Efficient BI-RME Method Implementation For The Full-Wave Analysis Of Passive Devices Based On Circular Waveguides With Arbitrary Perturbations

C. Carceller[1], S. Cogollos[1], P. Soto[1], J. Gil[2], V. E. Boria[1], C. Vicente[2], B. Gimeno[3]
Correspondence author: carcarc2@upvnet.upv.es

[1] Departamento de Comunicaciones,
Instituto de Telecomunicaciones y Aplicaciones Multimedia,
Universidad Politécnica de Valencia, E-46022, Valencia, Spain.

[2] Aurora Software and Testing S.L.,
E-46022, Valencia, Spain.

[3] Departamento de Física Aplicada,
Instituto de Ciencia de Materiales,
Universidad de Valencia, E-46100, Burjassot, Spain.

Abstract

In this paper, the efficient full-wave analysis of passive devices composed of circular and arbitrarily-shaped waveguides is considered. For this purpose, the well-known Boundary Integral - Resonant Mode Expansion (BI-RME) method has been properly extended. Circular waveguides are used for the resonant mode expansion, whereas the arbitrary contour is defined by any combination of straight, circular and elliptical segments, thus allowing the exact representation of the most widely used geometries. The proposed algorithm extends previous implementations of the BI-RME method based on circular waveguides by considering circular and elliptical arcs for defining arbitrary geometries. Likewise, it allows the efficient analysis of passive devices based on circular waveguides with arbitrary perturbations, thus providing more accurate results with less computational efforts than a rectangular waveguide based BI-RME approach. The extended method has been successfully tested with several practical application examples, having compared its performance with the BI-RME method based on rectangular waveguides.

Keywords: Waveguide components, filters, integral equations, circular waveguides, Green function methods

1. Introduction

Nowadays, many waveguide components for satellite applications are based on cylindrical cavities. Examples of such components include dual-mode filters, polarisers, sidewall-coupled cylindrical cavity filters, etc. (see [1]). The high electrical response sensitivity found in some of these components, e.g. dual-mode filters, has encouraged the development of full-wave electromagnetic analysis tools for its accurate and efficient modelling.
The analysis of complex waveguide components has been traditionally carried out by means of segmenting the structure into simpler building blocks: waveguide sections, discontinuities and planar junctions, as described in [2]. Instead of considering the structure as a whole, it is simpler and computationally more efficient to analyse different types of blocks independently, and eventually combine them to obtain the component response. In order to perform a high-accuracy analysis, the characterization of these blocks needs to be multimodal, especially if discontinuities are in close proximity. Waveguide sections are characterized by their modal charts. For the full-wave characterization of planar junctions and discontinuities, the modal coupling coefficients of the involved waveguides are also required. Consequently, full-wave modal analysis methods are generally focused on computing these two sets of parameters.

Over the last decades, a wide number of analysis techniques have been reported in the technical literature. On the one hand, there are techniques based on the solution of an integral equation by the method of moments (MoM) [3]-[4] which solve a non-linear eigenvalue problem of small size. On the other hand, there are techniques based on discretization methods leading to large algebraic problems, such as Finite-Element (FE) [5] or Finite Difference Time Domain (FD-TD) methods [6]. Recently, hybrid techniques have

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been proposed in order to mitigate the drawbacks of both groups. Some methods that fall into this category are the mode-matching finite-element (MM/FE) method [7], the boundary contour mode-matching (BCMM) method [8], and the combination of the mode-matching, finite-element, method of moments and finite difference methods (MM/FE/MoM/FD) [9].

In this paper, a technique which combines the flexibility of discretization methods with the efficiency of modal techniques is extended, the so called 2D Boundary Integral - Resonant Mode Expansion (BI-RME) method [10]. The first original publication of this technique [11] considered its application to the modal analysis of arbitrary-contour waveguide structures by means of the combination of an integral equation with the modal expansion of a two-dimensional resonant contour. After solving a linear matrix eigenvalue problem, the BI-RME method provides the modal chart of the arbitrarily shaped waveguide structure.

The linear character of the matrix problem offers a great advantage over methods that solve integral equations through frequency-dependent eigenvalue problems, which typically result in larger computational efforts. Moreover, the moderate size of the matrices involved in the BI-RME method, reduces the amount of required memory resources, especially when compared with discretization techniques. Furthermore, the use of the BI-RME method within optimization procedures offers great advantages since, from one iteration to the next, only the integrals that involve altered geometries need to be recomputed.

After the first publication of the BI-RME method, the technique was revisited to additionally provide the coupling coefficients between the arbitrarily shaped waveguide and the basic resonant contour [12]. For this purpose, the same matrices involved in the solution of the eigenvalue problem were used, thus adding very little computational effort. Further efforts were done in the direction of extending the original method in order to include circular and elliptical arcs to describe the arbitrarily-shaped structure, since the original work [11] only considered straight segments. In [13], these two kinds of segments were added for the BI-RME method formulated in terms of rectangular waveguide modes. For such case, it was proved that the accuracy can be increased, especially when computing the cut-off frequencies of the lower order modes of such arbitrary waveguides.

