RADIO SCIENCE, VOL. 42, RS6002, doi:10.1029/2006RS003591, 2007

Efficient integral equation formulation for inductive waveguide components with posts touching the waveguide walls

F. J. Pérez-Soler,[1] F. D. Quesada-Pereira,[1] D. Cañete Rebenaque,[1]
J. Pascual-García,[1] and A. Alvarez-Melcon[1]

Received 20 November 2006; revised 29 June 2007; accepted 17 July 2007; published 20 November 2007.

[1] In this paper a surface integral equation technique is employed for the analysis of inductive waveguide problems containing metallic or dielectric objects of arbitrary shape, focusing on the case where these objects are connected to the waveguide walls. Using the extinction theorem, the main problem is split into two problems. In the first one the parallel plate waveguide Green's functions are used. Because of the choice of these functions, the side of the object touching the waveguide wall is not considered for discretization in a method of moments analysis. The second problem is applied inside the dielectric object, and uses the free space Green's functions. It is shown that an additional spatial image is needed to impose the proper boundary conditions for the fields on the side touching the waveguide wall in the original problem. Results show the importance of including this additional image in the formulation for the correct behavior of the fields. With the proposed technique, the paper explores some alternatives for designing specific filter responses using dielectric posts inside cavity filters. Comparisons with a commercial finite elements tool demonstrate the accuracy of the proposed integral equation formulation.

Citation: Pérez-Soler, F. J., F. D. Quesada-Pereira, D. Cañete Rebenaque, J. Pascual-García, and A. Alvarez-Melcon (2007), Efficient integral equation formulation for inductive waveguide components with posts touching the waveguide walls, *Radio Sci.*, *42*, RS6002, doi:10.1029/2006RS003591.

1. Introduction

[2] Surface integral equation (IE) formulations are one of the most well known techniques for computing electromagnetic fields in scattering problems involving conducting bodies. These formulations also allow for the analysis of homogeneous dielectric or magnetic objects applying the surface equivalence principle [*Peterson et al.*, 1998; *Arvas and Sarkar*, 1989; *Harrington*, 1989]. Even though the main usage of these formulations in previous references is the calculation of radar cross sections (RCS) of arbitrarily shaped objects, the scattered fields can be used for other important applications [*Reiter and Arndt*, 1995; *Catina et al.*, 2005]. For instance, *Pérez-Soler et al.* [2007] employed a surface IE formulation for the analysis of inductive multiport microwave components containing obstacles. By means of the extinction theorem, the method considers two equivalent problems separated by a ground plane imposed on the excitation port. Also, *Quesada-Pereira et al.* [2006b] combined the Kummer and Ewald transformations in a surface, i.e., formulation for the analysis of metallic and dielectric objects. These techniques were used for the acceleration of the series involved in the parallel plate waveguide (PPW) Green's functions calculations. Finally, *Reiter and Arndt* [1995] and *Catina et al.* [2005] combined an integral equation formulation with a mode matching technique for the analysis of waveguide components.

[3] A common feature of the previous techniques is that they fail if special care is not taken when a dielectric object is touching one of the waveguide walls. This is because the waveguide walls introduce special boundary conditions for the fields, which are not appropriately imposed by these formulations. In this context, this paper presents an integral equation technique, specializing the formulation for the case of inductive waveguides which contain metallic or dielectric obstacles with one side touching one of the walls of the waveguide. Therefore

[1]Departamento de Tecnologías de la Información y las Comunicaciones, Technical University of Cartagena, Cartagena, Spain.

0048-6604/07/2006RS003591$11.00

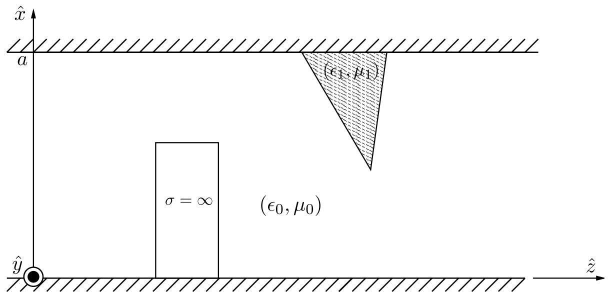

Figure 1. Original problem under study: a rectangular waveguide of width *a* with different metallic and homogeneous bodies connected to the walls.

the most important new feature of the proposed technique, with respect to previous works, is that the obstacles under consideration are attached to one of the waveguide walls, where some important considerations must be taken into account.

[4] It is important to notice that the formulation derived can be used for the analysis of practical inductive waveguide components. Inductive devices are widely used in satellite and other high power applications, thus the interest in their analysis. In inductive waveguide devices, the obstacles are all uniform along the height of the waveguide. This symmetry is exploited in the formulation presented, in order to reduce the computational cost. Another advantage of using this symmetry is that the two-dimensional (2-D) parallel plate Green's functions of infinite line sources can be used in the kernel of the integral equation. In this way, efficient formulations available for these Green's functions can be exploited [*Quesada-Pereira et al.*, 2006b]. The use of these parallel plate Green's functions is convenient, since then the lateral walls of the waveguide are automatically included in the kernel of the integral equation. Therefore they do not need to be discretized during the numerical solution of the integral equation, thus reducing the size of the linear systems to be inverted.

[5] On the contrary, the main drawback of the formulation is that nonuniform posts along the height of the waveguide cannot be studied directly with this approach, due to the infinite line sources Green's functions used in the kernel of the integral equation. The extension of the formulation, however, to full 3-D obstacles inside waveguide structures is possible by modifying the kernel with full 3-D waveguide Green's functions due to elementary point sources.

