Simulation of the effects of a ground plane on the radiation charateristics of self-complementary arrays

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Abstract

Self-complementary arrays potentially exhibit a very large bandwidth. However, their bi-directional radiation characteristic limits their range of applications, and the introduction of a ground plane below the array strongly reduces the achievable bandwidth. We have confirmed the latter point using infinite-array MoM simulations. However, we also show that, when the required instantaneous bandwidth is not very large, simple reconfigurations of the array allow it to be operated over a quite large total frequency band. The reconfigurations consists of moving the ground plane and of switching a fraction of the ports of the array. Simulation results show that two bands, of respectively 45% and 25%, made of 10% instanstaneous bands can be opened in these ways.

1 Introduction

As shown by Mushiake [1], self-complementary antennas exhibit a constant impedance equal to $\eta/2$, where η is the free-space impedance. Of course, to be exactly self-complementary, the antennas should be infinite. In fact, there exists a relationship between the volume occupied by an antenna and its lowest achievable Q [2]. As for large arrays, the largest dimension of the whole structure may, in principle, be sufficient to achieve a large bandwidth. An elegant solution, proposed by McGrath and Baum [3], consists of ensuring that the array itself, rather than the array elements, has a self-complementary structure. This is, for instance, the case for arrays made of square plates connected at the corners, where they are also fed ("planar bicone" array). A unit-cell of the array is represented in Figure 4.

Such arrays are compact and naturally exhibit a very wide bandwidth. However, these structures radiate on both sides of the plane, which makes them practically useless for most applications. The simplest structure to avoid radiation on the back-side probably consists of placing a ground plane. It has been shown in the literature that the presence of a ground plane may have a dramatic effect on the bandwidth of isolated elements. Based on this, it may be expected that a ground plane may destroy the wideband behavior of self-complementary arrays. However, for the particular case of self-complementary arrays, this problem has received very little attention.

The objective of this paper is to analyze numerically this configuration, and to propose some partial solutions for the particular situation where the required instantaneous bandwidth of the system is small, compared to the total bandwidth to be covered by the system. In Section 2, simulation results are shown for the periodic array with and without a ground plane. In the two next sections, partial solutions, consisting of simple re-configurations of the antennas, are shown. The effect of moving the ground plane is shown in Section 3, and the effect of swithing the antennas is shown in Section 4. Conclusions are drawn in Section 5.

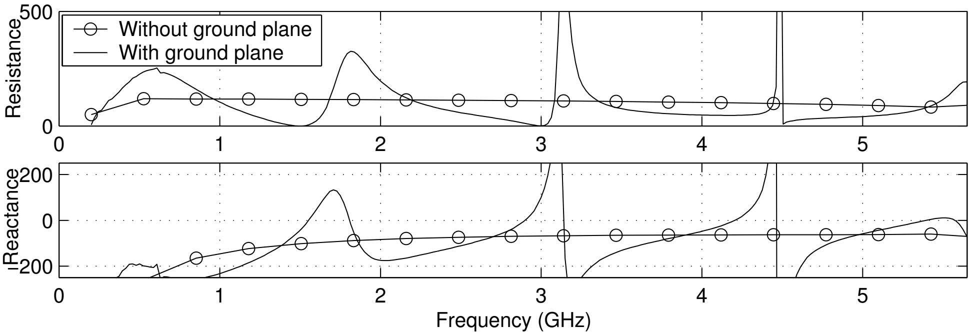

Figure 1: Impedance of self-complementary array without ground plane and with ground plane at d=10cm.

2 Self-complementary array and effect of the ground plane

Figure 4 shows the geometry of the 5cm wide unit cell. The square antennas, are fed at the corners, where they connect with the neighboring elements. In order to include efficiently the effects of the very strong couplings between the antennas, the array is supposed to be infinitely periodic (the effects of array truncation are omitted). We developed a MoM code to analyse this structure, using the Galerkin testing procedure. The basis functions consist of rootop vector functions defined on rectangular and triangular domains (RWG basis functions [4]). The feeds are implemented as delta-gaps sources. To be effective, this source representation required the use of a few more basis functions in the source region, which slightly degrades the self-complementarity of the structure. The free-space periodic Green's function in the on-plane case has been computed using a method described in [5], while the out-of-plane Green's function (when a ground plane is used), has been computed based on the formulation presented in [6].

