DESIGN OF MODE CONVERTERS USING THE COUPLED-INTEGRAL-EQUATIONS TECHNIQUE

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INTRODUCTION

Mode converters in circular waveguide technology are widely used in high-power microwave and horn antenna applications, e.g. [1-8]. Several designs to convert a TE/TM_{mn} to a TE/TM_{ik} mode have been presented, and, among the varieties of mode converters, those involving the special case of rotationally symmetric structures with m=i have attracted special attention [3-8]. However, except for optimization techniques, general methods or guidelines towards initial designs are available only very sparsely.

This paper closes that gap. Based on the coupled-integral-equations technique (CIET) as an accurate analysis tool, e.g. [9, 10], a synthesis approach for the design of rotationally symmetric mode converters (c.f. Fig. 1) is developed:

1. The diameters of input and output guides are chosen such that the wavelength of the two modes involved are identical.
2. The power transmitted from the incident to the output mode, i.e., the magnitude squared of the coupling integral between the two modes, is analyzed with respect to maximum excitation of the desired output mode.
3. The number of required discontinuities is determined from the desired efficiency of the mode converter.
4. The entire length is adjusted to encompass one wavelength at midband frequency.

The approach is demonstrated at the example of a TE_{11}-to-TM_{11} converter.

THEORY

a) Analysis

The general principle of computing the generalized scattering matrix with the coupled-integral-equations technique is outlined below. For details the reader is referred to [9]. A structure with multiple cascaded discontinuities, such as the mode converter in Fig. 1, can be analyzed by expanding the electromagnetic fields in each waveguide section as a sum of the respective eigenmodes. At each discontinuity, the fields are related to aperture functions which fulfill the boundary and edge conditions at the respective interfaces through series of suitable basis functions. By relating the fields at the discontinuities (in terms of basis functions) to those at the immediate neighbour discontinuities and using Galerkin's technique in a method-of-moments algorithm, a blockdiagonal matrix is obtained which, e.g. for six discontinuities, can be written as

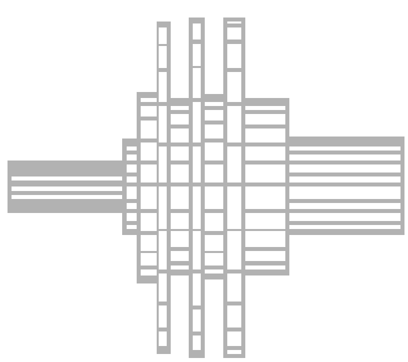

Fig. 1 Profile of TE_{11}-to-TM_{11} mode converter in circular waveguide technology

$$\begin{bmatrix} \underline{A}_{11} & \underline{A}_{12} & \underline{0} & \underline{0} & \underline{0} & \underline{0} \\ \underline{A}_{21} & \underline{A}_{22} & \underline{A}_{23} & \underline{0} & \underline{0} & \underline{0} \\ \underline{0} & \underline{A}_{32} & \underline{A}_{33} & \underline{A}_{34} & \underline{0} & \underline{0} \\ \underline{0} & \underline{0} & \underline{A}_{43} & \underline{A}_{44} & \underline{A}_{45} & \underline{0} \\ \underline{0} & \underline{0} & \underline{0} & \underline{A}_{54} & \underline{A}_{55} & \underline{A}_{56} \\ \underline{0} & \underline{0} & \underline{0} & \underline{0} & \underline{A}_{65} & \underline{A}_{66} \end{bmatrix} \begin{bmatrix} \underline{c}_1 \\ \underline{c}_2 \\ \underline{c}_3 \\ \underline{c}_4 \\ \underline{c}_5 \\ \underline{c}_6 \end{bmatrix} = \begin{bmatrix} \underline{e}_i \\ \underline{0} \\ \underline{0} \\ \underline{0} \\ \underline{0} \\ \underline{0} \end{bmatrix}, \begin{bmatrix} \underline{0} \\ \underline{0} \\ \underline{0} \\ \underline{0} \\ \underline{0} \\ \underline{e}_o \end{bmatrix} . \tag{1}$$