However, that work has proven to be inefficient for the analysis of devices based on circular waveguides. In such cases the rectangular-based implementation of the BI-RME method requires a large number of resonant modes to compute the modal chart of the arbitrary waveguide with a high degree of accuracy. Likewise, the arbitrary waveguides that typically compose these devices are usually connected to other circular waveguides. Therefore the rectangular-based implementation does not take advantage of the efficient computation of coupling coefficients provided by the BI-RME method [12]. These drawbacks can be avoided with the new BI-RME implementation presented in this paper, which combines the use of a circular waveguide as the resonant contour with the possibility of using circular and elliptical arcs (together with straight segments) for defining the arbitrary geometry. With this implementation based on circular waveguides, many practical passive devices can be analysed and designed more accurately and with less CPU time than using the rectangular-based algorithm.

2. Arbitrary waveguide analysis by the BI-RME method

The basic structure under analysis (see Fig. 1) is an arbitrarily-shaped waveguide whose cross section Ω is defined by the contour σ. In order to analyse this waveguide, it will be enclosed within a standard circular waveguide S_0 and the original BI-RME formulation [11] will be applied.

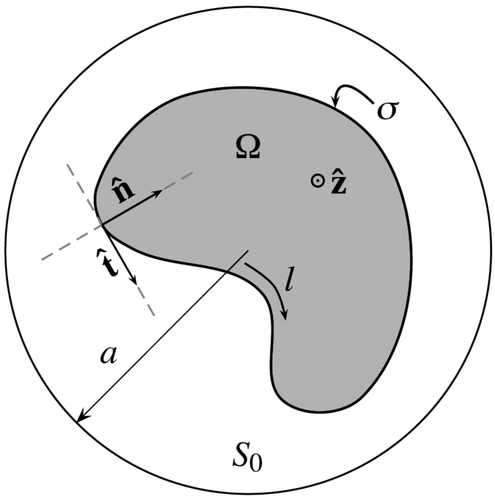


Figure 1. *Basic contour of the arbitrary waveguide enclosed within a basic circular contour.*

2.1. Computation of the TM modes

To compute the Transversal Magnetic (TM) modes of an arbitrarily shaped waveguide by means of the BI-RME method, it is necessary to compute two matrices, named **L'** and **R'** in [11]. The matrix **R'** is related to the resonant-mode expansion of the basic circular waveguide. The matrix **L'** involves the scalar Green's function g for the cylindrical resonator. This paper deals only with the **L'** matrix, since the computation of the **R'** matrix can be easily performed using standard numerical integration methods. The elements of **L'** can be expressed as follows:

$$L'_{ij} = \int_\sigma \int_\sigma w_i(l) g(\mathbf{s},\mathbf{s}') w_j(l') dl\, dl' \qquad (1)$$

where w_i, w_j are the basis and testing functions related to the implementation of the Method of Moments. These functions are piece-wise parabolic splines defined in two or three segments of the arbitrary contour σ. In our proposed enhanced algorithm, these segments can be straight, circular or elliptical arcs, and the basis functions are expressed in terms of a suitable variable l defined on σ. Furthermore, $\mathbf{s}=\mathbf{s}(l)$ and $\mathbf{s'}=\mathbf{s}(l')$ represent field and source vectors in the arbitrary contour σ, and g represents the scalar Green's function for two-dimensional resonators of circular cross section. Since g is singular when $\mathbf{s}=\mathbf{s'}$, the diagonal components of $\mathbf{L'}$ manifest a singular behaviour; in these cases the singularity has to be extracted from the computation of the matrix and solved analytically. The non-diagonal components can be easily computed using standard numerical integration techniques (e.g. the Gauss quadrature).

According to [11], the expression of the scalar Green's function for this structure is:

$$g(r,\phi,r',\phi') = \frac{1}{2\pi}\ln(r'R_i/aR) \quad (2)$$

where

$$R=(r^2+r'^2-2rr'C)^{1/2} \quad (3a)$$

$$R_i=(r^2+a^4/r'^2-2ra^2C/r')^{1/2} \quad (3b)$$

$$C=\cos(\phi-\phi') \quad (3c)$$

and a is the radius of the bounding circular contour. It can be easily observed that the singular behaviour of g is of the type $\ln(R)$ when the field point $s(r,\phi)$ approaches the source point $\mathbf{s}'(r',\phi')$, since R represents the distance between these two sets of points. To isolate the problematic behaviour of this term, it is necessary to split the Green's function into a regular and a singular term, dealing with each of them separately

$$g=g^{reg}+g^{sing}=\frac{1}{4\pi}\ln\left(\frac{r'R_i}{a}\right)^2-\frac{1}{4\pi}\ln(R^2) \quad (4)$$

where g^{reg} is regular since

$$\lim \ln\left(\frac{r'R_i}{a}\right)^2=\ln\left(\frac{(r'^2-a^2)^2}{a^2}\right) \quad (5)$$

Following this division of g into a regular and a singular part, the double integral of (1) can be split accordingly. On the one hand, the double integral involving g^{reg} can be solved numerically, as it is done with the rest of the integrals that do not present a singular behaviour (such as the elements of matrix $\boldsymbol{R'}$). On the other hand, the double integral involving g^{sing} can be performed in two steps. First, the line integral with respect to the primed coordinates is solved analytically, due to its singular behaviour. For circular and elliptical arcs, this singular integral can be computed analytically using a procedure totally equivalent to the one described in [13]. Then, the line integral with respect to the non-primed coordinates is computed numerically, since it has now a regular form.