Figure 1 shows the active input impedance without a ground plane (bullets). As expected, it is essentially flat over a very wide bandwidth. However, the obtained value is not very close to $\eta/2$, which may probably be ascribed to the approximate representation of the feed points. In [3], where simulations are performed with the finite-element method, the results also are very sensitive to the representation of the feed points.

The active input impedance in the presence of a ground plane located at d=10 cm from the array is represented by solid line lines in Figure 1. The ground plane dramatically modifies the behavior of the impedance over the frequency band. It can be verified that, each time the distance between the array and the ground plane is a multiple of $\lambda/2$, the resistance drops to zero (destructive interference between the array and its image). This dramatic change raises the question of the usefulness of starting from a self-complementary configuration. However, a few simulations were performed with elements having non-complementary shapes and led to even worse changes. This suggests that the planar bicone array still is a good starting point.

Figures 2 and 3, respectively, show the element patterns without and with a ground plane at d=2.5cm. These patterns were computed as $(1-|\Gamma_a|^2)\cdot cos(\theta)$, where Γ_a is the active reflection coefficient. For these simulations, only the feed 1 (cf. Fig. 4) was connected while the other one was short-circuited. As we can see, the ground plane narrows the 3db beamwidth. This one is about 120 degrees without the ground plane and about 70 degrees with it.

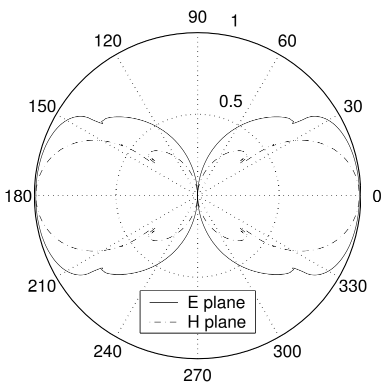

Figure 2: Radiation pattern without ground plane, f=3.75GHz.

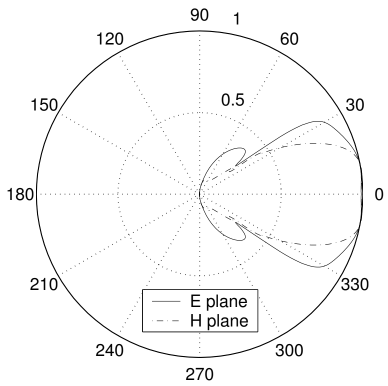

Figure 3: Radiation pattern with ground plane, f=3.75GHz, d=2.5cm.

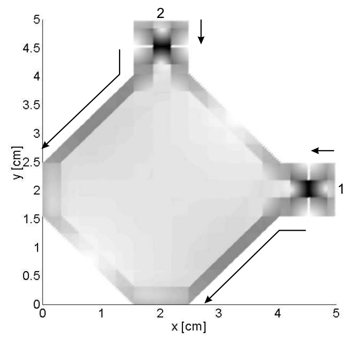

Figure 4: Unit cell with a single antenna, current flow and feedpoints.

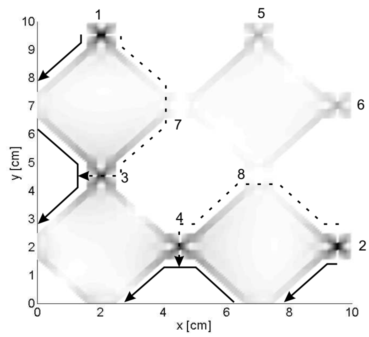

Figure 5: Unit cell with 4 antennas, current flow and feedpoints.

3 Moving the ground plane

The presence of the ground plane reduces the fractional bandwidth to about 10%. But, as the ground plane is moved, the nulls in the reactance (cf. Fig. 1) and the operational frequency band is shifted along the frequency axis. Figure 6 shows the standing wave ratio simulated for several ground plane positions between 1.5 cm and 3.5 cm from the array plane. The total frequency band over which the array can be operated now extends from 3.5 GHz to 5.5 GHz, which corresponds to a total fractional bandwidth of 45%. We should stress that, given that this does not correspond to an instantaneous bandwidth, this system cannot be used for transmitting or receiving very short pulses. However, such a configuration may be useful for some communication or astronomic systems, which should be able to shift their relatively narrow bandwidth within very broad limits.

