INTEGRATED CAD PROCEDURE FOR IRIS DESIGN IN A MULTI-MODE WAVEGUIDE ENVIRONMENT

Werner Steyn, Robert Lehmensiek and Petrie Meyer

Department of Electric and Electronic Engineering, University of Stellenbosch, Stellenbosch, 7600, South Africa. E-mail: wsteyn@ing.sun.ac.za

***Abstract* — A fast integrated CAD procedure for designing irises in Multi-Mode Coupled Cavity Filters is presented. A reduced Generalized Scattering Matrix (GSM), obtained by using Adaptive Frequency Sampling for analysis, is combined with Aggressive Space Mapping for optimization of coupling structures. The technique dramatically reduces the number of computational electromagnetic (CEM) analysis points needed for the design of an iris, achieving a reduction factor of up to 50 for a design coupling 3 modes accross one iris.**

I. Introduction

Irises for multi-mode coupled cavity filters are generally designed in two ways. The first is based on Bethe's small aperture theory where the coupling factor between two microwave cavities such as in figure 1 can be expressed as [1],[2]:

$$K = \frac{\text{Energy lost per cycle by coupling}}{2 \cdot E\text{nergy stored by degeneracy}} = p_m \frac{H_{pt} \cdot H_{pt}}{\iiint_v H_p \cdot H_p} + p_e \frac{E_{pn} \cdot E_{pn}}{\iiint_v E_p \cdot E_p} \quad (1)$$

where p_m and p_e are the magnetic and electric polarisabilities of the aperture, H_{pt} the tangential magnetic field and E_{pn} the normal electric field incident on the aperture. This method is used extensively in literature [3], [4], but is based on approximations that cause inaccuracies in complex structures.

The second method utilizes numerical methods to find resonant frequencies of propagating modes inside a coupled cavity structure. For each propagating mode, two resonant frequencies are found from which the coupling factor can be derived [5]:

$$K = \frac{f_h^2 - f_l^2}{f_h^2 + f_l^2} \quad (2)$$

The Mode-Matching technique is well-suited to iris coupling problems and is widely used in coupled cavity filter design [6], [7]. The Generalized Scattering Matrix representation of a symmetrical coupled cavity structure is found and the resonant frequencies are determined by finding the roots of:

$$G(f) = \text{Det}\,[\mathbf{S}+\mathbf{I}] \quad (3)$$

where **S** is the GSM of the structure, **I** is the unity matrix and *G* is a complex-valued function of frequency.

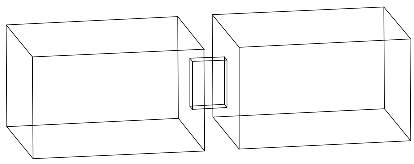


Fig. 1. Typical coupled cavity structure.

Generally, the roots of (3) will yield the *2n* resonant frequencies (where *n* is the number of propagating modes) required to determine the coupling coefficients, plus roots containing frequency of coupling information. For a triple-mode cavity the imaginary part of (3) could have as many as nine roots, most of which are very closely placed. While this is a well-known method, little information is given on how the roots of (3) are obtained, or how different propagating modes are isolated to determine specific coupling coefficients.

- This paper shows how a reduced GSM can be used to decrease the complexity of (3) and isolate specific modes by reducing the number of roots. An equivalent network theory representation is also used to expand this method to the finding of coupling coefficients of cross-coupling, and coupling between dissimilar cavities.
- Finding the roots of (3) for both the full and reduced GSM cases involves many EM-evaluations which could be very time-consuming. In this proposed procedure, the number of EM-evaluations is greatly reduced by applying an Adaptive Sampling algorithm using Rational Interpolation [8] where (3) is approximated by a Thiele continued fraction, the roots of which can be found by any root finding algorithm.
- Efficiency of optimization procedures for coupling iris structures is inversely proportional to the number of EM-evaluations performed. The Least-Squares technique is well suited to such *n*-dimensional problems,

but optimization of a single coupling factor typically requires in excess of 30 coupling coefficient evaluations, each requiring a large number of EM-evaluations. A fast integrated CAD procedure is achieved by using Aggressive Space Mapping to reduce the number of EM-evaluations required for optimization.

