On the Sensitivity of Coupled Resonator Filters Without Some Direct Couplings

Smain Amari, *Member, IEEE,* and Uwe Rosenberg, *Senior Member, IEEE*

***Abstract*—This paper presents an analysis of the sensitivity of coupled resonator filters in which some direct couplings are missing. The effect of changes in the coupling coefficients and resonant frequencies of the resonators is investigated by directly computing the gradient of the scattering parameters. It is shown that structures that are modular in the input-to-output direction are much less sensitive than those with modularity in the orthogonal direction for the same frequency response.**

***Index Terms*—Bandpass filters, elliptic function filters, filter synthesis, sensitivity.**

I. Introduction

ELLIPTIC and pseudoelliptic function filters are finding widespread application in modern communication systems where sharp cutoff skirts are required for efficient use of an already crowded and limited electromagnetic spectrum. The sharpness of the cutoff rate of this class of filters stems from the fact that they exhibit transmission zeros at finite frequencies in the complex plane. Most of the research efforts over the last three decades have been focused on finding new and ingenious ways of implementing topologies that have been shown to produce specific pseudoelliptic responses. Recently, a new direction was taken by three research groups. In this approach, topologies that exhibit specific features were sought and presented independently and at the same conference by two research groups using different synthesis techniques [1] and [2]. Similar structures of order 8 were patented even earlier by a third group [3]. A salient feature of these new topologies is the crucial role played by easily accessible filter parameters such as the resonant frequencies of the resonators. Indeed, it can be shown rigorously that the return and insertion loss of these topologies are mirrored with respect to the center of the passband when the frequency shifts of all the resonators undergo a sign change while all the other coupling coefficients are kept unchanged [4]. For some topologies, especially those of higher orders, this feature may turn out to be a disadvantage. Such is the case when the frequency shifts in the resonant frequencies are small in comparison to the bandwidth of the filter, especially for asymmetric responses. In other words, if the diagonal elements of the normalized coupling matrix are much smaller than unity in magnitude, the corresponding filter may be too sensitive to be of practical value unless the resonant frequencies can be controlled very precisely. Other configurations that are built around a seed, which does not contain one or more direct couplings, may turn out to be too sensitive as well, especially when more than two transmission zeros are to be generated. The sensitivity of “cul-de-sac” and “box” configurations was investigated in a very recent report by Cameron *et al.* [5]. Both Monte Carlo simulation and selective variations of the coupling coefficients to mimic temperature effects were carried out on a filter of order 11 with three transmission zeros. It was concluded that the cul-de-sac configuration is more sensitive than the box configuration for the same frequency response [5]. There are, however, a host of questions yet to be investigated in regards to the sensitivity of the coupling schemes reported in [1]–[5].

This paper presents an analysis of the sensitivity to random errors in the entries of their coupling matrices of coupling schemes in which some of the direct couplings are missing. The sensitivity of one, two, or more coupling schemes that implement a given pseudoelliptic response is determined in order to establish simple results that may help a designer choose the least sensitive scheme. It will be shown that some configurations are extremely sensitive, while others offer sensitivities comparable to those of traditional configurations such as cascaded triplet sections with the additional flexibility of zero shifting [4].

Manuscript received October 29, 2002; revised January 15, 2003.

S. Amari is with the Department of Electrical and Computer Engineering, Royal Military College of Canada, Kingston, ON, Canada K7K 7B4 (e-mail: smain.amari@rmc.ca).

U. Rosenberg is with Marconi Communications GmbH, D-71520 Backnang, Germany (e-mail: Uwe.Rosenberg@marconi.com).

Digital Object Identifier 10.1109/TMTT.2003.812582

II. Sensitivity and Gradient Evaluation

The model used for the set of coupled resonators is the same as the one described in [6], where the source and load are allowed to couple to more than one resonator and possibly to each other. The coupling coefficients are assumed frequency independent and the resonators are modeled as lumped *LC* circuits. This model is expected to be accurate for narrow-band filters [6].

The synthesis problem consists in determining a coupling matrix whose response meets the specifications of the filter. Under the assumptions made above, only rational functions of the frequency can be implemented by this model. We, therefore, limit the class of response functions investigated to those described by generalized Chebyshev responses [6], [7].

The components of the gradient of the reflection and transmission coefficients with respect to the entries of the coupling matrix are given by [6]

$$\frac{\partial S_{11}}{\partial M_{pq}} = -4jP_{pq}\left[A^{-1}\right]_{1p}\left[A^{-1}\right]_{q1}, \qquad p \neq q \tag{1a}$$

$$\frac{\partial S_{11}}{\partial M_{pp}} = -2jP_{pp}\left[A^{-1}\right]_{1p}\left[A^{-1}\right]_{p1} \tag{1b}$$

$$\frac{\partial S_{21}}{\partial M_{pq}} = 2jP_{pq}\left(\left[A^{-1}\right]_{n+2,p}\left[A^{-1}\right]_{q1} + \left[A^{-1}\right]_{n+2,q}\left[A^{-1}\right]_{p1}\right), \qquad p \neq q \tag{1c}$$

$$\frac{\partial S_{21}}{\partial M_{pp}} = 2jP_{pq}\left[A^{-1}\right]_{n+2,p}\left[A^{-1}\right]_{p1}. \tag{1d}$$