[6] The formulation is first presented in full detail in section 2, and it is then illustrated with some example results. The possibility of performing an accurate analysis of dielectric objects attached to the walls is exploited for the study of new inductive filters that present interesting bandpass frequency responses. Also, important properties such as the reduction of multipactor risk for space applications can be obtained with dielectric objects attached to the waveguide walls, as it was pointed out by *Quesada-Pereira et al.* [2006a]. All the presented results prove the efficiency and the accuracy of the proposed new integral equation technique, when applied to the design of inductive waveguide microwave problems containing dielectric objects attached to the walls. Results obtained with a commercial finite elements tool (HFSS©) are also included for validation of the new technique.

2. Theoretical Outline

[7] The problem under study consists of a rectangular waveguide which contains metallic and dielectric elements, as shown in Figure 1. By means of the surface equivalence principle, this original structure can be replaced with two different equivalent coupled problems. The first one, called external, considers the presence of electric and magnetic current densities which radiate inside an empty waveguide as showed in Figure 2a. On the other hand, the second equivalent problem, known as internal, considers the radiation of electric and magnetic currents of opposite signs inside an unbounded homogeneous medium with constitutive parameters (ϵ_1, μ_1) (Figure 2b). Because of the fact that the fields are zero inside a perfect conducting area, the electromagnetic problem need not to be explicitly formulated inside metallic obstacles.

[8] For the external problem, the total electric and magnetic fields $\mathbf{E}^{(\mathrm{ext})}$, $\mathbf{H}^{(\mathrm{ext})}$ are expressed as follows:

$$\mathbf{E}^{(\mathrm{ext})} = \mathbf{E}^{s}_{\mathrm{ext}}(\mathbf{J}_d, \mathbf{M}_d, \mathbf{J}_c) + \mathbf{E}^{i} \tag{1}$$

$$\mathbf{H}^{(\mathrm{ext})} = \mathbf{H}^{s}_{\mathrm{ext}}(\mathbf{J}_d, \mathbf{M}_d, \mathbf{J}_c) + \mathbf{H}^{i} \tag{2}$$

where the incident fields ($\mathbf{E}^i$, $\mathbf{H}^i$) are generally derived from an incident TE_{10} fundamental mode, and ($\mathbf{E}^s$, $\mathbf{H}^s$) are the fields scattered by the inductive obstacles.

[9] For the internal problem, as the excitation is not present, the total fields are

$$\mathbf{E}^{(\mathrm{int})} = \mathbf{E}^{s}_{\mathrm{int}}(-\mathbf{J}_d, -\mathbf{M}_d) \tag{3}$$

$$\mathbf{H}^{(\mathrm{int})} = \mathbf{H}^{s}_{\mathrm{int}}(-\mathbf{J}_d, -\mathbf{M}_d) \tag{4}$$

The integral equation formulation continues with the imposition of the boundary conditions for the fields inside the structure. First, the tangential electric field on

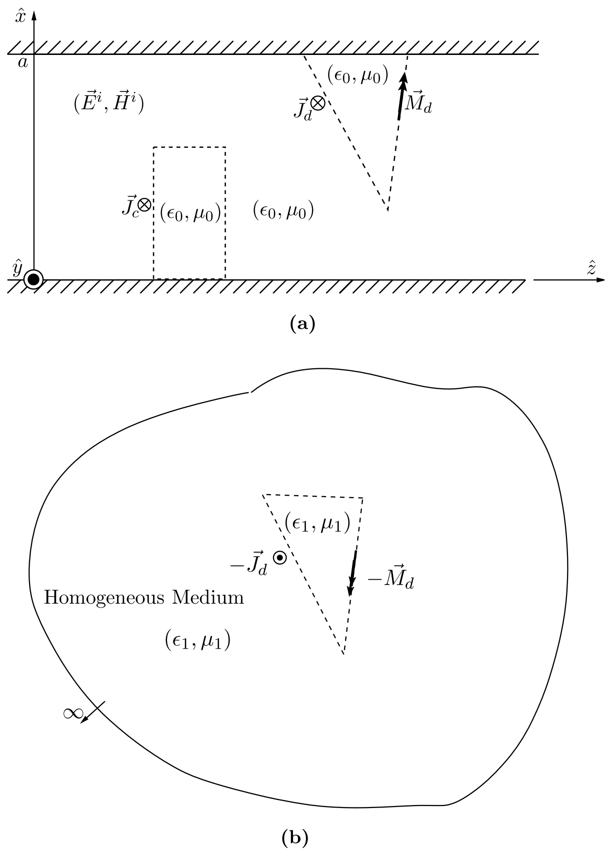

Figure 2. Decomposition of the problem in Figure 1, in two equivalent problems by means of the surface equivalence principle. (a) External problem. (b) Internal problem.

conducting surfaces is null (EFIE), and second, the total tangential electric and magnetic fields must be continuous across the dielectric post surfaces (PMCHWT formulation [*Lloyd et al.*, 2004]). In that reference, it was shown that the PMCHWT formulation is one of the most robust from the numerical point of view, since it is free from internal resonances. Therefore this is our selection for the surface, i.e., implemented in this paper.

