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A FLEXIBLE CIET ANALYSIS FOR THE DESIGN OF ON-AXIS CIRCULAR WAVEGUIDE COMPONENTS

Jens Bornemann
University of Victoria, Victoria, BC V8W 3P6, Canada (jbornema@ece.uvic.ca)

Smain Amari
Royal Military College of Canada, Kingston, ON K7K 7B4, Canada (Smain.Amari@rmc.ca)

Rüdiger Vahldieck
Swiss Federal Institute of Technology, 8092 Zurich, Switzerland (vahldieck@ifh.ee.ethz.ch)

Abstract: A flexible and efficient yet accurate coupled-integral-equations technique (CIET) for the design of on-axis circular waveguide components is presented. The analysis process features on-off switchable edge conditions, sparse-matrix formulation and selections of mode numbers. The design is carried out by linking the analysis module to an optimization routine. Several examples of circular waveguide components are presented to highlight the flexibility of the design strategy. Comparisons with data obtained by other numerical techniques validate the results.

1. Introduction

Circular waveguide components are primarily used in front ends of microwave communication systems, e.g. [1], and in high-power microwave applications, e.g. [2]. Although initial design guidelines for such components are available, they usually fail to accurately meet modern system specifications. This is mostly due to the interactions of fields generated at individual parts of a component. Consequently, all modern waveguide designs are subject to fine-tuning through computer optimization. However, given the very high number of spectral terms, both propagating and evanescent, which are usually required for an accurate performance prediction, the design by optimization is time-consuming and cumbersome. In order to reduce time frames for component design, the individual analysis step within the optimization process must be significantly accelerated.

Therefore, in this paper, a coupled integral equation technique is presented which lends itself to a fast, accurate and reliable analysis and design process for components in circular waveguide technology. The method is highly flexible and allows the computation of stepped as well as continuously profiled components. In the event of stepped transitions, edge conditions for the accurate representations of field singularities are readily incorporated. Components with continuous wall profile can be approximated by several hundred individual sections. Although this number appears high, the method still produces accurate computations within reasonable CPU times. This is mainly due to a formulation using coupled integral equations which, when solved by Galerkin's method within the method of moments, produces a highly sparse, block-diagonal matrix system [3]. A customized LU decomposition guarantees a speedy solution of the parameters in question.

A further advantage of this approach lies in the flexibility of selecting specific input and output field configurations of interest. Although the number of spectral terms are high within the structure, only the coefficients of basis functions at the input/output ports need to be computed. From those coefficients, the mode parameters with respect to a defined set are easily extracted.

2. Theory

The general formulation of the coupled integral equation technique (CIET) for a cartesian coordinate system is presented in [3] and will not be repeated here. Instead, we are focusing on the differences resulting from applications in circular waveguide structures [4].

Let the respective TE- and TM-mode spectra of two on-axis connected circular waveguides, denoted I and II, be given by

$$
\begin{aligned}
T^{\upsilon}_{hi[i \leftarrow m,n]}(\rho,\varphi) &= A^{\upsilon}_{mn} J_m\left(\frac{p'_{mn}}{a_\upsilon}\rho\right)\begin{cases}\cos(m\varphi)\\ \sin(m\varphi)\end{cases}\\
T^{\upsilon}_{ek[k \leftarrow m,n]}(\rho,\varphi) &= D^{\upsilon}_{mn} J_m\left(\frac{p_{mn}}{a_\upsilon}\rho\right)\begin{cases}\sin(m\varphi)\\ \cos(m\varphi)\end{cases}
\end{aligned}
\qquad (1)
$$

where $\upsilon \in \{I, II\}$; a_ν are the radii; J_m is the bessel function of the first kind with zeroes p_{mn}; p'_{mn} refer to the zeroes of the derivative; and A and D are known normalization coefficients. Let $\vec{e}_z$ be the unit vector in axial direction and let region 0 denote the smaller cross section of regions I and II. Then the basis functions are chosen such that