The scattering parameters are given by

$$S_{11} = 1 + 2j\left[A^{-1}\right]_{11} \tag{2a}$$

$$S_{21} = -2j\left[A^{-1}\right]_{n+2,1}. \tag{2b}$$

The matrix $[A]$ is related to the coupling matrix $[M]$ by $[A] = -j[R]+\Omega[W]+[M]$, where the matrix $[R]$ is diagonal such that $[R]_{11} = [R]_{(n+2,n+2)=}1$ and $[R]_{ij} = 0$ otherwise. The matrix $[W]$ is equal to the unit matrix, except that the first and last diagonal elements are equal to zero. The normalized frequency of the low-pass prototype is denoted by Ω. The topology matrix $[P]$ in (1a)–(1d) is defined by $[P]_{ij} = 0$ if $[M]_{ij} = 0$ and $[P]_{ij} = 1$ otherwise.

Since the return and insertion loss involve only the magnitude of the scattering parameters, the following expression is used to determine the gradient of the magnitude of a complex quantity Z in terms of the gradient of Z:

$$\frac{\partial |Z|}{\partial x} = \mathrm{Re}\left[\frac{|Z|}{Z}\frac{\partial Z}{\partial x}\right] \tag{3}$$

where Re is the real part of a complex number. Once the coupling matrix that satisfies the desired specifications is obtained, (1)–(3) are used to determine the sensitivities of the topology. A similar approach was followed in the investigation of the sensitivity of coupled resonator filters with standard topologies and where the source and load are coupled to only one resonator each [8].

Although the individual components of the gradients can be evaluated using the equations given above and examined separately, in this study, we define two parameters K_1 and K_2 as follows:

$$K_1 = \sum_{i,j}\left|\frac{\partial |S_{11}|}{\partial M_{ij}}\right| \tag{4a}$$

$$K_2 = \sum_{i,j}\left|\frac{\partial |S_{21}|}{\partial M_{ij}}\right|. \tag{4b}$$

These sums correspond to the worst case scenario when all the errors have their effects added, thereby leading to maximum deterioration in the response. The individual terms are determined from (1a)–(3). In (4a) and (4b), the sums run over all the entries of the coupling matrix that are not known exactly. In particular, all shifts in resonant frequencies should be included since these cannot be determined exactly for any practical situation. Even for synchronously tuned resonators, the terms corresponding to M_{ii}, which are themselves zero, should be included in these sums. On the other hand, some coupling coefficients are known not to vary for certain implementations and should not be included in the summation. This is the case of coupling coefficients that are known to be exactly zero for a given implementation despite the effect of any errors such as manufacturing tolerances or temperature effects. If symmetry, such as that of the field distribution of a given mode, is used to force a coupling coefficient to vanish, the sums should include such a coupling coefficient.

Although a more common and intuitive definition of the sensitivity would require dividing each of the terms in (4a) and (4b) by $|S_{11}|/M_{ij}$ and $|S_{21}|/M_{ij}$, respectively, we choose not to include these terms for several reasons. First, some of the coupling coefficients may be zero (e.g., diagonal elements of synchronously tuned resonators) for the exact coupling matrix and would not contribute to such normalized sensitivities. In reality, they have sizable effects on the response of the filter and should be included. Second, the scattering parameters vanish at reflection and transmission zeros. At these frequencies, normalized sensitivities are not well defined. Third, if the normalized sensitivities are needed, they can be straightforwardly calculated following the approach described here. Situations may also arise where specific groups of coupling coefficients do not vary independently.