Circular-based BI-RME implementation benefits from lower number of resonant modes required to model accurately the arbitrary sections, as well as the efficient computation of coupling coefficients between circular and arbitrary-shaped waveguides.

2.2. Computation of the TE modes

The accurate computation of the Transversal Electric (TE) modes depends on the capability to evaluate matrices $\boldsymbol{C}$ (not to be confused with variable C defined in (3c)) and $\boldsymbol{L}$, whose elements are [11]:

$$C_{ij}=\int_\sigma\int_\sigma g(\mathbf{s},\mathbf{s'})\,\frac{\partial w_i(l)}{\partial l}\,\frac{\partial w_j(l')}{\partial l'}\,dl\,dl' \quad (6)$$

$$L_{ij}=\int_\sigma\int_\sigma w_i(l)w_j(l')\hat{\mathbf{t}}(l)\cdot\bar{\mathbf{G}}_{st}(\mathbf{s},\mathbf{s'})\cdot\hat{\mathbf{t}}(l')\,dl\,dl' \quad (7)$$

where $w_n(l)$ and $\partial w_n(l)/\partial l$ are, respectively, the basis functions and their derivatives, $\hat{\mathbf{t}}=t_r\hat{\mathbf{r}}+t_\phi\hat{\phi}$ is the vector tangent to the contour σ, and $\bar{\mathbf{G}}_{st}$ is the solenoidal part of the dyadic Green's function for the circular cross-section resonator.

As it can be observed, equation (6) is very similar to (1), with the only difference being the presence of the derivatives instead of the basis functions. Therefore, the procedure to solve the singularity inherent to the scalar Green's function in the $\boldsymbol{C}$ matrix is completely equivalent to the one previously described for the $\boldsymbol{L'}$ matrix of TM modes (1), with the consideration that the derivatives of the basis functions are linear splines.

The computation of the $\boldsymbol{L}$ matrix requires managing the solenoidal part of the aforementioned dyadic Green's function, which can be expressed as follows

$$\bar{\mathbf{G}}_{st}(r,\phi,r',\phi')=G_{rr}\,\hat{\mathbf{r}}\hat{\mathbf{r}}'+G_{\phi r}\,\hat{\phi}\hat{\mathbf{r}}'+G_{r\phi}\,\hat{\mathbf{r}}\hat{\phi}'+G_{\phi\phi}\,\hat{\phi}\hat{\phi}' \quad (8)$$

where the specific expressions for the dyadic components can be found in [11].

This dyadic Green's function has a logarithmic singular behaviour equivalent to the one of g. Following a similar procedure to the one used with the TM modes, $\bar{\mathbf{G}}_{st}$ can be split into a regular part and a singular part, being the latter as shown next:

$$\bar{\mathbf{G}}_{st}^{sing}=\frac{1}{8\pi}\,C\ln(R^2)\hat{\mathbf{r}}\hat{\mathbf{r}}'-S\ln(R^2)\hat{\phi}\hat{\mathbf{r}}'+S\ln(R^2)\hat{\mathbf{r}}\hat{\phi}'+C\ln(R^2)\hat{\phi}\hat{\phi}' \quad (9)$$

where C is defined in (3c) and S is

$$S=\sin(\phi-\phi') \quad (10)$$

As it has been done for the TM modes, the double integral of (7) will be split into an inner line integral that will be solved analytically, due to its singularities, and an outer line integral that will be solved numerically. The singular integral to be solved analytically is

$$L_{sing} = \int_\sigma w_i(l') \frac{1nR^2}{8\pi} \left[C(t_r t_{r'} + t_\phi t_{\phi'}) + S(-t_\phi t_{r'} + t_r t_{\phi'})\right] dl' \quad (11)$$

where $\mathbf{t} = t_r \hat{\mathbf{r}} + t_\phi \hat{\phi}$ is the vector tangent to the contour. Given that

$$t_r t_{r'} + t_\phi t_{\phi'} = C(t_x t_{x'} + t_y t_{y'}) + S(t_y t_{x'} - t_x t_{y'}) \quad (12a)$$

$$-t_\phi t_{r'} + t_r t_{\phi'} = S(t_x t_{x'} + t_y t_{y'}) - C(t_y t_{x'} - t_x t_{y'}) \quad (12b)$$

it is immediate to rewrite the singular integral (11) as

$$L_{sing} = \int_\sigma w_i(l') \frac{1nR^2}{8\pi} (\hat{\mathbf{t}} \cdot \hat{\mathbf{t}}') \, dl' \quad (13)$$

If the contour σ includes circular and/or elliptical arcs, the analytical computation of this singular integral can be carried out using the technique explained in [6] for TE modes.

