Reconstruction of Microwave Structures using two-dimensional Inverse TLM (Transmission Line Matrix) Method

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***Abstract* — This work proposes a new reconstruction procedure of two-dimensional microwave structures based on the inversion of the two-dimensional TLM (Transmission Line Matrix) method. The technique is based on the solution of the inverse scattering problem using a TLM based algorithm. The procedure consists of determining the geometry of the obstacle that generates the desired scattered field. In the case of TLM this field is the time-domain input reflection coefficient at all input terminals and the geometry is the impedance at all nodes of the TLM mesh. The procedure can be used to reconstruct objects with arbitrary characteristics in small TLM meshes.**

I. INTRODUCTION

The solution of inverse problems is a promising area in Electromagnetics. This kind of problem is quite different from the problems handled by popular field solvers. In field analysis problems, one uses computational tools to determine the unknown field created by a particular known configuration of sources and boundaries. In the inverse problem, it is necessary to determine what is the unknown configuration of sources and boundaries that result in a particular known field.

There are several algorithms used to estimate the geometry of a structure that causes a known field configuration [1]. Most of the proposed solutions use some degree of approximation. This work presents a new solution procedure based on the inversion of the two-dimensional TLM method. The one-dimensional inversion of TLM was presented in an earlier work [2]. The technique presented in this paper expands the concepts and ideas developed for 1D cases to 2D problems.

The two-dimensional inverse TLM procedure can be applied to several kinds of problems. It can be used with problems with dispersion, higher order modes and two-dimensional space variations of the structure. This kind of problem can not be solved with 1D TLM.

II. THEORY

In the one-dimensional case, the inverse TLM was used to determine an impedance profile of a discrete non-uniform transmission line. This profile was calculated by decomposing the time-domain input reflection coefficient. The input reflection coefficient is decomposed in terms of the reflection waves on all sections of the discrete transmission line. This was accomplished by using an iterative calculation of the inverse TLM algorithm at each section of the line. The result was exact within the sampling limits of the time-domain input reflection coefficient.

The use of TLM to solve two-dimensional inverse problems has some similarities with the inverse one-dimensional case. In both cases, the impulse sequences that compose the input reflection coefficient are used to determine the geometry of the problem. However the 2D inverse problem consists of the determination of an unknown geometry (obstacle) immersed in a particular region of space. The 1D algorithm works only with impedance profiles of transmission lines.

If an impulsive plane wave is incident in that particular region of space, the scattered field is the parameter used to calculate the geometry of the obstacle. Since 2D TLM can be used to determine the scattered field from a 2D obstacle for TMm0 and TEm0 waves, a TLM mesh can model the two-dimensional space. In this model, the geometry is represented by arbitrary variations of the impedance of the transmission lines.

Since TLM models the region by a NxM mesh of transmission lines [3-4], the TEM incident wave will be represented by incident impulses on each input line that composes the mesh. Similarly, other features of the obstacle will be represented by modifications in regions of the mesh. For instance, metallic regions can be modeled either by null impedance regions (short circuits) or by metallic walls between nodes. However, the reconstruction procedure (inverse 2D TLM) demands some modifications to the representation of impedances on the TLM mesh. In most implementations of 2D TLM [3-4], different dielectric constants are modeled by open circuited stubs connected to the TLM nodes (junction between two transmission lines). The value of the stub is calculated from the relative dielectric constant. If the relative permeability of the medium is one, this is equivalent to local impedances in the mesh.

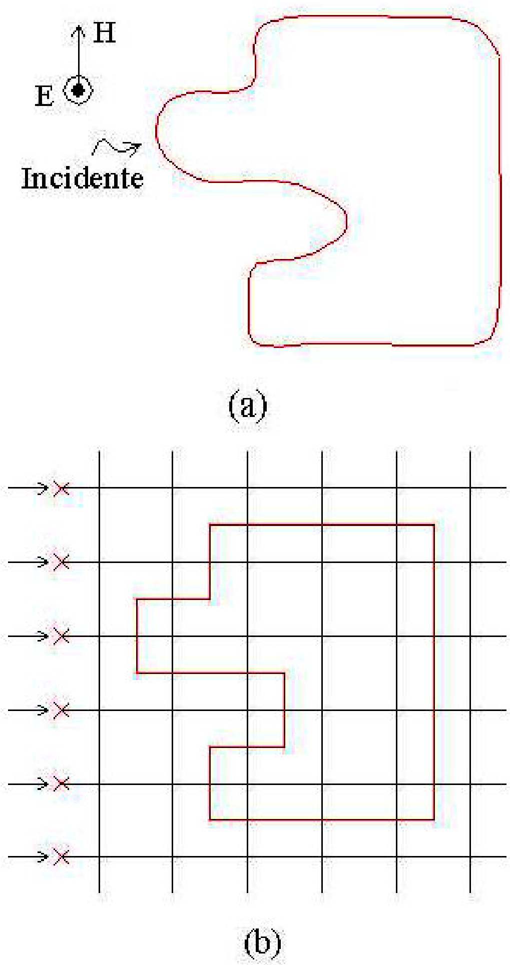

Fig. 1. Obstacle in free space: (a) continuous representation and (b) discrete model in 2D TLM.