II. Coupling Coefficient

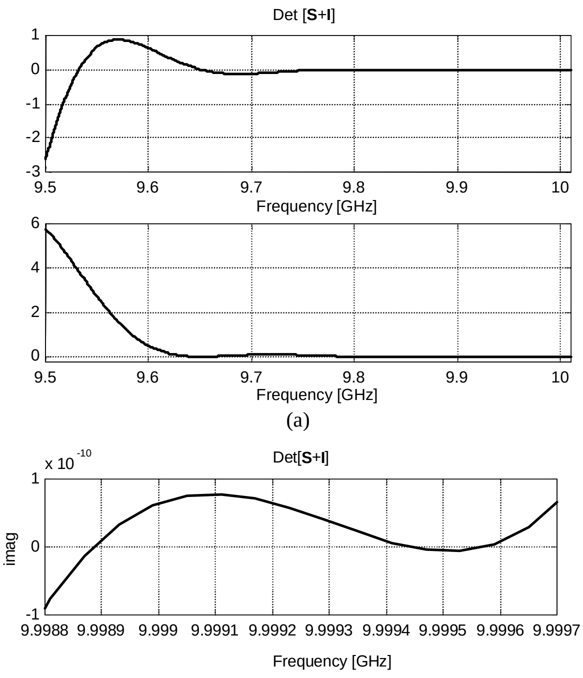
For the sake of clarity, this section will briefly discuss the standard procedure by which the GSM is used to calculate coupling coefficients in section A, followed by the proposed improvements in section B and C.

A. Resonant Frequencies of Iris Coupling Structures

Since (3) is a complex valued function, both the roots of the real and the imaginary parts must be determined and the roots are:

$$\text{Re}\{\text{Det}\,[\mathbf{S}+\mathbf{I}]\} = 0 \text{ and } \text{Im}\{\text{Det}\,[\mathbf{S}+\mathbf{I}]\} = 0 \qquad (4)$$

For a triple-mode coupling iris at 10GHz a typical response can be seen in figure 2.



(b)

Fig. 2. (a). Typical Det[**S**+**I**] of 10GHz triple-mode iris in frequency band of interest.
(b). Det[**S**+**I**] of the same iris showing cluster of roots.

In the region 9.9GHz to 10GHz both the real and the imaginary parts have 6 zeros. Figure 2b clearly shows the proximity of roots. EM-evaluations at a large number of frequency points is required to find such roots accurately. The key to the positions of roots is found by examining the equivalent structure of 2 symmetrical cavities as can be seen in figure 3. By placing a Perfect Electric Conductor (PEC) at the symmetry plane A-A, a resonant frequency f_e that is close to the unperturbed resonant frequency of a single cavity can be found [8]. Placing a Perfect Magnetic Conductor (PMC) at A-A results in a another lower resonant frequency f_m. These are the two natural frequencies of resonance of the structure for a particular propagating mode. The coupling coefficient can be given from equation (2):

$$K = \frac{f_h^2 - f_l^2}{f_h^2 + f_l^2} = \frac{f_e^2 - f_m^2}{f_e^2 + f_m^2} \qquad (5)$$

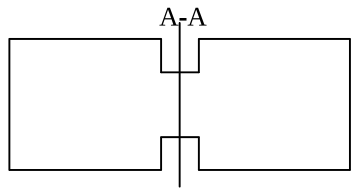


Fig. 3. Symmetrical Cavities

Since the triple-mode cavity is designed to be resonant for 3 modes at a given frequency, the f_e 's will be close to that frequency. For modes with small coupling coefficients, f_m will also be close to f_e , forming a cluster of roots surrounding the design frequency.

B. Finding and Identifying Resonant Frequencies

The number of EM-evaluations in finding the roots of (3) can be greatly reduced by applying an Adaptive Sampling algorithm [8]. EM-evaluations are required only at support points determined by the Adaptive Sampling algorithm while Rational Interpolation is used to interpolate between support points. The output of such an algorithm is in the form of a Thiele continued fraction, which can be converted to a quotient of polynomials (rational function). For the specific complexity and frequency band of figure 2, (3) was approximated with an estimated relative error of 10^{-10} using only 20 support points (EM-evaluations).

Rational functions are often used to approximate scattering matrices because of their ability to model both zeros and poles. For the case of (3), only the zeros are of interest and only the roots of the numerator polynomial, which can be found with any root-finding algorithm, must be determined.

Once all the required roots have been found, another EM-evaluation at each root frequency can be used to determine which propagating mode is at resonance. There should be 2 roots for each propagating mode with the roots corresponding to the natural resonant frequencies of equation (5). This method of isolating resonant frequencies of the modes has only been used for symmetrical cavities and is not valid for dissimilar cavities. There is also no information regarding cross-coupling between modes, which could be essential in a multi-mode environment.

