Coupling-Matrix Design of Dual/Triple-Band Uni-Planar Filters

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***Abstract* — Dual-band and triple-band filters in uni-planar technology are designed using cross-coupled networks represented by coupling matrices. The multiband response is created by placing transmission zeros within the bandwidth of a wideband filter. Realizable planar topologies can be imposed and associated coupling coefficients enforced during optimization. The design method is demonstrated using three different planar resonator configurations: hairpin, open-loop and quasi-dual-mode resonators. Designs are verified by commercially available software packages and, in principle, by measurements.**

***Index Terms* — Filter design, coupling matrix, dual-band filters, microstrip filters, planar resonators.**

I. INTRODUCTION

Dual-band and multi-band filters are in demand for multi-frequency applications in wireless communication, e.g. [1]. In planar circuitry, they can be implemented using four basic approaches: First, by switching between two separate filters at two different frequencies [1]; this approach increases size and cost. Secondly, by employing stubs to create transmission zeros, which separate passbands [2]; as this is essentially a stopband approach, far-out-of-band rejection is impossible to achieve. Thirdly, by using stepped impedance resonators, e.g. [3]; however, it is often difficult to achieve proper coupling coefficients for a simultaneous, yet independent control of both midband frequencies and bandwidths. The fourth approach consists of coupled resonator pairs [4] but suffers from an independent option for the locations of transmission zeros.

Therefore, in this paper, we propose cross-coupled networks, which are characterized by a coupling matrix similar to those used in waveguide topologies, e.g. [5], [6], for the design of uni-planar dual-band and triple-band filters. In order to demonstrate that the basic design is independent of the type of planar resonator, three different commonly used planar resonator configurations are presented as examples: hairpin resonators [7], open-loop resonators [8] and quasi-dual-mode resonators [9].

II. DESIGN

For given passband frequencies and associated bandwidths, the design procedure commences by initially assuming that a wideband filter covering all passbands will be created. The underlying approach to create a coupling matrix is presented in [6], [10] and will not be repeated here. Its main advantages with respect to the design of multiband filters are, first, that the topology of coupled resonators can be specified in advance and, secondly, that the signs and limits of coupling coefficients can be enforced during optimization.

Since the maximum number N of realizable transmission zeros is dictated by the topology, any number $n \leq N$ of transmission zeros can now be placed within the initial broad passband in order to separate individual passbands. Optimization [10] is employed to adjust the entries of the coupling matrix. Their maxima and minima can be controlled via closed-form expressions for the electric and magnetic coupling coefficients of, e.g., open-loop resonators [11].

As a design example, let us consider a four-pole cross-coupled dual-band filter utilizing hairpin resonators on RT6006 substrate. The center frequency of the wideband approach is 3 GHz, and 3.5 percent bandwidth in each pass-band is to be retained after placing transmission zeros at 2.95 GHz and 3.05 GHz. Following the above procedure and specifying the topology such that the two transmission zeros be created by cross-coupling between the first and the last (fourth) resonators, the coupling matrix for this filter is found as:

$$M = \begin{bmatrix} 0 & 0.6033 & 0 & 0 & 0 & 0 \\ 0.6033 & 0 & 0.8998 & 0 & 0.4040 & 0 \\ 0 & 0.8998 & 0 & -0.0063 & 0 & 0 \\ 0 & 0 & -0.0063 & 0 & 0.8998 & 0 \\ 0 & 0.4040 & 0 & 0.8998 & 0 & 0.6033 \\ 0 & 0 & 0 & 0 & 0.6033 & 0 \end{bmatrix} \quad (1)$$

Fig. 1 shows the simulated performance of this filter obtained from the coupling matrix in (1).

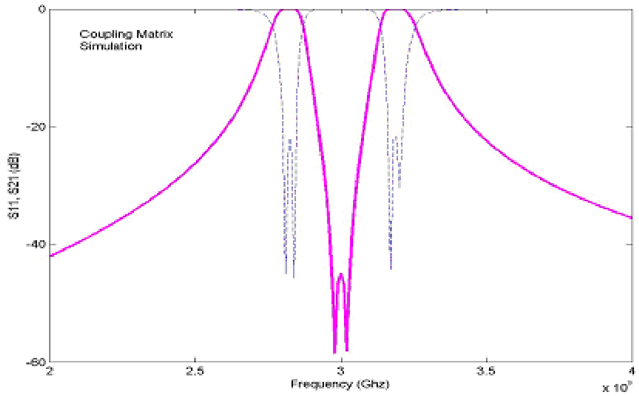

Fig. 1. Response of dual-band filter from (1).

