THE EXPANSION WAVE CONCEPT: A FUNDAMENTAL WAY TO REDUCE THE PROBLEM SIZE IN MULTILAYERED STRUCTURES

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1. Introduction

In recent years, the EM (ElectroMagnetic) analysis and design of devices (antennas, circuits, boards, airplanes, rockets, …) is performed more and more in a "rigorous" manner with the aid of numerical techniques. The basic line of reasoning is always the same. Maxwell's equations are transformed into a set of matrix equations, either using a differential or an integral equation approach. The solution of this set of matrix equations yields a discrete approximation of the solution of the original problem. If the transformation is done correctly, demanding a higher accuracy results in a large size of the matrix problem. In most practical devices, the number of unknowns in the matrix problem rapidly becomes too large to be solved on workstations or PCs in an acceptable calculation time. A very thorough overview concerning fast solution methods in electromagnetics can be found in [1].

In this paper, the Expansion Wave Concept (EWC) is discussed. This concept was specially developed to reduce the number of unknowns in problems involving layer structures. The direct goal of this paper is not to explain in full detail the working mechanism of the EWC, this can be found in [2]. The direct goal is to prove that the application of the EWC is one example of the use of modularity and hierarchy in the solution of electromagnetic systems. Modularity is defined here as "treating each problem at its own level of complexity". However, it will be shown that a reduction of the number of unknowns with at least one to two orders of magnitude and thus a drastic reduction of calculation time is typical.

2. "Small" and "large" structures

A study of the range of commercial CAD software packages for the analysis and design of electromagnetic structures points out that there are a lot of these packages. For 2.5D multilayered structures for example: HP-momentum, Ensemble, IE3D, SAPHIR, … For 3D structures one can mention: HP-HFSS, Ansoft HFSS, EMPIRE, MAFIA, Sonnet em, … Most of these CAD packages are based on a single numerical technique (Moment Method, FE, FDTD, …). The drastic consequence is that they can handle only so-called "small" structures. The size of "small" strongly depends on the computer power being used. In practice, one can say that in most cases, with the workstations or PCs of today, these software packages are able to handle typically a single component or an assembly of a few components. They are by no means ready to handle complete complex systems, the so-called "large" structures. However, due to the accuracy of designing using a full-wave approach, even nowadays there is a clear trend towards the use of EM CAD software for sub-assemblies. Industry already is looking at the future and a lot of requests for EM software able to handle complete systems are being investigated at universities. The steady increase of computer power is certainly a factor. However, in my view the current trend in the EM modeling community, using modularity and hierarchy in the EM modeling code, will prove to be a crucial factor in order to reach the ultimate goal: the full-wave analysis of complete systems.

3. Modularity and hierarchy

In my view, the only way to reach the goal of analyzing and designing complete systems with EM software is to use modularity and hierarchy in the analysis engine. Each problem has to be solved at its own level of complexity. A modular and hierarchical scheme to analyze a 2.5D system in a multi-layer environment is illustrated in Fig. 1. Practical devices like planar antenna arrays, planar circuits, PCBs, etc. can be described in this way.

Although designers indeed tend to follow this modular scheme while thinking about the structure, a look at the analysis engines of most of the commercial CAD packages today reveals that they treat the complete system as just a single physical entity, using the same numerical technique throughout. This is like shooting at a mosquito with a cannon ball. In a large planar antenna array for example, the mutual coupling between two elements far apart is described with the same number of unknowns as the mutual coupling within the elements themselves. This is a waste of computer power. The coupling between two elements far apart can be described with much less unknowns than the coupling within the elements. How to implement this in a practical procedure?

4. The Expansion Wave Concept

The key idea is to use the characteristic waves of the layer structure to describe the mutual coupling at a higher level. First, the coupling between the components is solved at the element type level with a moment method applied to the component integral equations. This means that each so-called “element type” is solved in more or less the same way as done in HP-momentum, Ensemble, and IE3D. The number of unknowns is depending on the size and complexity of the element type. Note that the element types have to be solved, and not each element separately. In the case of identical elements, this yields a first considerable reduction in calculation time. The coupling between the elements is described with expansion waves travelling between the elements. Each element has a number of “outgoing waves” generated by the element, and a number of “incoming waves”, incident on the element and generated by the rest of the planar structure. The number of waves per element depends on the layer structure and the lateral size (in the plane parallel to the layer structure) of the element type under consideration, not on its internal complexity. It is typically an order of magnitude smaller than the number of unknowns in the moment method technique used to solve the internal coupling of the element type.

