Full-Wave Design of Canonical Waveguide Filters by Optimization

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Abstract— **Full-wave design of canonical waveguide filters by optimization is presented. For full-wave modeling, the filter structure is decomposed into the cascade connection of waveguide step discontinuities, waveguide T-junction discontinuities with branch waveguide cascaded with waveguide step or bifurcation discontinuities. Generalized scattering matrices of each discontinuity are obtained using mode matching method, from which the filter response can be obtained using cascading procedure. Interpolation tables of each discontinuity are used to speed up the optimization process. Full-wave synthesis of coupling iris dimensions is also described. A four-cavity filter design example is presented to demonstrate the feasibility of the approach.**

I. Introduction

In canonical waveguide filters, coupling between nonadjacent resonators can be realized to achieve a true elliptic-function filter response. Compared with conventional direct cascaded Tchebyscheff filters, canonical filters have the advantages of sharp selectivity, flat in-band, light weight, and compact size [1]. In practice, however, it is difficult to determine precisely the coupling iris dimensions, because of the interactions among adjacent and nonadjacent coupling irises and tuning screws for the cavity resonant frequency. Considerable experimental characterization and manual tuning efforts are required [2]. To eliminate or at least to reduce the time-consuming efforts, some works have been carried out [3]-[5]. In this paper, full-wave design of canonical single-mode rectangular waveguide filters by optimization is presented.

II. Modeling

Fig. 1 shows the configuration of a canonical single-mode rectangular waveguide filter. It consists of two identical halves. Each rectangular cavity resonates in its fundamental TE_{101} mode at a common center frequency. Each cavity in one half is coupled with its neighboring cavity or input/output waveguide in the same half by means of magnetic fields through a narrow slot or window in the side wall of the cavity. Each cavity in one half is coupled with its corresponding cavity in the other half by means of either electric fields through a square aperture in the center of the cavity or magnetic fields through one or two narrow slots at the edge of the cavity. The couplings produced by means of electric fields and magnetic fields have the opposite signs, which may result in an elliptic-function filter response.

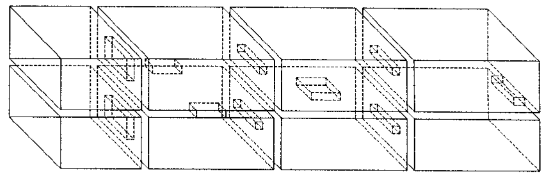
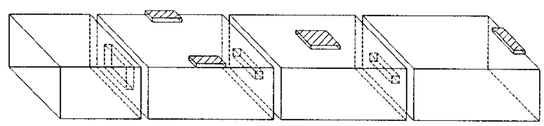
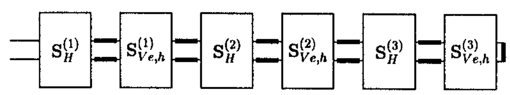


Fig. 1. A canonical waveguide filter



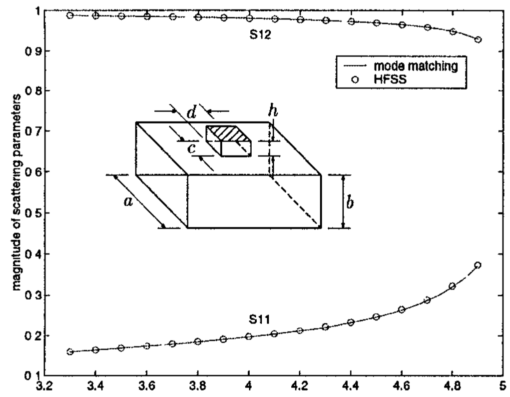
(a)



(b)

Fig. 2. Modeling of the canonical waveguide filter. (a) Configuration. (b) Network representation.

Since the filter structure consists of two identical halves, by putting PEC (Perfect Electric Conductor) and PMC (Perfect Magnetic Conductor) boundary



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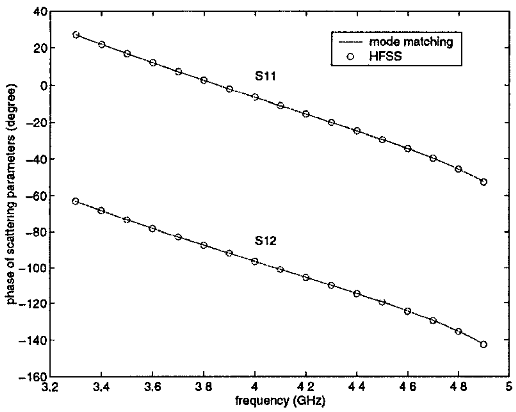
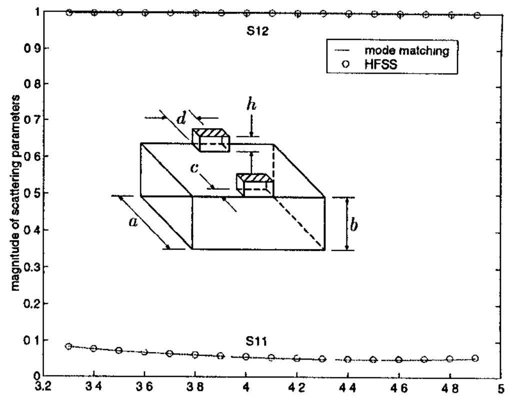
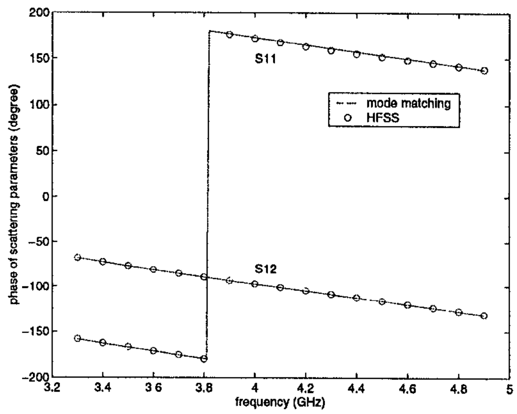


