lambda \times 4.31\lambda$, is performed. Moreover, all the elements of the antenna (ground plane, active and parasitic elements) are simulated using the electromagnetic characteristics of the copper, thinking in a future construction of the antenna. The power pattern of the resulting antenna (see Fig. 4), has a directivity of 21.68 dB, a *SLL* of −14.2 dB, and a back radiation of −25 dB. This *SLL* value is nearly the same as the *SLL* of the resulting antenna obtained after the optimization (−14.2 dB vs. −14.3 dB). For comparison, a uniform distribution aperture with the size of the finite ground plane has a directivity of 24.16 dB.

An analysis of the bandwidth reveals a value of 3.91% for the 3 dB absolute gain bandwidth, as Fig. 5 shows. The absolute gain of this figure has been calculated considering that the feeding dipole is matched to the generator at the central frequency. Since this figure includes the mismatch losses when the antenna does not operate at the design frequency, there is no need of considering the scattering parameter $|S_{11}|$ separately.

Starting with the antenna geometry obtained in the previous example, a study modifying the height of the parasitic array above the ground plane, Δz, is shown in Fig. 6. This figure shows that the directivity have four maxima separated approximately $\lambda/2$. Taking these results into account, and using the initial antenna of 49 elements above mentioned, one optimization per each maximum was performed. These optimizations follow the same procedure as above, but the value of Δz is restricted to be around $\pm 0.1\lambda$ of each maximum detected. Table 1 lists the results obtained: note that as the distance between the planar array and the feeding dipole increases, the *SLL* and directivity of the pattern are worse, but the gain bandwidth is better. This

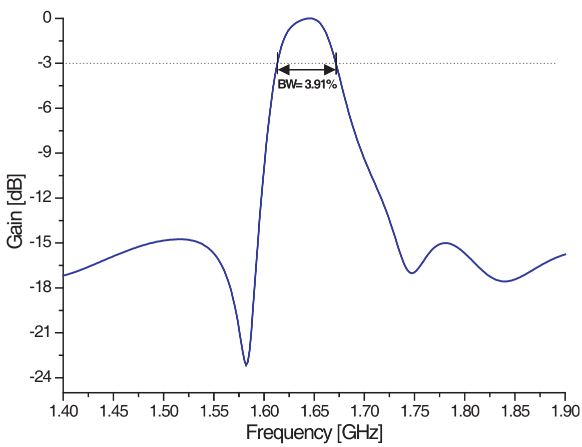

Figure 5. Antenna gain versus frequency for the antenna of Fig. 4.

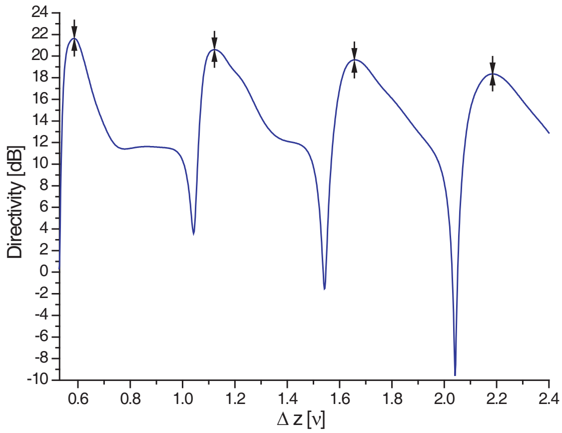

Figure 6. Antenna directivity versus the distance between the planar array and the ground plane, Δz.

is expected: since the coupling between the feeding dipole and the parasitic array decreases, the pattern is more similar to that of the isolated dipole (which has a poor performance in terms of *SLL* and directivity but a good bandwidth). The corresponding values of the active impedance Z_A for each case, that have not been included in the optimization, are also shown in Table 1.

Using the antenna geometries corresponding to the results of Table 1 as a starting point, a final optimization based on the downhill simplex method was performed in order to optimize also Z_A and thus to simplify impedance matching. For each case, we have considered three target values for Z_A using different values of Z_0 in (2): a) Z_A pure real — using $c_3 = 0$ in (2), b) $Z_0 = 75\,\Omega$, and c) $Z_0 = 50\,\Omega$. The results are shown in Table 2. In the case a), where no particular

Table 1. Antenna performance after a PSO optimization using different values of Δz obtained from Fig. 6. The length of the driven dipole is fixed to $\lambda/2$.

