MODAL- S- MATRIX DESIGN OF MICROWAVE FILTERS COMPOSED OF RECTANGULAR AND CIRCULAR WAVEGUIDE ELEMENTS

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ABSTRACT

The rigorous CAD of a class of cavity filters is introduced which are composed of rectangular and circular waveguide structures. Based on the rectangular-to-circular and circular-to-circular waveguide junction key-building block modal S-matrices, the design takes rigorously into account both the finite iris thickness and the higher order mode interaction at all step discontinuities, as well as asymmetric irises. This allows the stopband characteristic to be included in the filter design, and dual-mode resonance effects may be utilized to achieve improved edge steepness and rejection characteristics. The theory is verified by measurements.

INTRODUCTION

Electromagnetic coupling of cavities by circular irises [1] - [5] is a common technique extensively employed in microwave engineering to produce relatively easy-to-fabricate waveguide filters for many applications, [5] - [10]. For the case of small irises and thin walls, the coupling coefficients are available in form of approximate formulas [1] - [5], large irises and finite wall thicknesses may be treated by correction factors, [10] - [13]. Although more recent solutions are based on the mode-matching [14] or the moment method [15], these techniques have been restricted hitherto to the analysis of single diaphragms by presenting improved equivalent transmission line [14] or fundamental mode scattering parameters [15]. The designer of complete filters, therefore, was still left to use the standard network theory methods [5] - [10], with the frequent need of post assembly fine tuning, e.g. by screws [10]. Moreover, only centered circular holes have been investigated so far.

When more stringent requirements are placed on the filter, when intermodulation effects often caused by additional screws should be avoided, or when low-cost mass-production is desired, the need arises for more accurate design methods which are capable to include the higher-order mode interactions along the complete filter section. This paper presents the rigorous CAD of a class of circular iris coupled cavity filters (Fig. 1) which are composed of rectangular or circular waveguide structures.

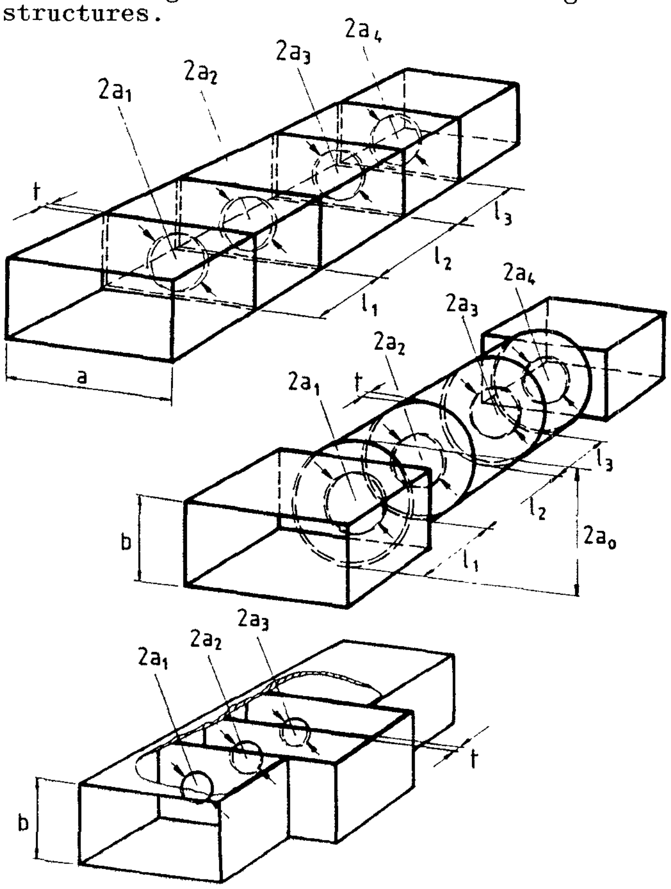


Fig. 1:
Circular iris coupled cavity filters.
a) Rectangular cavities,
b) Circular cavities with rectangular waveguide instrumentation,
c) Rectangular cavities with asymmetric irises.

The design is based on the orthogonal expansion method [17], [18], which yields directly the modal S-matrix of the rectangular-to-circular or circular-to-circular waveguide junction key-building block elements. The immediate generalized modal S-matrix combination of all interacting structures includes the higher-order mode coupling effects, the finite thickness of all irises, and allows the stopband characteristic to be taken into account in the filter design. This is advantageous for many purposes, such as for channel filters, when frequency selectivity and high stopband attenuation are important filtering properties. Moreover, dual-mode resonance effects [9], [16] may be utilized to achieve improved edge steepness and rejection characteristics.