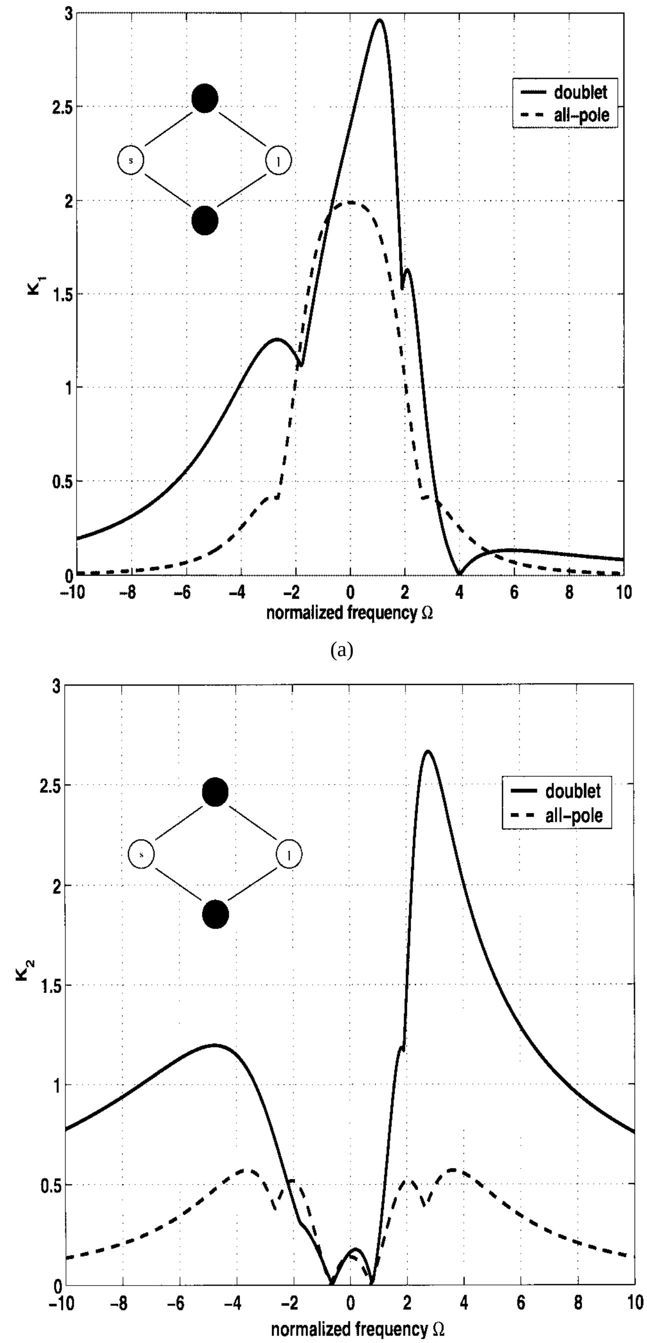
An examination of the derivatives of the magnitudes of the scattering parameters may be very useful for specific applications. For example, it is found that the response of a doublet is very stable when the coupling coefficients in one branch vary in the opposite direction to those of the other branch. Large errors that satisfy this property can be tolerated by this structure. Other configurations, such as the cul-de-sac configuration, also show strong resilience to correlated errors in the coupling coefficients of the main doublet, as will be discussed later. Although these features can be very important in selecting the proper coupling scheme, they are case specific and depend on the physical realization of the filter.

III. Results

Several topologies in which some of the direct couplings are not present have been investigated using the procedure outlined above. Representative examples, which may be important for the implementation of dual-mode filters in particular, are now discussed and compared with other standard configurations. The examples are chosen to highlight the sensitivity of two classes of filters. The first class includes filters that are modular in the input-to-output direction such as cascaded doublets and triplets, while those in the second class are modular in the orthogonal direction such as cul-de-sac configurations. Since both of these classes contain a doublet (or box) as a seed, we first examine a single doublet.

A. Doublet

A doublet is a two-resonator building block for modular design of pseudoelliptic filters in which the source and load are coupled to each of the two resonators. The two resonators are not coupled to each other [9]. Possible implementations of this structure involve single-mode resonators, as well as dual-mode cavities without intra-cavity coupling. The inset in Fig. 1 shows the coupling and routing scheme of this structure. The dark disks represent the resonators, while the empty disks show the source and load. As a specific example, we assume that a doublet is to be synthesized to produce a generalized Chebyshev response of



(a)

(b)

Fig. 1. Variation of: (a) K_1 and (b) K_2 against normalized frequency. Solid lines: doublet. Dashed lines: second order all-pole.

order 2 with a normalized transmission zero at $\Omega = 4$ and an in-band return loss of $R = 23$ dB. Applying the synthesis technique in [6], we get the following coupling matrix:

$$M = \begin{bmatrix} 0.000 & 0.7152 & -1.1859 & 0.0000 \\ 0.7152 & -1.9002 & 0.0000 & 0.7152 \\ -1.1859 & 0.0000 & 1.7732 & 1.1859 \\ 0.0000 & 0.7152 & 1.1859 & 0.0000 \end{bmatrix}. \quad (5)$$

To assess the sensitivity of this structure, the parameters K_1 and K_2 were computed as a function of the normalized frequency Ω and are shown in Fig. 1(a) and (b) (solid lines). The dashed lines show the corresponding parameters of an all-pole Chebyshev filter of second order with the same in-band return loss.

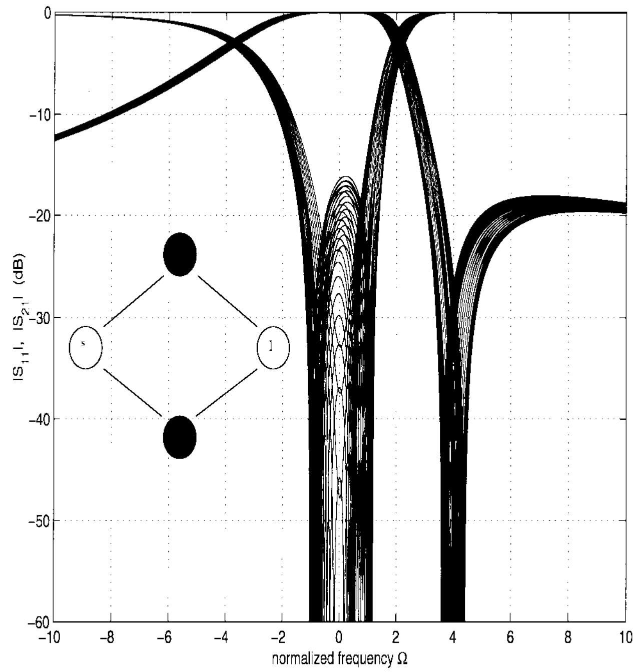


Fig. 2. Reflection and transmission coefficients versus normalized frequency Ω of doublet when the diagonal elements of the coupling matrix undergo random errors of 10% or less.

