EDGE-CONDITIONED VECTOR BASIS FUNCTIONS FOR THE ANALYSIS AND OPTIMIZATION OF RECTANGULAR WAVEGUIDE DUAL-MODE FILTERS

Jens Bornemann*, Uwe Rosenberg#, Smain Amari+ and Rüdiger Vahldieck+

*University of Victoria, Canada, #Bosch Telecom, Germany, +ETH Zürich, Switzerland

Abstract: The reliable computer-aided design of narrowband dual-mode filters is usually hampered by extensive CPU-time and memory requirements of commercially available software packages. This paper introduces a new concept within the coupled-integral-equations-technique (CIET) which takes into account all edge conditions simultaneously and, therefore, permits the analysis and optimization of such filter components in a timely fashion. A 12.3GHz four-pole dual-mode filter in rectangular waveguide is chosen as design example. Comparison with HP's HFSS shows good agreement, whereas the mode-matching technique (MMT) did not converge with up to 600 modes. The CIET routine converges with up to 23 edge-conditioned vector basis functions and up to 1750 modal summation terms. Due to its speed, the new approach can also be used for a Monte-Carlo-based tolerance analysis which shows a manufacturing accuracy of 0.02mm for this critical dual-mode filter example.

I. INTRODUCTION

Dual-mode filters play an essential role in modern satellite and terrestrial communication systems, e.g. [1]. Traditionally, such components have been constructed in circular waveguide technology requiring manual tuning to adjust resonator lengths and inter-cavity coupling. Recently, some effort has been made to improve computer-aided design procedures in order to eliminate the manual-tuning component in the design. Applications focused on circular/elliptic, e.g. [2, 3], as well rectangular, e.g. [4-7], cavity arrangements involving various coupling elements. Since commercial field solvers require extremely fine meshing to capture the salient features of narrowband dual-mode filters, theoretical approaches are mainly based on mode-matching algorithms which appear to be the most appropriate choice, especially for inline dual-mode configurations [2-5].

However, with smaller bandwidths and the lack of symmetry planes (as typical for filters involving negative cross-coupling), the number of modes needs to be significantly increased, thus resulting in extensive CPU times which make a timely design impracticable.

Therefore, this paper focuses on introducing edge-conditioned vector basis functions in the coupled integral-equations technique [8] to handle a variety of rectangular waveguide discontinuities. The advantages over traditional MMT algorithms are as follows: First, edge conditions at all discontinuities are simultaneously taken into account; second, modal components enter the calculation only as summation terms; and third, the overall system matrix is block-diagonal. Therefore, an efficient and reliable code is obtained which permits the analysis, optimization and tolerance analysis of narrowband dual-mode filters in time frames consistent with industry requirements.

II. THEORY

Each discontinuity within the structure of Fig.1 is treated as two offset-connected waveguides as shown, for example, in Fig. 2. Although the actual dual-mode filter structure does not exhibit such a connection, this approach makes the CIET applicable to general optimization algorithms. Since an optimization routine may completely alter the nature of a discontinuity during the optimization process, the implementation of edge conditions must be flexible and adaptable to the individual structure to be analyzed.

The TE and TM modes in the two waveguides and in the aperture are derived from well-known potentials $T^{\nu}_{h(m,n)}(x,y)$ and $T^{\nu}_{e(m,n)}(x,y)$ with $\nu \in 1, 0, 2$, e.g. [1]. Let us assume that the actual electric field distribution at z=0 (Fig. 2) is given by a function $\vec{X}$ which is expanded in a series of the form

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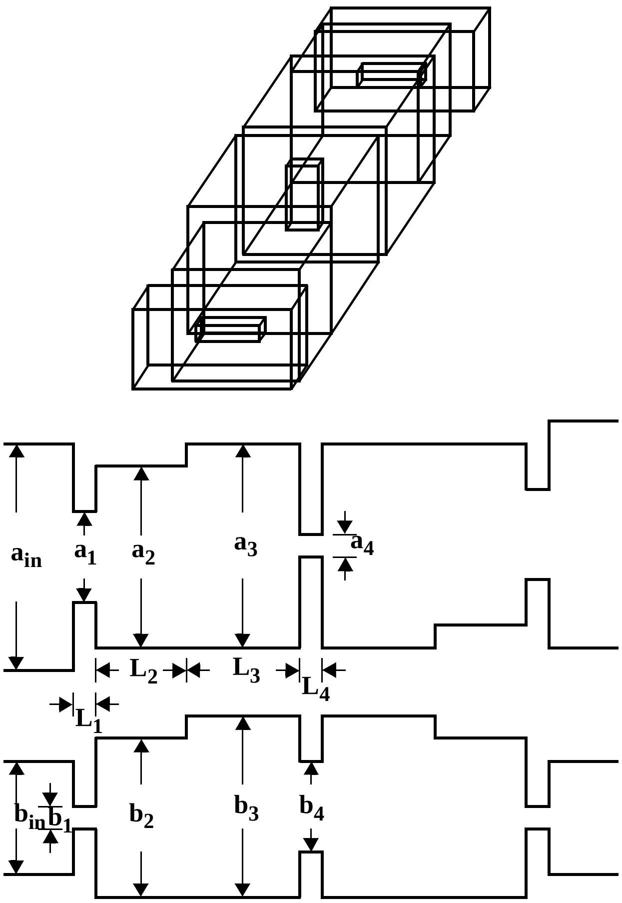