In (1), $\underline{e}_i$ and $\underline{e}_o$ represent excitations at the input and output, respectively, $\underline{c}_n$ are the vectors of coefficients of basis functions for discontinuity n and a given excitation, and matrix $[\underline{A}]$ contains inner products of basis functions with the individual waveguide modes and the transformation terms relating one discontinuity to its neighbours. After a LU decomposition of the matrix $[\underline{A}]$, coefficient vectors of the first and last discontinuities are computed for the desired numbers of excitations at the input and output. The final generalized S-matrix is extracted according to [9].
At an individual discontinuity, the vector basis functions are formed by the modes of the smaller waveguide at the junction (section I of radius r_1) modified by the appropriate edge condition.

$$\vec{\Phi}(\rho, \varphi) = \sum_r \frac{[\nabla T^I_{hr}(\rho, \varphi) \times \vec{e}_z] c_r}{[1 - (\rho/r_1)^2]^{1/3}} + \sum_s \frac{[-\nabla T^I_{es}(\rho, \varphi)] c_s}{[1 - (\rho/r_1)^2]^{1/3}} \tag{2}$$

The two sums correspond to TE and TM modes, respectively. Coefficients c_r and c_s at discontinuity i form the entries of vectors $\underline{c}_i$ in (1).

At the example of a TE_{11}-to-TM_{11} mode converter in [6], this analysis procedure was verified by comparison with the finite-element method (HFSS). Excellent agreement is demonstrated in Fig. 2. Note that due to the poor return loss performance of this mode converter, most of the power will be reflected rather than converted. It this sense, neither the CIET nor HFSS confirm the performance claim of 98 percent conversion efficiency in [6].

b) Design
In order to develop some design guidelines, the discontinuity between a smaller TE_{11}-mode waveguide of radius r_1 and a larger TM_{11}-mode waveguide of radius r_2 is investigated. Let $\vec{e}$ represent the transverse electric field, then the power transfer between the two modes is proportional to the coupling integral

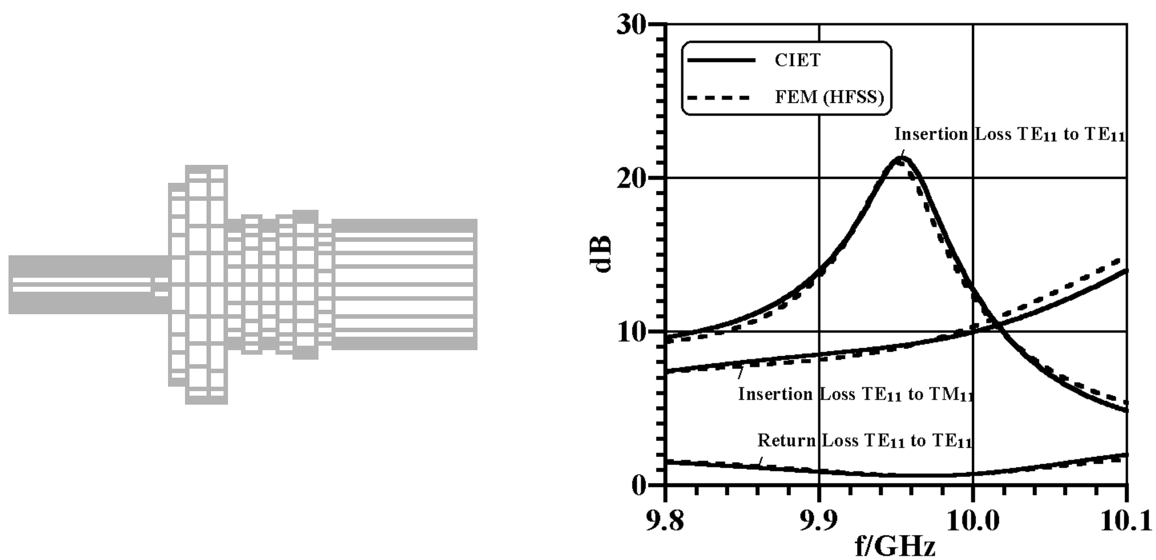

Fig. 2 Profile and performance of TE_{11}-to-TM_{11} mode converter in [6] and comparison with HFSS.