(b)

Fig. 3. Scattering parameters of a vertical discontinuity. (a) Magnitude. (b) Phase. Dimensions in inches are: $a = 2.29$, $b = 1.145$, $c = d = 1$, and $h = 0.5$. The iris is terminated with PMC.



(a)



(b)

Fig. 4. Scattering parameters of a vertical discontinuity. (a) Magnitude. (b) Phase. Dimensions in inches are: $a = 2.29$, $b = 1.145$, $c = 0.5$, $d = 1$, and $h = 0.5$. The iris is terminated with PEC.

conditions at the symmetry plane, only half structure is to be modeled, as shown in Fig. 2. For full-wave modeling, it can be decomposed into the cascade connection of waveguide discontinuities. For the convenience of description, the discontinuities introduced by coupling irises (which are shaded in Fig. 2(a)) between two corresponding cavities in the top and bottom halves are named vertical discontinuities hereafter, while the discontinuities introduced by coupling irises between two neighboring cavities in the same half are named horizontal discontinuities hereafter.

The horizontal discontinuity can be viewed as a back-to-back cascade connection of two waveguide step discontinuities. The waveguide step discontinuity is modeled using mode matching method, from which the generalized scattering matrix $\mathbf{S}_H$ of the two-port horizontal discontinuity is obtained using cascading procedure.

The vertical discontinuity can be viewed as a waveguide T-junction discontinuity cascaded with either waveguide step or waveguide bifurcation discontinuities at its branch waveguide, with termination conditions of PEC or PMC. The waveguide T-junction discontinuity is modeled using mode matching method, from which its generalized scattering matrix is obtained [6]. The waveguide bifurcation discontinuity is virtually the same as the waveguide step discontinuity. With termination conditions of PEC or PMC, the generalized scattering matrix $\mathbf{S}_{Ve}$ or $\mathbf{S}_{Vh}$ of the two-port vertical discontinuity is obtained using cascading procedure. Figs. 3 and 4 show the comparison of scattering parameters of two vertical discontinuities obtained using mode matching method described above and HFSS. A good agreement is observed.

Once the individual generalized scattering matrices of each discontinuity are obtained, the generalized scattering matrices of the half structure (with termination conditions of PEC and PMC) can be obtained using cascading procedure, from which the filter response can be found.

For optimization design, an error function to be minimized is constructed according to the design specification. In order to speed up the optimization process, interpolation tables of each discontinuity are used [7]. In optimization, the initial values of optimization variables are important. In next Section, full-wave synthesis of coupling iris dimensions will be described.

III. Synthesis of Coupling Iris Dimensions

For the input/output coupling iris, a structure composed of a rectangular cavity (which represents the first/last cavity) coupled with a input/output rectangular waveguide through a coupling iris is considered. Other inter-cavity couplings associated with the input/output (or first/last) cavity are neglected. Using the modeling approach mentioned above, the reflection coefficient ($S_{11} = e^{j\theta}$) of the model can be obtained. It can be shown that the loaded resonant frequency f_l of the cavity is the one at which $|d\theta/df|$ is maximum. The normalized input/output coupling bandwidth R in units of frequency is given by [8]

$$R = 2\,(f - f_l)\,\frac{1-\cos\theta}{\sin\theta}$$

where θ is the phase of reflection coefficient at frequency f.

For the mutual coupling iris, a structure composed of two identical rectangular cavities coupled together through one or two coupling irises is considered. Other inter-cavity couplings associated with the two cavities are neglected. By putting PEC and PMC boundary conditions at the symmetry plane, using the modeling approach mentioned above, two natural resonant frequencies f_e (PEC) and f_m (PMC) can be found. The normalized coupling coefficient k is calculated as

$$k = \frac{f_e^2 - f_m^2}{f_e^2 + f_m^2}$$

If the coupling is mainly dominated by electric fields, then $f_e < f_m$ and hence $k < 0$. On the other hand, if the coupling is mainly dominated by magnetic fields, then $f_m < f_e$ and hence $k > 0$.

