# Synthesis of Advanced Microwave Filters Without Diagonal Cross-Couplings

Richard J Cameron[(1)], A. R. Harish[(2)] and C. J. Radcliffe[(3)]
[(1)]Com Dev International (UK), [(2)]Com Dev Wireless Group (UK) [(3)]Pentire Associates (UK)

***Abstract*** **— Asymmetric filtering characteristics are frequently used for the design of microwave filters for the cellular telephony industry, particularly for the transmit/receive diplexers for base stations. Typically such filters have to be manufactured in large quantities at lowest possible cost. However, because of the asymmetric filtering characteristics, the designs often include diagonal cross couplings between non-adjacent resonators in addition to the usual 'straight' couplings. Diagonal couplings tend to be mechanically difficult to manufacture and assemble, can be electrically awkward to tune and be sensitive to temperature, vibration etc. all of which drives up unit costs again. This paper introduces the methods for the synthesis of two novel filter network configurations which do not require diagonal couplings, but which nonetheless are able to realize asymmetric filtering functions.**

## I. Introduction

In order to cope with the increasing demand for capacity in restricted spectral bandwidths, specifications for channelizing filter rejections have tended to become asymmetric. This is particularly true for the front-end transmit/receive diplexers in the base stations of mobile communications systems, and requires the use of advanced filtering characteristics, optimally tailored to the rejection requirements whilst as the same time maintaining maximum in-band amplitude and group delay linearity and lowest insertion loss.

In the course of synthesizing the networks for such characteristics, and then reconfiguring the inter-resonator main-line and cross-couplings to give a convenient realization, it is frequently found that diagonal couplings are required. Diagonal couplings are those that interconnect resonators arranged in a grid pattern at an angle relative to the gridlines, where 'straight' couplings are parallel to the gridlines (eg Fig. 1).

In this paper two novel synthesis methods are presented that allow the realization of symmetric or asymmetric filtering characteristics without the need for diagonal cross-couplings. The first is the 'box' configuration, and the second is a derivative of the box configuration, the 'cul-de-sac' filter configuration.

## II. Box Sections

The box section is similar to the cascade quartet section, ie 4 resonator nodes arranged in a square formation, however with the input to and the output from the quartet from opposite corners of the square. Fig. 1(a) shows the conventional quartet arrangement for a 4th degree filtering characteristic with a single transmission zero, realized with the diagonal cross coupling $M_{13}$. Fig 1(b) shows the equivalent box section realizing the same transmission zero but without the need for the diagonal coupling. Application of the 'minimum path' rule indicates that the box section can only realize a single Tx zero.

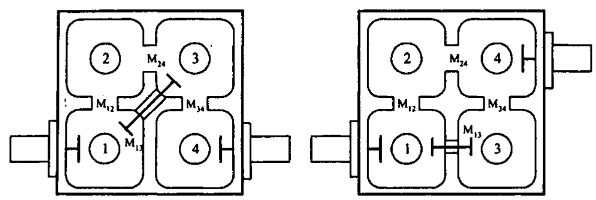


Fig. 1. 4-1 asymmetric filtering function: (a) realized with conventional diagonal cross coupling ($M_{13}$) (b) realized with the box configuration.

The box section is derived from the application of a 'cross-pivot' similarity transform to a trisection in the coupling matrix for the filter. A cross-pivot similarity transform is one where the coordinates of the element to be annihilated are the same as the pivot of the transform, ie the element to be annihilated lies on the cross-points of the pivot. The angle of the similarity transform for the annihilation of an element at the cross-point is different to that of a regular annihilation [1], and is given by:

$$\theta_r = \frac{1}{2}\tan^{-1}\left[\frac{2M_{ij}}{(M_{jj} - M_{ii})}\right] \quad (1)$$

where $i, j$ are the coordinates of the pivot and also of the element to be annihilated, and $\theta_r$ is the angle of the similarity transform. For the box section the pivot is set to annihilate the second main line coupling of the trisection in the coupling matrix ie $i = 2$ and $j = 3$ in the 4th degree example of Fig. 1 and its equivalent coupling and routing schematic Fig. 2(a). In the process of annihilating the main line coupling $M_{23}$, the coupling $M_{24}$ is created (Fig. 2(b)), and then by 'untwisting' this section the box section is formed (Fig. 2(c))



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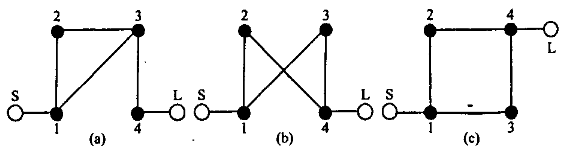


Fig. 2: 4-1 filter - formation of the box section: (a) trisection (b) annihilation of $M_{23}$ and creation of $M_{24}$ (c) 'untwisting' to obtain box section.