It can be clearly seen that K_1, which accounts for the sensitivity of the return loss, is larger for the doublet, but still at acceptable levels. There is also a substantial increase in the parameter K_2 of the doublet with respect to that of the second-order Chebyshev filter, especially in the stopband close to the transmission zero of the doublet. Still, the values of K_2 of the doublet are much smaller than those of Chebyshev filters of orders 4 and higher, as will be seen below. Furthermore, the level of attenuation achievable by this doublet (second-order filter with a transmission zero at $\Omega = 4$) are of the order of 20 dB for normalized frequencies in the range of ten. A value of K_2 in the range shown in Fig. 1(b) is not prohibitively large under these conditions since the corresponding relative change in the transmission coefficient (insertion loss) is not substantial, except in the close vicinity of the transmission zero of the doublet.

An alternative way to display the sensitivity of the doublet, or any other structure for that matter, is to investigate the effect of random errors in the coupling coefficients on the frequency response. Fig. 2 shows the response of the previous doublet when a maximum error of 10% is assumed in the diagonal elements of the coupling matrix. We limited the variations to only these coefficients since the transmission zero can be shifted from one side of the passband to the other one by simply changing their signs [9]. These results clearly demonstrate that the filter is not degraded beyond acceptable levels. It is also worth mentioning that the individual components of the gradient of the scattering parameters with respect to the entries of the coupling matrix contain valuable information for fine tuning and even slight adjustment by hand on a computer.

B. Two Cascaded Doublets

The next structure consists of two cascaded doublets with an additional resonator between the two doublets to preserve the zero-shifting property. As a specific example, the in-band return loss is 23 dB and the two transmission zeros are at $\Omega = -3$ and $\Omega = 2$. A coupling matrix that satisfies these requirements is shown in (6) at the bottom of the following page.

The response of this matrix can be straightforwardly obtained from (2a) and (2b) and is not shown here. A structure consisting of two cascaded triplets and giving the same response was also synthesized for comparative purposes.

To investigate the sensitivity of this coupling scheme, the parameters K_1 and K_2 were computed as a function of the normalized frequency and are shown in Fig. 3(a) and (b) as solid lines. The dashed lines are those of two cascaded triplets giving the same response.

It is evident from this figure that the sensitivity of two cascaded doublets is basically identical to that of two cascaded triplets over the entire frequency range. Moreover, the doublets have the additional feature of zero shifting, which can be exploited for more flexible filter designs. Note that, in this coupling scheme, the pivot resonator (third resonator from the input in Fig. 3) is loaded with four main couplings. This may slightly reduce the unloaded-Q factor of this cavity. Cascaded triplets have similarly loaded pivot resonators that are coupled to four resonators, but some of the coupling coefficients are weaker than those of the cascaded doublets and, hence, have less impact on the cavity's unloaded Q-factor.

The sensitivity of more cascaded doublets was also investigated and compared with that of cascaded triplets. It was found that the two coupling schemes have similar performance in regard to sensitivity.

The structures of the two previous examples are modular in the input-to-output direction. The following examples examine the sensitivity of structures, which are modular in the orthogonal direction.