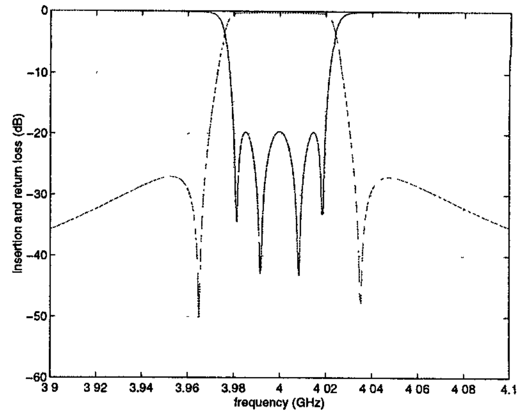


Fig. 5. Ideal circuit response of the prototype filter

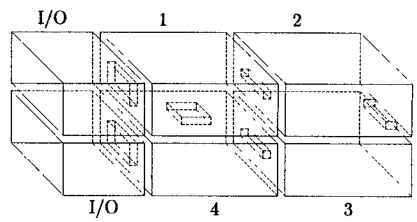


Fig. 6. Configuration of the four-cavity filter

IV. Results

A four-cavity canonical waveguide filter with center frequency of 4 GHz and bandwidth of 40 MHz is designed to demonstrate the feasibility of the above approach.

The synthesized prototype filter has the following normalized input/output resistance and coupling matrix:

$$R_i = R_o = 1.014288$$

$$M = \begin{bmatrix} 0 & 0.84135 & 0 & -0.22423 \\ 0.84135 & 0 & 0.78212 & 0 \\ 0 & 0.78212 & 0 & 0.84135 \\ -0.22423 & 0 & 0.84135 & 0 \end{bmatrix}$$

Fig. 5 shows the ideal circuit response of the prototype filter. In the calculation, an unloaded Q of 8000 is used.

The configuration of the physical filter is shown in Fig. 6. The negative coupling between cavities 1 and 4 is achieved through a square aperture in the center of the cavity. The input/output rectangular waveguide and the rectangular cavities have cross-section dimensions of 2.29×1.145 inch^2. All coupling irises are assumed to have a thickness of 0.05 inch. Other

TABLE I

DIMENSIONS OF THE FILTER IN INCHES. THE THICKNESS OF ALL COUPLING IRISES IS 0.05 INCH.

	before opt	after opt
I/O R	1.000×0.3	1.001×0.3
M_{12} (M_{34})	0.706×0.05	0.713×0.05
M_{23}	0.720×0.05	0.815×0.05
M_{14}	0.350×0.350	0.414×0.414
L_1 (L_4)	1.855	1.812
L_2 (L_3)	1.905	1.900

remaining dimensions of the filter are first synthesized according to the synthesis approach described above. They are used as initial values for optimization. Table I gives the dimensions of the filter before and after optimization. The computed response of the physical filter before and after optimization is shown in Fig. 7. In Fig. 7(b), the solid curves are the computed response using interpolation tables, while the circle points are the computed response without interpolation. They agree well with each other.

V. SUMMARY

Full-wave design of canonical waveguide filters by optimization is presented. For full-wave modeling, the filter structure is decomposed into the cascade connection of waveguide step discontinuities, waveguide T-junction discontinuities with branch waveguide cascaded with waveguide step or bifurcation discontinuities. Generalized scattering matrices of each discontinuity are obtained using mode matching method, from which the filter response can be obtained using cascading procedure. Interpolation tables of each discontinuity are used to speed up the optimization process. Full-wave synthesis of coupling iris dimensions is also described. A four-cavity filter design example is presented to demonstrate the feasibility of the approach.

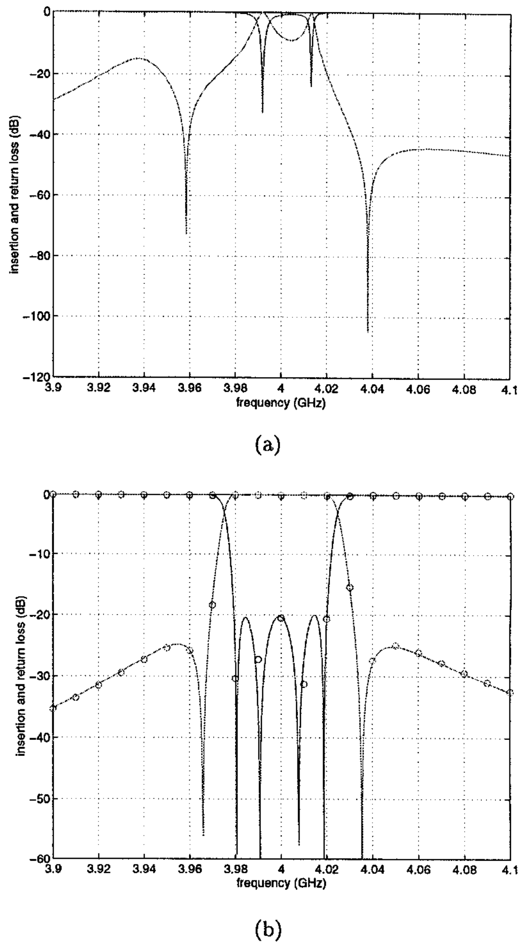


Fig. 7. Computed response of the filter. (a) Before optimization. (b) After optimization.

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