[10] Combining these conditions, a set of coupled integral equations is obtained, as explained by *Quesada-Pereira et al.* [2006b]. It is important to point out that the Green's functions employed for each one of the equivalent problems are different: for the inner problem, unbounded homogeneous Green's functions are used (see Figure 2b), whereas the external problem is treated with the parallel plate waveguide Green's functions (see Figure 2a), which have been efficiently calculated by a combination of several acceleration techniques of *Quesada-Pereira et al.* [2006b].

2.1. Treatment of Surfaces Attached to the Waveguide Walls

[11] First, let us consider the case of a metallic post attached to one of the waveguide walls. This situation does not have any implication for the internal problem, as conducting objects are not considered there. However, for the external problem, the parallel plate waveguide Green's functions will short-circuit any electric current density placed on the side attached to the waveguide wall. We can take this situation into account in an easy way, by discretizing only the inner sides of the objects when applying method of moments (MoM) for solving the surface integral equation, as shown in Figure 3.

[12] Next, we consider a more complex case formed by a homogeneous dielectric and/or magnetic object (ϵ_1, μ_1) with one side touching one of the waveguide walls (see Figure 1). This obstacle leads to the presence of both electric and magnetic current densities defined on its surface. As we have already pointed out, the external problem is formulated in terms of the parallel plate waveguide Green's functions (see Figure 2a). These Green's functions impose particular boundary conditions to the side of the obstacle touching the waveguide wall. In fact, the waveguide wall is a perfect electric conductor, so that it will short-circuit again the equivalent electric currents on the side of the dielectric object attached to this wall. In addition, the waveguide wall imposes the nullity of the tangent electric field in the original problem. Since the magnetic current density defined on the surface of the object is related to the tangent electric field, this means that the magnetic currents must also be zero on the touching side of the object.

[13] Since the magnetic currents are zero on the waveguide wall due to the boundary conditions of the tangent

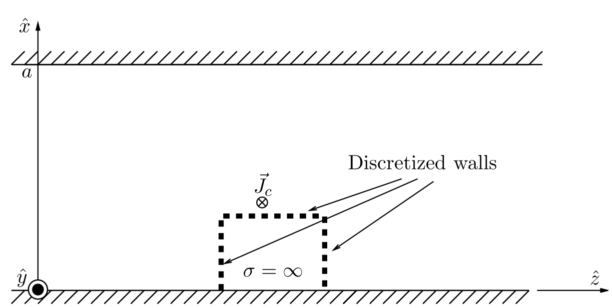

Figure 3. Conducting object attached to the lower plate. As surface electric current $\mathbf{J_c}$ does not exist on the plate, only the internal walls are discretized for a MoM analysis.

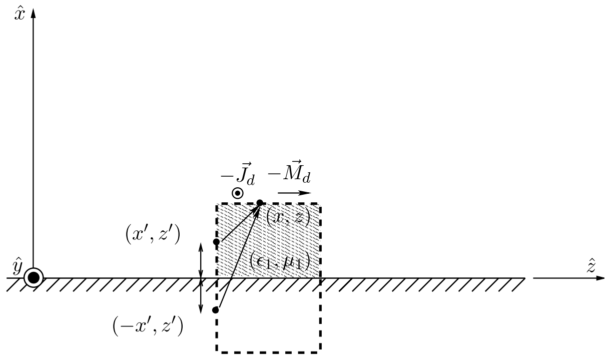

Figure 4. Homogeneous object with constitutive parameters (ϵ_1, μ_1) attached to the lower plate. In this case, for each interaction between two points (x, z) and (x', z'), a spatial image with respect to the plate ($-x'$, z') is also considered.

electric field, and the boundary conditions for the tangent magnetic field are already imposed by the Green's functions, then we do not need to consider equivalent currents on the side of the dielectric object touching the waveguide wall. The easiest way to proceed, then, is not to mesh this side of the dielectric object during the numerical solution of the integral equation by the MoM. We observe that, for this external problem, the treatment of the dielectric objects is the same as of the metallic objects touching one of the waveguide walls.

[14] The main difference when treating dielectric objects is that an internal problem, as shown in Figure 2b, must be formulated inside the object. For this internal problem the Green's functions for an unbounded homogeneous medium of constitutive parameters (ϵ_1, μ_1) are used. However, if one side of the object touches one of the waveguide walls, the equivalent electric and magnetic current densities are removed from this side due to the boundary conditions imposed by the walls in the external problem. If we just use the homogeneous medium Green's functions, as usual, then the boundary conditions for the fields are not imposed on the touching side for this internal problem. Normally, the equivalent electric and magnetic currents are used to take care of this boundary conditions. However, we are not considering these currents on this side of the object, due to the considerations made in the external problem. Therefore another mechanism for imposing the boundary conditions on this side must be investigated.

[15] The right way to proceed for the internal problem is to use different more complex Green's functions, which can automatically account for the boundary conditions of the fields on the side of the object touching, in the original problem, one of the waveguide walls. This can be easily done by using Green's functions composed of the original source placed in a semi-infinite medium, radiating in the presence of an infinite ground plane, located at the position of the intervening waveguide wall in the original problem. This situation is illustrated in Figure 4. In this way, the boundary conditions for the fields on the side of the object attached to the wall will also be automatically enforced. Using these new Green's functions, electric and magnetic current densities on this side of the object are also removed for this internal problem. With this formulation, then, only the remaining sides of the dielectric object need to be discretized during the numerical solution of the integral equation using MoM, simplifying considerably this last step. Also, the efficiency of the technique is increased, since the strict minimum unknowns are used during the numerical solution.