The reconstruction requires that the representation of impedances on the mesh be realized by transmission and reflection coefficients between nodes. These coefficients simulate the behavior of junction of lines of different impedances. This can be seen in Fig. 2.

In the TLM model of the problem the scattered field can be seen and the total reflection coefficient at the input lines of the TLM mesh. Each line (numbered from x=1…M) will have a time domain response. This response is composed by the sum of the delayed reflected impulses from every element of the mesh. Therefore, the total input reflection coefficient is:

$$\Gamma_i(x,t) = \sum_{k=0}^{\infty} a_k(x)\, d(t - 2k\Delta t) \qquad (1)$$

Where ak(x) is a combination of the impulse response of all transmission lines up to column y=(k+2)/2 of the TLM mesh.

The analytical expression of ak(x) contains all the information necessary to determine the obstacle. However, its calculation is very complex and seldom can be performed. We propose the inversion of two-dimensional TLM to solve this problem.

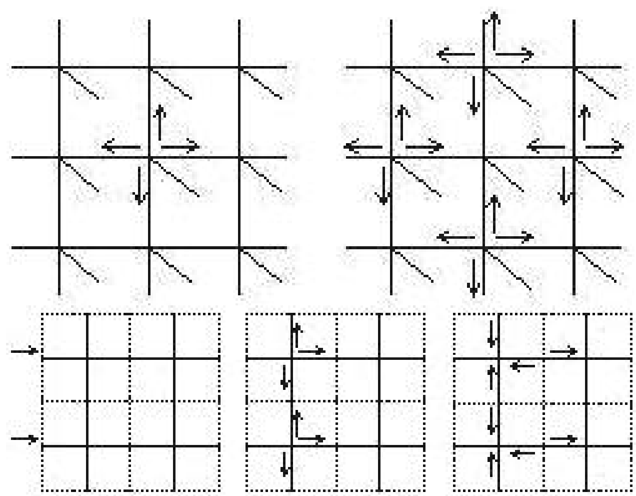

Fig. 2. TLM representations: (a) Stub loaded 2D TLM and (b) modified TLM mesh.

Using Fig. 2 and Fig.3 as references, it can be observed that the effect of the longitudinal propagation (through columns) appears at the input lines only at odd timesteps. This is a feature is similar to the one-dimensional case.

As in the one-dimensional case, the 2D TLM algorithm is used to describe the reflection and transmission of impulses at each node of the mesh. The procedure is performed in time-domain for an appropriate number of timesteps. At each node and timestep, the reflected waves are calculated using:

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix}^r = \frac{1}{2}\begin{bmatrix} -1 & 1 & 1 & 1 \\ 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \end{bmatrix}\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix}^i \qquad (2)$$

The transmitted waves are calculated with:

$$ {}_{k+1}V_1^i(x,y) = \frac{2\cdot Y_{x,y}}{Y_{x+1,y}+Y_{x,y}} \cdot {}_kV_3^r(x+1,y) + \frac{Y_{x+1,y}-Y_{x,y}}{Y_{x+1,y}+Y_{x,y}} \cdot {}_kV_1^r(x,y) \quad (3) $$

$$ {}_{k+1}V_2^i(x,y) = \frac{2\cdot Y_{x,y}}{Y_{x,y-1}+Y_{x,y}} \cdot {}_kV_4^r(x,y-1) + \frac{Y_{x,y-1}-Y_{x,y}}{Y_{x,y-1}+Y_{x,y}} \cdot {}_kV_2^r(x,y) \quad (4) $$

$$ {}_{k+1}V_3^i(x,y) = \frac{2\cdot Y_{x,y}}{Y_{x-1,y}+Y_{x,y}} \cdot {}_kV_1^r(x-1,y) + \frac{Y_{x-1,y}-Y_{x,y}}{Y_{x-1,y}+Y_{x,y}} \cdot {}_kV_3^r(x,y) \quad (5) $$

$$ {}_{k+1}V_4^i(x,y) = \frac{2\cdot Y_{x,y}}{Y_{x,y+1}+Y_{x,y}} \cdot {}_kV_2^r(x,y+1) + \frac{Y_{x,y+1}-Y_{x,y}}{Y_{x,y+1}+Y_{x,y}} \cdot {}_kV_4^r(x,y) \quad (6) $$

This implementation differs from traditional approaches as mentioned in a previous topic.

