Direct EM Based Optimization of Advanced Waffle-Iron and Rectangular Combline Filters

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Abstract — **A fast hybrid mode-matching (MM)/finite-element (FE) method is applied for the direct EM based optimization of advanced waffle-iron filters and coax-fed rectangular combline filters. The proposed technique, which combines the efficiency of the MM with the flexibility of the FE technique, achieves the direct EM based optimization of these components within typically an overnight run on a PC. The CAD method is verified by measurements.**

I. INTRODUCTION

WAFFLE-IRON-FILTERS [1] are useful filter types well-known in industry for offering the potential of wide pass bands and high-attenuation stop bands up to several harmonics. For such kind of filters, the fast and accurate MM/FE method [2], [3] has already been employed in [4]. The present paper describes the application of the MM/FE method to the optimization of waffle-iron filters of improved performance, Fig. 1: Enlarged waveguide heights between the waffle-sections as additional design parameters yield higher edge steepness without increasing the filter length and without the necessity to reduce the gap widths. Moreover, the 2D FE eigenvalue solution can easily handle different cross-section types, such as half teeth at the side walls (instead of the usual half slot) which helps to facilitate fabrication, and teeth with rounded corners which reduce power handling problems.

The FE solution of the cross-section eigenvalue problem is extended by a separate special boundary problem for TEM waves to include coaxial structures of general shape. This achieves the fast and accurate full-wave MM/FE calculation of rectangular combline filters (Fig. 2). The attractive feature of the MM/FE method is the high CPU speed which allows the direct optimization of such filters within typically an overnight run on a PC.

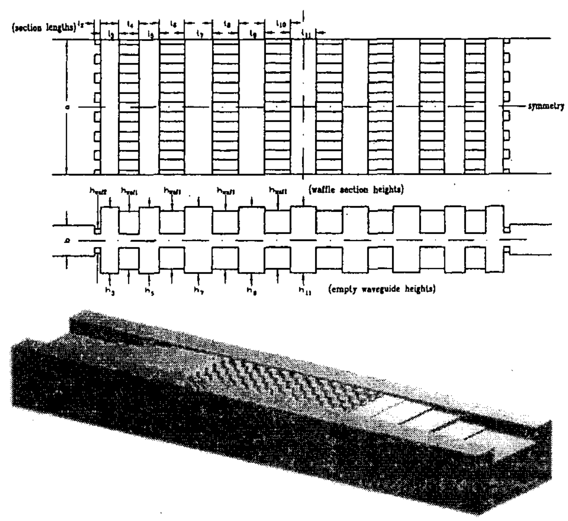

Fig. 1. Waffle-iron filter with enlarged waveguide heights between the waffle-sections and half teeth at the side walls

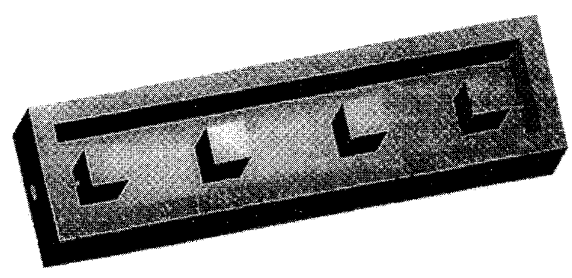

Fig. 2. Rectangular combline filter calculated with the fast MM/FE method

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II. THEORY

The design method is based on the hybrid mode-matching finite-element (MM/FE) technique, which leads to a direct standard generalized matrix eigenvalue problem [2] for the considered waveguide cross-sections of more general shape

$$\left[\mathbf{K} - k_c^2\mathbf{M}\right]\overline{\Psi} = 0\,, \qquad (1)$$

where

$$\mathbf{K}_{JK} = \iint_{\Omega} \nabla_t N_J \nabla_t N_K d\Omega\,,$$

$$\mathbf{M}_{JK} = \iint_{\Omega} N_J N_K d\Omega\,, \qquad \overline{\Psi} = \left(\Psi_1, \Psi_2 \cdots, \Psi_N\right)^T,$$