Fig. 1 *Rectangular waveguide dual-mode filter: 3-D view (top), top view (middle), side view (bottom). Note that the cross-sectional dimensions are symmetric but that the structure is asymmetric due to different offsets.*

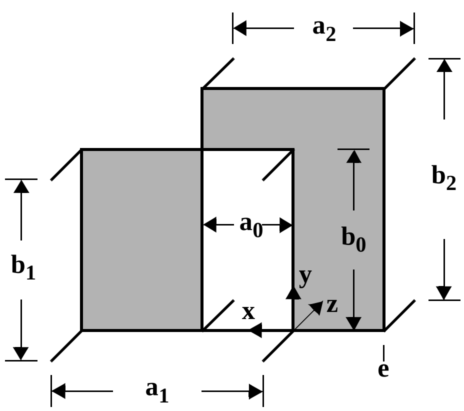

Fig. 2 *Example discontinuity showing two connected waveguides ($a_1 x b_1$, $a_2 x b_2$) and common aperture ($a_0 x b_0$).*

$$\vec{X}(x, y) = \sum_{(i,k)=1}^{M_h} c_{h(i,k)} \vec{B}_{h(i,k)}(x, y) + \sum_{(i,k)=1}^{M_e} c_{e(i,k)} \vec{B}_{e(i,k)}(x, y) \; . \qquad (1)$$

To include the edge conditions at the metallic corners, two sets of vector basis functions of the form

$$\vec{B}_{h(i,k)} = \frac{\vec{e}_z \times \nabla_t T^0_{h(i,k)}(x, y)}{[x(a_0 - x)(y + b_0)(b_0 - y)]^{1/3}} \qquad (2)$$

and

$$\vec{B}_{e(i,k)} = \frac{\nabla_t T^0_{e(i,k)}(x, y)}{[x(a_0 - x)(y + b_0)(b_0 - y)]^{1/3}} \qquad (3)$$

are introduced. Note that in this specific example of Fig. 2, an edge condition at y=0 is not required and, therefore, the image at $y=-b_0$ is included.

Following the procedure of the coupled-integral-equations technique [8], each coefficient vector $c_{h,e(i,k)}$ is related to those of the immediate neighbor discontinuities. Applying the continuity of the transverse magnetic field components yields a set of coupled integral equations which is solved using the method of moments. Note that the resulting matrix is block diagonal [8], thus requiring relatively low computational effort. For the dual-mode filter, convergence was reached with up to $M_h+M_e=23$ edge-conditioned vector basis functions and up to 1750 modal summation terms. Further increase of the number of basis functions yields results within the plotting accuracy.

III. RESULTS

Fig. 3 shows the performance of the optimized [9] dual-mode filter (solid line) using this method (CIET). The design dimensions (c.f. Fig. 1) in mm are: $a_{in} x b_{in}$=19.05x9.52, $a_1 x b_1$=9.90x 2.94, $a_2 x b_2$=13.84x13.77, $a_3 x b_3$=15.39x16.82, $a_4 x b_4$=3.18x6.01, $L_1=L_4$=1.50, L_2=8.55, L_3= 11.81. A 23dB return-loss bandwidth of 100 MHz is obtained when limiting the optimization accuracy to 0.01 mm. Results obtained by the finite-element field solver HFSS (dashed lines) are shown for comparison. The agreement is very good considering the fact that HFSS went through 35 mesh refinement steps, at which point calculations exceeded our memory allocation of 500MB. Agreement with the mode-matching technique (MMT) could only be obtained in principle (not shown), since MMT did not converge with up to 600 modes in the largest cross-section; (smaller sections use a reduced mode set according to the aperture ratios).

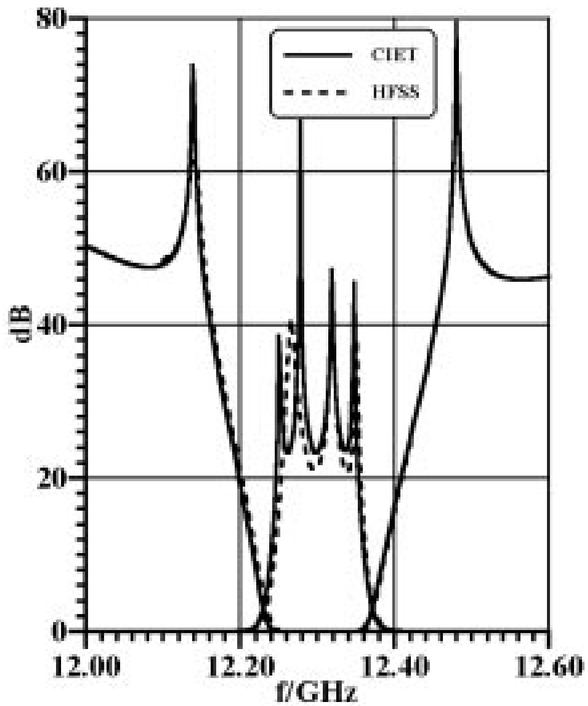

Fig. 3 *Response of optimized dual-mode filter according to Fig. 1. This method (solid lines) and HFSS (dashed lines).*