C. Third-Order Branching Doublet

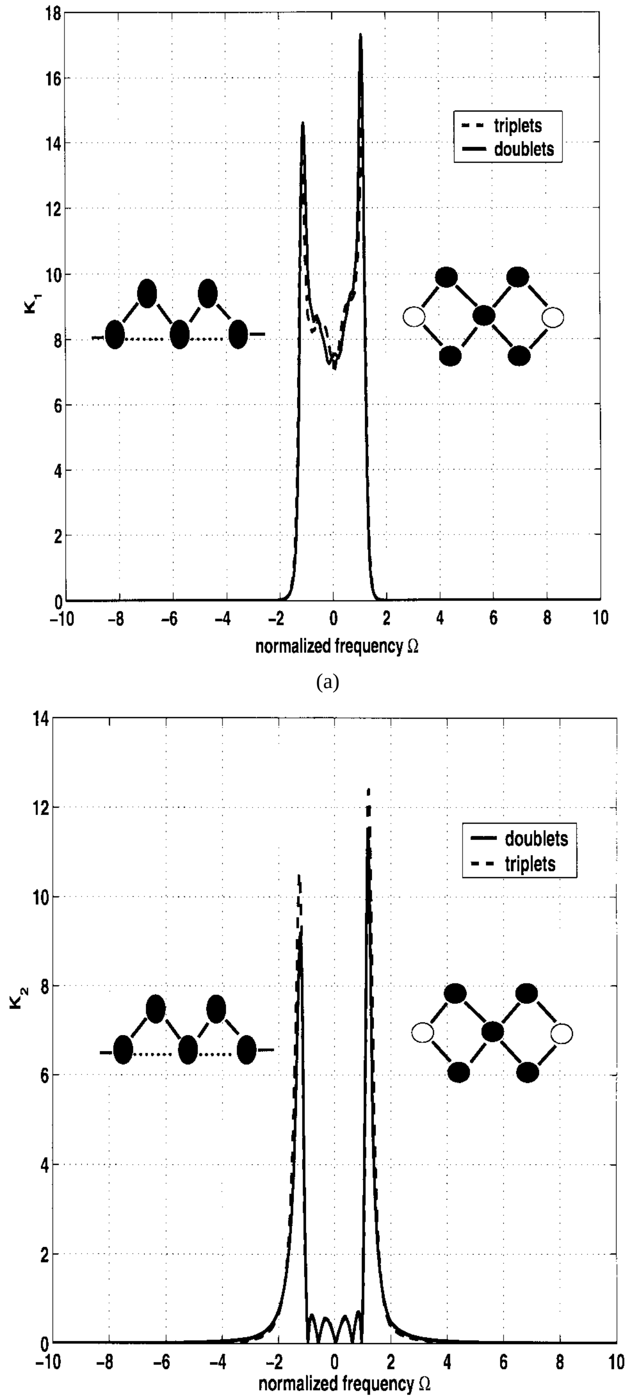
A branching doublet is a structure where a doublet is used as a seed to grow other branches that contain resonators. A third-order version is shown in the inset of Fig. 4. As a specific example, we first consider a symmetric response with two transmission zeros at -2 and $+2$ at an in-band return loss of 20 dB. A coupling matrix that yields this response is

$$M = \begin{bmatrix} 0.0000 & 0.8613 & 0.6202 & 0.0000 & 0.0000 \\ 0.8613 & 0.0000 & 0.0000 & 0.0000 & -0.8613 \\ 0.6202 & 0.0000 & 0.0000 & 1.3878 & 0.6202 \\ 0.0000 & 0.0000 & 1.3878 & 0.0000 & 0.0000 \\ 0.0000 & -0.8613 & 0.6202 & 0.0000 & 0.0000 \end{bmatrix}. \quad (7)$$

The corresponding response can be obtained from (2a) and (2b) and is not shown here.

The variation of the parameters K_1 and K_2 as a function of the normalized frequency is shown in Fig. 4(a) and (b) (solid lines). For comparison, we also included the same parameters for an all-pole Chebyshev filter of the same order and in-band return loss (dashed line).

It is evident that the stopband isolation is much more sensitive than the Chebyshev response. On the other hand, the in-band return loss has practically the same sensitivity as a Chebyshev filter of the same order [see Fig. 4(a)]. The large value of K_2 in the stopband can set a limit on the usefulness of this coupling scheme, especially when high isolation is required. This is not the case in the present example where the isolation is around



(a)
(b)

Fig. 3. Parameters: (a) K_1 and (b) K_2 of two cascaded doublets (solid lines) and two cascaded triplets (dashed lines) with the same frequency response versus normalized frequency.