In the resultant box section, one of the couplings will always be negative, irrespective of the sign of the cross-coupling ($M_{13}$) in the original trisection.

To illustrate the procedure, an example is taken of a $4^{th}$ degree 25dB return loss Chebychev filtering characteristic, with a single transmission zero at $+j2.3940$ to give a lobe level of 41dB on the upper side of the passband.

Fig.3(a) below gives the coupling matrix for the trisection showing the $M_{13}$ cross-coupling, corresponding to the coupling diagram of Fig. 2(a). Fig. 3(b) shows the coupling matrix after transformation to the box configuration. Fig. 4 shows the measured results of a coaxial resonator realization of the 4-1 filter configured as in Fig. 1(b). Good correlation is obtained between the measured and simulated results.

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | 0.0530 | 0.9777 | 0.3530 | 0 |
| 2 | 0.9777 | -0.4198 | 0.7128 | 0 |
| 3 | 0.3530 | 0.7128 | 0.0949 | 1.0394 |
| 4 | 0 | 0 | 1.0394 | 0.0530 |

(a)

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | 0.0530 | 0.8507 | -0.5973 | 0 |
| 2 | 0.8507 | 0.5954 | 0 | 0.8507 |
| 3 | -0.5973 | 0 | -0.9203 | 0.5973 |
| 4 | 0 | 0.8507 | 0.5973 | 0.0530 |

(b)

Fig. 3: 4-1 Filter coupling matrices. (a) trisection (b) after transformation to box section.

If the transmission zero is placed at $-j2.3940$ below the passband instead of above, then the transformation to the box section will result in the same values for the inter-resonator couplings, but complementary values for the self couplings ($M_{11}$, $M_{22}$, ... etc. along the principal diagonal of the coupling matrix). Since the self couplings represent offsets from centre frequency and are adjustable by tuning screws, it means that the same filter structure may be used for the complementary filters in a Tx/Rx diplexer (Fig. 4(b))

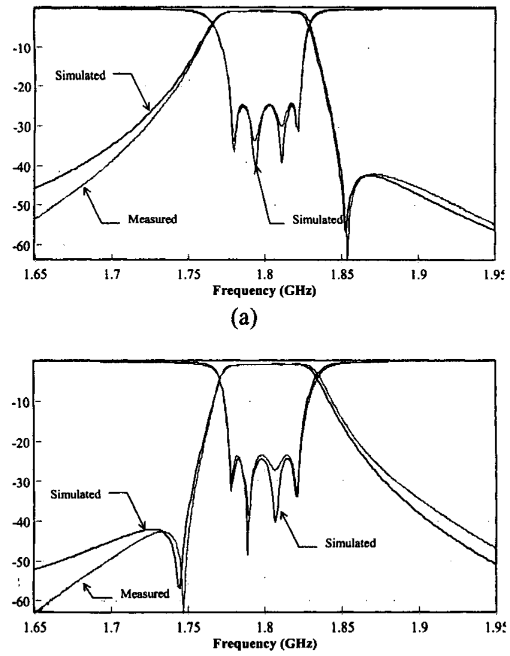


Fig. 4: 4-1 Filter – measured results. (a) transmission zero on upper side (b) transmission zero on lower side.

Box sections may also be cascaded within higher degree filters, indexing the coordinates of the pivots in eq(1) appropriately to correspond correctly with the position of each trisection. Fig. 5 gives the coupling and routing diagrams for a $10^{th}$ degree example with 2 transmission zeros on the lower side of the passband,

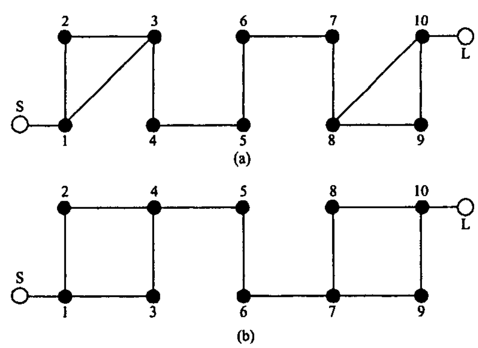


Fig. 5: 10-2 Asymmetric filter – coupling and routing diagrams (a) synthesized with 2 trisections (b) after transformation of trisections to 2 box sections. This form is suitable for realization in dual-mode technology