3. Numerical results

In this section, the proposed implementation of the BI-RME method using a circular resonant contour is validated with results from measurements and the technical literature. The results[1] obtained with the circular-based implementation have proven to be highly accurate when compared with available numerical or experimental data. This implementation has also shown a more efficient performance than the rectangular-based implementation for the analysis of all the structures considered in this section.

3.1. Elliptical waveguide

The first example involves exclusively elliptical arcs. An elliptical waveguide with major semi-axis a=20mm and eccentricity e=0.5 has been analyzed, and the cut-off wavelengths have been compared with those computed in [14], using the classical calculation of the parametric zeros of the modified Mathieu functions. To obtain the results shown in Table 1, the elliptical waveguide has been segmented into 176 elliptical segments, and the first 357 modes have been computed in just 7 s.

Mode	Type	λ_c[cm] ref. [14]	λ_c[cm] (BI-RME)	Relative Error (%)
1	TE_{c11}	3.39447796	3.39444689	0.0009
2	TE_{s11}	2.97448032	2.97445612	0.0008
3	TM_{c01}	2.41960702	2.41957384	0.0014
4	TE_{c21}	1.94968828	1.94962872	0.0031
5	TE_{s21}	1.90795125	1.90788986	0.0032
10	TE_{s31}	1.39790700	1.39780978	0.0070
50	TM_{s61}	0.59214500	0.59200839	0.0231
100	TE_{c04}	0.41616300	0.41598496	0.0428

Table 1: *Relative error in the cut-off wavelength computation of an elliptical waveguide with major semi-axis a=20 mm and eccentricity e=0.5.*

3.2. Multi-ridged circular waveguide

Next, the modal chart of a multi-ridge circular waveguide (Fig. 2a) is presented. This structure is especially suitable to be analysed by the circular-based implementation. Thus, it serves the purpose of showing how the proper election of the resonant contour has an impact on the

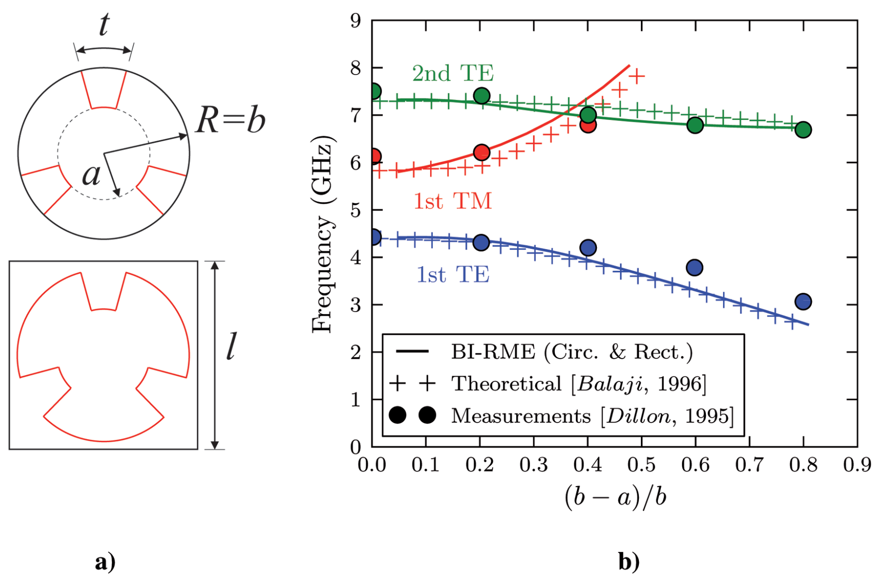


Figure 2: ***a)*** *Dimensions of the multi-ridged circular waveguide as well as the circular and square contours used by the BI-RME method. Red lines indicate those segments that have to be considered for the application of the BI-RME method in each case.* ***b)*** *Cut-off frequency for the first two TE modes and the first TM mode of the multi-ridge circular waveguide for different insertion depths (a). Simulations are compared with [15] and measurements of [16].*

[1] *All the CPU times in this section have been obtained using a standard PC with a 2.83 GHz Intel Core 2 Quad processor.*

# Resonant Modes	Circular-based			Rectangular-based		
	f_c [GHz]	Error (%)	Time (s)	f_c [GHz]	Error (%)	Time (s)
300	34.9050	0.075	0.8	35.0293	0.431	2.2
400	34.8913	0.036	0.9	34.9630	0.241	2.9
500	34.8873	0.024	1.2	34.9363	0.165	3.2
600	34.8861	0.021	1.5	34.9186	0.114	4
700	34.8848	0.017	2	34.9096	0.088	4.9
800	34.8839	0.015	2.3	34.9043	0.073	5.9
900	34.8823	0.010	2.7	34.9003	0.062	6.6
1000	34.8815	0.008	3.2	34.8971	0.052	8