$$\vec{\Phi}(\rho, \varphi) = \sum_r [\nabla T^0_{hr}(\rho, \varphi) \times \vec{e}_z] C_r + \sum_s [-\nabla T^0_{es}(\rho, \varphi)] C_s \quad (2)$$

in case of a smooth (small-step) transition and

$$\vec{\Psi}(\rho, \varphi) = \sum_r \frac{\nabla T^0_{hr}(\rho, \varphi) \times \vec{e}_z}{[1-(\rho/a_0)^2]^{1/3}} C_r + \sum_s \frac{-\nabla T^0_{es}(\rho, \varphi)}{[1-(\rho/a_0)^2]^{1/3}} C_s \quad (3)$$

for an abrupt transition incorporating the edge condition. C_r and C_s are the basis function coefficients. Note that the number of basis functions, r+s, is much smaller than the number of field expansion terms (modes), i+k in (1). The required number of modes can be tested by tracking the convergence in the inner products of expansion terms and basis functions. This leaves the number of basis functions as the only variable in the system. That number is small for abrupt discontinuities (3) since the edge condition accelerates the convergence of inner product. However, the related integrals have to be evaluated numerically. Smooth transitions usually require a higher number of basis functions, but the inner products can be solved analytically.

In order to analyze components with many discontinuities, the field at each discontinuity is expressed in terms of basis functions and related to the respective expressions at the immediate neighbour discontinuities. The resulting integral equation system is solved using Galerkin's technique in a method-of-moments algorithm. Since basis function coefficients are connected only to those of their immediate neighbours, a blockdiagonal matrix is obtained. This matrix is quickly solved by a taylored LU decomposition which respects the blockdiagonal structure. Backsubstitution yields the coefficient vectors at the first and last discontinuity from which the entries of the generalized scattering matrix can be obtained.

Once the analysis module is completed and an initial set of design parameters obtained, a component is fine-tuned by employing a MiniMax strategy of optimization [5].

3. Results

In this section, we show a few application-oriented examples and verify the theoretical approach by comparison with another method, the Mode-Matching Technique (MMT). In all of these cases and for the majority of other components studied, the CPU times using the CIET described above were found to be at least one order of magnitude less than those involving other numerical techniques. Specific components might be calculated two orders of magnitudes faster.

Fig. 1 shows the performance of a four-section circular waveguide transformer [1]. The return loss is better than 40 dB between 16 GHz and 25 GHz, the common TE_{11}-mode bandwidth of the two interfacing waveguides. Excellent agreement is obtained with results from the MMT.

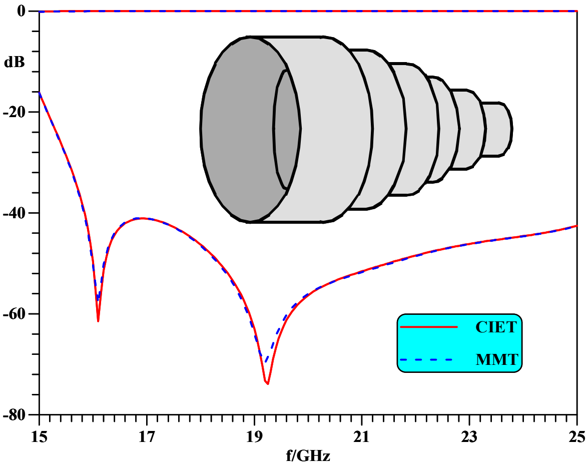

Fig. 1 Performance of a four-section TE_{11}-mode transformer and comparison with the MMT.

A circular iris filter has an inherently weak attenuation performance in the stopband region between the fundamental and second passband, as is demonstrated in Fig. 2 between 21 GHz and 25 GHz. By replacing the first iris with a radial stub, which now acts as a frequency-dependent inverter, two transmission zeroes are introduced (Fig. 3). Compared to Fig. 2, the upper transmission zero is used to increase the attenuation of the filter between 21 GHz and 23 GHz. For details on the design procedure of such filters, the reader is referred to [6].