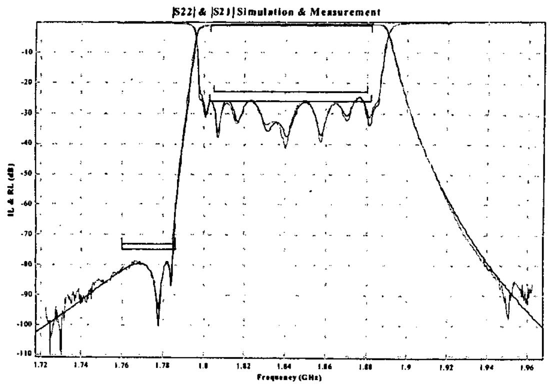


Fig. 6: 10-2 Asymmetric filter - RF simulated and measured return loss and rejection.

whilst Fig. 6 shows the measured and simulated return loss and rejection characteristics of a test filter.

It may be seen from Fig. 5 that because there are no diagonal cross couplings, it would be possible to realize this asymmetric characteristic in dual-mode cavities

## III. 'Cul-de-Sac' Configuration

The cul-de-sac configuration is restricted to double-terminated networks and will realize a maximum of $N$-3 transmission zeros. Otherwise it will accommodate even- or odd-degree symmetric or asymmetric prototypes. Moreover its form lends itself to a certain amount of flexibility in the physical layout of its resonators.

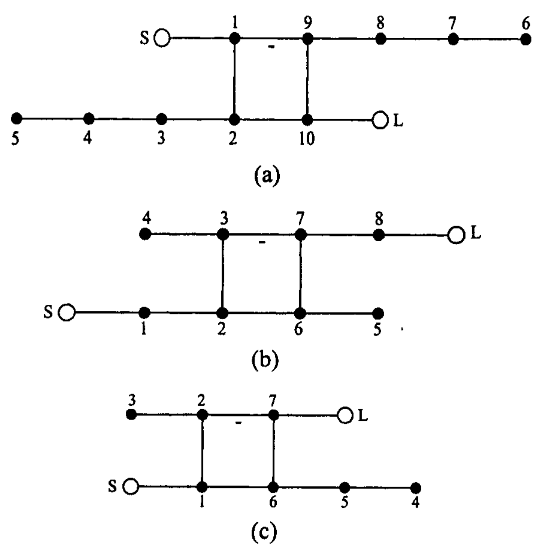

Fig. 7: Cul-de-sac network configurations (a) 10-3-4 network (b) 8-3 network (c) 7-1-2 network

A typical cul-de-sac configuration is shown in Fig. 7(a) for a 10th degree prototype with the maximum-allowable 7 Tx zeros (in this case 3 imaginary-axis and 2 complex pairs). There is a central 'core' of a quartet of resonators in a square formation (1, 2, 9 and 10 in Fig. 7(a)), straight-coupled to each other (ie no diagonal cross-couplings). One of these couplings is always negative; the choice of which one is arbitrary. The entry to and exit from the core quartet are from opposite corners of the square (1 and 10 respectively in Fig. 7(a)).

Some or all of the rest of the resonators are strung out in cascade from the other two corners of the core quartet in equal numbers (even-degree prototypes) or one more than the other (odd degree prototypes). The last resonator in each of the two chains has no output coupling, hence the nomenclature 'cul-de-sac' for this configuration. Other possible configurations are shown in Fig. 7(b) (8th degree) and Fig. 7(c) (7th degree).

Fortunately the synthesis of the cul-de-sac network is very simple and is entirely automatic. Starting with the folded coupling matrix [1]-[2], elements are annihilated using a series of regular similarity transforms (for odd-degree filters), and cross-pivot transforms (for even-degree filters), beginning with a main line coupling near the centre of the matrix, and working outwards along or parallel to the anti-diagonal.

Note that for cross-pivot annihilations of $M_{ij}$ ($\neq 0$) where the self-couplings $M_{ii} = M_{jj}$, $\theta_r = \pm\pi/4$ (see eq(1)). It is also allowable to have $\theta_r = \pm\pi/4$ for when $M_{ij}$ = zero, which will give a slightly different configuration alternative. For odd-degree filters the angle formula takes the more conventional form:

$$\theta_r = \tan^{-1}(M_{i,j-1} / M_{j-1,j}) \qquad (2)$$

Table I gives the pivot coordinates and angle formula to be used for the sequence of similarity transforms to be applied to the folded coupling matrix for degrees 4–9, and a general formula for the pivot coordinates for any degree ≥ 4.