Beyond a cutoff frequency of 13.2 GHz, the next two modes (TE_{11}, TM_{11}) propagate in the largest cross-section ($a_3 x b_3$, Fig. 1). Obviously, the resonances of these modes are also coupled by the cavity structure resulting in a spurious passband (3dB bandwidth of 40 MHz) at 13.76 GHz as demonstrated in the wideband selectivity evaluation of Fig. 4.

Fig. 5 shows a Monte-Carlo-based tolerance analysis, e.g. [10], for manufacturing tolerances of up to $\Delta x = \pm 0.02$ mm (0.8mil). It is further assumed that the propability density at $x \pm \Delta x$ is one half of that at the nominal value x. Under these assumptions, a 20dB return-loss bandwidth of 52 MHz is retained.

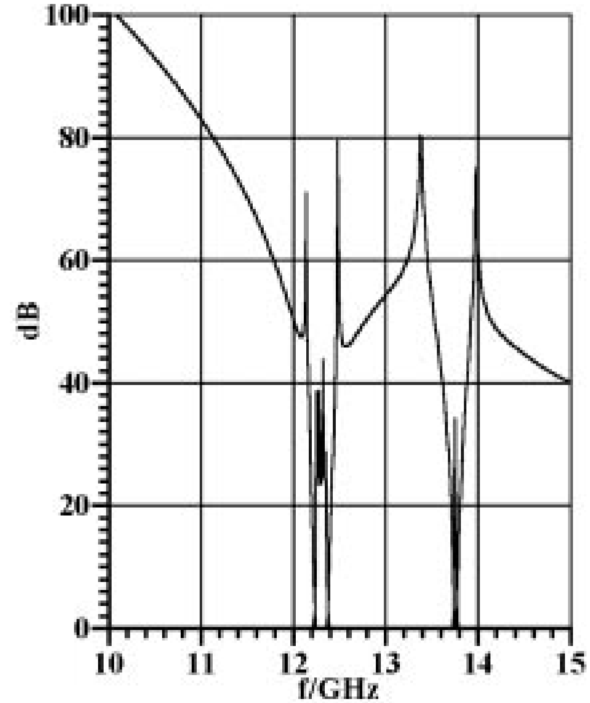

Fig. 4 *Wideband selectivity of optimized dual-mode filter.*

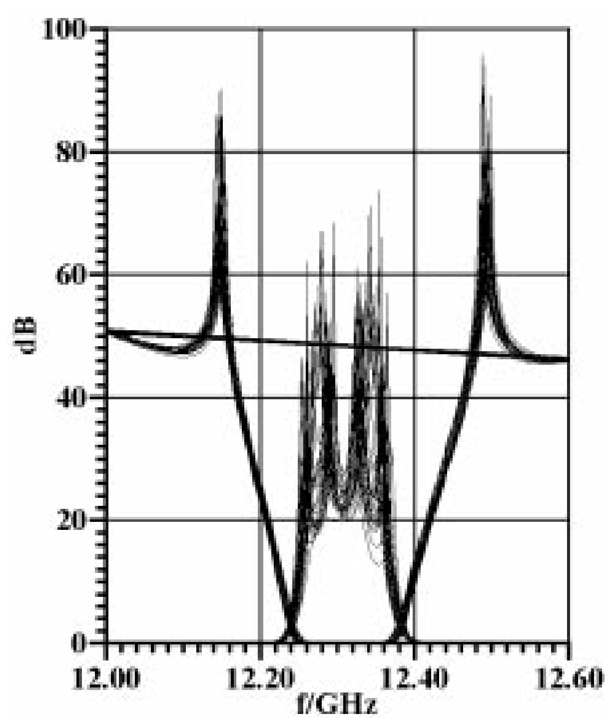

Fig. 5 *Monte-Carlo-based analysis for manufacturing tolerances of up to 0.02mm (0.8mil). (Almost horizontal lines around 50 dB caused by back trace.)*

IV. CONCLUSIONS

Edge-conditioned vector basis functions for general waveguide discontinuities are introduced in the coupled-integral-equations technique. This approach permits the analysis, optimization and tolerance analysis of narrowband dual-mode filters in time frames suitable for industrial environments. A new four-pole dual-mode filter in rectangular waveguide is chosen as design example. Good agreement with results from the finite-element method is obtained. Due to the narrowband nature of the design, manufacturing tolerances are expected to be within 0.02mm (0.8mil) to retain approximately half the bandwidth..

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