and the potentials $\overline{\Psi}$ are approximated by their nodal values Ψ_K and first order Lagrangian interpolation polynomials $N_K(x,y)$ by

$$\Psi(x,y) \approx \sum_K \Psi_K N_K(x,y)\,. \qquad (2)$$

In contrast to remarks in recent MM/FE papers where edge elements are used, nodal functions expansion of scalar potentials achieves - according to our experience - the fastest approach for metallic boundaries (and this without spurious modes).

The generalized eigenvalue problem (1) is transformed into standard form by a Cholesky separation technique, and is solved iteratively by the Lanczos algorithm after suitable preconditioning which includes the boundary problem for the TEM wave as a special case.

Matching the transverse fields at the common interface of the general waveguide step discontinuity leads to the corresponding generalized scattering matrix (GSM). The involved frequency independent coupling integrals can be formulated in terms of line integrals by using the common definition of the transversal eigenvectors

$$\begin{array}{ll}
\dfrac{k_{cII}^2}{k_{cII}^2 - k_{cI}^2} \oint\limits_{\Gamma_{II}} \Psi^{II} \dfrac{\partial \Psi^{I}}{\partial n} dc & \text{TE-TE} \\
0 & \text{TE-TM and TE-TEM} \\
-\oint\limits_{\Gamma_{II}} \Psi^{II} \dfrac{\partial \Psi^{I}}{\partial \tau} dc & \text{TM-TE and TEM-TE} \\
\dfrac{k_{cI}^2}{k_{cI}^2 - k_{cII}^2} \oint\limits_{\Gamma_{II}} \Psi^{I} \dfrac{\partial \Psi^{II}}{\partial n} dc & \text{TM-TM} \\
\oint\limits_{\Gamma_{II}} \Psi^{I} \dfrac{\partial \Psi^{II}}{\partial n} dc & \text{TM-TEM and TEM-TEM} \\
0 & \text{TEM-TM}
\end{array} \qquad (3)$$

For discontinuities involving analytical expressions for the eigenvectors, the line integral formulations (3) have been preferred to surface integrals: The accuracy is identical, and there is a slight reduction in calculation time concerning the individual coupling integrals.

However, for discontinuities of waveguides with arbitrary cross-section where the eigenvectors are numerical solutions of the corresponding 2D FE eigenvalue problem, the accuracy of the line integral calculation is significantly lower than for coupling integrals with analytical expressions; this is due to the increased influence of errors caused by finite discretization and by numerical approximations of the line integral contour. Moreover, the factor $(1 - k_{cI}^2/k_{cII}^2)$ - effective in the near of degenerate modes - still further increases the errors, particularly in cases where the accuracy of the determination of eigenvalues is poor.

The GSMs of all involved transition substructures are combined in the usual way [2].

III. RESULTS

For the optimization of waffle-iron filters, in order to meet desired specifications without tuning screws and with a minimum number of sections, all adequate design parameters, e.g. all individual lengths l_i (Fig. 1), are taken into account. The first investigated example is an X-band (WR-75) waffle-iron filter, optimized for the desired values of 24dB return loss between 8.5 and 10.8 GHz, and a rejection of 80 dB from 15 to 37 GHz. Fig. 3 shows the optimized structure which consists of fifteen waffle iron sections. For this example, 245 modes have been taken into account in the waffle-iron sections. The CPU time is 30 seconds for the complete filter analysis (including the transformer sections) for 200 frequency points (1.4 GHz AMD PC), i.e. 0.15 seconds per frequency point, which demonstrates the high appropriateness of the MM/FE method for the adequate optimization of such components.

A prototype has been fabricated by milling techniques (Fig.3), with fabrication tolerances of less than ± 0.01 *mm*. The measurements concerning the return loss (Fig. 4) verify the theory by good agreement. The same is true for the rejection, not shown here. Note that there are no tuning screws.