$$P_{TE_{11} \to TM_{11}} \propto \left| \int_{s_1} (\vec{e}^{\,I}_{TE_{11}} \cdot \vec{e}^{\,II}_{TM_{11}}) ds \right|^2 \propto \left| J_1(\chi_{11} r_1 / r_2) \right|^2 / \sqrt{\left| 1 - [\chi_{11}/(k_0 r_2)]^2 \right|} \quad (3)$$

where χ_{11} denotes the first zero of Bessel function J_1. A plot of this power as a function of r_1/r_2 is shown in Fig. 3. The maximum is located at r_1/r_2=0.538 which corresponds to one radius being slightly less than twice the other. The number of discontinuities required in a mode converter can now be chosen by the desired efficiency of the converter assuming that each discontinuity contributes the same amount of mode conversion. Since the ratio of nearly two cannot be steadily extended, a corrugation-type profile similar to that of Fig. 1 results. The length of each individual section is chosen by one TM_{11}-mode wavelength, which is identical to the TE_{11}-mode wavelength at the input, divided by the number of sections. Due to the currugated profile and the given ratio r_1/r_2, one or more sections of equal radius might have to be used to arrive at the given output radius. The performance of this initial design is shown in Fig. 4. Note that not only has the return loss been significantly improved, but also the bandwidth has been broadened compared to the design in [6] (Fig. 2). A 90 percent conversion efficiency (see Fig. 5, lower right) over a 3.6 percent bandwidth with 13 dB minimum return loss has been achieved by this initial design. Similar results have been obtained in many other applications tested so far.

RESULTS

Using the above guidelines for the initial design, the CIET for analysis and a MiniMax strategy for optimization [11], the final design profile and performance verification are shown in Figs. 1 and 5, respectively. As confirmed by our own routine using the mode-matching technique (MMT) and HFSS, the efficiency of the optimized design is better than 99 percent over a 5.5 percent bandwidth with return loss better than 20 dB, or better than 96 percent over a 20dB-return-loss bandwidth of six percent (Fig. 5). Moreover, this design is reduced 30 percent in length compared to that of [6]. For high-power applications, the discontinuities in the final design need to be rounded. An investigation using staircase approximations (not shown here due to lack of space) has shown that the performance of the final design is not degraded by rounding the corners of the discontinuities involved.

CONCLUSIONS

Guidelines for the design of rotationally symmetric circular waveguide mode converters are presented. The initial design shows very good performance which is further improved by using optimization techniques in connection with the coupled-integral-equations technique. The final design offers improved conversion efficiency and bandwidth and is verified by the CIET, MMT and HFSS. Performance claims in a recent publication [6] could not be verified by either of these three numerical techniques.

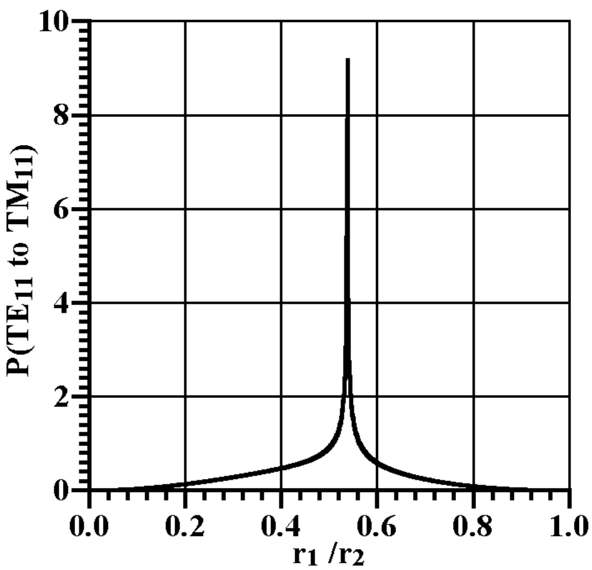

Fig. 3 TE_{11}-to-TM_{11} mode power conversion at a single discontinuity (r_1=9.8933mm, f=9.94GHz).

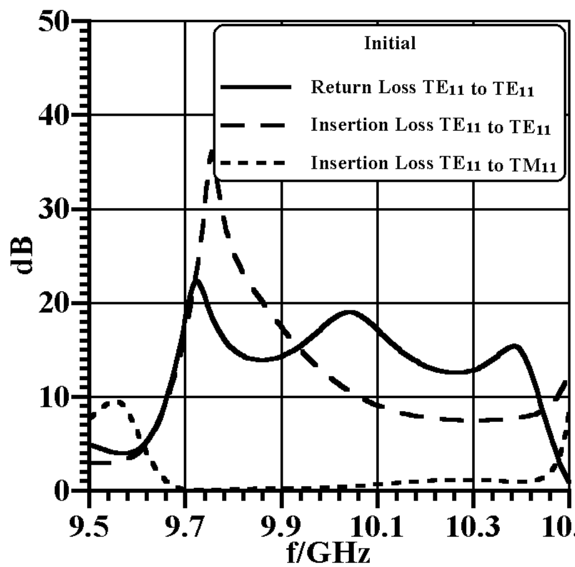

Fig. 4 Performance of initial TE_{11}-to-TM_{11} mode converter design.