Δz $[\lambda]$	Directivity [dB]	*SLL* [dB]	Z_A $[\Omega]$	Bandwidth gain [%]			
				-3 dB	-1.5 dB	-1 dB	-0.5 dB
0.59	21.68	-14.2	$220.6 + j163.9$	3.91	3.00	2.48	1.77
1.12	20.82	-13.4	$158.0 + j108.5$	5.07	3.67	3.20	2.38
1.67	20.50	-12.0	$124.0 + j91.0$	6.48	4.32	3.57	2.62
2.20	19.91	-11.0	$117.5 + j75.8$	9.59	6.09	4.56	3.00

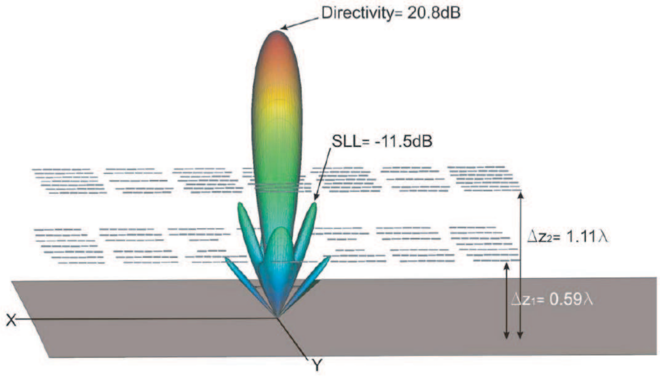

Figure 7. Geometry and power pattern radiated by the antenna of two layers composed by 49 parasitic elements placed 0.59λ and 1.11λ in front of a finite ground plane.

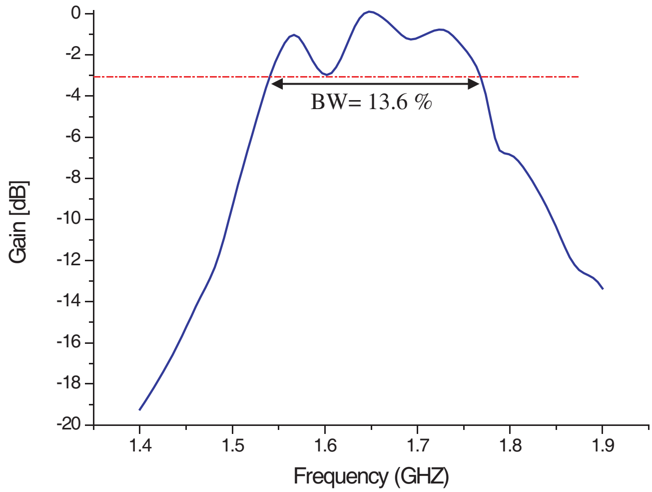

Figure 8. Antenna gain versus frequency for the antenna of Fig. 7.

value of Z_0 is considered, the results are very similar to the obtained in Table 1 thanks to the perturbation of the driven dipole length. In the case b), the obtained Z_A fits very well to the target value at the expense of slightly reducing the pattern performance. Finally, the case c) was successfully applicable to $\Delta z = 0.59\lambda$ only: for larger distances, the price to pay in the antenna performance to achieve a value of active impedance near $50\,\Omega$ is too high to make the design feasible.

An additional example of an antenna composed by two layers is also presented. This antenna has two parasitic layers of 49 elements each: they are placed at $\Delta z = 0.59\lambda$ and $\Delta z = 1.11\lambda$ in front of a finite ground plane respectively. The interspacing in the X-axis and Y-axis are $\Delta y = 0.5\lambda$ and $\Delta x = 0.55\lambda$. After all the optimization process 8 elements in the first layer and 4 in the second were removed. The total size of the planar array is $4.8\lambda \times 4\lambda$ including the ground plane that exceeds $\lambda/2$ the size of the parasitic array in each direction. The resulting antenna has a directivity of 20.8 dB (0.9 dB lower than the antenna with only one layer), a SLL of -11.2 dB (see Fig. 7), and -22 dB of back radiation. The bandwidth reveals a value of 13.6% for the 3 dB absolute gain bandwidth, see Fig. 8, that represents an increase of about a 10% with respect to the single layer parasitic array. Furthermore, using as starting point the above mentioned example, the process of matching impedance was applied obtaining an antenna with an active impedance of $75.6\,\Omega + 0j$ and essentially the same directivity, SLL and size as the last example, Fig. 9. The resulting feeder length is 0.43λ.

