CAD-ORIENTED EQUIVALENT CIRCUIT MODELS FOR RIGOROUS FULL-WAVE ANALYSIS AND DESIGN OF WAVEGUIDE COMPONENTS AND CIRCUITS

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Abstract— **A new multi-mode equivalent circuit model for cascaded waveguide step discontinuities is presented. This CAD-oriented equivalent circuit model enables rigorous and efficient full-wave analysis of waveguide components and circuits entirely by circuit simulation. The method has been implemented on the microwave circuit simulator Libra. Comparisons of circuit simulation results for single and cascaded inductive irises with the standard mode-matching method show perfect agreement. Results of a Ka-band bandpass filter analysis show good agreement with other mode-matching solutions.**

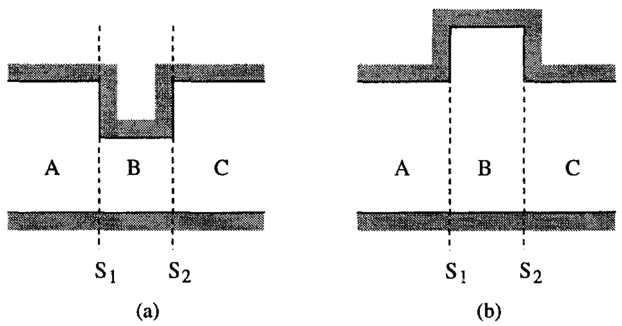

Fig. 1. Geometry of (a) a thick iris and (b) a stub discontinuity.

I. INTRODUCTION

COMPUTER aided design of waveguide filters and components generally requires use of a rigorous full-wave analysis technique such as the finite element and finite difference methods or the mode-matching method. Although general purpose tools such as, for example, full-wave finite-element solvers [1] are commercially available, modal analysis methods are often preferred since they are computationally more efficient [2]-[4] and provide physical insight [5]. However, available modal analysis tools are typically stand-alone programs which are often developed for a particular type of problem.

We introduce a rigorous multi-mode equivalent circuit model for cascaded steps including interacting steps such as thick irises and stubs which form basic building blocks of many waveguide filters and components. Using this new multi-mode equivalent circuit representation for cascaded steps, a large class of waveguide components and circuits, including filters and phase shifters, can be analyzed and designed entirely with commercial circuit simulators. Since the equivalent circuit model is derived from a modal analysis, a full-wave analysis can be performed directly by *circuit simulation* thus eliminating the need for additional matrix inversion software.

In the following sections, the equivalent circuit model of cascaded steps is presented and the accuracy of the circuit simulation is demonstrated for both interacting and non-interacting steps. As an example of a practical application of the new circuit model approach, a comparison of a waveguide filter analysis by circuit simulation on Libra [6] and standard mode-matching simulation [3], [7] including the correct edge behavior [8] is shown. Advantages of the proposed equivalent circuit model implementation in commercial circuit simulators include the direct and full use of available design, optimization, and graphical user interface capabilities of the CAD tool. A particularly attractive feature of the equivalent circuit model approach is the dynamic decoupling of higher-order modes between interacting step discontinuities which leads to an intrinsically stable analysis and design tool.

II. MULTI-MODE EQUIVALENT CIRCUIT FOR CASCADED STEP DISCONTINUITIES

Figure 1 shows the geometries of a thick iris and a stub discontinuity as two representative examples of interacting step discontinuites. First, the single step discontinuity is analyzed in terms of a modal expansion in the transverse modal fields, as described in [3], [7]. With reference to the thick iris in Fig. 1(a), the modal voltage and current amplitude coefficients representing the transverse electric and magnetic fields in region A at interface S_1 are denoted by $\mathbf{V}_A$ and $\mathbf{I}_A$,