The concept allows to describe not only mutual coupling, but also interactions with the edge of the layer structure (which means that finite layer structures can be solved) and periodic interactions in infinite arrays.

It can also be applied in a multi-level scheme in order to reduce further the number of unknowns for the overall system problem. This would allow analyzing very large structures of thousands of elements, without having to restrict the design flexibility of the element type. These topics are under investigation.

5. Example

As example an 11x11 array of a complex aperture type radiating element, embedded within a layer structure involving 7 layers is considered. This antenna is currently under investigation for satellite TV reception [3]. The number of unknowns used to solve the internal element coupling is 720. This means that the commercial software packages would have to solve a system of 87120 unknowns (= 121 elements x 720 unknowns per element), involving a full matrix. The expansion wave concept only uses in total 48 unknowns per element, which is 15 times smaller. The calculation time was about 3 hours per frequency point on an HP 9000/780 160 MHz 512 MB RAM workstation. The inversion at the array level took about 1.5 hours. Extrapolation yields an inversion time at the array level 15^3 times larger for the commercial software packages.

6. References

[1] W. Chew et al., “Fast solution methods in electromagnetics”, IEEE-AP, vol. 45, no. 3, March 1997

[2] G. A. E. Vandenbosch and F. J. Demuynck, “The expansion wave concept – part II: A new way to model mutual coupling in microstrip arrays”, IEEE-AP, vol. 46, no.3, pp. 407-413, March 1998

[3] M. Vrancken and G. A. E. Vandenbosch, “Characteristic modes for the multiple stacked aperture problem with application to the finite array analysis of flat plate slot array antennas”, submitted to IEEE-AP

