Multiport MM/FE Technique for the Efficient CAD of Folded and Cross-Coupled Rectangular Combline Filters

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Abstract **— The hybrid mode-matching/finite-element (MM/FE) technique extended to multiports yields generalized scattering matrix (GSM) building blocks for the CAD of advanced coax-fed rectangular combline filters of improved performance. The novelty of the formulation consists in the very efficient EM based modeling of folded and cross-coupled rectangular combline filters that allows their optimization within typically an overnight run on a PC. Usual coax feeds (direct post, disc, probe or loop coupling) are directly included. The attractive feature of the hybrid MM/FE approach is the combination of the computational speed of the MM technique with the flexibility of the FE method also for this class of components. Design examples demonstrate the flexibility of the CAD method; experimental results show its validity for practical applications.**

I. Introduction

Combline filters [1] – [5], [8] – [9] are finding increasing application in mobile communications due to their many useful features, such as – in particular – extremely low insertion loss at comparably compact size, and the potential for low-cost production. Both rectangular [1], [8] – [9] and circular post elements [2] - [5] are commonly used for resonator structures. In the present paper, combline filters with rectangular posts (Fig. 1) are preferred; they are directly amenable to fast mode-matching/finite-element (MM/FE) modeling, and they can conveniently be fabricated by computer controlled milling techniques [6] – [9]. Moreover, application of simple conversion considerations between square and circular rods yields rather adequate design data for circular combline resonators [9] when necessary.

For the advanced design of combline filters, accurate and fast CAD methods are indispensable in order to meet the commonly rather hard specifications of modern industrial filter applications by timely optimizations and, hence, allow quick time to market for such components. For compact sizes while maintaining high filter performance, the inclusion of folded and cross-coupled combline filter types (Fig. 1) is highly desirable.

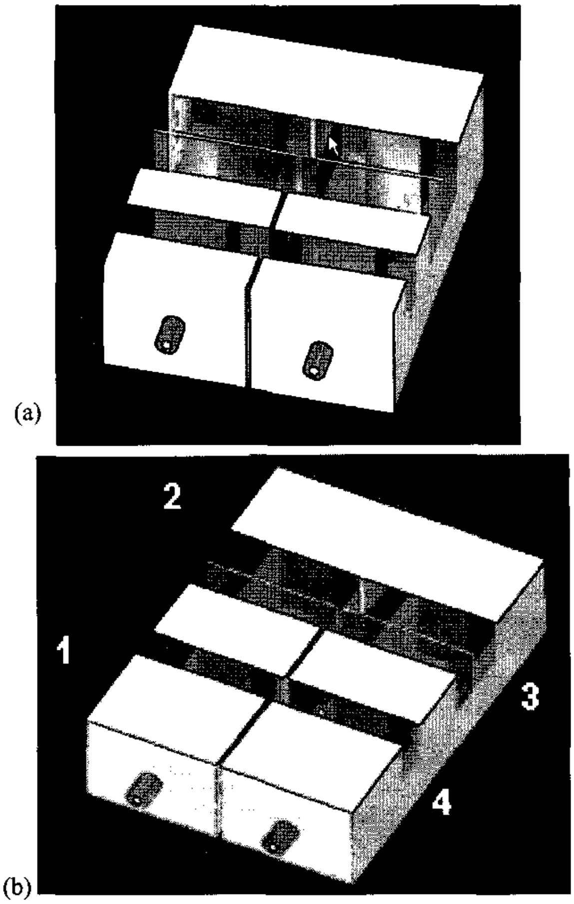

Fig. 1. Folded (a) and cross-coupled (b) rectangular combline filters. The cross-coupling is achieved by magnetic iris coupling between resonators 1 and 4

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Efficient mode-matching (MM) solutions have been restricted so far to investigations of the coupling behavior between single posts via calculating the resonance frequencies [2], [3]. An MM/finite-difference (MM/FD) technique for circular rod combline filters based on the overall generalized S-parameter (GSM) combination has been reported in [4]. A FD-TD modeling is presented in [5]. The MM solutions in [2], [3] are judged being not flexible enough, FD modeling of 3D post sections and coaxial feeds in [4], [5], does not meet the desirable high CPU speed for optimizations.

Fast and flexible MM/FE techniques have successfully been introduced for simple rectangular combline filters recently [8], [9]. Advanced folded and cross-coupled combline filter types have not yet been taken into account by MM/FE techniques, so far. The purpose of this paper is to remove this lack.

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 [10] for the considered waveguide cross-sections of more general shape

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

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

$$\Psi(x,y)\approx\sum_K \Psi_K N_K(x,y)\,. \tag{2}$$

In contrast to remarks in some recent other MM/FE papers e.g. [11] 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 for coaxial feed elements as a special case.