[16] Using the proposed approach, the Green's functions for the internal problem can be finally written as

For lower plate

$$G^{(\mathrm{int})}(x,x',z-z') = G(x,x',z-z') + s_g\, G(x,-x',z-z'), \tag{5a}$$

For upper plate

$$G^{(\mathrm{int})}(x,x',z-z') = G(x,x',z-z') + s_g\, G(x,2a-x',z-z'), \tag{5b}$$

$$G(x,x',z-z') = \frac{\xi}{j4} H_0^{(2)}(k_0\,\rho), \quad \rho = \sqrt{(x-x')^2+(z-z')^2} \tag{5c}$$

where the factor ξ and the sign operator $s_g = \pm 1$ depend on the kind of dyadic component, and are also defined by *Quesada-Pereira et al.* [2006b]. Figure 4 shows an example for an object joined to the lower plate. By adding an spatial image located in the other side of the plate, the new Green's functions force the right boundary conditions, which were obviated by the absence of equivalent currents on the connected wall. The consideration of these new Green's functions for the internal problem is essential in order to obtain the right solution, as it will be shown with an example in section 3.

2.2. Numerical Considerations

[17] In addition, another important consideration must be taken into account when dealing with homogenous objects. It is known that, on this kind of surfaces, the singular interactions associated to the curl integrals must be extracted in the Cauchy sense [*Peterson et al.*, 1998]. Because we are using the PMCHWT formulation, the

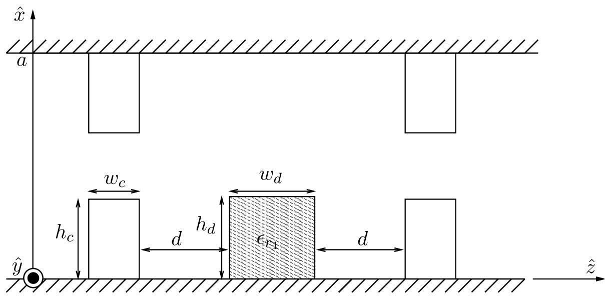

Figure 5. A single cavity filter with a dielectric post connected to one of the walls and placed between the two inductive windows. The waveguide width is $a = 19.05$ mm. The dimensions have been set to $d = 7.5$ mm, $h_c = 4.2$ mm, $w_c = 4$ mm, $h_d = w_d = 6$ mm. The value of the relative permittivity is $\epsilon_{r_1} = 4$.

Cauchy principal value is cancelled out between the external and the internal problems. However, this cancellation only occurs for the original source in free space. However, in the internal problem we now have an additional spatial image in the Green's functions. The resulting situation is that the singular interaction for the curl operator gives rise to two terms. The first is due to the original source, which only exists in the Cauchy sense, and it is annihilated by the external problem in the PMCHWT formulation. The second one is due to the spatial image, and it is not annihilated. Fortunately enough, this term is not singular, since the spatial image is always placed outside the observation region. Then, the resulting term can be easily evaluated using standard integration techniques.

[18] The general form of these singular curl integrals is

$$I_c = \int_0^L \mathbf{f}(l) \int_0^L \mathbf{f}(l') \times \nabla \Big[G^{(\mathrm{int})}(x, x', z - z') - G(x, x', z - z') \Big] \, dl' \, dl \tag{6}$$

where $\mathbf{f}$ is a general basis or test function previously chosen for the MoM procedure, and $G^{(\mathrm{int})}$ and G were shown in (5). In equation (6), the expression $(G^{(\mathrm{int})} - G)$ refers to the internal problem. Here, the term $-G$ only compensates the source contribution in (5), but not the one corresponding to the spatial image, which remains in the curl integral. However, the overall function $(G^{(\mathrm{int})} - G)$ is not singular and can be easily evaluated with standard numerical integration cubature rules [*Cools*, 1999].

[19] The curl integrals are due to the cross interactions between electric and magnetic currents and fields. A part from these cross interactions, we will also have to face the traditional singular situation for the noncross interactions (electric field with electric source or magnetic field with magnetic source). For these interactions, the curl operator is not present in the kernel of the integral equation. Consequently, these interactions lead to the well known weak singularity of the mixed potential Green's functions. The treatment of this singularity follows the extraction of the typical logarithmic asymptotic term of the Hankel function for small arguments [*Peterson et al.*, 1998].

[20] For the numerical solution of the formulated integral equation we have implemented a MoM algorithm using triangular basis and test functions (Galerkin technique). An interesting question that must be addressed, is how to model the currents at the contact points between the dielectric posts and the waveguide wall. In particular, we must study whether we need to consider or not the presence of half triangular functions in the segments of the objects that are just in contact to the waveguide walls. If we do not include half triangular functions, then the currents will be forced to be zero at the contact point. On the contrary, the use of half triangular functions will allow the currents to flow through the contact point toward the waveguide wall.

[21] To answer this question, we must think what happens to the electric and magnetic currents on the attached side of the object. First, the electric current, which is always tangent to the waveguide wall, will be forced to be zero by the spatial image added to the Green's functions. Therefore this current will naturally tend to go to zero at the contact point. Second, the magnetic current must also be zero. This magnetic current can have two components, one tangent and one normal to the waveguide wall. The tangent component of the magnetic current is related to the tangent component of the electric field, which must be zero on the waveguide wall to satisfy its boundary condition. On the other hand, the normal component of the magnetic current will be forced to be zero, again by the action of the spatial image added to the Green's functions. As a conclusion, both electric and magnetic currents will tend to be zero at the contact point. This conditions can be easily imposed in the formulation, by terminating the mesh of the sides of the dielectric objects without half triangular basis functions.