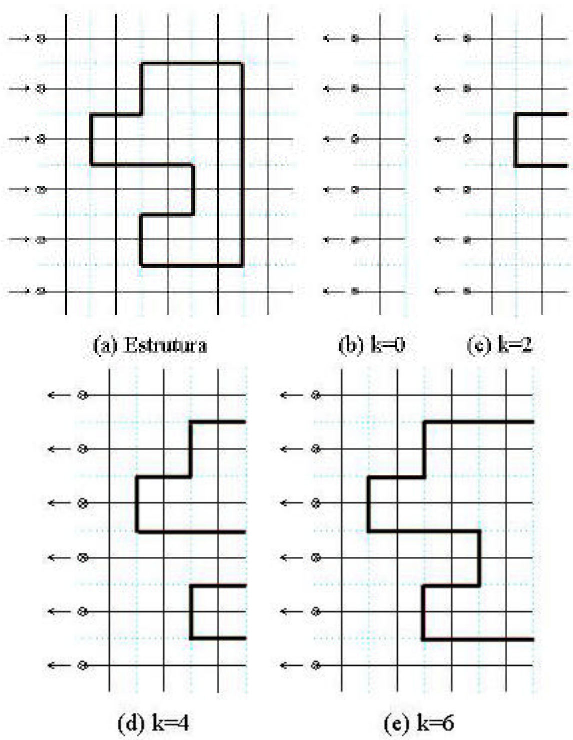

Fig. 3. 2D TLM mesh representing arbitrary electromagnetic structure that will be reconstructed (a), mesh section reconstructed for k=0 (b), k=2 (c), k=4 (d) and k=6 (e).

The inverse TLM procedure described in [2] can be applied in this case. Since the differences in impedance values are represented in the connections between nodes, the impulse propagation takes the form described in Fig. 4. Therefore, only the impulses travelling in the longitudinal directions will be responsible for the reflection coefficient information. Using this coefficient the impedance of the section can be determined as shown in [2].

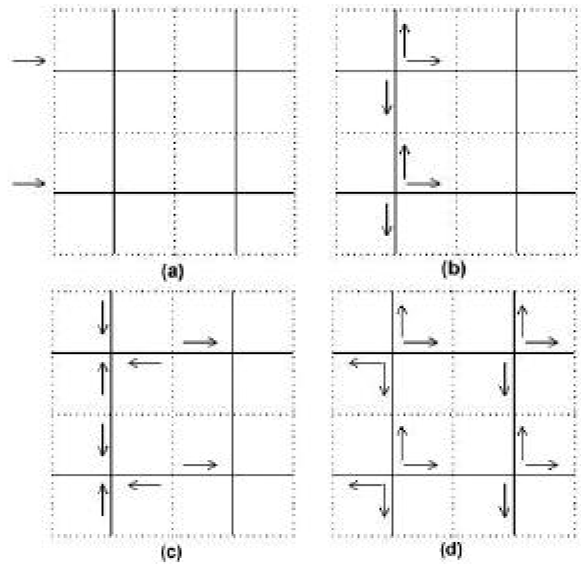

Fig. 4. Impulse propagation on 2D TLM mesh.

If two TLM simulations are performed, the reflection coefficient can be uniquely determined. In the first simulation the longitudinal travelling wave finds an open circuit. In the second simulation the wave finds a matched load. With these simulations the reflection coefficient at the point x1,y1 of the mesh is:

$$ \Gamma_{x_1,y_1} = \frac{a_{2k+1}(x_1,0) - a_{2k+1}^{matched}(x_1,0)}{a_{2k+1}^{open}(x_1,0) - a_{2k+1}^{matched}(x_1,0)} \quad (7) $$

With this coefficient the impedance at point x1,y1 can be calculated. This procedure will be repeated at each timestep up to the point when the time-domain input reflection coefficient can be truncated. This will yield the impedance matrix of the TLM mesh. This procedure can be performed in a parallel implementation.

