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# Fast Analysis of Large Finite Arrays With a Combined Multiresolution—SM/AIM Approach

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**Abstract**—We present a synthesis of the sparse matrix/adaptive integral method (SM/AIM) and the multiresolution (MR) approach for the analysis of electrically large finite arrays, with planar or 3-D radiating elements; the two methods were separately introduced previously. The use of the MR has the effect of a preconditioner and speeds up the convergence rate of the SM/AIM of almost two orders of magnitude, with a total reduction of the numerical complexity with respect to the standard MoM of almost three orders of magnitude.

**Index Terms**—Antenna arrays, method of moments (MoM), multiresolution, numerical methods, wavelets.

## I. INTRODUCTION

AS WELL-KNOWN, an efficient cure to the limitation of the standard method of moments (MoM) is represented by the so-called “fast methods”, that have been essentially developed for the analysis of scattering problems (e.g., [1], [2]), or for planar structures, as single-layer printed antennas [3]. Its efficient extension to antenna problems involving 3-D radiating elements, as stacked patches or radiators connected to the ground plane (e.g., Fig. 1, bottom) is, however, not straightforward.

For this reason part of these authors have improved the BMIA/AIM formulation introduced in [5] for the analysis of stacked patch antennas to the sparse matrix—adaptive integral method (SM/AIM), able to handle efficiently 3-D structures, including also vertical connection, by introducing an *ad hoc* version of the AIM [2]. As the other fast (iterative) methods (e.g., see [1]–[4]), the SM/AIM acts on the operation count of matrix-vector multiplication: the number of iterations remains essentially the same as with the standard MoM. To accelerate convergence, one needs a suitable preconditioner, that has to satisfy three constraints; low memory storage, low computational cost for its generation and application, compatibility with a fast method, in which the MoM matrix is never fully computed and stored. Results presented in literature (e.g., [6]) show that techniques as the sparse LU or the sparse iterative method can be adopted to generate a preconditioner suitable also for fast methods. However they are not able to both reduce the number of iterations and require a low memory space, and this may undo the computational advantages of the use of the preconditioner itself.

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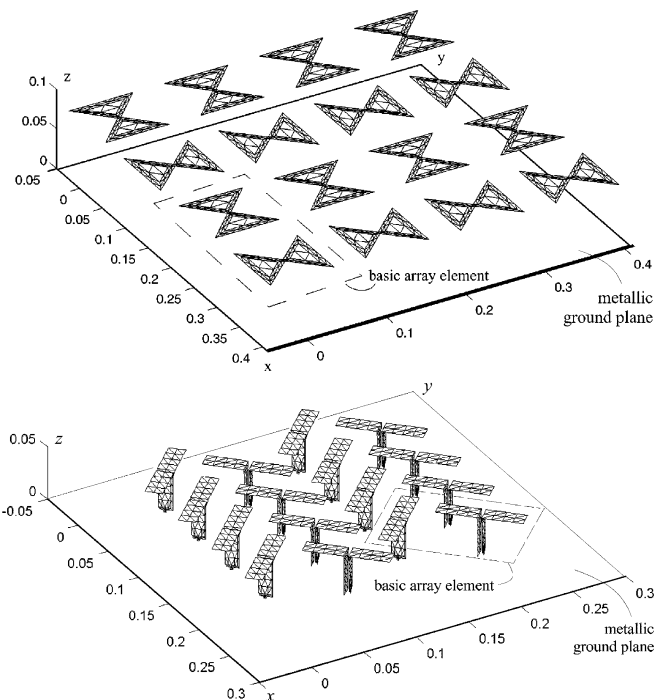


Fig. 1. Geometry of the test problems.

In this paper, we demonstrate that the multiresolution (MR) [8] technique produces an efficient MoM preconditioner for antenna problems, that is fully compatible with the SM/AIM algorithm. The MR approach was first introduced in [7] (for a rectangular grid) then extended in [8] to the generation of wavelet-like vector functions that can be adopted for the analysis of arbitrary-shape 2.5-D or 3-D antenna problems. The employed approach allows expressing the MR functions as linear combination of RWG [10] functions, and the MR basis is represented by a matrix  $\mathbf{T}$  whose rows represent the MR functions in the RWG basis. For the reader interested in more theoretical MR issues, [9] shows that the approach in [8] produces indeed a MR analysis.