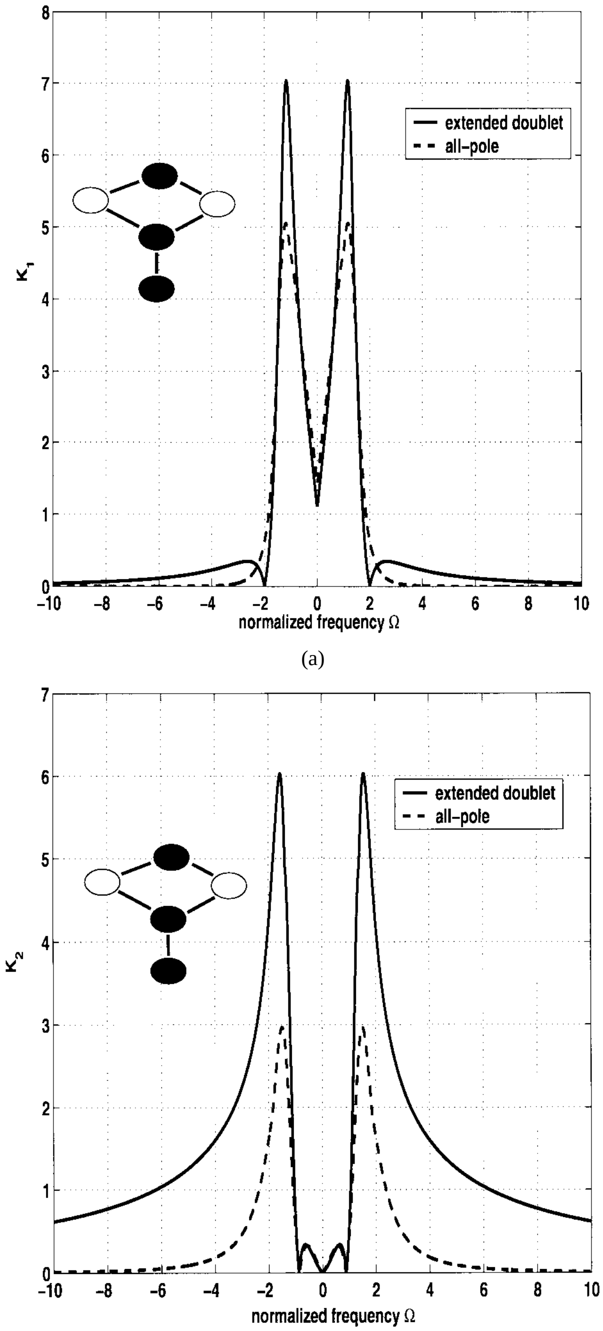


Fig. 4. Parameters: (a) K_1 and (b) K_2 of the third-order branching doublet (solid lines) and a third-order all-pole Chebyshev filter versus normalized frequency Ω.

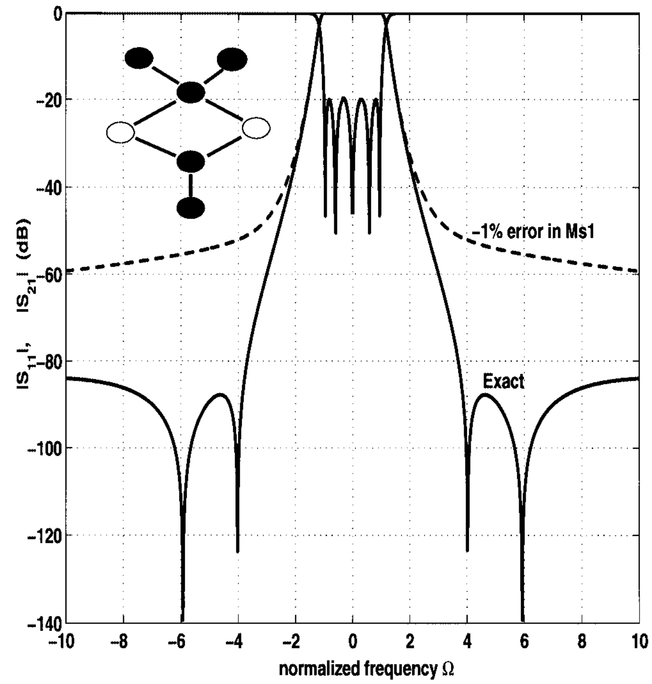


Fig. 5. Reflection and transmission coefficient of a fifth-order branching doublet versus normalized frequency Ω. Solid lines: exact coupling matrix. Dashed lines: -1% error in M_{s1}.

20 dB in the frequency range shown in Fig. 4. The situation is illustrated in more dramatic terms by the following example.

D. Fifth-Order Branching Doublet

The topology in this example involves a doublet with branches out of each of its two resonators, as shown in the inset of Fig. 5. One branch contains one resonator and the other contains two resonators. This coupling scheme is slightly more "exotic" than the cul-de-sac topology presented by Cameron *et al.* or Williams *et al.* [2], [3]. The source and load are also coupled to more than one resonator, but this is not the case for the cul-de-sac configuration in [2] and [3].

As a specific example, we consider a response with transmission zeros at $\Omega = -6, -4, 4,$ and 6 and an in-band return loss of 20 dB. The coupling matrix, shown in (8) at the bottom of the following page, satisfies these specifications. The corresponding response is shown in Fig. 5.

The parameters K_1 and K_2 as a function of frequency are shown in Fig. 6. It can be clearly seen that the parameter K_2

$$\begin{bmatrix} 0.0000 & 0.6929 & 0.8202 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.6929 & 1.0677 & 0.0000 & 0.3491 & 0.0000 & 0.0000 & 0.0000 \\ 0.8202 & 0.0000 & -0.7461 & -0.5718 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 0.3491 & -0.5718 & 0.0271 & 0.2740 & -0.6280 & 0.0000 \\ 0.0000 & 0.0000 & 0.0000 & 0.2740 & -1.1101 & 0.0000 & 0.6525 \\ 0.0000 & 0.0000 & 0.0000 & -0.6280 & 0.0000 & 0.6649 & 0.8526 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.6525 & 0.8526 & 0.0000 \end{bmatrix}. \quad (6)$$

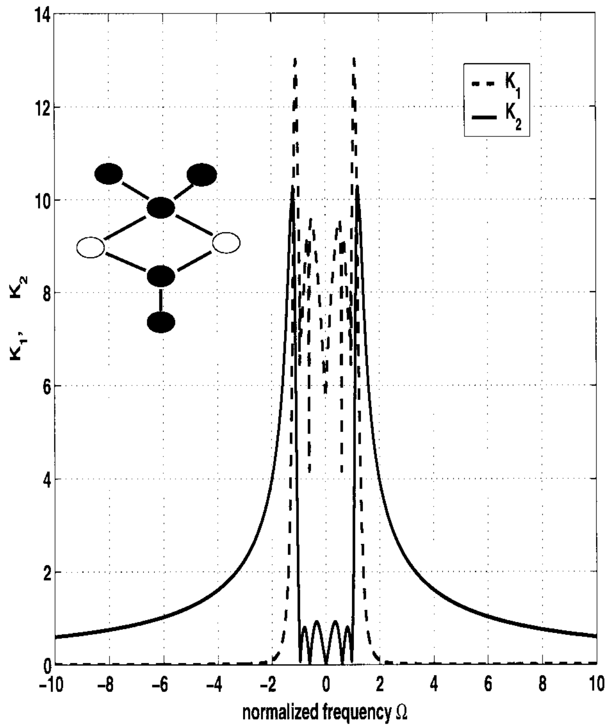


Fig. 6. Parameters K_1 (dashed line) and K_2 (solid line) of fifth-order branching doublet. Note the large values of K_2 in the stopbands.