3. Results

[22] In order to show the importance of the correct treatment of the internal problem when dealing with dielectric objects attached to the waveguide walls, let us consider a useful example consisting in a single cavity filter with a square dielectric inductive post connected to the lower plate, as shown in Figure 5.

[23] Figure 6 shows the simulated scattering parameters obtained by using different theoretical models. First, in Figure 6a we consider the case of the dielectric

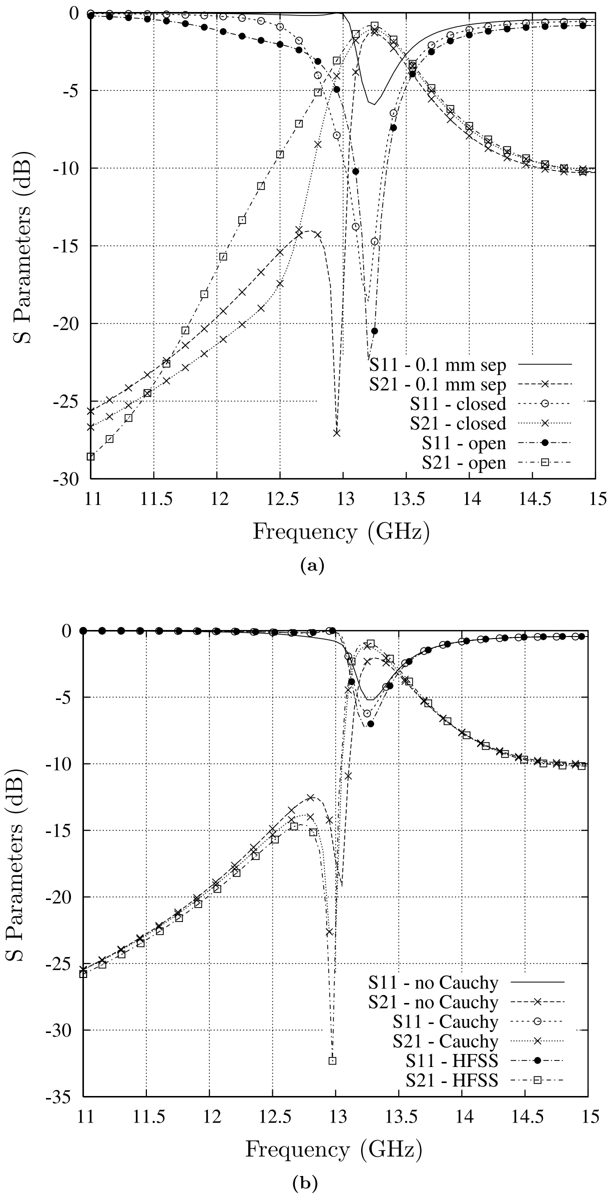

Figure 6. Scattering parameters of the filter shown in Figure 5, using different theoretical models. (a) Using free space Green's functions. (b) Using an additional spatial image in the internal problem.

post close to the waveguide wall, but not attached to it (a 0.1 mm distance is considered). In this case all the four sides of the dielectric object are discretized during the MoM application, and the standard Green's functions of a simple homogeneous medium are used. The results obtained in this situation are correct, and they are shown in Figure 6a with the label "0.1 mm sep."

[24] Next, we attach the square dielectric post to the wall, still considering discretization of the four sides of the post. In this case, the tangent electric field is zero on this wall, so the equivalent magnetic currents must also be zero on the touching side of the object. Since this boundary condition is not explicitly imposed by the PMCHWT formulation, the computed scattered fields are wrong, as it can be noticed in the results of Figure 6a for the "closed" case. The next test is to analyze the dielectric post discretizing only the three internal sides. Again, the standard free space Green's functions are used for the internal problem. Since no equivalent currents are considered in the side touching the wall, the appropriate boundary conditions for the fields must be imposed inside the Green's functions. However, the free space Green's functions used do not satisfy the proper boundary conditions in the internal problem along the side of the object attached to the waveguide wall. The results are presented in Figure 6a ("open" case), showing again a wrong behavior. This is because the proper boundary conditions are not imposed in the internal problem along the side of the object attached to the waveguide wall.

[25] In the next test we analyze the dielectric post attached to the wall, discretizing only the three internal sides, but using the new Green's functions shown in equation (5). Still, we do not take into account the singular integrals of the curl operator given in equation (6). The results for this test are shown in Figure 6b ("no Cauchy" case). We observe that the results are closer to the right solution, but still the transmission and reflection levels are wrong. Finally, Figure 6b shows the results using the new Green's functions, and the correct singular curl integrals (Cauchy case in Figure 6b). Results obtained with the finite elements software HFSS are also included for validation. We can observe that in this last case the agreement with HFSS is excellent. It is also worth noticing, that the right results obtained in Figure 6b when the dielectric post is attached to the wall, are very similar to the results obtained in Figure 6a when the dielectric is close (but not attached) to the waveguide wall. This additional result also validates the general theory presented in this paper. In addition, all these results show the necessity of applying the right Green's functions for the internal problem in order to compute the right values of the fields, and therefore for obtaining exact scattering parameters when analyzing filter responses. For all cases, the MoM has been solved employing triangular basis and testing functions (Galerkin approach).