Unlike other preconditioners (see e.g., [6], [11]), the results in Section IV will show that the MR allows a strong reduction of the iterative solver number of iterations (more than one order of magnitude) with a negligible increase of memory storage and of computational effort for its construction and application. This is related to two aspects of the MR preconditioner. The first is that the matrix  $\mathbf{T}$  is very sparse ( $O(2N \log_2 N)$  non-zero elements) and frequency independent; this is important in antenna problems, where the resulting linear system has to be solved for

several frequencies. The second is that the eigenvalue distribution of the MoM matrix in the MR basis can be controlled by application of a simple diagonal preconditioner.

The present work can be considered a synthesis of the SM/AIM and MR techniques. A preliminary stage of this work was reported in the conference paper [12]. To the best of authors' knowledge, this is the first work reporting how the MR properties in [8] can be implemented in an AIM like formulation resulting in a preconditioner that is direct, i.e., that does not require any inversion, and with storage and operational count compatible with the intrinsic structure of AIM.

## II. THE SM/AIM FORMULATION

Let us consider a metallic structure, located over an infinite ground plane extending along the  $x, y$  directions, two examples of which are shown in Fig. 1. The EFIE-MoM linear system  $\mathbf{Z}\mathbf{I} = \mathbf{V}$  is set up for the RWG basis [10].

In the classical SMC [13], computational efficiency is achieved by defining a distance  $r_d$  which separates two regions: a near-interaction region and a weak-interaction region. One can then write the matrix  $\mathbf{Z}$  as a superposition of a strong interaction—matrix  $\mathbf{Z}^s$  and a weak-interaction matrix  $\mathbf{Z}^w$  (i.e.,  $\mathbf{Z} = \mathbf{Z}^s + \mathbf{Z}^w$ ). The elements of  $\mathbf{Z}^s$  are related to weighting and basis functions having distances  $d_{xy} = \sqrt{(x-x')^2 + (y-y')^2} < r_d$ . This matrix is evaluated using the standard MoM and results very sparse. The weak-interaction region is defined as that in which  $h = |z - z'| = |f(x, y) - f(x', y')| \ll d_{xy}$  for all  $x, y, x', y'$ ; in it, we can approximate the Green's function in a Taylor series with respect to height  $h$ ; keeping terms up to  $h^{\tilde{M}}$  one obtains

$$G(d_{xy}, z, z') = \sum_{m=0}^M A_m(d_{xy}) R_m(z) Q_m(z') \quad (1)$$

where  $M = (\tilde{M} + 1)^2 - 1$ . Therefore, by assuming the Galerkin discretization scheme, each element of the weak-interaction matrix  $\mathbf{Z}^w$  can be expressed as a linear combination of four elements of the form [5]

$$Z_{i,j}^\alpha = \sum_{m=0}^M \int \int_S R_m(z) \psi_i^\alpha(x, y, z) \cdot \int \int_S A_m(x-x', y-y') Q_m(z') \psi_j^\alpha(x', y', z') dS' dS. \quad (2)$$

where  $\alpha = x, y, z$  refers to the components of the vector potentials, and  $\alpha = \phi$  to the scalar potential, and  $\psi_i^\alpha$  is the pertinent basis or weighting function. Each term (2) has a two-dimensional (2-D) convolution form and can be efficiently evaluated by means of a 2-D fast Fourier transform (FFT). This formulation, however, cannot be directly applied to the analysis of non planar antenna structures: it either requires a regular grid to describe the structure or does not allow the use of basis functions along the  $z$  direction.

