ALTERNATIVE DESIGNS FOR DUAL-MODE FILTERS

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ABSTRACT

Alternatives to conventional dual-mode filter designs are revealed by introducing an independent variable into a filter's coupling matrix through a sequence of plane rotation similarity transformations. A graphical means of evaluating the resulting alternatives is described. The procedure is demonstrated with the design of an improved six-resonance longitudinal dual-mode dielectric resonator filter without irises.

INTRODUCTION

Dual-mode filters play an important role in satellite communications and are likely to perform an increasingly important role in base stations. Dual-mode resonators can exhibit higher unloaded Q's than their single-mode counterparts and offer the potential for significant reductions in filter size and cost. Yet, the conventional 'longitudinal' [1,2] and 'canonical' [3,4] dual-mode filter implementations have attributes that limit this potential and adversely influence filter cost, size, isolation, insertion loss, and environmental stability.

Some of the undesirable attributes of longitudinal and 'canonical asymmetric' dual-mode designs (Fig. 1(a), (b)) stem from the relative magnitudes of two types of coupling which occur between dual-mode resonances: "intra-coupling" between orthogonal modes in an individual resonator, and "inter-coupling" between parallel modes in adjacent resonators. In conventional designs, one inter-coupling often differs substantially from the other paired with it. Typically, these inter-couplings are defined by irises, which increase filter cost and loss. Dielectric resonator filters without irises (Fig. 2) have been proposed [5]. But, their size can be excessive, since the smaller of the two inter-couplings between each pair of adjacent resonators determines the distance between these resonators. Also, a screw protruding into this inter-resonator gap creates the larger inter-coupling. Disproportionate inter-couplings lead to deep cavity penetrations by these screws, damaging filter performance due to screw loss, screw self-resonance, and effects on the other, smaller, inter-coupling sharing the same gap. Finally, intra-coupling is generally created by a screw driven toward a resonator's ceramic. Consequently, the conventionally large intra-couplings can degrade filter stability and loss due to the close proximity of tuning screws to the concentrated fields in the ceramics.

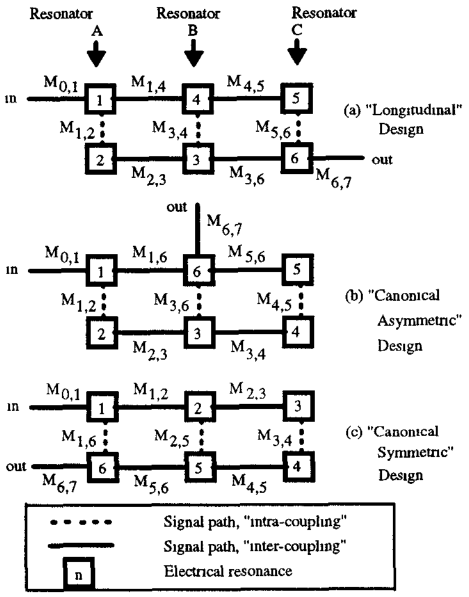

Fig. 1. Coupling and signal-routing schematics for various 6th order dual-mode bandpass filters.

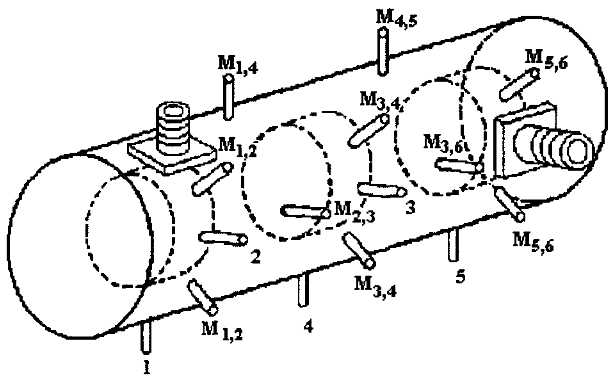

Fig. 2. Longitudinal dual-mode dielectric resonator filter without irises.