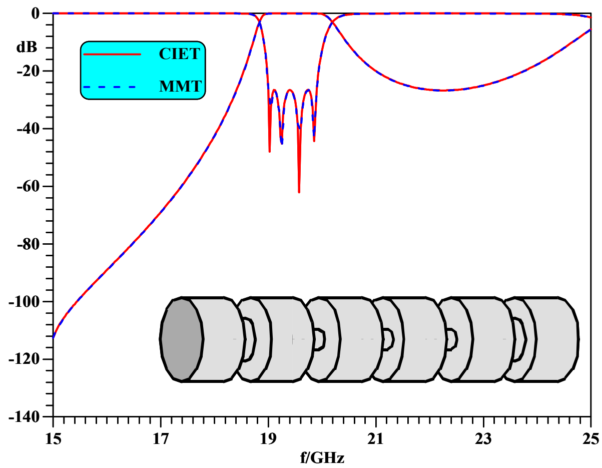

Fig. 2 Performance of a standard four-resonator TE_{11}-mode iris filter and comparison with the MMT.

The next example is related to periodic structures. In [7], we proposed an approximation to determine the number of unit cells required to achieve a certain attenuation:

$$N \approx L_{obj}/(8.686 \alpha p) \quad (4)$$

where L_{obj} is the desired insertion loss in dB , α is the attenuation of the (infinite) periodic structure, and p is the period of the unit cell. Let us assume that 100 dB attenuation at 7.34 GHz is to be achieved and that the dimensions of the unit cell are: waveguide diameter/length = 26mm/4.55mm, iris diameter/thickness = 14.3mm/0.13mm. Applying the analysis of [7], we find αp=0.95 for the periodic structure. Thus 12 unit cells should satisfy the attenuation specifications. This is demonstrated in Fig. 4 for a varying number of unit cells. Note that the curve for N=12 produces an attenuation just below the required 100 dB (black bar in Fig. 4), thus validating our approach presented in [7].

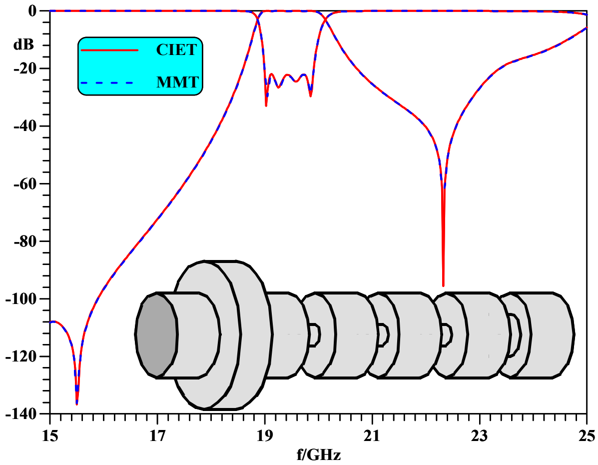

Fig. 3 Performance of a four-resonator TE_{11}-mode filter with a single frequency-dependent inverter and comparison with the MMT.

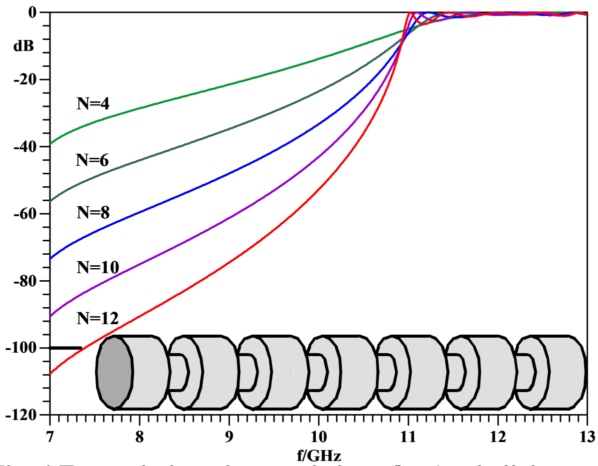

Fig. 4 Transmission characteristics of a ‘periodic’ waveguide structure with N unit cells.