[26] Once proved that structures with dielectric objects connected to the walls can be analyzed correctly, it is possible to obtain interesting filter responses using these off-centered dielectrics. The first filter is based on the structure shown in Figure 5, and its response is optimized by adjusting the height of the dielectric post h_d to 4 mm. Results for the filter using the integral equation

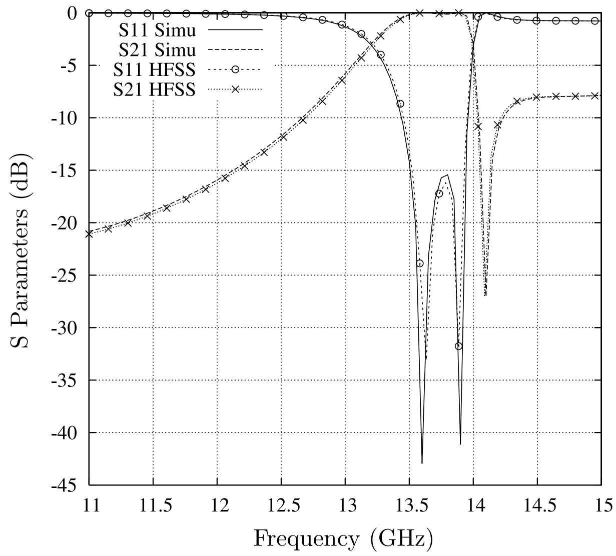

Figure 7. Scattering parameters of the same filter presented in Figure 5, when h_d is changed to 4 mm.

developed in this paper are compared in Figure 7 with results obtained with HFSS. The filter was analyzed employing 44 basis functions for each inductive window and 56 basis functions for the dielectric post (a total of 144 unknowns). The new software tool takes 1.4 s per frequency point on a computer with a 3.2 GHz processor. The results agree with those obtained with HFSS, which needs 31 s per frequency point on the same computer. It is worth noticing that the response synthesized with this structure is of the same type as those presented by *Guglielmi et al.* [2001] for elliptic inductive filters. Only in our case it is not necessary to change the volume of the initial structure, while it is still possible to implement transmission zeros in the insertion loss response of the filter.

[27] It is important to point out that to obtain the HFSS results, a full 3-D waveguide structure must be analyzed. This is because the finite elements technique implemented in this software needs to discretize the whole volume of the structure. In this case we have taken as the base waveguide the standard WR-75 waveguide (a = 19.05 mm, b = 9.525 mm). Therefore, in the HFSS model all inductive obstacles have a fixed height equal to b = 9.525 mm (along the y axis shown in Figure 1). On the contrary, with the formulation presented in this paper the invariance of the structure along this axis is exploited. In this way it is possible to reduce the real 3-D waveguide structure to a 2-D problem, thus gaining in efficiency. The good agreement obtained with HFSS results shows the capability of the new formulation to study practical inductive waveguide devices.

[28] More interesting filter responses can be obtained by adding more dielectric objects, and by adjusting their dimensions and distances from the inductive windows. Figure 8 shows the case of two dielectric posts of different heights placed asymmetrically inside the cavity. For this example, a convergence study in terms of the

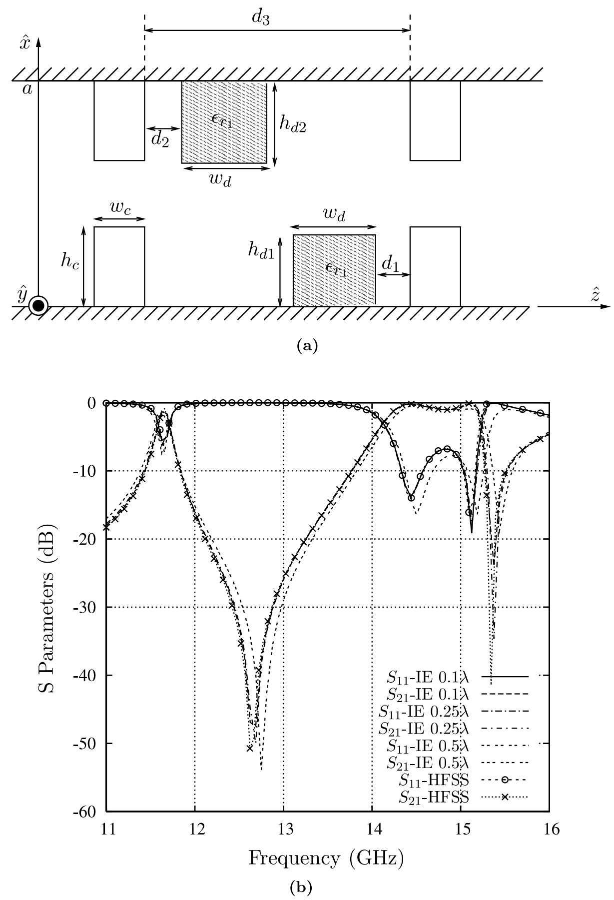

Figure 8. Analysis of a single cavity inductive filter with two rectangular dielectric posts attached to the walls. The waveguide width is a = 19.05 mm. The dimensions have been set to d = 7.5 mm, h_c = 4.2 mm, w_c = 4 mm, w_d = 6, h_{d1} = 4.05 mm, and h_{d2} = 5.05 mm. Distances from the dielectric objects to inductive windows are d_1 = d_2 = 3.4 mm, and the distance between inductive windows is d_3 = 21 mm. The value of the relative permittivity is ϵ_{r_1} = 4. (a) Geometry of the structure. (b) Convergence study of the scattering parameters of the proposed filter in terms of the number of basis functions used in the integral equation, as compared to HFSS results.