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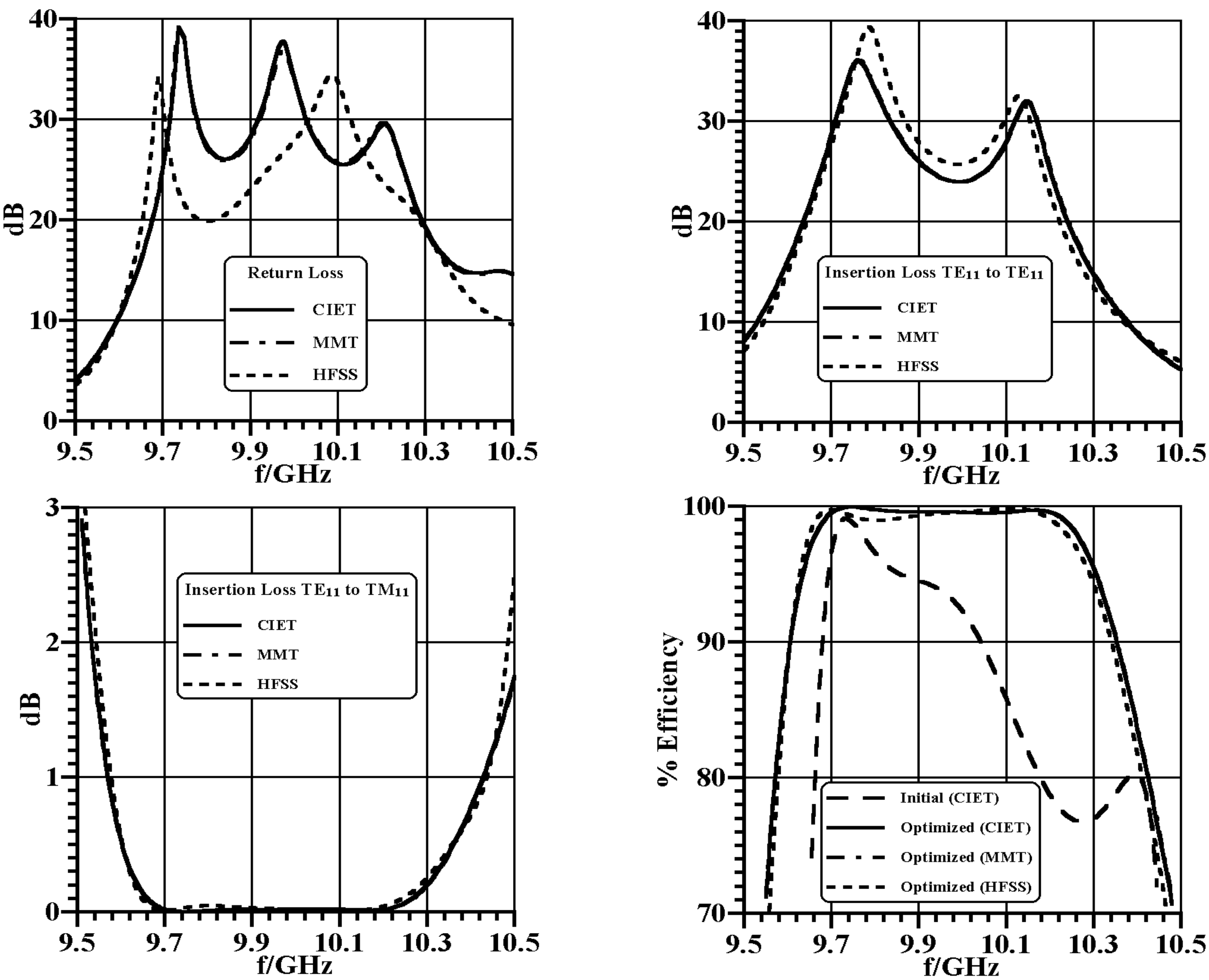

Fig. 5 Performance of optimized TE_{11}-to-TM_{11} mode converter and comparison with MMT and HFSS. Notice the efficiency of the initial design in the lower right figure.