To overcome this limitation, we consider the products  $Q_m(z') \psi_j^\alpha(x', y', z')$  or  $R_m(z) \psi_j^\alpha(x', y', z')$  and we approximate them with equivalent sets of point-like currents. We

choose the point-like current elements located at the nodes of a regular Cartesian 2-D grid, parallel to the  $x, y$  plane. Both the basis and weighting functions are approximated as a linear combination of Dirac delta functions; denoting by  $P_m(z) = Q_m(z)$  or  $P_m(z) = R_m(z)$ , the generic term of the expansion is then

$$P_m(z) \psi_n^\alpha(x, y, z) \simeq \sum_{i=0}^L \Lambda_{n,i}^{\alpha,m} \delta(x-x_i) \delta(y-y_i) \delta(z-z_c) \quad (3)$$

with  $(x_i, y_i) \in C_n$ , where  $C_n$  is the set of  $L+1$  grid nodes closest to the center  $(x_c, y_c, z_c)$  of the basis or weighting function support. This procedure is similar to the classical AIM approach [2]; however, by approximating not only the basis (weighting) functions but their product with the part of the factorized Green's function (1) depending on  $z'(z)$ , we require that point-like current elements belong only to a regular Cartesian 2-D grid having  $N_g$  nodes. Hence, we enforce the equality

$$\int \int_S P_m(z) \psi_n^\alpha(x, y, z) (x-x_c)^{m_1} (y-y_c)^{m_2} dS = \sum_{i=0}^L \Lambda_{n,i}^{\alpha,m} (x_i-x_c)^{m_1} (y_i-y_c)^{m_2} \quad (4)$$

for  $0 \leq m_1, m_2 \leq L$ . By inserting (3) into (2), the weak-interaction matrix can readily be written as

$$\mathbf{Z}^w \mathbf{I} = \sum_{m=0}^M \sum_{\alpha=x,y,z,\phi} \Lambda_{\alpha,m}^R \mathbf{A}_m \Lambda_{\alpha,m}^Q \mathbf{I} \quad (5)$$

where  $\mathbf{A}_m = \{A_m(x_i - x_j, y_i - y_j)\}$ , and  $\Lambda_{\alpha,m}^{R,Q} = \{\Lambda_{n,i}^{\alpha,m}\}$ . Furthermore, the matrix  $\mathbf{A}_m$  is a block Toeplitz matrix, while the matrices  $\Lambda_{\alpha,m}^{R,Q}$  are extremely sparse. While the  $\mathbf{Z}^w$  matrix is a full matrix with  $O(N^2)$  elements and usually cannot be stored for large-scale problems, we now have to store only  $O(4N_g)$  elements for each matrix  $\mathbf{A}_m$ , where  $N_g$  is the number of nodes on the regular 2-D grid, and a few other matrices that need the overall storage of  $O(4(L+1)N_g)$  elements. Furthermore, when a conjugate gradient is used to solve the matrix equation, based on the discrete convolution theorem, the product  $\mathbf{A}_m \cdot (\Lambda_{\alpha,m}^Q \mathbf{I})$  can be suitably evaluated by means of two 2-D-FFTs, since  $\mathbf{A}_m$  is a block Toeplitz matrix. This allows us to calculate the  $\mathbf{Z}^w \mathbf{I}$  product using  $O(16N_g(M+1)[2\log_2(4N_g)+1])$  operations instead of  $O(N^2)$ .

## III. MULTIREOLUTION PRECONDITIONER

The effect of the MR system [8] on the MoM matrix spectrum is a complex topic, presently under investigation and beyond the scope of this paper; a preliminary account is presented in [14] and briefly outlined here. A key point is that the MR functions of [8] possess both spatial (as the RWG) and spectral resolution [7], since they are defined on meshes of different levels, and have different spectral occupations. Because of the spectral resolution, the evaluation of the matrix entries in the spectral domain results in sampling the spectral Green function in correspondence of the peaks of the Fourier transform of the basis

TABLE I

TEST ARRAY SIMULATION FEATURES FOR DUAL-POLARIZATION ARRAYS OF BOWTIE DIPOLES SHOWN IN FIG. 1, TOP. (Freq. = 1 GHz, TAYLOR GREEN FUNCTION EXPANSION ORDER = 2, BASIS FUNCTIONS MULTIPOLE EXPANSION ORDER = 1,  $r_d = 0.288 m = 0.96\lambda$ ,  $\Delta_{\text{FFT}}^{\text{max}} = \lambda/20$ , CG Tol. =  $10^{-3}$ , CPU TIME IS RELEVANT TO A PENTIUM III 1 GHz)