4 Switching the feeds

It is interesting to realize that the self-complementary array shown above also resembles a self-similar structure, in an approximate sense, though. Indeed, at lower frequencies, a group of four antennas may play the role a single element plays at higher frequencies. This assumes that some ports are either opened or short-circuited. For instance, we simulated the structure containing 4 squares per unit cell, and where ports 3,4,5 and 6 are short-circuited, while ports 7 and 8 are left open. Hence, the unit cell is only fed at ports 1 and 2 (cf. Fig.5). The simulation results obtained for different positions of

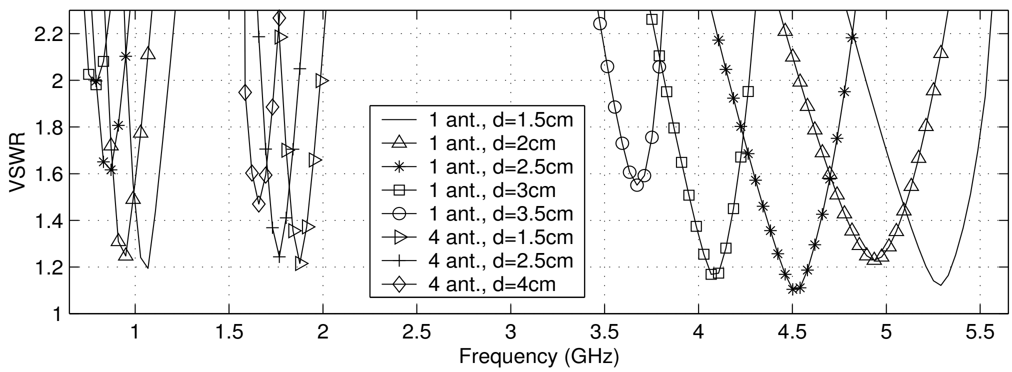

Figure 6: Simulated VSWR w.r.t. 50Ω for several ground plane distances for one and four antennas per unit cell.

the ground plane are shown in Figure 6, As expected, the operational frequency band is located at about half of the center frequency of the original structure. However, the total fractional bandwidth is narrower. It is is reduced from 45% to 25%. Nevertheless this is an apreciable bandwidth, achieved with a very simple modification of the array structure.

5 Conclusion

Planar self-complementary arrays exhibit a very broadband characteristic but are not very useful because they radiate on both sides of the array plane. Introducing a ground plane solves this problem, but it dramatically reduces the array bandwidth and also introduces a smaller distorsion on the element pattern. Infinite-array simulations showed that, when the whole bandwidth does not need to be covered instantaneously, a large fraction of the operational band can be recovered by resorting to simple and rapid reconfigurations of the array. The first approach consists of moving the ground plane. Our simulation results provided a total bandwidth of 45%, while the instantaneous bandwith is of the order of 10%. The second approach consists of allowing a low-frequency operation of the array by leaving open or short-circuited a fraction of the ports of the array. In that case, we achieved a bandwidth of 25%, also with an instantaneous bandwidth of about 10%.

References

[1] Y Mushiake, "Self-Complementary Antennas," *IEEE Antennas and Propagation Magazine*, vol. 34, pp. 23-29, December 1992.

[2] A. K. Skrivervik, J.-F. Zurcher, O. Staub and J. R. Mosig, "PCS Antenna Design: The Challenge of miniaturization", *IEEE Antennas and Propagation Magazine*, vol. 43, pp. 12-27, August 2001.

[3] D. T. McGrath and C. E. Baum, "Scanning and Impedance Properties of TEM Horn Arrays for Transient Radiation," *IEEE Trans. Antennas Propagat.*, vol. 47, pp. 469-473, March 1999.

[4] S. M. Rao, D. R. Wilton, and A. W. Glisson, "Electromagnetic Scattering by Surfaces of Arbitrary Shape",*IEEE Trans. Antennas Propagat.*, vol. 30, pp. 409 - 418, May 1982.

[5] C. Craeye, A. B. Smolders, D. H. Schaubert and A.G. Tijhuis, "An Efficient Computation Scheme for the Free Space Green's Function of a Two-Dimensional Semi-Infinite Phased Array," *IEEE Trans. Antennas Propagat.*, In press.

[6] R. E. Jorgenson and R. Mittra, "Efficient Calculation of the Free-Space Periodic Green's Function," *IEEE Trans. Antennas Propagat.*, vol. 38, pp. 633-642, May 1990.