III. Numerical Results

The first point to study in this procedure is the numerical stability. After several reconstructions, we verified that the technique is marginally stable. The reason is small numerical errors, which are present in the calculation of (7) for small reflections. These errors tend to grow since the procedure is done recursively. Nevertheless there are some ways to minimize the problem. If the reconstructed structure known to be metallic, a simple verification of the calculated impedance can prevent the stability problem. If it has mixed boundaries (dielectric and metal) a reduction of the significant algarisms of the response can delay the problem. In the latter case, the effective computational domain for a reconstruction is 20 x 20 TLM nodes.

The second point is the study of processing time. In the case of a TLM mesh with N2 nodes, 2N simulations will be performed. The processing time of the algorithm is of the order N4 as shown in Fig. 5. Therefore, if the number of elements is doubled the processing time will be roughly 16 times greater. The inverse 2D TLM was validated by numerical reconstructions of arbitrary structures in TLM meshes. The structure had the TLM response calculated and used in the reconstruction. The time-domain response at the input terminals is shown in Fig. 6. Fig. 7 shows the reconstructed structure. Since TLM was used in the calculation of the response, the reconstruction error is zero.

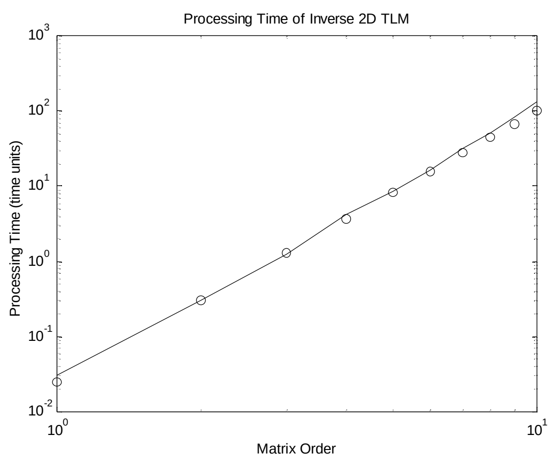

Fig. 5. Order of processing time of the inverse 2D TLM algorithm. (__)Numerical results and (o) Theory.

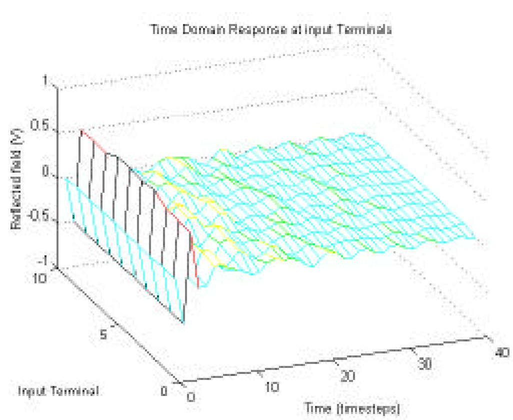

Fig. 6. Time-domain response at the input terminal of the mesh.

This technique allows the synthesis of microwave structures with arbitrary time-domain responses. It can also be used to design filters and other microwave structures. However, if only the dominant propagation mode is considered in the reconstruction, the resulting structure will be composed by a longitudinal sequence of dielectrics. The reason is that any filter designed using resonators is based on discontinuities (which cause higher order modes).

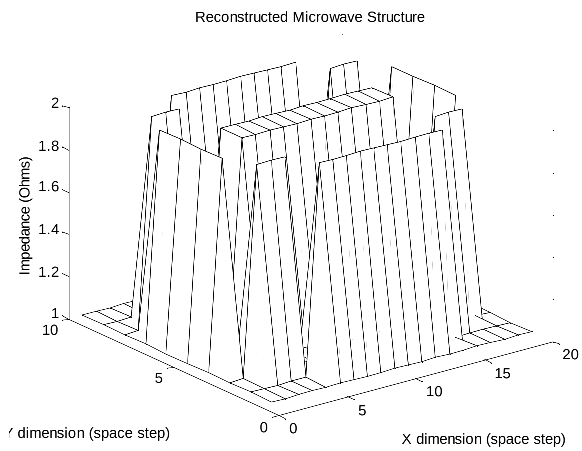

Fig. 7. Reconstructed object by inverse 2D TLM.

V. Conclusion

This work presented a new reconstruction technique for microwave structures using inverse scattering two-dimensional TLM. The procedure consists of using the inverse TLM method as a tool for determining the impedance in a 2D TLM mesh that represents an unknown microwave structure. This is accomplished using its the time domain input reflection coefficient at all input terminals of the TLM mesh. The procedure was validated with numerical simulations. The results show good agreement (within 0.1%). Research is being pursed in a three dimensional version of the procedure.

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