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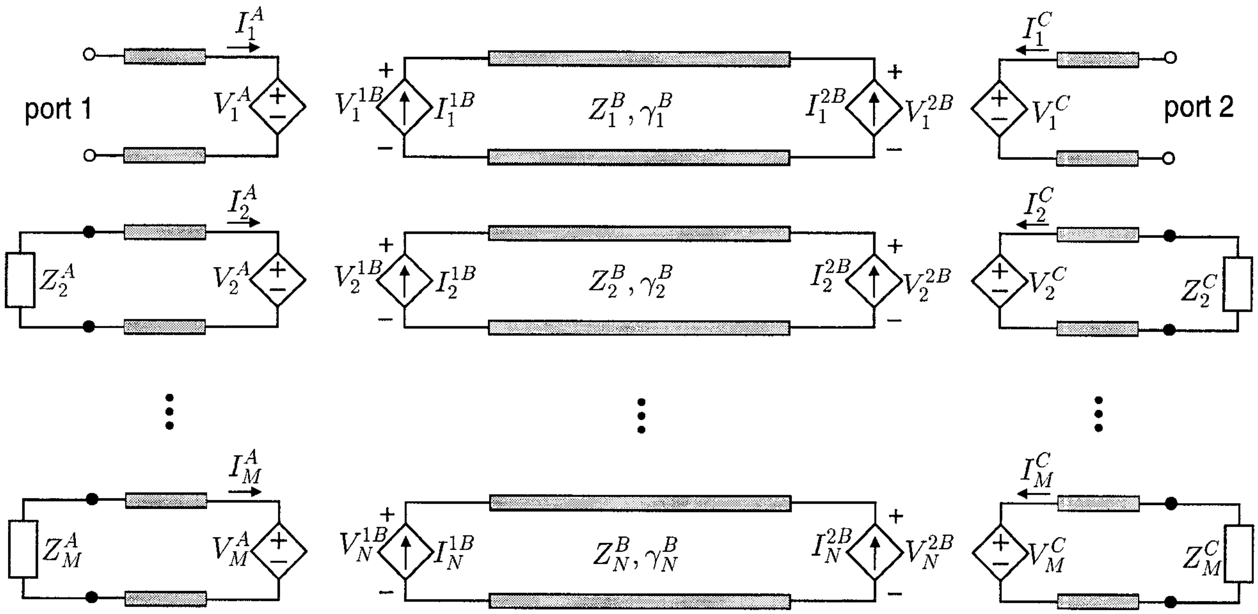

Fig. 2. Multi-mode equivalent circuit of a thick iris. The voltages and currents are defined in the paper. The impedance Z_p^q and propagation constant γ_p^q correspond to mode p in region q, respectively.

respectively. Similarly, the voltage and current coefficients representing the transverse field amplitudes in region B at interface S_1 are given by $\mathbf{V}_{1B}$ and $\mathbf{I}_{1B}$, respectively. The relationship between the amplitude coefficients is found from a standard mode-matching procedure as shown in [9] and is given by

$$\begin{aligned} \mathbf{V}_A &= \mathbf{C}_1 \mathbf{V}_{1B} \\ \mathbf{I}_{1B} &= \mathbf{C}_1^T \mathbf{I}_A \end{aligned} \tag{1}$$

where $\mathbf{C}_1$ represents the mode-coupling at the S_1 interface and superscript T denotes matrix transposition. A similar analysis for the step discontinuity at interface S_2 gives

$$\begin{aligned} \mathbf{V}_C &= \mathbf{C}_2 \mathbf{V}_{2B} \\ \mathbf{I}_{2B} &= \mathbf{C}_2^T \mathbf{I}_C \end{aligned} \tag{2}$$

The voltage and current coefficients at the two interfaces S_1 and S_2 of region B are related through standard transmission line equations for each waveguide mode in region B with characteristic impedances corresponding to the modal wave impedances. Similar equations are obtained for the stub discontinuity shown in Fig. 1(b).

As shown in [9], eqs. (1) lead to a simple multi-mode equivalent circuit description for the mode-coupling at the single step discontinuity at interface S_1 in terms of voltage-controlled voltage sources and current-controlled current sources. In the case of cascaded steps, the dependent sources in region B are connected by "modal" transmission lines. The complete equivalent circuit representation of a thick iris is shown in Fig. 2 where the voltages and currents at interface S_1 are given by

$$V_1^A = \sum_{n=1}^{N} C_{1n} V_n^{1B}$$

$$V_2^A = \sum_{n=1}^{N} C_{2n} V_n^{1B}$$

$$V_M^A = \sum_{n=1}^{N} C_{Mn} V_n^{1B}$$

$$I_1^{1B} = \sum_{m=1}^{M} C_{m1} I_m^A$$

$$I_2^{1B} = \sum_{m=1}^{M} C_{m2} I_m^A$$

$$I_N^{1B} = \sum_{m=1}^{M} C_{mN} I_m^A$$

Similar expressions are obtained for the voltages and currents at interface S_2. The impedance Z_p^q and propagation constant γ_p^q correspond to mode p in region q, respectively.