An optimizing computer program varies the filter parameters until passband and stopband insertion loss correspond to predicted values. Computer-optimized examples demonstrate the efficiency of the presented method. The theory is experimentally verified.

THEORY

For the rigorous computer-aided design of the filter structures to be investigated (Fig. 1), the modal S-matrix method [17], [18] is applied. Two key-building block discontinuities are required to include all general cases under consideration: the asymmetric rectangular-to-circular (Fig. 2a) and the circular-to-circular waveguide junction (Fig. 2b). Note that for the corresponding inverse discontinuity merely the port designations of the related modal scattering matrix need to be interchanged. The total scattering matrix of the filter structure is formulated by suitable direct combination of the individual modal scattering matrices of the double-step junction and the inverse discontinuity, respectively, by an iteration process already described in [18], and by including appropriately the known scattering matrices of a homogeneous waveguide section, for adequate consideration of the iris thicknesses and the resonator lengths. This procedure preserves numerical accuracy, avoids instabilities, and requires no symmetry of modes [18].

The fields

$$\vec{E} = \frac{1}{j\omega\epsilon} \nabla \times \nabla \times (\vec{Q}_{ez}) + \nabla \times (\vec{Q}_{hz}) \qquad (1)$$
$$\vec{H} = -\frac{1}{j\omega\mu} \nabla \times \nabla \times (\vec{Q}_{hz}) + \nabla \times (\vec{Q}_{ez})$$

in the homogeneous subregions (1), (2) (Figs. 2) are derived from the z-components of the electric (e) and magnetic (h) vector potentials, respectively,

$$Q^o_{ez} = \sum_{i^o} N^o_{i^o} \cdot T^o_{ei^o} \cdot (A^{o\pm}_{ei^o} \cdot e^{\mp jk^o_{zei^o} z})$$
$$Q^o_{hz} = \sum_{i^o} N^o_{i^o} \cdot T^o_{hi^o} \cdot (A^{o\pm}_{hi^o} \cdot e^{\mp jk^o_{zhi^o} z}) , \qquad (2)$$

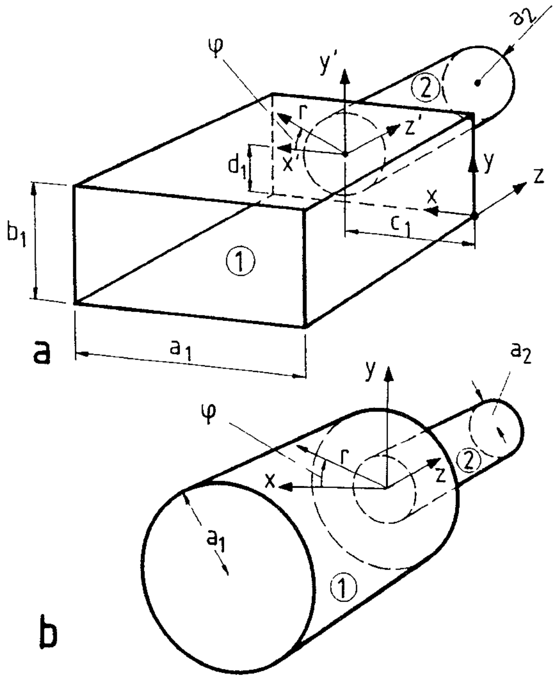
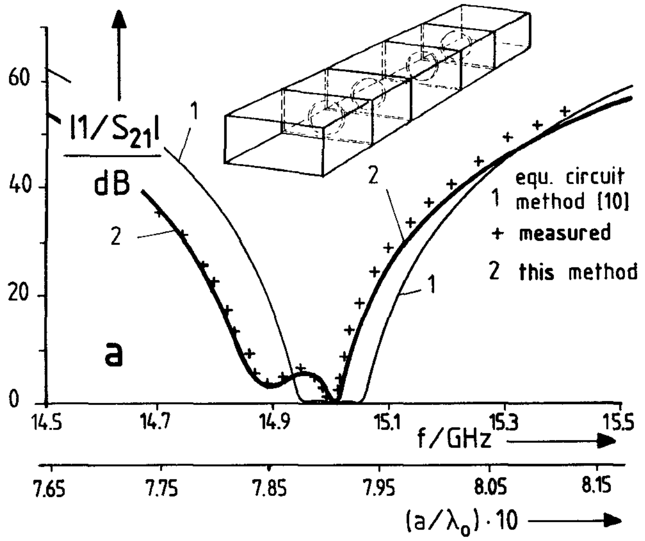


Fig. 2:
General key-building block discontinuities
a) Asymmetric rectangular-to-circular waveguide junction.
b) Circular-to-circular waveguide junction.

where o = 1,2 (number of subregions), i^o is the index for all TE-, and TM-modes in each subregion, N are the normalization factors due to the complex power, and T are the eigen-functions in the corresponding subregions. A^+ are the amplitude coefficients of the forward (-), A^- of the backward (+) waves, and k_z are the wavenumbers of the corresponding TE- and TM-modes.