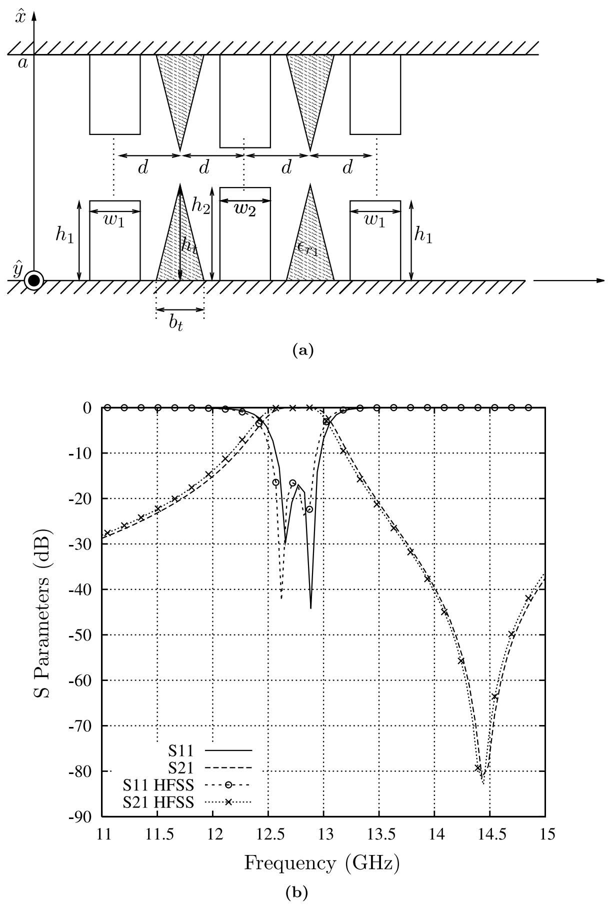

Figure 9. Analysis of a two-pole inductive filter loaded with inductive dielectric triangular posts attached to the walls. The waveguide width is $a = 19.05$ mm. Dimensions of the inductive windows are $w_1 = w_2 = 2$ mm, $h_1 = 4.675$ mm, and $h_2 = 6.125$ mm. All triangles are equal sized with $h_t = 8$ mm and $b_t = 2$ mm. Distance between object centers is $d = 4$ mm. The relative permittivity constant is $\epsilon_{r_1} = 11$. (a) Geometry of the structure. (b) Scattering parameters of the proposed filter as compared to HFSS results.

number of basis functions employed is also included. The first result has been obtained by using the common rule of using one basis function per tenth of the wavelength. This is the common criterion followed in the method of moments (MoM) problems to assure good convergence, for point matching formulations. Since we use a Galerkin formulation with triangular basis and test functions, we expect that lower number of basis functions will be needed to achieve convergence. In this case we use a total of 100 unknowns, taking into account that on the dielectric surfaces the electrical length is greater than in the metallic areas because of the reduction of the wavelength by the permittivity. The agreement obtained with HFSS is very good in this case. The finite elements technique employed 54.3 s per frequency point, whereas the IE approach needed 1.6 s on the same computer.

[29] To show the convergence properties of the method with the mesh density, we have next considered two less strict discretization criteria. The first uses a cell size of 0.25 λ (with a total of 48 unknowns), and the second uses a larger cell size of 0.5 λ (with a total of only 28 unknowns). The results obtained show that even in these cases the numerical convergence is good. Only a small frequency shift can be observed for the large cell size of 0.5 λ. These results show that the choice of triangular basis functions in the MoM procedure allows to use a limited number of unknowns, for achieving acceptable accuracy. Even in the third case, using a cell size of 0.5 λ, the response still offers a reasonable agreement with HFSS. Even though the overall structure is electrically large, the walls of the waveguide are not discretized, since they are included inside the Green's functions of the problem. The only objects that need to be discretized are the steps and posts placed inside the waveguide, and these are of small electrical size, ranging from 0.22 λ for the metallic steps to 0.64 λ in the case of the dielectric posts. Because of this fact, reasonable convergence is attained even using only 28 basis functions. We can observe from the results, that the obtained scattering parameters exhibit a response with two poles and two zeros within the frequency band between 13 and 15.5 GHz. This behavior is obtained by means of the asymmetry of the dielectric obstacles attached to the walls. This structure can be used to implement two transmission zeros on both sides passband, for maximum selectivity.

[30] Another interesting application concerning the placement of dielectric obstacles connected to the waveguide walls is the possibility of reducing multipactor risk for space applications. Multipactor phenomenon is a serious problem for space devices, where the vacuum conditions and the usage of high power levels may cause electrons to bounce from one side of the cavities to the other, therefore severely damaging electrical devices [*Vicente et al.*, 2005]. *Quesada-Pereira et al.* [2006a] performed a serious study on the influence of several factors in multipactor risk in inductive filters (i.e., bandwidth, shape of inductive windows, order of the filter). Their study showed that the presence of dielectric posts inside the filters, wisely placed on the waveguide walls, can reduce the multipactor risk. Figure 9 presents the case of a two-pole inductive filter with triangular dielectric posts attached to the walls, which has been analyzed with the formulation proposed in this paper. *Quesada-Pereira et al.* [2006a] showed that this struc-

ture can reduce the multipactor risk in 30%, as compared to a filter with similar response and no dielectric posts. For the analysis of this structure, a total of 259 basis functions were employed. The IE took 3.9 s per frequency point, whereas HFSS needed 63.75 s on the previously mentioned computer.