Table 2: *Cut-off frequency of the 100th mode of the triple-ridged circular waveguide (b=20 mm, a=16 mm, t=20º) computed with the circular and rectangular-based implementations for different number of resonant modes. The exact cut-off frequency for the computation of the relative error is taken as* $f_C = 34.8788$ GHz*. This value has been obtained as the convergent cut-off frequency value (difference smaller than* 0.1 MHz*) of the circular-based implementation. The CPU time required for each analysis is included.*

accuracy of the algorithm. This example consists of a circular waveguide of radius b=20 mm with three equidistant metal insertions of angular thickness t=20º. Sweeping the inner radius from a=1 to 19 mm, a series of simulations have been performed using the circular-based implementation (R=20 mm) and the rectangular-based approach (l=41 mm).

The results of these simulations can be seen in Fig. 2b, where the cut-off frequencies for the first two TE modes and the first TM mode have been computed and successfully compared with [15] and the measurements of [16]. For low order modes, as the ones considered in Fig. 2b, both the circular and the rectangular-based implementations achieve rapidly convergent results. For instance, only 100 resonant modes have been used with both implementations, requiring less than 0.65 s per simulation point with the rectangular-based code and 0.45 s with the circular-based one.

However, typical analysis of complex passive devices requires the use of higher order modes (usually up to 100 modes) for a proper characterization of the structure. In those cases, the performance of the circular-based implementation excels that of the rectangular-based approach, since the structure is based on a circular waveguide. To show this, we have analysed the multi-ridge waveguide setting the inner radius to a=16 mm and studied the convergence of both implementations through the computation of the 100-th mode cut-off frequency. The results of this study are summarized in Table 2, where the superior performance of the circular-based implementation over the rectangular one can be observed. In approximately 0.8 s the circular-based algorithm computes the cut-off frequency of this mode with a relative error smaller than 0.1%, while the rectangular-based takes 5.9 s to achieve a similar level of accuracy. The main reason for this important improvement is that the number of segmented portions (red portions in Fig. 2a is smaller since the majority of the segments are coincident with the outer circular contour, and do no need to be segmented by the circular-based implementation. With a smaller number of portions the size of the eigenvalue problem decreases, so the time devoted to its construction and solution is drastically reduced.

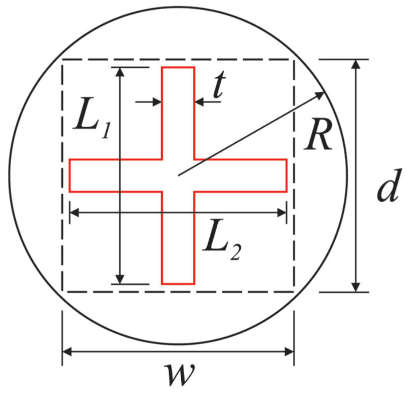
3.3. Cross-shaped iris

In the previous example, it has been demonstrated how the election of the resonant contour has an effect on the accuracy and efficiency of the modal chart calculation. Now, it is shown how this election also affects the computation of coupling coefficients, another key factor when analysing the electromagnetic response of complex devices. For such study, a structure consisting of a cross-shaped iris connected to a circular waveguide is considered, as seen in Fig. 3a. On the one hand, this structure has been analysed with the circular-based algorithm, using the connected circular waveguide (radius R=12 mm) as the resonant contour. This analysis has automatically provided the desired coupling integrals. On the other hand, the structure has been analysed using the rectangular-based algorithm, which computes the coupling coefficients as follows:

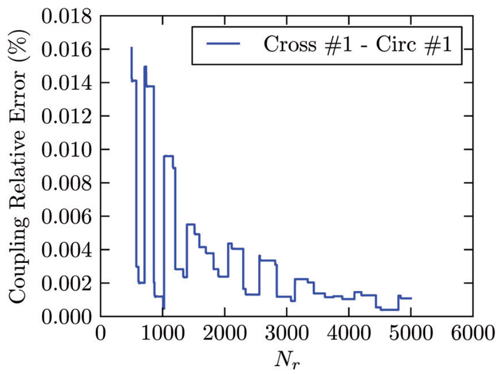
$$I_{\mathrm{O}}^{\Delta} = \sum_{n=1}^{N_r} \langle \boldsymbol{e}_i^{\mathrm{O}}, \boldsymbol{e}_n \rangle \langle \boldsymbol{e}_j^{\Delta}, \boldsymbol{e}_n \rangle \qquad (14)$$

where $\boldsymbol{e}_i^{\mathrm{O}}$ are the modal vectors of the circular waveguide connected to the iris, $\boldsymbol{e}_n$ are the modal vectors of the rectangular box and $\boldsymbol{e}_j^{\Delta}$ are the modal vectors of the cross-shaped iris. Note that the first inner product in (14) is analytical, whereas the second one is provided by BI-RME.