The final two examples are designs of mode converters. Fig. 5 shows the performance of a TE_{11}-to-TM_{11} converter which was redesigned after three different numerical techniques failed [8] to confirm efficiencies stated in [9]. This new design, which is confirmed by results obtained with the MMT, significantly improves bandwidth and efficiency. Note that the dimensions are such that the input (left) is restricted to fundamental TE_{11}-mode propagation, while the output (right) supports both TE_{11} and TM_{11} modes. With the input reflection coefficient and the transmission coefficient of the fundamental mode below -25 dB, the theoretical efficiency of TE_{11}-to-TM_{11} conversion is better than 99 percent over a wide frequency range.

The performance of a continuous-profile TE_{02}-to-TE_{01} mode converter according to [2] is shown in Fig. 6. In this case, the edge condition within the CIET was disengaged, and the continuous profile was approximated by 200 steps. It is one of the outstanding features of the CIET that such a large number of steps can be handled within a reasonable CPU time. An optimization attempt, although possible even with up to 300 steps, has not produced a better design without substantially altering the shape of the profile, thus verifying the excellent original design by Buckley and Vernon [2]. The actual profile is shown in the inset of Fig. 6 and incorporates a correction [10] of the profile specified in [2].

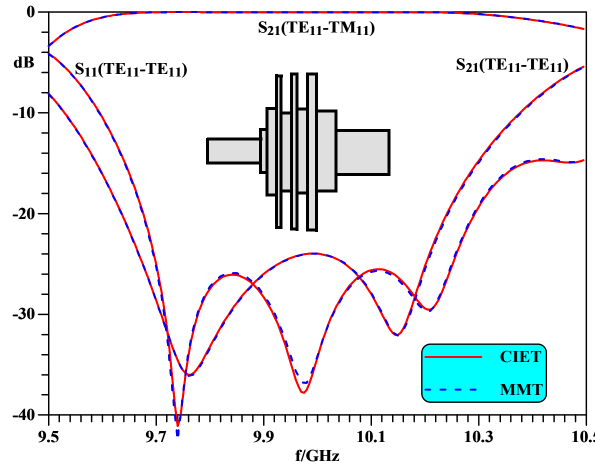

Fig. 5 Performance of an optimized TE_{11}-to-TM_{11}mode converter and comparison with MMT.

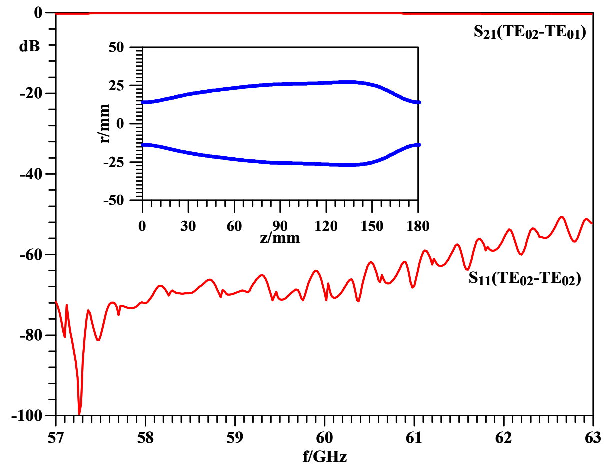

Fig. 6 Performance of continuous-profile TE_{02}-to-TE_{01} mode converter according to [2, 10].

4. Conclusions

It is demonstrated that the coupled integral equation technique offers an attractive solution as an analysis module in software packages for circular waveguide components. Compared with other techniques, CIET is usually one order of magnitude faster and produces accurate results. Several examples involving waveguide transitions, standard and advanced band-pass filters, stepped- and continuous-profile mode converters as well as periodic structures demonstrate the versatility of this method. Verification is achieved by comparison with results obtained by the mode-matching technique.

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