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Canonical symmetric designs (Fig. 1(c)) exhibit the opposite coupling characteristics. They have large, balanced pairs of inter-couplings, making elimination of irises practical [5,6]. Unfortunately, since input and output are coupled to the same resonator, isolation is conventionally limited to 30 dB [5]. Also, disparity between intra-couplings results in different coupling screw loading of the resonators - degrading stability.

Ideally, a design would exhibit only relatively large and balanced pairs of inter-couplings, relatively small intra-couplings, and an input and output coupled to different resonators. Of these attributes, the first allows for small filter size without irises, the second for more stable filter characteristics, and the last for good input-to-output isolation. Traditional versions of the design topologies of Fig. 1 lack at least some of these attributes. By examining other electrically equivalent filter designs, better alternatives might be found.

TRADITIONAL DESIGN TRANSFORMATIONS

Consider a chair observed from the side, the top, or from any other point of view. It appears different from each viewpoint, although it is still the same. Likewise, a single filter design *characteristic* can be observed from different viewpoints, each representing different, but equivalent, designs. Mathematical transformations are a means of obtaining these different views.

$$\mathbf{m} = \begin{matrix} 0 & m_{0,1} & 0 & 0 & 0 & 0 & 0 & 0 \\ m_{1,0} & 0 & m_{1,2} & 0 & m_{1,4} & 0 & m_{1,6} & 0 \\ 0 & m_{2,1} & 0 & m_{2,3} & 0 & m_{2,5} & 0 & 0 \\ 0 & 0 & m_{3,2} & 0 & m_{3,4} & 0 & m_{3,6} & 0 \\ 0 & m_{4,1} & 0 & m_{4,3} & 0 & m_{4,5} & 0 & 0 \\ 0 & 0 & m_{5,2} & 0 & m_{5,4} & 0 & m_{5,6} & 0 \\ 0 & m_{6,1} & 0 & m_{6,3} & 0 & m_{6,5} & 0 & m_{6,7} \\ 0 & 0 & 0 & 0 & 0 & 0 & m_{7,6} & 0 \end{matrix}$$

(a)

$$M_{1,2} = m_{1,2}\, c_{2,4} - m_{1,4}\, s_{2,4}$$
$$M_{1,4} = m_{1,4}\, c_{2,4}\, c_{4,6} + m_{1,2}\, s_{2,4}\, c_{4,6} - m_{1,6}\, s_{4,6}$$
$$M_{1,6} = m_{1,6}\, c_{4,6} + m_{1,2}\, s_{2,4}\, s_{4,6} + m_{1,4}\, c_{2,4}\, s_{4,6}$$
$$M_{2,3} = m_{2,3}\, c_{2,4}\, c_{3,5} - m_{3,4}\, s_{2,4}\, c_{3,5} + m_{4,5}\, s_{2,4}\, s_{3,5} - m_{2,5}\, c_{2,4}\, s_{3,5}$$
$$M_{2,5} = m_{2,3}\, c_{2,4}\, s_{3,5} - m_{3,4}\, s_{2,4}\, s_{3,5} - m_{4,5}\, s_{2,4}\, c_{3,5} + m_{2,5}\, c_{2,4}\, c_{3,5}$$
$$M_{3,4} = m_{2,3}\, s_{2,4}\, c_{3,5}\, c_{4,6} + m_{3,4}\, c_{2,4}\, c_{3,5}\, c_{4,6} - m_{4,5}\, c_{2,4}\, s_{3,5}\, c_{4,6} - m_{2,5}\, s_{2,4}\, s_{3,5}\, c_{4,6} - m_{3,6}\, c_{3,5}\, s_{4,6} + m_{5,6}\, s_{3,5}\, s_{4,6}$$
$$M_{3,6} = m_{2,3}\, s_{2,4}\, c_{3,5}\, s_{4,6} + m_{3,4}\, c_{2,4}\, c_{3,5}\, s_{4,6} - m_{4,5}\, c_{2,4}\, s_{3,5}\, s_{4,6}$$
$$M_{4,5} = m_{2,3}\, s_{2,4}\, s_{3,5}\, c_{4,6} + m_{3,4}\, c_{2,4}\, s_{3,5}\, c_{4,6} + m_{4,5}\, c_{2,4}\, c_{3,5}\, c_{4,6} + m_{2,5}\, s_{2,4}\, c_{3,5}\, c_{4,6} - m_{3,6}\, s_{3,5}\, s_{4,6} - m_{5,6}\, c_{3,5}\, s_{4,6}$$
$$M_{5,6} = m_{2,3}\, s_{2,4}\, s_{3,5}\, s_{4,6} + m_{3,4}\, c_{2,4}\, s_{3,5}\, s_{4,6} + m_{4,5}\, c_{2,4}\, c_{3,5}\, s_{4,6} + m_{2,5}\, s_{2,4}\, c_{3,5}\, s_{4,6} + m_{3,6}\, s_{3,5}\, c_{4,6} + m_{5,6}\, c_{3,5}\, c_{4,6} - m_{2,5}\, s_{2,4}\, s_{3,5}\, c_{4,6} + m_{3,6}\, c_{3,5}\, c_{4,6} - m_{5,6}\, s_{3,5}\, c_{4,6}$$
$$M_{0,1} = m_{0,1}\ ,\ M_{4,7} = -\, m_{6,7}\, s_{4,6}\ ,\ M_{6,7} = m_{6,7}\, c_{4,6}$$