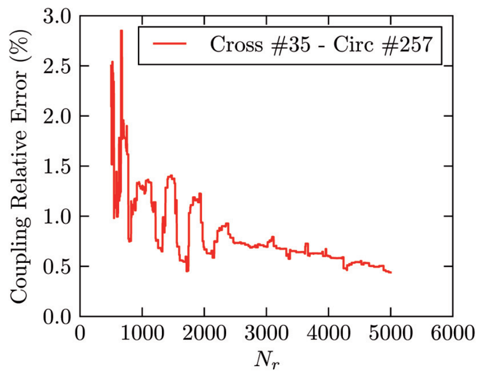
Figure 3 depicts the relative error in the computation of coupling integrals between two sets of modes using the rectangular-based implementation. In all cases the exact value for the coupling integrals is taken as the convergent value provided by the circular-based implementation. In Fig. 3b the coupling integral between the first mode of



a)



b)



c)

■ **Figure 3:** ***a)*** *Cross-shaped iris of dimensions* L_1=17.3 mm, L_2=15.3 mm, t=2 mm *connected to a circular waveguide of radius* R=12 mm*. Dashed lines represent the contour of dimensions* w=15.4 mm, d=17.4 mm *used for the application of the rectangular-based algorithm.* ***b)*** *Relative error in the computation of coupling integrals between the first cross-shaped mode and the first circular waveguide mode using the rectangular-based implementation. The exact value to compute the error is taken as the one provided by the circular-based implementation.* ***c)*** *Relative error in the computation of coupling integrals between the 35th cross-shaped mode and the 257th circular waveguide mode using the rectangular-based implementation.*

the cross-shaped waveguide and the first mode of the circular waveguide is shown, for different values of N_r. In Fig. 3c, the coupling coefficient between a high-order mode (35th) of the cross-shaped waveguide and a high-order mode (257th) of the circular waveguide is depicted. The criteria for choosing these particular combinations of modes has been that a significant coupling (I_0^A>0.1) between them should exist.

The main conclusion that can be drawn from both graphs is that the rectangular-based implementation, even though it provides accurate results when low-order modes are involved, lacks some accuracy when dealing with higher order ones. The reason for this loss in accuracy is that high-order modes have complex field patterns, which are represented in a less accurately way by a series of rectangular waveguide modes. Meanwhile, the circular-based implementation does not need to represent these arbitrary modes by any series, but instead defines them by the modal current density computed by the BI-RME method. Therefore, the computation of the coupling coefficients of these high-order modes has the same accuracy level as the corresponding modal chart computation.

Considering high-order modes is important when complex structures are studied, especially when the arbitrary waveguide is used as an iris. In such cases, the circular-based implementation offers an important advantage over the rectangular-based algorithm when some of the interconnections involve arbitrary and circular waveguides.

Finally, it is worth noting the oscillatory behaviour of the coupling integrals with the different number of rectangular modes, which may produce inaccurate results if a proper convergence study is not previously carried out.

3.4. Design of a dual-mode filter with cross-shaped irises and tuning elements

The last example deals with the design of a complex passive device in circular waveguide technology. The structure under consideration is the four-pole dual-mode filter depicted in Fig. 4, along with its dimensions. It is based on two circular waveguides coupled through a cross-shaped iris and includes two sets of tuning elements, a classical structure widely used in satellite communications [17]. After designing the device, a prototype of this dual-mode filter has been manufactured with real rectangular insets to validate the analysis tool presented in this article. Figure 5 depicts the response of this manufactured prototype compared with the simulated response obtained with the circular-based and the rectangular-based BI-RME implementations. The response simulated with the circular-based code is almost identical to the measured one, confirming the accuracy of this tool when dealing with these complex devices. Regarding the rectangular-based response, a small frequency shift of approximately 7 MHz is observed. Additionally, the out-of-band response up to 20 GHz is successfully compared with measurements.

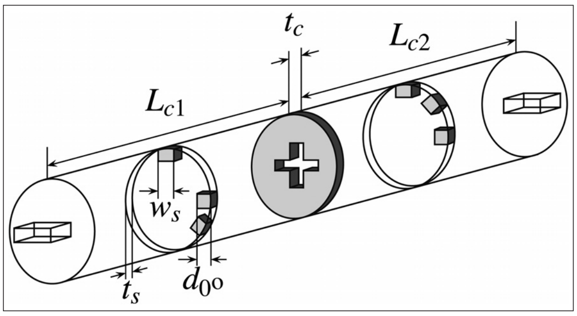


Figure 4: *Physical structure of the designed dual-mode filter in a circular waveguide of radius 13.3 mm. The dimensions are as follows. Cavities:* L_{c1}=54.4366 mm, L_{c2}=54.4436 mm. *Input and output rectangular irises dimensions: 10.6441x2 mm, thickness 1 mm. Cross iris:* L_{c1}=7.688 mm *and,* L_{c2}=4.407 mm, t=1 mm, t_c=1 mm. *First triple-inset coupling section:* $t_s=w_s$=2 mm *with screws located at 0° (horizontal), 90° (vertical) and 315° of depths,* d_{0^o}=2.8956 mm, d_{90^o}=1 mm *and* d_{315^o}=1.9345 mm, *respectively. Second triple-inset coupling section:* $t_s=w_s$=2 mm *with screws located at 0°, 45° and 90° of depths,* d_{0^o}=2.9023 mm, d_{45^o}=2.0364 mm *and* d_{90^o}=1 mm.