# of bow-tie pairs	antenna surface	Nr. of unknowns	$\mathbf{Z}^s$ non zero elements	$\mathbf{Z}^s$ filling time	MR basis			RWG basis		
					CG iter.time	# iter.	Ram Mb	CG iter.time	# iter.	Ram Mb
2 × 4	2.16 $\lambda^2$	1, 968	2, 540, 932	43''	0.55''	32	62	0.42''	2925	62
4 × 8	9.61 $\lambda^2$	7, 872	14, 084, 712	239''	2.82''	89	248	2.20''	3388	248
5 × 10	15.34 $\lambda^2$	12, 300	23, 329, 258	398''	5.59''	114	409	4.60''	2157	409
6 × 12	22.09 $\lambda^2$	17, 712	38, 529, 538	604''	7.69''	132	593	6.21''	3681	592
7 × 14	29.88 $\lambda^2$	24, 108	48, 763, 662	854''	10.20''	112	810	8.20''	3354	809
8 × 16	39.27 $\lambda^2$	31, 488	64, 953, 520	1156''	13.46''	155	1066	10.34''	3190	1064

TABLE II

TEST ARRAY SIMULATION FEATURES FOR ARRAYS OF DUAL-POL. DIPOLES SHOWN IN FIG. 1, BOTTOM. (Freq. = 2.1 GHz) : TAYLOR GREEN FUNCTION EXPANSION ORDER = 2, BASIS FUNCTIONS MULTIPOLE EXPANSION ORDER = 1,  $r_d = 0.2 m = 1.4\lambda$ ,  $\Delta_{\text{FFT}} = 0.0025 m = 0.028\lambda$ , CG Tol. =  $1.e-4$ ; (CPU TIME IS RELEVANT TO A PENTIUM III 1 GHz).(\*) : RESIDUE =  $5.9 \times 10^{-4}$  (STAGNATION)

# of dipoles pairs	Unk-nowns	$\mathbf{Z}^s$ non zero elements	FFT-2D points	$\mathbf{Z}^s$ filling time	MR basis - Prec MR		Ram Mb	RWG basis - No Prec		Ram Mb
					CG iter. time	# iter.		CG iter. time	# iter.	
4 × 8	8, 000	21, 119, 018	256 × 1024	392''	6.73''	53	269	7.75''	5641(*)	269
6 × 10	15, 000	49, 413, 620	512 × 1024	938''	19.16''	55	622	17.51''	12291	621
8 × 12	24, 000	87, 363, 560	512 × 2048	1689''	36.17''	69	1057	32.31''	13524	1055
10 × 14	35, 000	134, 968, 764	512 × 2048	2567''	39.16''	77	1659	34.74''	13543	1656

and test functions. As a result of all of the above, the MoM matrix in the MR basis,  $\mathbf{Z}_{\text{MR}}$ , presents a peaked diagonal, whose entries are very close to the matrix eigenvalues [7, Sec. VII]. Thanks to this, the application of a simple diagonal preconditioner improves the distribution of the eigenvalues [14], that is the main responsible of the convergence rate of iterative solvers. In this sense, the MR scheme induces an efficient physics-based preconditioner.

The construction and application of this preconditioner can be summarized in the following three steps:

- construction of the matrix  $\mathbf{T}$  whose rows represent the MR functions in the RWG basis, i.e., it is the basis change matrix. Note that  $\mathbf{T}$  is very sparse and frequency independent;
- extraction of the symmetric diagonal preconditioner  $\mathbf{D} = \text{diag}(\mathbf{Z}_{\text{MR}}) = \text{diag}(\mathbf{T}\mathbf{Z}^s\mathbf{T}^T)$ ;
- construction of the preconditioning matrix  $\mathbf{S} = \mathbf{T}\mathbf{D}^{-1/2}$ , that share the same memory space of matrix  $\mathbf{T}$ .