where

$s_{x,y} = \sin\theta_{x,y}$, $c_{x,y} = \cos\theta_{x,y}$, $m_{x,y} = m_{y,x}$, and $M_{x,y} = M_{y,x}$.

(b)

Fig. 3. The initial coupling matrix, (a), for a six resonance, bandpass filter and the mapping, (b), of elements of **m** to elements of **M** in terms of angles $\theta_{2,4}$, $\theta_{3,5}$, and $\theta_{4,6}$.

A filter comprised of N-2 resonances can be characterized by an N x N coupling coefficient matrix, **m**. A method of eliminating elements of any N x N matrix, **m**, while preserving its defining characteristics, is to apply successive 'orthogonal similarity transformations', or 'plane rotation similarity transformations',

$$\mathbf{R}_{[p,\,q]}^{T} \bullet \mathbf{m} \bullet \mathbf{R}_{[p,\,q]}, \tag{1}$$

where **m** is post-multiplied by an N x N 'plane rotation matrix', $\mathbf{R}_{[p,q]}$, and pre-multiplied by its transpose [7]. (Rotation matrix $\mathbf{R}_{[p,q]}$ is a modified identity matrix with a rotation angle $\theta_{p,q}$, elements $R_{p,p} = R_{q,q} = \cos\theta_{p,q}$, and elements $R_{p,q} = -R_{q,p} = \sin\theta_{p,q}$ -- where subscripts p and q represent the row and column indices, p or q $\neq$ 0 or N-1, and p $\neq$ q.) Consequently, orthogonal similarity transformations can be applied to convert an intial filter design, represented by **m**, into other forms with equivalent characteristics. Procedures have been demonstrated which convert initial filter designs into canonical and longitudinal forms [1,8] and which annihilate specific circuit couplings, generating other useful circuit forms [9–12]. But, these conventional methods, aimed only at eliminating certain elements of **m**, provide no means of examining the variety of alternative designs or guidance as to whether certain coupling relationships are possible.

DESIGN SPACE TRANSFORMATIONS

To go beyond these limitations, sequences of plane rotation similarity transformations were determined that map conventional designs into 'design spaces' *ranging over independent variables*. The rotation matrices are selected and sequenced to ensure that some coefficients in the transformed coupling matrix are functions of an *independent* rotation angle, and that each undesirable coupling is a function of an additional rotation angle, whose value is chosen to eliminate the coupling. Alternative designs can be examined by plotting the transformed couplings versus the independent angle.