The next example is a WR-34 waffle-iron filter (Fig. 5) with increased interim waveguide section heights (25% higher as compared with the inner height of the waffle-iron sections). Only the central waffle-iron filter section with 12 waffle-iron sections is shown in Fig. 5, without transformer sections.

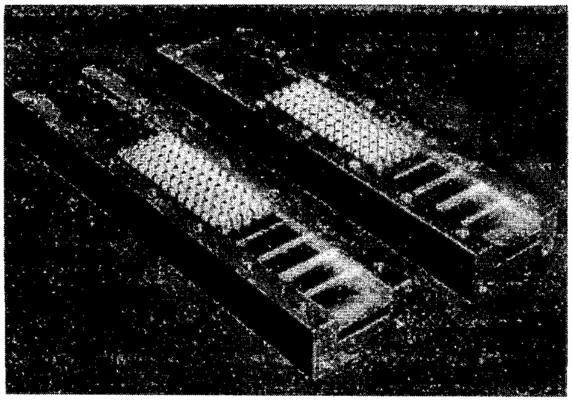

Fig. 3. WR-75 waffle-iron filter, fabricated by milling techniques

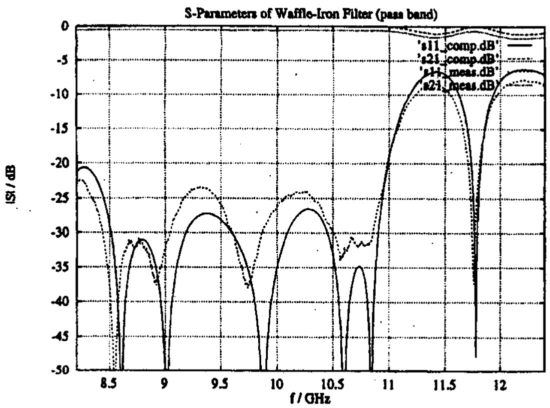

Fig. 4. WR-75 waffle-iron filter, calculated and measured return loss.

The optimization result yields about 23 dB return loss (28 - 41 GHz), and a high edge steepness: 60 dB rejection already for 44 GHz. The total length of the central waffle-iron filter section (without transformers) is 12.5 *mm*, the gap width is 0.6 *mm*.

A coaxial transition in rectangular WR-62 waveguide band according to [5] is investigated as the third example. Fig. 6 shows the return loss calculated by the MM/FE method, compared with measured results according to [5]. The MM/FE CPU time for 100 frequency points is about 3 seconds (1.4 GHz AMD PC).

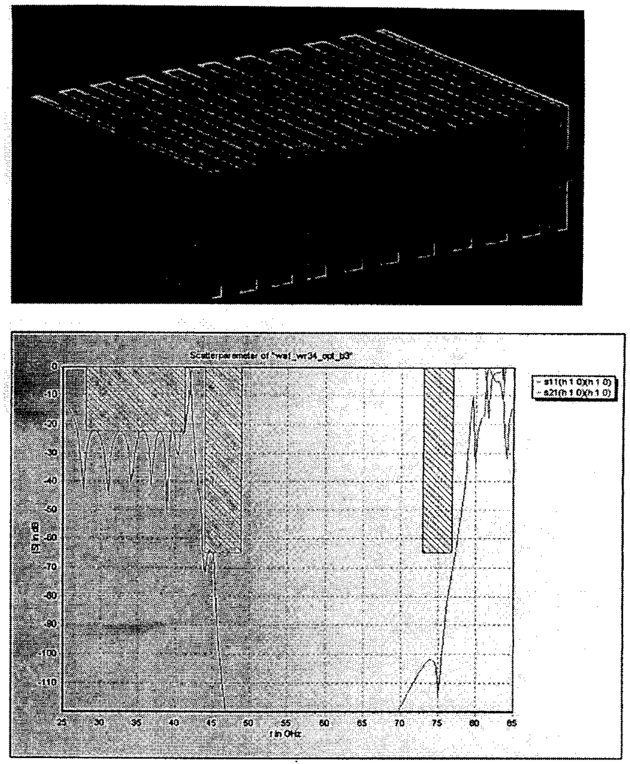

Fig. 5. Optimized WR-34 waffle-iron filter with increased heights (25% higher) of the interim waveguide sections as compared with the inner height of the waffle-iron sections.