Note that, unlike other commonly used preconditioner (see for instance [11], [6] and reference therein), this scheme presents the advantage of requiring a low memory occupation, since only the matrix  $\mathbf{S}$ , having  $\mathcal{O}(N \log_2 N)$  non-zero elements, has to be stored.

The procedure described above is general; however, the construction of the diagonal matrix  $\mathbf{D}$  requires the knowledge of the entire MoM matrix  $\mathbf{Z}$ , which is undesirable in fast methods. One then conveniently resorts to the approximate diagonal matrix  $\hat{\mathbf{D}}$  generated via the strong-interaction matrix  $\mathbf{Z}^s$ , i.e.,  $\hat{\mathbf{D}} = \text{diag}(\mathbf{T}\mathbf{Z}^s\mathbf{T}^T)$ , and uses  $\hat{\mathbf{S}} = \mathbf{T}\hat{\mathbf{D}}$  instead of  $\mathbf{S}$ .

For the specific array problem at hand, however, the radiating elements are not connected to one another, and the matrix  $\mathbf{T}$  is a block diagonal matrix, since in this case there are no functions covering more than one array element, not even those belonging to the  $j = 1$  mesh; therefore to construct the *exact* preconditioner  $\mathbf{S}$  we only need the diagonal blocks of  $\mathbf{Z}$ , that represent the interactions between RWG basis functions within the same

radiating element. As a result, this exact MR preconditioner can be computed and stored at a very low cost.

Once the matrix  $\mathbf{S}$  has been evaluated, the following equivalent linear system:

$$\mathbf{S}^T(\mathbf{Z}^s + \mathbf{Z}^w)\tilde{\mathbf{S}}\tilde{\mathbf{I}} = \mathbf{S}^T\mathbf{V} \quad (6)$$

can be solved adopting the scheme described in Section II. The solution  $\mathbf{I} = \tilde{\mathbf{S}}\tilde{\mathbf{I}}$  can be calculated, where  $\tilde{\mathbf{I}}$  and  $\mathbf{I}$  are the unknown currents in the preconditioned MR basis and in the RWG basis, respectively.

#### IV. RESULTS

As a first example, we considered dual-polarization arrays of bowtie dipoles of the type shown at the top of Fig. 1. Each element has been discretized with the mesh generated by the MR procedure [8], on which 125 unknowns are defined.

The efficiency of the MR-SM/AIM has been investigated for arrays with an increasing number of elements; its performance and those of the SM/AIM with the standard RWG functions are summarized in Table I.

From these data, it appears that the introduction of the MR functions slightly increases the time taken to complete one CG iteration compared to that taken when the RWG basis is used, since it introduces two additional products with the basis-change and preconditioning matrices (columns 6 and 9 in Table I), but strongly reduces the number of iterations required to achieve the desired tolerance, as it appears comparing columns 7 and 10. Therefore, if for instance we consider the largest array, corresponding to about 30 000 unknowns, the *total* time needed to solve the linear system using the SM/AIM with the RWG functions is almost 9 hr., 45 min., while, using the MR functions, it is reduced to almost 54 min., with a gain of almost a factor of eight.

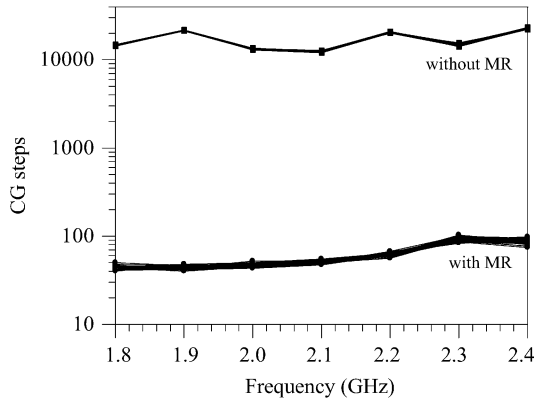


Fig. 2. Number of iterations for reaching the tolerance of  $10^{-4}$  versus the frequency for an array of  $6 \times 10 \times 2$  dipoles of the type in Fig. 1, bottom.