For a reciprocal, six resonance filter with initial coupling matrix, **m**, the transformed coupling matrix, **M**, is

$$\mathbf{M} = \mathbf{R}_{[4,6]}^{T} \bullet \mathbf{R}_{[2,4]}^{T} \bullet \mathbf{R}_{[3,5]}^{T} \bullet \mathbf{m} \bullet \mathbf{R}_{[3,5]} \bullet \mathbf{R}_{[2,4]} \bullet \mathbf{R}_{[4,6]}. \tag{2}$$

This mapping is detailed in Fig. 3. Solving for either longitudinal or canonical asymmetric designs ($M_{2,5} = 0$),

$$\theta_{3,5} = \tan^{-1}[(m_{4,5}\tan[\theta_{2,4}] - m_{2,5})/(m_{2,3} - m_{3,4}\tan[\theta_{2,4}])]. \tag{3}$$

For longitudinal, pseudo-elliptic designs ($m_{1,6} = 0$, $M_{4,7} = 0$), there is the further requirement that $\theta_{4,6} = 0$. Alternatively, for canonical asymmetric, elliptic designs ($m_{1,6} \neq 0$, $M_{1,4} = 0$),

$$\theta_{4,6} = \tan^{-1}[(m_{1,4}\cos[\theta_{2,4}] + m_{1,2}\sin[\theta_{2,4}])/m_{1,6}] \tag{4}$$

Transformation of elliptic designs requires an additional degree of freedom - in the form of an additional input and/or output coupling [12] - that $M_{4,7}$ provides.

Alternative designs are discovered by inspecting an overlayed graph of each coupling magnitude, $|M_{x,y}|$, with $\theta_{2,4}$ ranging over 180°. The couplings defined by a particular value of $\theta_{2,4}$ correspond to the coupling magnitudes of a valid design. To aid in comparing the attributes of alternative designs, the definitions of various "figures of merit" (FOM) relating to dual-mode dielectric resonator filters are proposed in Fig. 4.

FOM_{size} = A measure inversely related to the design's relative size.
$= \Sigma_{i=1 \text{ to } N}\{-1/(N \ln(|\text{"Min gap}_i \text{ inter-coupling"}|/(2.718\, k_o)))\}$
FOM_{no_iris} = A measure of the realizability without irises.
$= N / \Sigma_{i=1 \text{ to } N}\{|\text{" Max/Min gap}_i \text{ inter-coupling ratio"}|\}$
$FOM_{stability}$ = A rough measure of the design's environmental stability.
$= 1 / (2\, |\text{"Max intra-coupling"}| - |\text{"Min intra-coupling"}|)$

Note: N = number of inter-resonator gaps in the design.
k_o = Max |"Min gap_i inter-coupling"| of all designs being compared.
FOM_{size} is derived from an approximation of coupling as a function of resonator spacing appearing in [13].

Fig. 4. Figures of merit for designs with dual-mode dielectric resonators axially-oriented in a cut-off waveguide.

DESIGN EXAMPLES

An unconventional, narrow-band, longitudinal, HEH_{11} dual-mode dielectric resonator filter without irises (Fig. 2) was designed using the new technique. Equations (2) and (3) were applied to transform the elements of an existing normalized coupling matrix, **m** (Fig. 5), of a canonical symmetric filter into a longitudinal filter design space, plotted in Fig. 6, where the transformed coupling magnitudes are functions of $\theta_{2,4}$. The vertical lines, (a) and (b), of Fig. 6 indicate conventional and alternative designs, respectively, which correspond to the element values of coupling matrices $\mathbf{M_a}$ and $\mathbf{M_b}$ in Fig. 5. Alternative design, $\mathbf{M_b}$, was constructed, and its measured performance agrees well with theory, as shown in Fig. 7.

To demonstrate the transformation for canonical asymmetric filters, equations (2), (3), and (4) were applied to Pfitzenmaier's elliptic design [3, 12]. The element values of the initial, conventional, and alternative coupling matrices - **m**, $\mathbf{M_a}$, and $\mathbf{M_b}$, respectively - appear in Fig. 8, while the corresponding design space plot appears in Fig. 9.