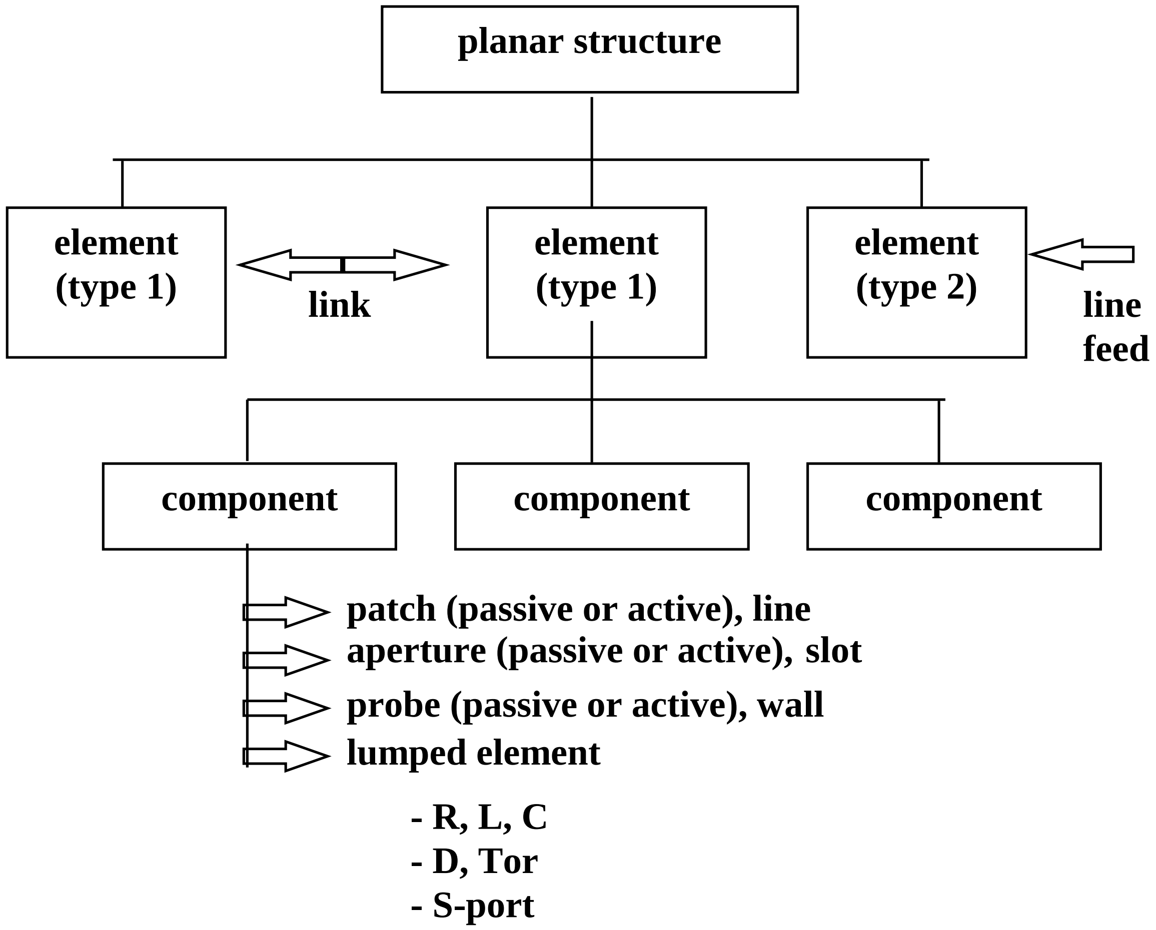

Fig. 1. Modular and hierarchical scheme for a 2.5D structure in a multilayer environment. The planar structure consists of elements of several types. Each element type consists of several components. The elements can be connected through transmission lines (microstrip line, strip line, coplanar waveguide, …). The planar structure is solved at different levels. First the internal coupling within the element types is described using a moment method to solve the integral equations on the components. For each coupling type, appropriate Green's functions have been calculated. This is the traditional approach. Second the mutual coupling between the elements is described using the Expansion Waves. This reduces the number of unknowns at the array level by an order of magnitude. Third the elements are linked through the transmission lines (= links), assuming the fundamental modes only on these links. This means that no mutual coupling with these links has to be taken into account. The procedure yields a calculation time which is far less than with commercial CAD packages.

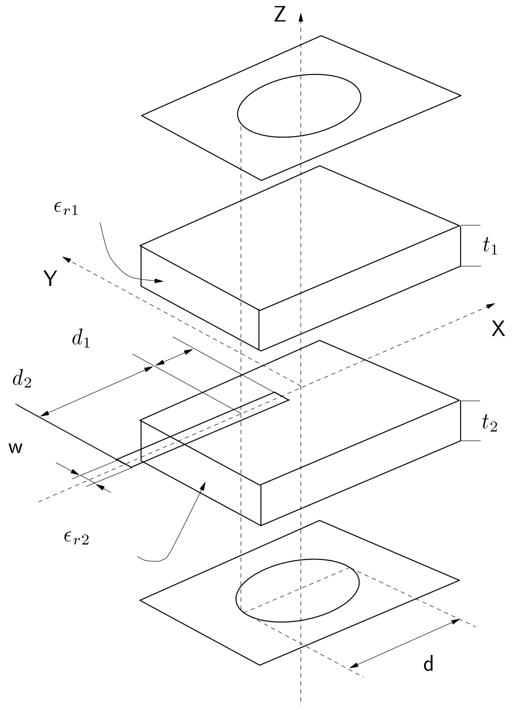

Fig. 2. Element type consisting of two stacked circular apertures in two conducting plates fed by a strip line in the middle region.

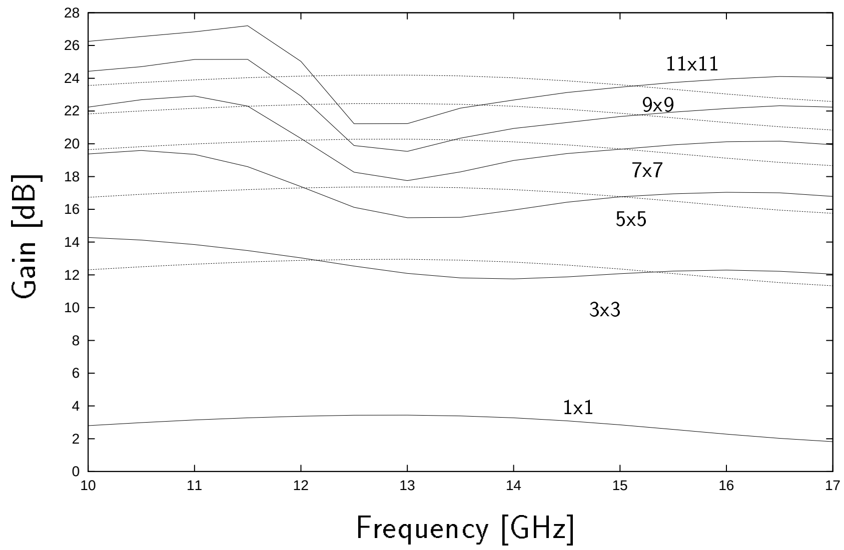

Fig. 3. Gain calculated with the EWC of a 1x1, 3x3, 5x5, 7x7, 9x9, and 11x11 array of the element type of Fig. 2. As a reference the gain calculated without taking into account mutual coupling is also depicted (curves without oscillation). The oscillation is at the frequency where the distance between the elements is one wavelength. It becomes more pronounced for larger arrays.