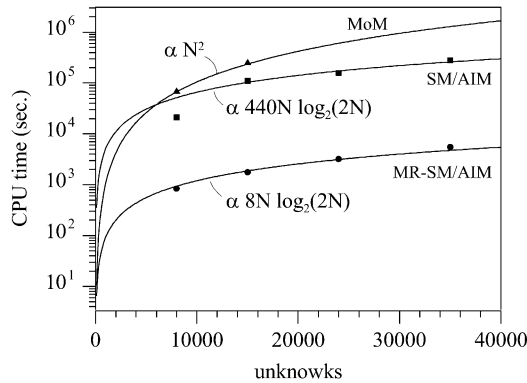


Fig. 3. CPU time for the whole analysis of arrays of dipoles of the type in Fig. 1, bottom.

Like Table I, Table II shows the relevant characteristics of the simulations carried out at a frequency of 2.1 GHz on arrays of the type sketched at the bottom of Fig. 1. Also, in this case, columns 6 and 9 in Table II show that it takes slightly more time to complete one CG iteration when the MR preconditioning is used than it does when the standard RWG basis is used; however, this increase is always less than 10%, and the total gain is very high, since the number of iterations required to achieve the set CG tolerance value ( $\text{tol} = 10^{-4}$ ) is reduced by almost two orders of magnitude when the MR scheme with the diagonal preconditioner is introduced, as shown in columns 7 and 10 of Table II. Fig. 2 shows the number of iterations necessary for the SM/AIM method to reach the set tolerance on the frequency interval  $1.8 \div 2.4$  GHz, with and without the MR preconditioner. These results refer to an array of  $6 \times 10$  dipole pairs (15 000 unknowns), feeding one dipole at a time as required to obtain the array admittance matrix. It is also clear from Table II, that the use of MR reduces the number of iterations of about a factor of 200. The slight increase in the number of iterations around 2.3 GHz can be connected to the strong variation of the impedance around this frequency, as evident in Fig. 4.

Fig. 3 reports the total CPU time needed to solve the MoM linear system for increasing problem dimensions (number  $N$  of unknowns). The three curves refer to the use of the SM/AIM approach with the MR (circle) or the RWG (square) functions

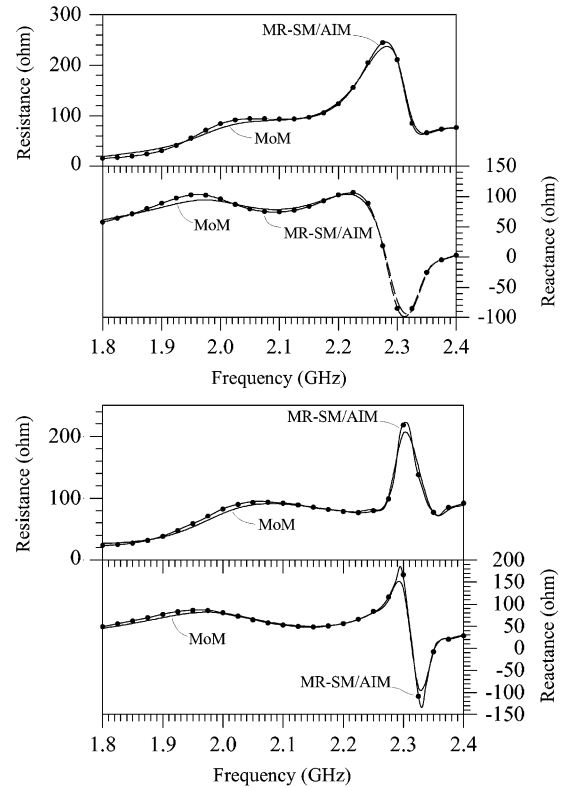


Fig. 4. Real and imaginary part of the input impedance of the 50th (top) and of the 59th (bottom) element of the  $6 \times 10$  dipoles pairs array of the type sketched in Fig. 1 bottom. Continuous line: standard MoM; marked line: MR-SM/AIM.