By matching the tangential field components at the common interfaces at the individual step discontinuities, the wave amplitude coefficients of equation (2) can be related to each other after multiplication with the appropriate orthogonal functions. This yields the corresponding key building block two-port modal scattering matrices.

A computer program was written using the preceding relations and utilizing the evolution strategy method, cf. [17], [18], for optimizing the geometrical parameters for given specifications, including the stopband characteristic. For the optimization, sufficient asymptotic behavior has been obtained by consideration of 15 TE- and TM-modes for the general key-building block junctions. In the resonator sections, the TM_{mn}- and TE_{mn}-modes are considered up to the order m=3, n=2, for the rectangular waveguide sections, and m=5 and n=8, for the circular waveguide sections. The final design results are verified by an inclusion of 35 TM- and TE-modes (together with 15 modes in the resonator region) for the rectangular waveguide, and 41 TM- and TE-modes (20 modes in the resonator region), for the circular waveguide, respectively.



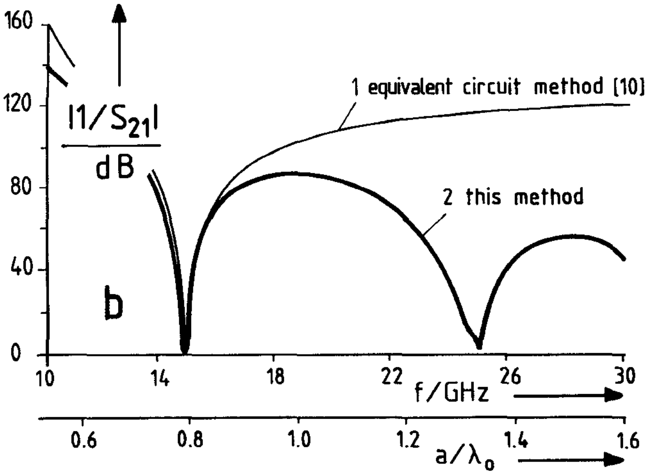


Fig. 3: Circular iris coupled three-resonator filter.
a) Comparison between the improved equivalent circuit method (thin line) this method (bold line), measurements (+++).
b) Extended frequency range.

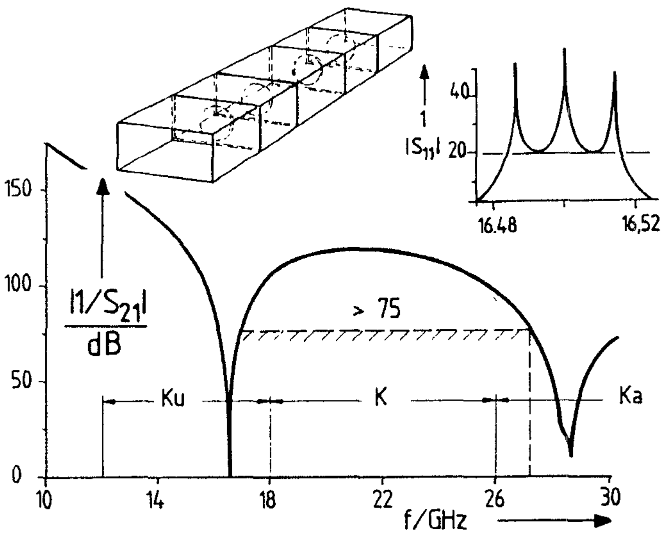


Fig. 4: Computer-optimized three-resonator filter with improved stop-band (R140 housing: 15.799mm × 7.899mm).

RESULTS

Figs. 3 show the comparison between the results obtained by the improved equivalent circuit design method [10] (curve 1) and the analysis with the rigorous method (curve 2). This example of the circular iris coupled three-resonator rectangular waveguide filter in the Ku-band (12 - 18 GHz, R140 waveguide housing: 15.799mm × 7.899mm) demonstrates that the equivalent circuit theory is not capable to predict the frequency response exactly (Fig. 3a) and fails, especially, for analyzing the filter behavior in the stopband region (Fig. 3b). Good agreement between theory and the measurements may be stated, however, by using the rigorous method (Fig. 3a).

The characteristic of a computer-optimized Ku-band circular iris coupled three-resonator filter is presented in Fig. 4. Due to the inclusion of the stopband in the design method, good rejection quality is obtained including the whole adjacent waveguide K-band (18 - 26 GHz).