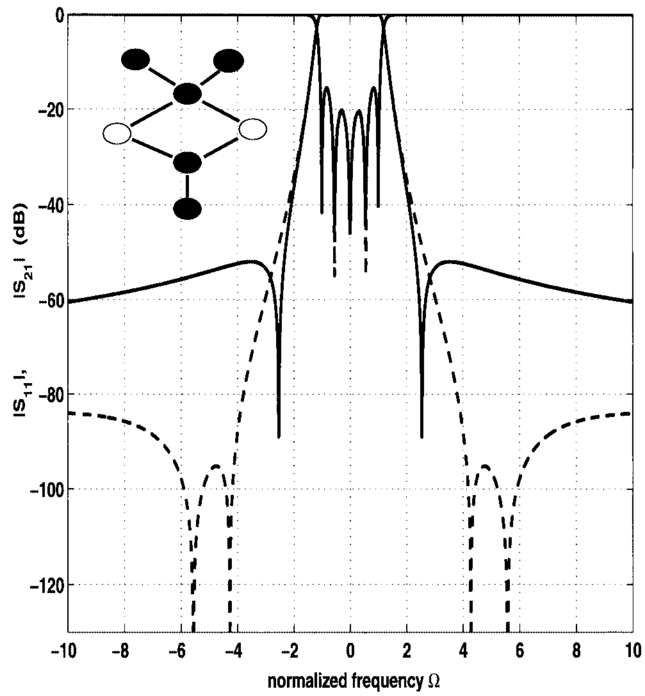


Fig. 7. Response of fifth-order branching doublet. Solid lines: 2% increase in self-couplings, -2% decrease in all others. Dashed lines: 2% increase in self-couplings, -1% decrease in M_{s1} and -2% in all others. The response of the exact solution is given by the solid line in Fig. 5.

of this configuration is substantial in the stopbands. As mentioned in the previous example, a large value of K_2 coupled with very small values in the magnitude of the transmission coefficient lead to extremely sensitive stopbands. In the present example, the transmission coefficient is in the range of 80 dB in the vicinity of the two transmission zeros, while K_2 is in the order of two for the same frequency range (cf. Fig. 6). If an entry in the coupling matrix is erroneous to within 1%, the insertion loss can change by as much as 20 dB. The situation is well illustrated in Fig. 5 (dashed lines), where the coupling coefficient between the source and one of the resonators of the doublet is changed by -1%. This minor change alters the response of the filter beyond recognition. It follows from this example that branching doublets (cul-de-sac) may be useful for practical applications only when small or moderate attenuations in the stopbands are required. Designs for high rejection need extremely precise tuning and, furthermore, an outmost homogeneous behavior of all structural filter elements regarding the desired operating environmental conditions. It is also interesting to note that the return loss is almost unaffected by the -1% change in the coupling coefficient, which has a dramatic effect on the insertion loss (cf. Fig. 5).

An interesting feature of the previous coupling scheme is its resilience against correlated changes in some coupling coefficients. For example, if all the self-coupling coefficients (diagonal elements of the coupling matrix) are changed by $+2\%$ and all the other coupling coefficients by -2%, the response is still acceptable, as shown by the dashed lines in Fig. 7. However, if one of the coupling coefficients of the main doublet is changed by an amount that is slightly different from all the other coupling coefficients, the response is severely degraded, as shown by the solid lines in this same figure. This response results when all the self-coupling coefficients are changed $+2\%$, M_{s1} by -1% and all the other coefficients by -2%. In practice, it is virtually impossible to maintain such a strong correlation between the changes in the different coupling coefficients; this coupling scheme may still turn out to be of limited use given the random nature of the errors in the coupling coefficients.

$$\begin{bmatrix} 0.0000 & 0.7153 & 0.7157 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.7153 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.8777 & 0.7153 \\ 0.7157 & 0.0000 & 0.0000 & 0.5978 & 0.5978 & 0.0000 & -0.7157 \\ 0.0000 & 0.0000 & 0.5978 & 0.9083 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & 0.5978 & 0.0000 & -0.9083 & 0.0000 & 0.0000 \\ 0.0000 & 0.8777 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 0.7153 & -0.7157 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \end{bmatrix} \quad (8)$$

IV. Conclusions

The sensitivity of coupling schemes for dual-mode and multimode filters without some couplings has been investigated by analytically calculating the gradient of the magnitudes of the scattering parameters with respect to the entries of the coupling matrix. Coupling structures, which are modular in the input-to-output direction (cascaded doublets and triplets), have been found to be much less sensitive than those modular in orthogonal direction (branching doublets, cul-de-sac). The doublet and cascaded doublets are found to have a sensitivity that is comparable to that of triplets and cascaded triplets for the same order. Branching doublets (e.g., cul-de-sac) configurations of order higher than three are found to be too sensitive to be of practical value, except for responses with low or moderate attenuation in the stopbands. Obviously, other configurations of higher orders or which include cascading and branching can be investigated following the same approach.