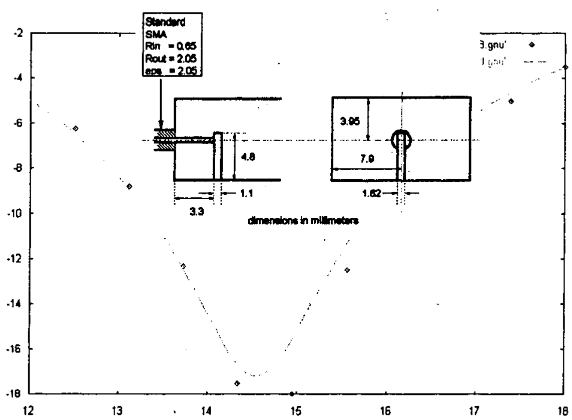

Fig. 6 Return loss of a coax-fed rectangular post in rectangular waveguide calculated by the MM/FE method. Dimensions, measurements according to [5]

The usefulness of the MM/FE CAD method for the fast design and optimization of rectangular combline filters is demonstrated at the example of an iris coupled rectangular combline filter where the inner conductor of the standard SMA coax port is connected in the usual way directly with the first and last post element, Figs. 1, 7. In the calculations, 70 modes for the ridge section have been taken into account. One iteration (with 44 frequency points) takes roughly 7 seconds on a 1.4 GHz AMD PC. The optimization results are plotted in the lower Fig. 7.

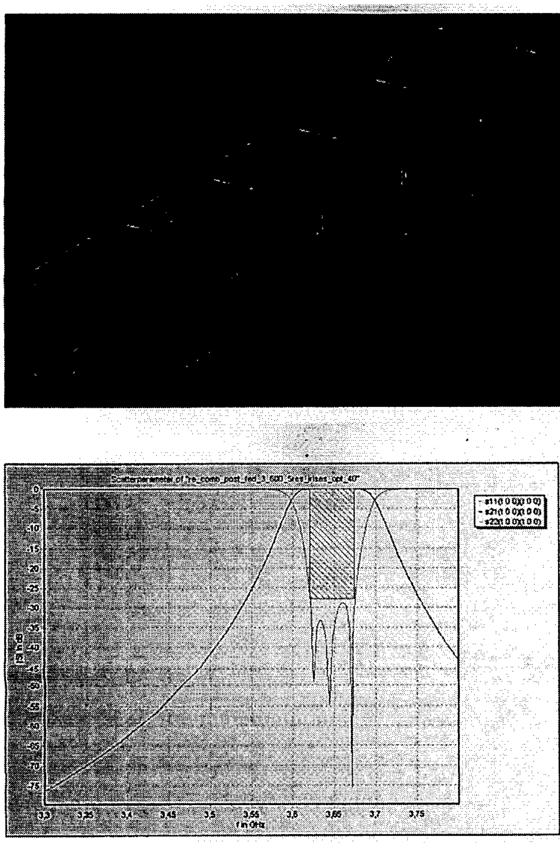

Fig. 7. Direct coax-fed iris coupled rectangular combline filter optimized by the MM/FE method

V. CONCLUSION

An efficient and accurate MM/FE method has been presented for the CAD and optimization of waffle-iron filters of improved performance, and of iris coupled rectangular combline filters. The accuracy of the method is verified by measurements. The advantage of the rigorous ME/FE technique is the high CPU speed which allows the direct optimization of such filters within typically an overnight run on a PC.

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