A more realistic simulation considering a design made of one parasitic layer has been performed. In this case, the copper parasitic elements are printed above a substrate plane of DICLAD 880 ($\varepsilon_r = 2.17$, $\tan\delta = 0.0009$), this plane is supported by four teflon screws over a metallic ground plane. After all the optimization process, the antenna has a directivity of 21.03 dB, a SLL of -12 dB with $\Delta z = 0.59\lambda$, $\Delta y = 0.6\lambda$, and $\Delta x = 0.55\lambda$ (see Fig. 10). The design frequency is 5 GHz and the total size of the antenna is $4.73\lambda \times 4.6\lambda$.

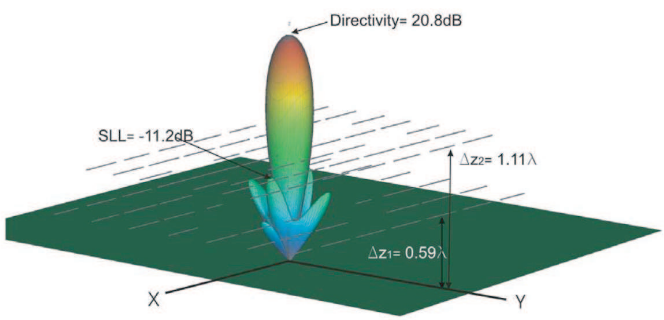

Figure 9. Geometry and power pattern radiated by the antenna of two layers composed by 49 parasitic elements placed 0.59λ and $1.11\ \lambda$ in front of a finite ground plane and with a pure real active impedance of $75\,\Omega$.

Table 2. Antenna performance after a downhill simplex optimization starting with the antenna geometries corresponding to the results of Table 1. The length of the driven dipole is also perturbated to optimize Z_A.

Δz [λ]	Z_0 [Ω]	Z_A [Ω]	Directivity [dB]	SLL [dB]	-1 dB Bandwidth gain [%]
0.59	—	$107.0 + j0.2$	21.49	-14.8	2.57
	75	$75.6 + j0.9$	21.22	-13.4	2.12
	50	$49.9 + j0.5$	20.37	-11.2	1.99
1.12	—	$99.2 + j0.7$	20.89	-13.7	3.36
	75	$73.8 + j0.1$	20.45	-11.4	2.78
1.67	—	$80.8 - j0.2$	20.23	-12.9	3.55
	75	$74.3 - j0.6$	20.15	-11.6	3.14
2.20	—	$80.7 - j0.1$	19.48	-11.2	3.80
	75	$73.2 - j0.0$	19.48	-11.1	3.71

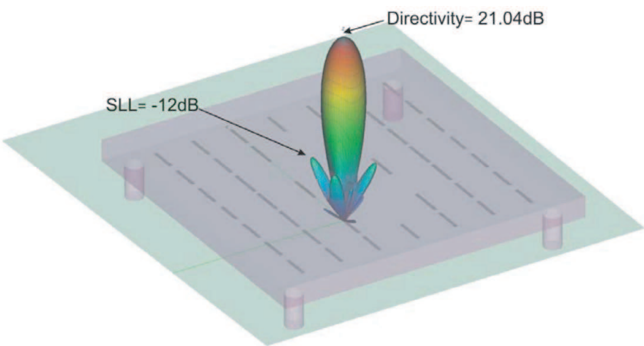

Figure 10. Geometry and power pattern radiated by a design of 49 parasitic elements placed 0.59λ in front of a finite ground plane and taking into account the dielectric substrate and the teflon screws.

4. CONCLUSIONS

The initial results of designing an antenna composed of a planar array of parasitic dipoles fed by only one active dipole are promising. The resulting pencil beam pattern has a moderate gain and bandwidth. The distance between the parasitic array and ground plane is an important parameter that restricts the performance of our antenna. Nevertheless, we found that it is possible to use different values of Δz

with a small penalty to the antenna performance, which provides more versatility in a hypothetic construction of the antenna. Moreover, the active impedance of the antenna can be optimized to be pure real in order to simplify the impedance matching of the feeding network. By introducing additional layers of parasitic arrays it is possible to obtain a better bandwidth with a small decrease in the directivity and SLL. Although this configuration is less compact than the single layer one, it could be necessary and justifiable in applications requiring a higher bandwidth.

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