As far as the computational efficiency of the analysis is concerned, the circular-based algorithm takes advantage of a more accurate characterization of the tuning sections, as well as a faster characterization of the different planar junctions to achieve convergent results in a shorter amount of time. While the rectangular-based implementation takes 100 s to compute 100 frequency points, the circular-based implementation takes just 43 s, a considerable reduction of the computation time just by using the appropriate resonant contour.

As shown, the analysis of devices based on circular and arbitrary waveguides is highly improved by the use of the proposed implementation.

4. Conclusions

In this paper, an important enhancement of previous implementations of the BI-RME method has been presented. This new implementation is intended to analyse passive devices based on circular and arbitrarily-shaped waveguides in a more accurate and efficient way. It combines a circular contour as resonant structure with the inclusion of straight, circular and elliptical arcs for defining the perturbed geometry. Compared with previous implementations of the same method based on rectangular waveguides, this implementation takes advantage of a lower number of resonant modes for the accurate modelling of the arbitrary sections, as well as the efficient computation of coupling coefficients between circular and arbitrary-shaped waveguides. Therefore, the analysis of devices based on circular and arbitrary waveguides is highly improved by the use of the proposed implementation, as it has been shown through some examples. The accuracy of this new implementation has also been successfully verified using several examples of practical interest, comparing the simulated responses with data taken from technical literature and experimental measurements. Furthermore, a dual-mode filter prototype has been designed and manufactured for this purpose. In all the examples, the performance of the new implementation has been optimum, especially when compared with the previous rectangular-based one.

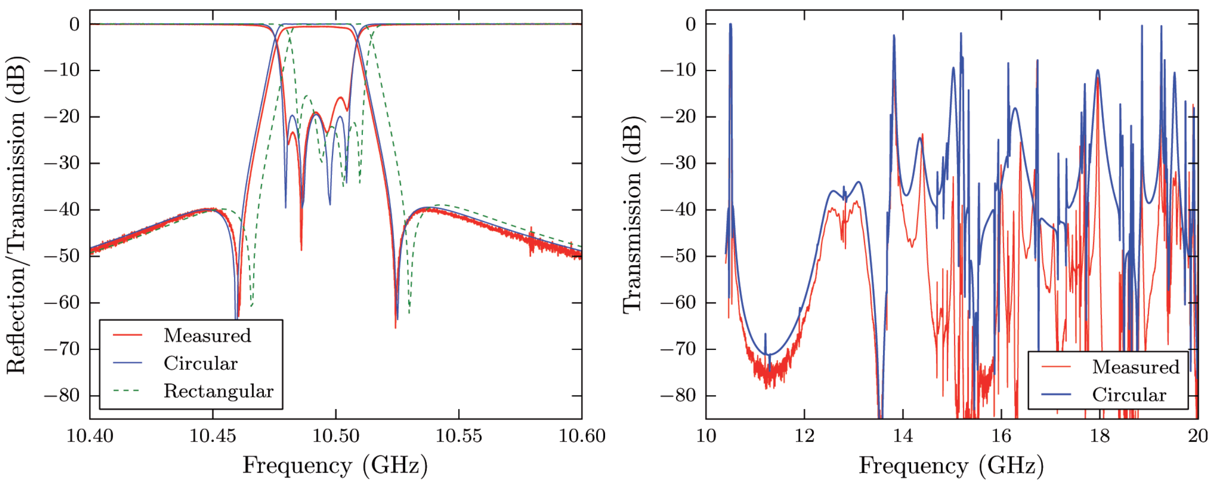


Figure 5: *In-band and out-of-band response of the designed dual-mode filter. Measurements of a manufactured prototype are compared with the simulation of the circular-based implementation.*

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Biographies

Carlos Carceller was born in Villarreal, Spain, in 1986. He received an Ingeniero de Telecomunicación degree in 2010 and a Máster Universitario en Tecnologías, Sistemas y Redes de Comunicación degree in 2012, both from the Universidad Politécnica de Valencia (UPV), Valencia, Spain. He is currently working toward a Ph.D. degree in telecommunications at the same institution. In 2009 he attended the University of Maryland (College Park MD, USA) through the PROMOE (UPV) program, where he worked in the design of microwave filters in LTCC technology. In 2010 he joined the Grupo de Aplicaciones de Microondas where he currently develops software tools for the electromagnetic analysis of passive microwave components in waveguide technology. His current research interests include numerical methods in electromagnetics and its application to CAD tools for passive microwave devices.