An example is made of a 23dB return loss 8th degree Chebychev prototype, with 2 TZ's on the lower side to produce 2 rejection lobe levels at 40dB, and a single TZ on the upper side to give a lobe level of 60dB on the upper side of the passband.

Applying a series of 3 similarity transforms to the folded coupling matrix for the 8-3 prototype, at pivots [4,5], [3,6] and [2,7] (Table I) and with angles according to eq(1), results in the configuration as shown in Fig. 7(b). The simulated rejection and return loss performances of this configuration are shown in Fig. 8, demonstrating that the characteristics have not been affected by the transformations.

TABLE I
PIVOT COORDINATES FOR THE REDUCTION OF THE FOLDED MATRIX TO THE 'CUL-DE-SAC' CONFIGURATION

| Degree | Pivot Position $[i, j]$ and Element to be Annihilated<br>Similarity transform number $r$<br>$r = 1, 2, 3, ..., R$ $R = (N-2)/2$ ($N$ even) $= (N-3)/2$ ($N$ odd) | | | | Transform Angle |
|---|---|---|---|---|---|
| $N$ | $r = 1$ | 2 | 3 | $r$ | $\theta_r$ |
| 4 | [2,3] $M_{23}$ | | | | eq(1) |
| 5 | [2,4] $M_{23}$ | | | | eq(2) |
| 6 | [3,4] $M_{34}$ | [2,5] $M_{25}$ | | | eq(1) |
| 7 | [3,5] $M_{34}$ | [2,6] $M_{25}$ | | | eq(2) |
| 8 | [4,5] $M_{45}$ | [3,6] $M_{36}$ | [2,7] $M_{27}$ | | eq(1) |
| 9 | [4,6] $M_{45}$ | [3,7] $M_{36}$ | [2,8] $M_{27}$ | | eq(2) |
| .. | .. | .. | .. | .. | .. |
| $N$ (even) | $[i, j]$ $M_{i,j}$<br>$i = (N+2)/2 - 1$<br>$j = N/2 + 1$ | .. | .. | $[i, j]$ $M_{i,j}$<br>$i = (N+2)/2 - r$<br>$j = N/2 + r$ | eq(1) |
| $N$ (odd) | $[i, j]$ $M_{i,j-1}$<br>$i = (N+1)/2 - 1$<br>$j = (N+1)/2 + 1$ | .. | .. | $[i, j]$ $M_{i,j-1}$<br>$i = (N+1)/2 - r$<br>$j = (N+1)/2 + r$ | eq(2) |

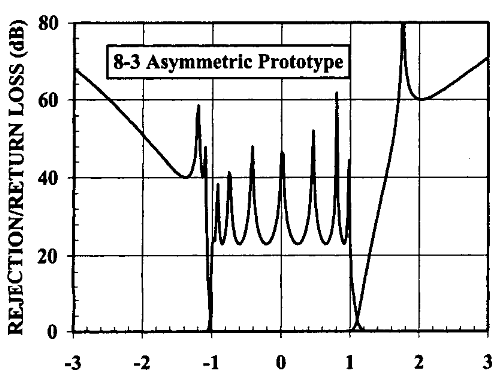


Fig. 8: 8-3 cul-de-sac filter - simulated rejection and return loss performance

As was noted above, all the couplings are positive except for one in the core quartet. This may be moved to any one of the four couplings for the greatest convenience and implemented as a probe, for example, if the filter is to be realized in coaxial-resonator technology and the other couplings are inductive irises or inductive loops. Also there are no diagonal couplings even though the original prototype was asymmetric.

The same basic housing may be used to embody a variety of filtering functions of the same degree (provided always that $N_{fz} \leq N$-3). If the changes in coupling values required to change from one characteristic to another are small, to correct a dispersion-induced distortion in the group delay characteristic or asymmetry in rejection lobe levels for example, the corrections may be made with tuning and iris adjustment screws alone, without the need to resort to a special predistorted design with extra cross-couplings. There are an absolute minimum number of internal couplings, and their values are relatively large lessening the impact of stray couplings. Also the cul-de-sac filter housing is a simple 2-dimensional body+lid construction with all the tuning screws on top, making it very amenable to volume production and tuning methods.

## IV CONCLUSION

In this paper the synthesis methods for two novel configurations for microwave filters have been introduced, the 'box' and the 'cul-de-sac' forms. The new forms feature some important constructional simplifications that should ease the volume production process for high performance microwave filters for the wireless industry.

## REFERENCES

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

[2] A. E. Atia and A. E. Williams, "Narrow-bandpass waveguide filters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 258-265, Apr. 1972.