C. Reducing the Generalized Scattering Matrix

An equivalent structure of two coupled cavities is given in figure 4, where each propagating mode on either side of the iris is treated as an independent resonator. Two modes are isolated by adding short circuits to their ports and terminating the remaining modes in their respective wave impedances. The reduced scattering matrix for determining the coupling coefficient between modes **a** and **b** then becomes:

$$\mathrm{GSM}_{\mathrm{reduced}} = \begin{bmatrix} S_{11}(\mathrm{a,\ a}) & S_{12}(\mathrm{a,\ b}) \\ S_{21}(\mathrm{a,\ b}) & S_{22}(\mathrm{b,\ b}) \end{bmatrix} \qquad (6)$$

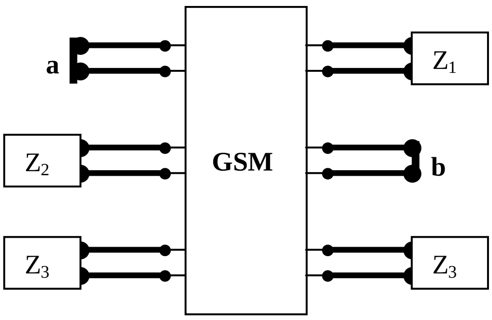


Fig. 4. Isolation and Termination of Modes for Reduced GSM

Using the reduced GSM in (3) and the Adaptive Sampling algorithm with Rational Interpolation yields figure 5 with only 7 EM-evaluations. It clearly shows the two natural resonance frequencies plus a third root of the imaginary part.

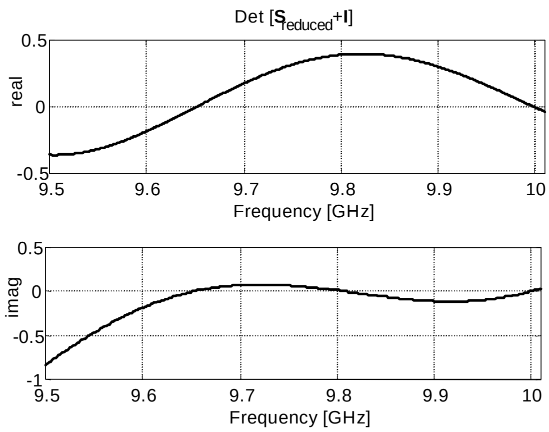
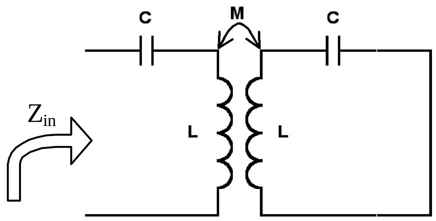


Fig. 5. Det [$\mathbf{S}_{\mathrm{reduced}}$ + **I**] of 10GHz triple-mode iris in frequency band of interest.

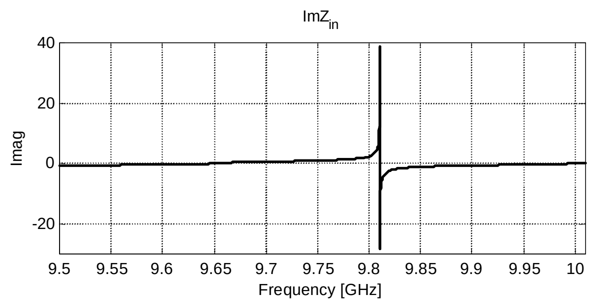
From network theory it is well known that resonance occurs at zeros of the imaginary part of the input impedance. For the equivalent network of figure 6a, a plot of Im{Z_{in}} with frequency (figure 6b) shows the exact three zeros of figure 5. The centre zero of figure 6b is known to correspond to the resonant frequency of the synchronously tuned resonators, i.e

$$\omega_o = \frac{1}{\sqrt{LC}} \qquad (7)$$

The zeros of Im{Det [$\mathbf{S}_{\mathrm{reduced}}$ + **I**]} can therefore be used to determine the coupling coefficient and frequency of coupling of all propagating modes efficiently. This method includes cross-coupling and is not limited to symmetrical cavity structures.



(a)



(b)

Fig. 6. (a). Equivalent Network for coupled cavity structure. (b) Im{Z_{in}} of equivalent network in (a).

The effect of the reduced GSM on the accuracy of the roots when compared to the roots of the full GSM is minimal. The roots used to determine the coupling coefficient show no change, but a small shift in the correct coupling frequency given by the full GSM, amounting to ≈0.1% has been found.