References

[1] U. Rosenberg and S. Amari, "Novel coupling schemes for microwave resonator filters," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Seattle, WA, May 2002, pp. 1605–1608.

[2] R. J. Cameron, A. R. Harish, and C. J. Radcliffe, "Synthesis of advanced microwave filters without diagonal cross-couplings," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Seattle, WA, May 2002, pp. 1437–1440.

[3] A. E. Williams, J. I. Upshur, and M. M. Rahman, "Asymmetric response bandpass filters having resonators with minimum couplings," U.S. Patent 6 337 610, Jan. 8, 2002.

[4] U. Rosenberg and S. Amari, "Novel coupling schemes for microwave resonator filters," *IEEE Trans. Microwave Theory Tech.*, vol. 50, pp. 2896–2902, Dec. 2002.

[5] R. J. Cameron, A. R. Harish, and C. J. Radcliffe, "Synthesis of advanced microwave filters without diagonal cross-couplings," *IEEE Trans. Microwave Theory Tech.*, vol. 50, pp. 2862–2872, Dec. 2002.

[6] S. Amari, U. Rosenberg, and J. Bornemann, "Adaptive synthesis and design of resonator filters with source/load-multi-resonator coupling," *IEEE Trans. Microwave Theory Tech.*, vol. 50, pp. 1969–1978, Aug. 2002.

[7] R. J. Cameron, "General coupling matrix synthesis methods for Chebyshev filtering functions," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 433–442, Apr. 1999.

[8] S. Amari, "Sensitivity of coupled resonator filters," *IEEE Circuits Syst. II*, vol. 47, pp. 1017–1022, Oct. 2000.

[9] S. Amari and U. Rosenberg, "The doublet: A new building block for modular design of pseudo-elliptic filters," in *Eur. Microwave Conf. Dig.*, vol. 1, Milan, Italy, Sept. 2002, pp. 405–407.

Smain Amari (M'98) received the DES degree in physics and electronics from Constantine University, Constantine, Algeria, in 1985, and the Master's degree in electrical engineering and the Ph.D. in physics from Washington University, St. Louis, MO, in 1989 and 1994, respectively.

From 1994 to 2000, he was with the Department of Electrical and Computer Engineering, University of Victoria, Victoria, BC, Canada. From 1997 to 1999, he was a Visiting Scientist with the Swiss Federal Institute of Technology, Zurich, Switzerland, and a Visiting Professor in Summer 2001. Since November 2000, he has been with the Department of Electrical and Computer Engineering, Royal Military College of Canada, Kingston, ON, Canada, where he is currently an Associate Professor. He is interested in numerical analysis, numerical techniques in electromagnetics, applied physics, applied mathematics, wireless and optical communications, computer-aided design (CAD) of microwave components, applied physics, and application of quantum field theory in quantum many-particle systems.

Uwe Rosenberg (M'90–SM'93) received the Dipl. Ing. degree (first-class honors) in electrical engineering (telecommunication technique) from the Fachhochschule der Deutschen Bundespost, Dieburg, Germany, in 1982.

From 1982 to 1983, he was with Hydro Therm, Dieburg, Germany, where he was involved with the design and development of automatic safety and heating control circuits. From 1983 to 1985, he was with the Technische Hochschule Darmstadt, Darmstadt, Germany, where he was involved with the design and development of experimental installations and software components for microcomputer control systems. In 1985, he joined the Space Division, ANT Nachrichtentechnik GmbH (now Tesat-Spacecom GmbH & Company KG), Backnang, Germany, where he was engaged in research and development on microwave filters, multiplexers, and passive subsystems for communications satellites. Since 1989, he has been Head of the Research and Development Laboratory for Passive Microwave Components and Subsystems, Marconi Communications GmbH (formerly Bosch Telecom GmbH, Public Networks Division), Backnang, Germany, where he has been responsible for research and development of integrated waveguide transceiver circuitries, channel branching networks (multiplexers), antenna feed and waveguide (feeder) systems for trunk and access radio applications, mobile base-stations, large Earth stations, and communications satellites. He coauthored *Waveguide Components for Antenna Feed Systems: Theory and CAD* (Norwood, MA: Artech House, 1993). He has also authored or coauthored over 50 technical papers. He holds 36 microwave design patents

Mr. Rosenberg is a member of Verband der Elektrotechnik Elektronik Informationstechnik (VDE), Informationstechnische Gesellschaft (ITG), and Verein Deutscher Ingenieure (VDI). He is a senior member of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) and the IEEE Antennas and Propagation Society (IEEE AP-S).