4. Conclusions

[31] In this paper a new surface integral equation formulation for the analysis of inductive structures with dielectric and metallic obstacles attached to the walls has been proposed. By means of the surface equivalence principle, it is possible to split the main problem into two equivalent problems, namely, the external and the internal, where different kinds of Green's functions are used. Because of the properties of the parallel plate waveguide Green's functions used in the external problem, only the inner walls of the attached objects are considered for meshing in a MoM analysis. Besides, special emphasis has been put in the case of dielectric obstacles touching the waveguide walls. It is shown the importance to include a spatial image with respect to an infinite ground plane in the internal problem, to properly impose the boundary conditions for the fields in the touching side. The necessity of these special considerations, in order to obtain correct results, has been stressed. The possibility of analyzing filters with dielectric objects connected to the walls allows to obtain interesting filter responses employing simple geometries. In addition, the study of this kind of structures is also important for the reduction of multipactor risk for space applications. The presented results prove that the CAD tool developed using the proposed method allows to analyze all these structures with the same accuracy as finite element methods, saving computational cost and, consequently, designing time.

[32] **Acknowledgments.** This work has been developed with support from the Spanish National Project (CICYT) with Ref TEC2004-04313-C02-02/TCM, and the Regional Seneca Project with Ref 02972/PI/05.

References

Arvas, E., and T. K. Sarkar (1989), RCS of two-dimensional structures consisting of both dielectrics and conductors of arbitrary cross section, *IEEE Trans. Antennas Propag.*, *37*(5), 546–554.

Catina, V., F. Arndt, and J. Brandt (2005), Hybrid surface integral equation/mode-matching method for the analysis of dielectric loaded waveguide filters of arbitrary shape, *IEEE Trans. Microwave Theory Tech.*, *53*(11), 3562–3567.

Cools, R. (1999), Monomial cubature rules since stroud: A compilation, part.2, *J. Comput. Appl. Math.*, *112*(1–2), 21–27.

Guglielmi, M., P. Jarry, E. Kerherve, O. Roquebrun, and D. Schmitt (2001), A new family of all-inductive dual-mode filters, *IEEE Trans. Microwave Theory Tech*, *49*(10), 1764–1769.

Harrington, R. F. (1989), Boundary integral formulations for homogeneous material bodies, *J. Electromagn. Waves Appl.*, *3*(1), 1–15.

Lloyd, T., J. Song, G. Kang, and C.-C. Lu (2004), Numerical study of surface integral formulations for homogeneous bodies, in *Antennas and Propagation Intenational Symposium*, vol. 4, pp. 3895–3898, Inst. of Electr. and Electron. Eng., New York.

Pérez-Soler, F. J., F. D. Quesada-Pereira, J. Pascual-García, D. Ca nete-Rebenaque, and A. Álvarez-Melcón (2007), Analysis of inductive waveguide microwave components using an alternative port treatment and efficient fast multipole, *Prog. Electromagn. Res.*, *68*, 71–90.

Peterson, A. F., S. L. Ray, and R. Mittra (1998), *Computational Methods for Electromagnetics*, 451 pp., IEEE Press, New York.

Quesada-Pereira, F., V. Boria, B. Gimeno, D. Cañete-Rebenaque, J. Pascual-García, A. Álvarez-Melcón, J. Hueso-González, D. Schmitt, D. Raboso, C. Ernst, and I. Hidalgo-Carpintero (2006a), Investigation of multipaction phenomena in passive waveguide filters for space applications, in *IEEE MTT-S International Microwave Symposium Digest*, Inst. of Electr. and Electron. Eng., New York.

Quesada-Pereira, F., F. Pérez-Soler, B. Gimeno-Martínez, V. E. Boria-Esbert, J. Pascual-García, J. L. Gómez-Tornero, and A. Álvarez-Melcón (2006b), Efficient analysis tool of inductive passive waveguide components and circuits using a novel space domain integral formulation, paper presented at uropean Microwave Conference, Inst. of Electr. and Electron. Eng., Manchester, U. K.

Reiter, J. M., and F. Arndt (1995), Rigorous analysis of arbitrarily shaped H- and E-plane discontinuities in rectangular waveguides by a full wave boundary contour mode matching method, *IEEE Trans. Microwave Theory Tech.*, *43*(4), 796–801.

Vicente, C., M. Mattes, D. Wolk, H. Hartnagel, J. Mosig, and D. Raboso (2005), Multipactor breakdown prediction in rectangular waveguide based components, in *IEEE MTT-S International Microwave Symposium Digest*, pp. 1055–1058, Inst. of Electr. and Electron. Eng., Long Beach, Calif.

A. Alvarez-Melcon, D. Cañete Rebenaque, J. Pascual-García, F. J. Pérez-Soler, and F. D. Quesada-Pereira, Departamento de Tecnologías de la Información y las Comunicaciones, Technical University of Cartagena, Antiguo Cuartel de Antigones, Campus Muralla del Mar. Plaza del Hospital, 1, E-30202 Cartagena, Murcia, Spain. (alejandro.alvarez@upct.es)