Matching the transverse fields at the common interfaces of MM/FE multiports (cf. e.g. Fig. 2) leads to the corresponding generalized scattering matrix (GSM). The

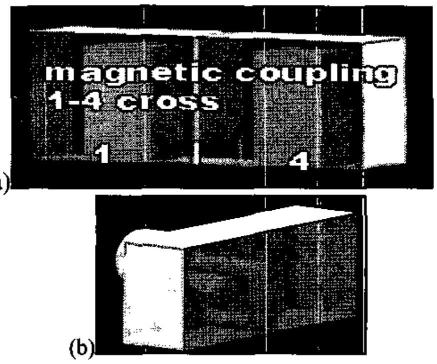

Fig. 2. Examples of MM/FE multiports: (a) Cross-coupling element, (b) coax loop coupling element

MM/FE multiport formulation includes also multiple TEM lines such as for conveniently modeling loop couplings, Fig. 2b. The involved frequency independent coupling integrals can be formulated also for multiports in terms of line integrals by using common definitions of the transversal eigenvectors

$$\begin{array}{ll}
\dfrac{k_{cII}^2}{k_{cII}^2-k_{cI}^2}\displaystyle\oint_{\Gamma_{II}}\Psi^{II}\frac{\partial\Psi^{I}}{\partial n}dc & \text{TE-TE}\\
0 & \text{TE-TM and TE-TEM}\\
-\displaystyle\oint_{\Gamma_{II}}\Psi^{II}\frac{\partial\Psi^{I}}{\partial\tau}dc & \text{TM-TE and TEM-TE}\\
\dfrac{k_{cI}^2}{k_{cI}^2-k_{cII}^2}\displaystyle\oint_{\Gamma_{II}}\Psi^{I}\frac{\partial\Psi^{II}}{\partial n}dc & \text{TM-TM}\\
\displaystyle\oint_{\Gamma_{II}}\Psi^{I}\frac{\partial\Psi^{II}}{\partial n}dc & \text{TM-TEM and TEM-TEM}\\
0 & \text{TEM-TM}
\end{array} \tag{3}$$

For discontinuities involving analytical expressions for eigenvectors, line integral formulations (3) provide a slight advantage as compared to surface integrals: The accuracy is nearly identical, and there is a small 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 can be an order of magnitude 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. Hence, in contrast to the opinion in [12], for general discontinuities, surface integral formulations are preferable.

The GSMs of all involved transition substructures are combined in the usual way [10].

III. Results

For accuracy verification, first a simple direct coaxial fed and direct coupled four resonator rectangular combline filter for 2.31 GHz midband frequency has been fabricated by computer controlled milling technique without any tuning screws, Fig. 3. Good agreement between theory and measurements, also for far-off selectivity, can be stated. For the MM/FE calculation, 170 modes have been taken into account; the CPU speed is 0.4 seconds per frequency point on a 2GHz P4 PC.

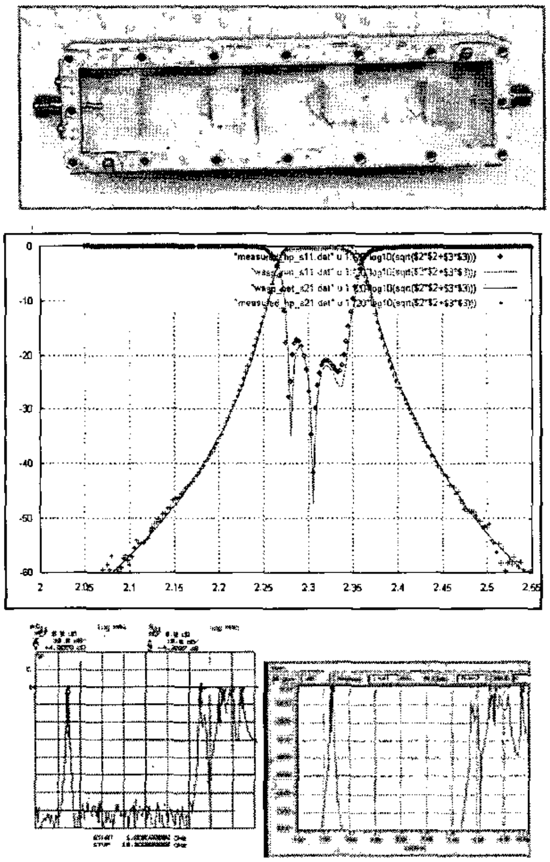

Fig. 3. Fabricated rectangular combline filter for 2.31 GHz. Comparison theory with measurements, including far-off selectivity

The next example is a folded electric iris coupled rectangular combline filter (Fig. 1a) optimized for 2.475 GHz midband frequency. For the required folded cavity section, the corresponding 4-port MM/FE element (Fig. 4) is short-circuited at the ports on the reverse side.