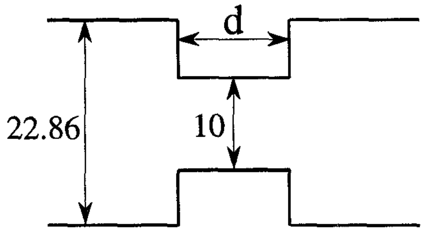

Fig. 3. Geometry of an inductive iris of variable thickness d. Dimensions are given in mm.

III. Results

We have implemented the new equivalent circuit approach in the commercial microwave simulator Libra [6]. In order to demonstrate the accuracy of the new equivalent circuit representation of cascaded steps, we have analyzed inductive irises of various thicknesses (Fig. 3), i.e. for various degrees of interaction between the steps via the higher order modes. The results for the transmission coefficient for different thicknesses d of the iris are shown in Fig. 4. Also included in the figure are the results obtained from a mode-matching analysis which considers the correct edge behavior [8]. Perfect agreement between the two methods is obtained.

As a second test, we consider two identical cascaded irises separated by distance d, as indicated in Fig. 5. The transmission coefficient computed by circuit simulation is compared with results obtained with a mode-matching method [8]. Again, perfect agreement between the two methods can be seen. Also included in the figure are the results for the case when the irises are defined as two-port circuit elements by terminating all higher-order modes in the wider regions in their modal impedances. In this case, the cascaded irises can only interact via the fundamental (propagating) mode. As expected, interacting higher-order modes can be neglected even for moderately separated irises (d = 10 mm) but must be included for correct analysis of closely spaced irises (d = 5 mm). The results shown in Fig. 6 also demonstrate the stability of the circuit simulation which dynamically decouples the higher-order modes with increasing separation d between the irises.

As a final application, we have implemented the equivalent circuit approach to analyze a bandpass filter which was designed in [10] for the Ka-band at 35 GHz and a bandwidth of 1 GHz. The filter dimensions are given in Fig. 7. The results obtained from a circuit simulation on Libra are shown in Fig. 8 and compared with the mode-matching method which includes the correct edge condition. The circuit simulation was done by retaining 10 modes in the wide regions, five modes in the irises of width 3.2 mm, and three modes in the irises of width 2.4 mm in order to avoid relative convergence problems [11]. The results obtained with the two different methods show very good agreement thus validating the equivalent circuit approach for waveguide filter analysis and design.

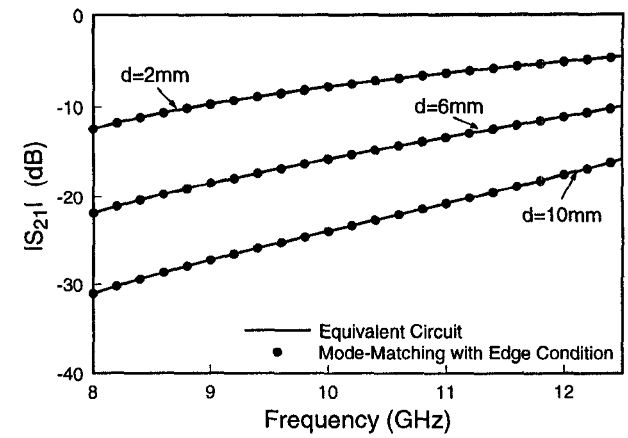

Fig. 4. Transmission coefficient of an iris for different thicknesses d as defined in Fig. 3.