and of the standard MoM (triangle). The marks correspond to computed values, while the continuous curves are the interpolating functions, which give the dependence of the CPU time on  $N$ , whose expression is also reported in the figure. The use of the SM/AIM instead of the classical MoM reduces the numerical complexity from  $\alpha \cdot N^2$  to  $\alpha \cdot 440N \log_2 2N$ ; in this case,  $\alpha = 1.05 \cdot 10^{-3}$  sec. This means that, starting from medium size problems ( $N \geq 25\,000$ ), the CPU time reduction achieved using the SM/AIM is almost one order of magnitude. The introduction of the MR functions within the SM/AIM frame reduces the solution time by about two orders of magnitude, so that the MR-SM/AIM always reduces the CPU time compared with the standard MoM, even for small size problems. In case of  $N \geq 25\,000$  the gain is of almost three orders of magnitude. Finally, it is worth noting that the increase of the dynamic memory in the MR formulation is negligible (see columns 8 and 11 in Tables I and II).

In addition to the numerical efficiency of the proposed method, we checked its accuracy, via the active (embedded) impedance for broadside scan. Fig. 4 shows the frequency performance of the real and imaginary part of the active impedance of two array elements on the frequency band  $[1.8 \div 2.4]$  GHz for the array consisting of the  $6 \times 10$  dipole pairs in Table II, when the standard MoM or the MR-SM/AIM are used. We intentionally placed the elements of the array very close one each other ( $\sim 0.4\lambda$ ) to point out the critical behavior of the active input impedance around 2.3 GHz: despite the sharp variation, the agreement between the two sets of results is very good.

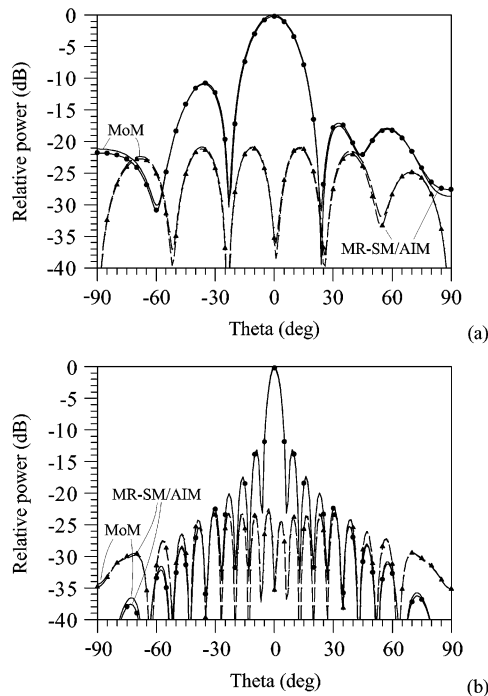


Fig. 5. Amplitude pattern at 2.1 GHz for the  $6 \times 10$  dipole pairs array of the type sketched in Fig. 1 bottom: (a)  $xz$  plane, (b)  $yz$  plane. Solid line: co-polar component, standard MoM; Dashed line: cross-polar component, standard MoM;  $\bullet$ : co-polar component, MR-SM/AIM  $\blacktriangle$ : cross-polar component, MR-SM/AIM.

Moreover, Fig. 5(a) and (b) shows the co-polar (solid) and the cross-polar (dashed) radiation patterns at the frequency of 2.1 GHz in the ( $xz$ ) and the ( $yz$ ) planes, respectively; the continuous lines refer to the radiated field evaluated with the MoM, while the marked lines to the standard MR-SM/AIM solution: the plots show the very good agreement between the results obtained with both approaches.

## V. CONCLUSION

We proposed and tested a combined application of the SM/AIM formulation and of the MR approach to antenna arrays of medium/large or large dimensions. It reduces the SM/AIM total solution time by about two orders of magnitude for medium-size problems, without affecting storage requirements. The total gain of the MR-SM/AIM over the standard MoM is of almost three orders of magnitude; the computational gain increases for larger problems. Extension of this work to other fast methods is presently underway [15].

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