III. OPTIMIZATION WITH AGGRESSIVE SPACE MAPPING

Optimization of microwave components is generally very time consuming. Figure 7 shows a typical iris used in triple-mode coupled cavity filters, along with some design variables. Other variables include iris thickness

0-7803-6540-2/01/$10.00 (C) 2001 IEEE

and cavity length. Such *n*-dimensional optimization problems are well-suited to the Least-Squares optimization algorithm. For optimization of an iris for a specific coupling coefficient at a specific coupling frequency, more than 35 calculations of the coupling coefficient is required to obtain a maximum error of 0.01%. Together with an estimated 8 EM-evaluations per coupling coefficient, this amounts to roughly 280 EM-evaluations.

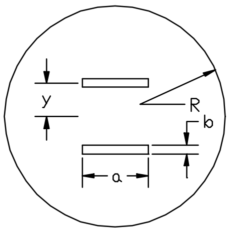


Fig. 7. Typical Iris for Triple-Mode Filter

Aggressive Space Mapping has been used successfully to increase the computational efficiency of EM-analysis and optimization [9]. The Space Mapping routine utilizes two equivalent descriptions of a microwave circuit. The 'coarse' model $f_{os}(\mathbf{x}_{os})$, with $\mathbf{x}_{os}$ the model input parameters, is assumed to be simple, fast to evaluate but less accurate. The 'fine' model $f_{em}(\mathbf{x}_{em})$, in this case the Mode-Matching EM-evaluation, is very accurate, but computationally very intensive. The routine strives to find a map between the 'coarse' model and the 'fine' model while performing the bulk of the CPU intensive optimization on the 'coarse' model.

A prerequisite for the success of the Space Mapping routine is a good mapping to the 'coarse' model. For this application it was found that an excellent 'coarse' model is supplied by Bethe's small aperture theory, since the design variables effect both the coarse and the EM-model in the same way.

Optimization in the coarse model space is performed by the Least-Squares algorithm, while the Adaptive Sampling algorithm is used to determine the EM-coupling coefficients efficiently. With this method, the same optimization example as above required only 4 calculations of EM-coupling coefficients to obtain a maximum error of 0.01%.

IV. Conclusion

An integrated CAD procedure for the efficient design of irises in multi-mode coupled cavity filters is presented. A reduced GSM is shown to decrease the complexity of the standard procedure used to calculate coupling coefficients in a multi-mode environment. The number of EM-evaluations required to determine the coupling coefficients is greatly reduced by applying an Adaptive Sampling algorithm using Rational Interpolation. Optimization time of iris design is further reduced by using Aggressive Space Mapping. The integrated procedure presented is not restricted to symmetrical cavities, but can be used to analyze and design for cross-coupling in dissimilar cavity structures.

References

[1] J. Uher, J. Bornemann, U. Rosenberg, "Waveguide Components for Antenna Feed Systems: Theory and CAD", Artech House, Boston, 1993.

[2] N. A. McDonald, "Electric and Magnetic Coupling through Small Apertures in Shield Walls of Any Thickness", *IEEE Trans. Microwave Theory Tech*, Vol. MTT-20, No. 10, pp. 689 - 695, October 1972.

[3] A. E. Atia, A. E. Williams, R. W. Newcomb, "Narrow-Band Multi-Coupled Cavity Synthesis", *IEEE Transactions on Circuits and Systems*, Vol. CAS-21, No. 5, pp. 649 - 655, September 1974.

[4] U. Rosenberg, D. Wolk, "Filter Design Using In-Line Triple-Mode Cavities and Novel Iris Couplings", *IEEE Trans. Microwave Theory Tech*, Vol. 37, No. 12, pp. 2011 - 2019, December 1989.

[5] X. Liang, K. A. Zaki, A. E. Atia, "Dual-Mode Coupling by Square Corner Cut in Resonators and Filters", *IEEE Trans. Microwave Theory Tech*, Vol. 40, No. 12, pp. 2294 - 2301, December 1992.

[6] L. Accatino, G. Bertin, "Design of Coupling Irises Between Circular Cavities by Modal Analysis", *IEEE Trans. Microwave Theory Tech*, Vol. 42, No. 7, pp. 1307 - 1313, July 1994.

[7] J. R. Montejo-Garai, J. Zapata, "Full-Wave Design and Realization of Multi-Coupled Dual-Mode Circular Waveguide Filters", *IEEE Trans. Microwave Theory Tech*, Vol. 43, No. 6, pp. 1290 - 1297, June 1995.

[8] R. Lehmensiek and P. Meyer, "Using efficient model-based parameter estimation for pole-free solutions of modal propagation constants, as applied to shielded planar structures," *Applied Computational Electromagnetics Society Journal*, to be published.

[9] J. W. Bandler, R. M. Biernacki, S. H. Chen, R. H. Hemmers and K. Madsen, "Electromagnetic optimization exploiting aggressive space mapping", *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2874-2882, 1995.