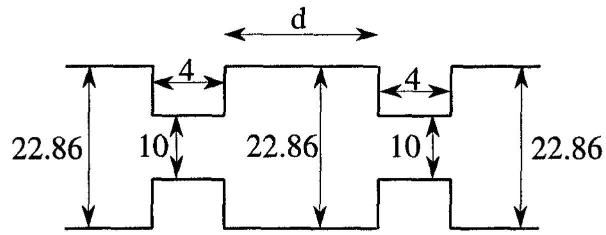

Fig. 5. Geometry of two cascaded irises separated by distance d. Dimensions are given in mm.

IV. Conclusion

We have presented a new equivalent circuit model of cascaded step discontinuities in a rectangular waveguide. This CAD-oriented equivalent circuit model enables full-wave analysis of a large class of waveguide components and circuits including irises, stubs, filters, and phase shifters on commercial microwave circuit simulators. The equivalent circuit model for inductive irises and H-plane step filters have been implemented on Libra to demonstrate the accuracy of the method. Results of the circuit analysis were found to be in virtually perfect agreement with solutions from a mode-matching technique which includes the correct edge behavior of the fields.

The potential benefits of using commercial simulators in the analysis and design of waveguide components include: customized codes for the design of these components are not required and full advantage of the available design, optimization, and graphical user interface capabilities of the

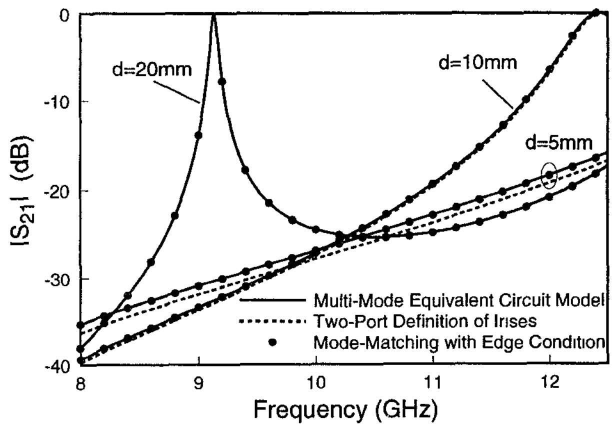

Fig. 6. Transmission coefficient for two cascaded irises with dimensions as shown in Fig. 5.

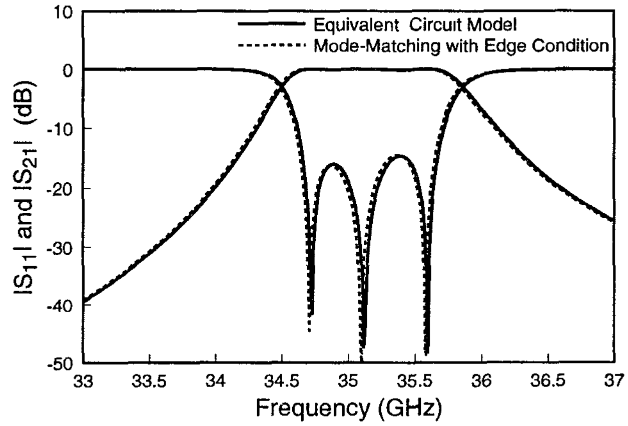

Fig. 8. Scattering parameters of a bandpass filter with dimensions given Fig. 7.

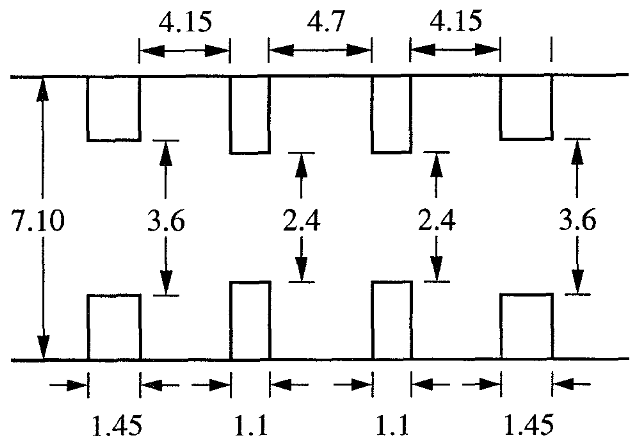

Fig. 7. Geometry of a bandpass filter for the Ka-band. Dimensions are given in mm.

CAD tool can be taken.

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