Santiago Cogollos was born in Valencia, Spain, on January 15, 1972. He received the degree in telecommunication engineering and the Ph. D. degree from the Polytechnic University of Valencia, Valencia, Spain, in 1996 and 2002, respectively. In 2000, he joined the Communications Department of the Polytechnic University of Valencia where he was an Assistant Lecturer from 2000 to 2001, a Lecturer from 2001 to 2002, and became an Associate Professor in 2002. He has collaborated with the European Space Research and Technology Centre of the European Space Agency in the development of modal analysis tools for payload systems in satellites. In 2005, he held a post doctoral research position working in the area of new synthesis techniques in filter design at University of Waterloo, Waterloo, Ont., Canada. His current research interests include applied electromagnetics, mathematical methods for electromagnetic theory, analytical and numerical methods for the analysis of waveguide structures, and design of waveguide components for space applications.

Pablo Soto was born in 1975 in Cartagena, Spain. He received the M.S. degree and Ph.D. degree (cum Laude) in Telecommunication Engineering from the Universidad Politecnica de Valencia in 1999 and 2012, respectively. In 2000 he joined the Departamento de Comunicaciones, Universidad Politecnica de Valencia, where he is Associatte Professor since 2012. In 2000 he was a fellow with the European Space Research and Technology Centre (ESTEC-ESA), Noordwijk, the Netherlands. His research interests comprise numerical methods for the analysis, synthesis and automated design of passive components in waveguide and planar technologies. Dr. Soto received the 2000 COIT/AEIT national award to the best Master Thesis in basic information and communication technologies.

Vicente E. Boria received the Ingeniero de Telecomunicación and the Doctor Ingeniero de Telecomunicación degrees from the Universistat Politècnica de València, València, Spain, in 1993 and 1997. In 1993 he joined the Universistat Politècnica de València, where he is Full Professor since 2003. In 1995 and 1996 he was held a Spanish Trainee position with the European Space research and Tecnology Center (ESTEC)-European Space Agency (ESA). He has served on the Editorial Boards of the IEEE Transactions on Microwave Theory and Techniques. His current research interests include numerical methods for the analysis of waveguide and scattering structures, automated design of waveguide components, radiating systems, measurement techniques, and power effects in passive waveguide systems.

Carlos Vicente was born in Elche, Spain, in 1976. In 1999, he received the Dipl. degree in physics from the Universidad de Valencia, Valencia, Spain, and the Dr. Ing. degree in engineering from the Technical University of Darmstadt, Darmstadt, Germany, in 2005. From 1999 to the beginning of 2001, he was a Research Assistant with the Department of Theoretical Physics, Universidad de Valencia. From 2001 to 2005, he was an Assistant Professor with the Institute of Microwave Engineering, Technical University of Darmstadt. Since 2005, he has been with the Multimedia Applications Group, Universidad Politécnica de Valencia, Valencia. In 2006, he cofounded the Aurora Software and Testing S.L., which is devoted to the telecommunications sector. His research interests include passive intermodulation, corona discharge, and multipaction in communications satellite applications.

Benito Gimeno was born in Valencia, Spain, on January 29, 1964. He received the Licenciado degree in Physics in 1987 and the PhD degree in 1992, both from the Universidad de Valencia, Spain. He was a Fellow at the Universidad de Valencia from 1987 to 1990. Since 1990 he served as Assistant Professor in the Departamento de Física Aplicada y Electromagnetismo and ICMUV (Instituto de Ciencia de Materiales) at the Universidad de Valencia, where he became Associate Professor in 1997 and Full Professor in 2010. He was working at ESA/ESTEC (European Space Research and Technology Centre of the European Space Agency) as a Research Fellow during 1994 and 1995. In 2003 he obtained a Fellowship from the Spanish Government for a short stay at the Universita degli Studi di Pavia (Italy) as a Visiting Scientific. His current research interests include the areas of computer-aided techniques for analysis of microwave and millimetre-wave passive components for space applications, waveguides and cavities structures including dielectric objects, electromagnetic band-gap structures, frequency selective surfaces, and non-linear phenomena appearing in power microwave subsystems and particle accelerators (multipactor effect, corona effect and passive inter-modulation phenomena).

Jordi Gil was born in Valencia, Spain, in 1977. He received the Licenciado degree in physics from the Universidad de Valencia, Valencia, Spain, in 2000, and the Ph.D. degree in telecommunications engineering from the Universidad Politécnica de Valencia, Valencia, Spain, in 2010. From 2001 to 2004, he was Researcher with the Aerospatiale Italian Company, Ingegneria Dei Sistemi-S.p.A., under the frame of the V European Framework Programme. From 2004 to 2006, he joined the Microwave Applications Group, Universidad Politécnica de Valencia, under the frame of a European reintegration grant funded by the VI European Framework Programme. In 2006, he cofounded the company Aurora Software and Testing S.L. which is devoted to the space sector. He is currently the Managing Director of the company, where he also continues his research activities. His current research interests include numerical methods in computer-aided techniques for the analysis of microwave and millimeter passive components based on waveguide technology, and nonlinear phenomena appearing in power microwave subsystems for space applications. He was the recipient, in 2011, of the PhD Thesis Extraordinary Award at the Universidad Politécnica de Valencia.