Fig. 5 demonstrates the design of a low-insertion loss circular iris coupled rectangular waveguide filter with three circular waveguide cavities. Good agreement with the measured results may be stated.

The characteristics of computer--optimized circular iris coupled filters with additional stopband poles are presented in Figs. 6. Fig. 6a shows the behavior of a circular waveguide TE_{01}-mode three-resonator filter. Due to the interactions of the fundamental TE_{01} with the higher-order TE_{02} cavity mode, an improved stopband characteristic towards higher frequencies, together with high edge steepness, is achieved similar to the behavior of an elliptic function filter.

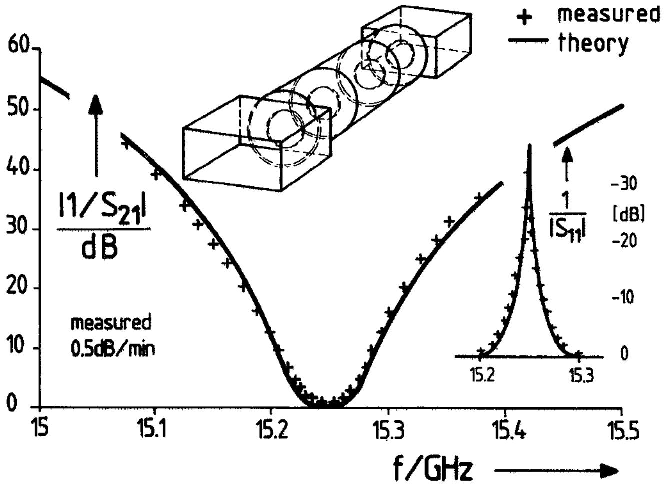


Fig. 5: Computer-optimized low-insertion loss circular iris coupled rectangular waveguide filter with three circular cavities (radius a_0 = 6.985mm).

As circular iris coupled filters may be manufactured by computer controlled techniques relatively easily and with high accuracy, this type of filters is considered to be attractive in the millimeter wave range, as well. Fig. 6b shows the results of one-resonator filters designed for a pass-band at about 94 GHz. The asymmetric iris type (bold line) utilizes the interactions between the fundamental TE_{10} and the next higher TE_{20} cavity mode to achieve an additional stopband pole. The comparison with a conventional symmetric filter (thin line) of nearly the same passband characteristic demonstrates the improvement of the stopband behavior.

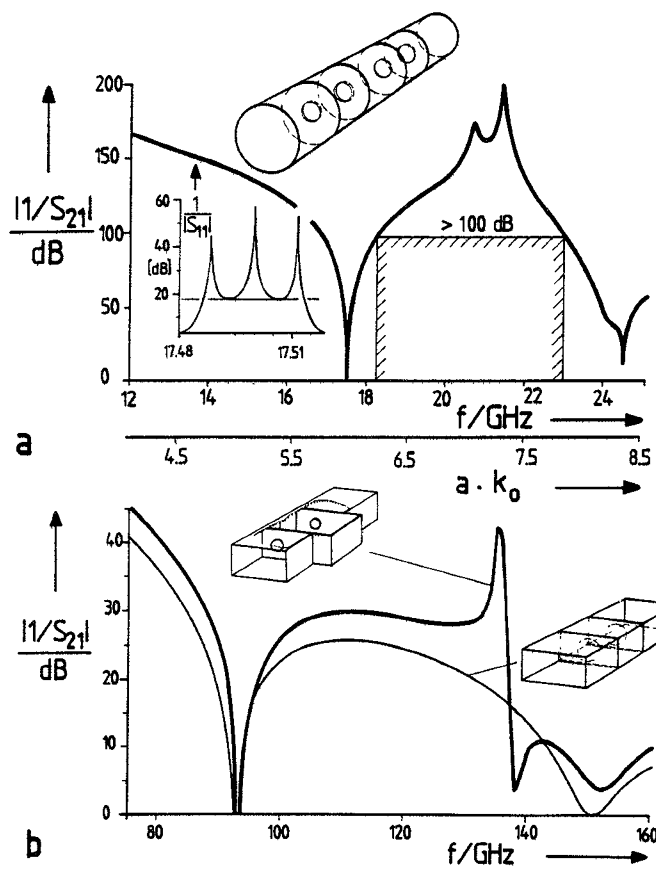


Fig. 6: Computer-optimized filters with additional stopband poles.
a) Circular waveguide TE_{01}-mode three-resonator filter (radius a_0 = 16.127mm).
b) Rectangular waveguide W-band (75 - 110 GHz) one-resonator filter (R900 housing, 2.54mm × 127mm) with symmetric (thin line) and asymmetric iris coupled resonators (bold line).

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