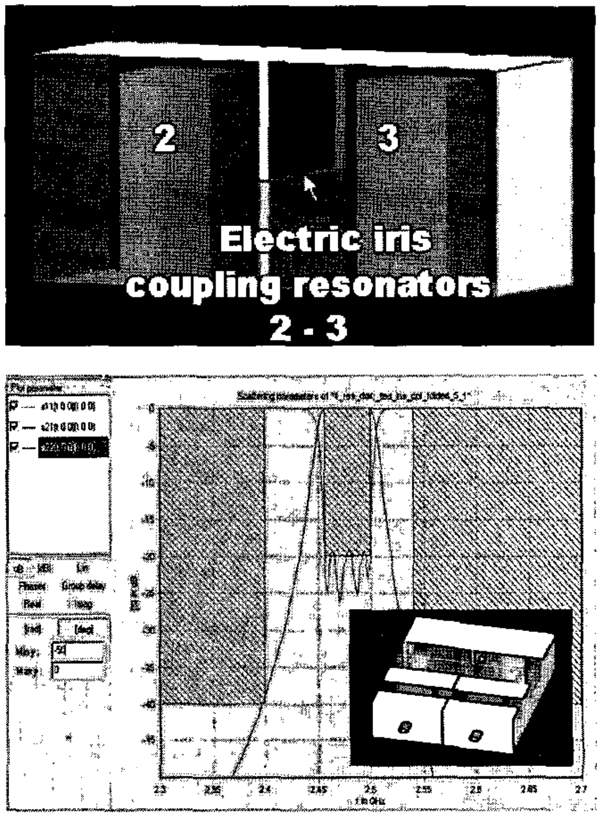

Fig. 4. Folded electric iris coupled rectangular combline filter, midband frequency 2.475 GHz

In order to demonstrate the flexibility of the applied MM/FE method, a cross-coupled rectangular combline filter (Fig. 1b) has been optimized for about 2.5 GHz midband frequency and 40 MHz pass-band bandwidth. SMA connector coupling via disc has been used, the direct coupling between resonators is provided by electric irises, the negative cross-coupling between resonators 4 and 1 is achieved by magnetic iris cross-coupling (Fig. 2a). The optimization results are shown in Fig. 5, together with the electric irises for direct couplings.

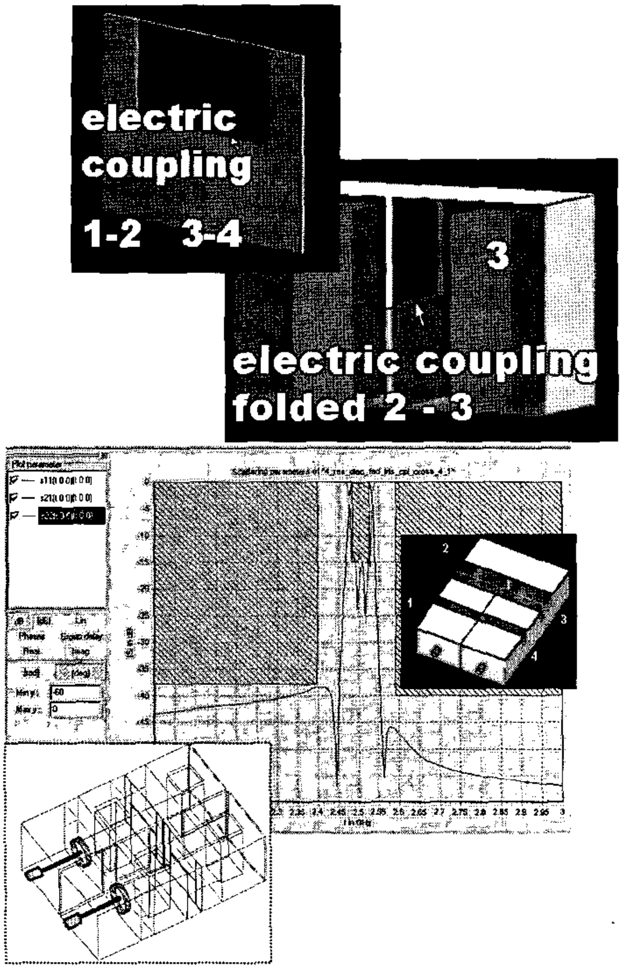

Fig. 4. SMA disc fed, magnetic iris cross-coupled, electric iris direct coupled rectangular combline filter, midband frequency about 2.5 GHz

IV. Conclusion

The MM/FE technique extended to multiports yields generalized scattering matrix (GSM) building blocks for the very efficient EM based modeling of folded and cross-coupled rectangular combline filters. The attractive feature of the hybrid MM/FE approach is the combination of the computational speed of the MM technique with the flexibility of the FE method also for this class of advanced components that allows their straightforward CAD and optimization.

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