Figures of merit for conventional designs **m** and $\mathbf{M_a}$, along with those for alternative designs $\mathbf{M_b}$, of Figs. 5 and 8 are calculated in Table 1. In both cases, it is apparent that the alternative design incorporates the best attributes of the conventional designs, without their shortcomings. And, although design $\mathbf{M_b}$ of Fig. 8 requires two output couplings, its structure has become almost longitudinal ($M_{b(6,7)} << M_{b(4,7)} \approx M_{b(0,1)}$), suggesting improved isolation over design $\mathbf{M_a}$.

Intra-couplings			
Resonator	**m**	$\mathbf{M_a}$	$\mathbf{M_b}$
A	$m_{(1,6)} = 0$	$M_{a(1,2)} = 1.07539$	$M_{b(1,2)} = 0.25258$
B	$m_{(2,5)} = -0.18010$	$M_{a(3,4)} = 0.74620$	$M_{b(3,4)} = 0.67232$
C	$m_{(3,4)} = 0.92630$	$M_{a(5,6)} = 0.98298$	$M_{b(5,6)} = 0.67232$
Inter-couplings			
Gap	**m**	$\mathbf{M_a}$	$\mathbf{M_b}$
A ⇔ B	$m_{(1,2)} = 1.08181$	$M_{a(1,4)} = -0.11767$	$M_{b(1,4)} = 1.05191$
A ⇔ B	$m_{(5,6)} = 0.98885$	$M_{a(2,3)} = 0.89589$	$M_{b(2,3)} = -1.05191$
B ⇔ C	$m_{(2,3)} = 0.79454$	$M_{a(3,6)} = -0.10756$	$M_{b(3,6)} = 0.72513$
B ⇔ C	$m_{(4,5)} = 0.75006$	$M_{a(4,5)} = 0.85141$	$M_{b(4,5)} = -0.72513$
Input/Output Couplings			
Resonator	**m**	$\mathbf{M_a}$	$\mathbf{M_b}$
A	$m_{(0,1)} = 1.09215$	$M_{a(0,1)} = 1.09215$	$M_{b(0,1)} = 1.09215$
A	$m_{(6,7)} = 0.99539$		
C		$M_{a(6,7)} = 0.99539$	$M_{b(6,7)} = 0.99539$

Fig. 5. Normalized couplings for three electrically equivalent filter designs: canonical symmetric (**m**), *conventional* longitudinal ($\mathbf{M_a}$), and *alternative* longitudinal ($\mathbf{M_b}$).

Design Space Plot for Longitudinal Filter

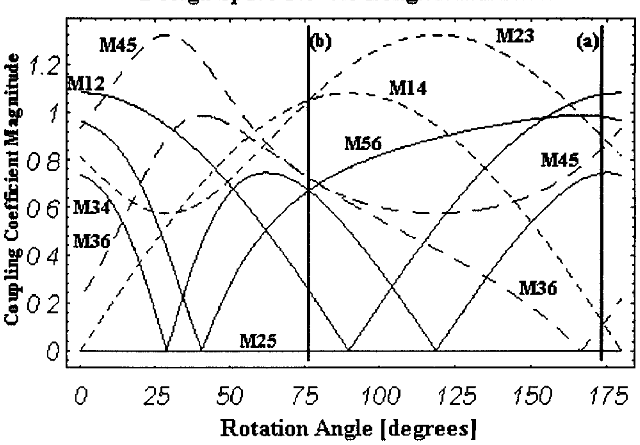

Fig. 6. (a) *Conventional* design, $\mathbf{M_a}$, at $\theta_{2,4}$ = 173.756°+180°.
(b) *Alternative* design, $\mathbf{M_b}$, at $\theta_{2,4}$ = 76.498°.
Short dashes are A-B inter-couplings, long dashes are B-C inter-couplings, and solid lines are intra-couplings.

CONCLUSIONS

An analytical method of transforming conventional filter designs into a range of electrically equivalent designs has been demonstrated - along with graphical means of inspecting the resulting alternatives. Also, criteria that these transformations must satisfy have been identified. And, although not all discussed here, transformations for 4, 6, and 8 resonance filters have been found. Use of the technique has led to the discovery of alternative, six-resonance, dual-mode filter designs with advantages over conventional designs. This technique is applicable to any reciprocal filter having multiple signal paths.

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