A possible realization is shown in the inset of Fig. 2. The response in Fig. 2 is obtained by equating the coupling coefficients of (1) with those in the actual structure. Of

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course, the achievable precision is limited in this step and slight differences between responses of the coupling matrix and that of an actual circuit must be accepted. Nevertheless, the response computed with Ansoft Designer® in Fig. 2 shows very good agreement with that of Fig. 1. The simulated passband insertion loss is about 1.2 dB, and the passband return loss is better than 10 dB.

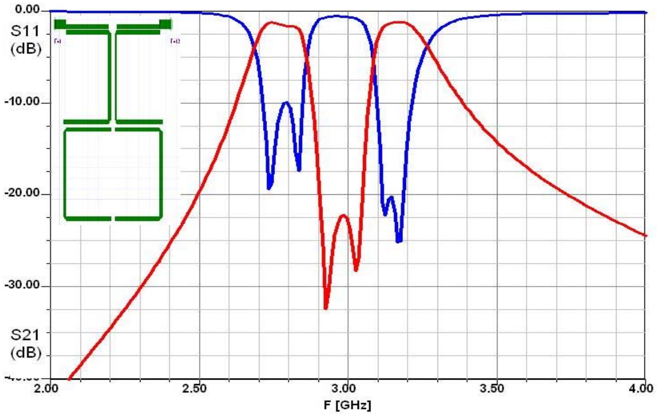


Fig. 2. Response of dual-band filter using hairpin resonators on RT6006 substrate.

III. RESULTS

As an extension of the previous example, Fig. 3 shows a triple-band filter using the same technology. The center frequencies of the three pass-bands are 2.65 GHz, 3 GHz and 3.35 GHz, and more than 50 MHz bandwidth is obtained in each of the bands. Four transmission zeros are created by cross couplings between hairpin resonators 1-6 (magnetic transmission-line coupling) and 2-5 (electric open-end coupling). Two transmission zeros each are placed between adjacent pass-bands. Note that it is almost impossible to design such filters with other design theories.

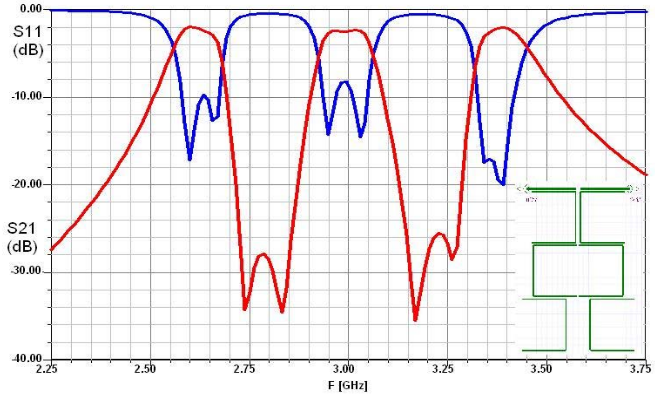
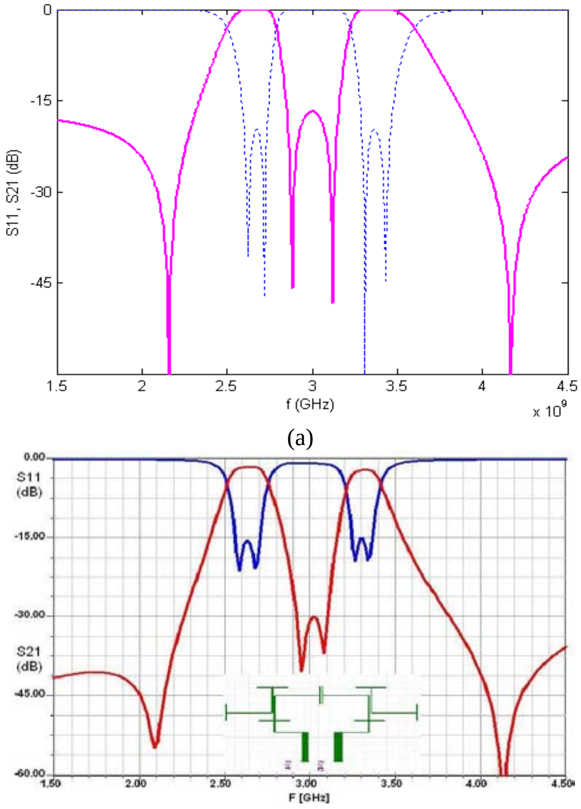


Fig. 3. Response of a triple-band filter using six hairpin resonators on RT6006 substrate and 1-6 / 2-5 cross coupling.

Out-of-band rejection can be controlled by placing transmission zeros not only between passbands but also to the left and/or right of all passbands. This is demonstrated in Fig. 4 using quasi-dual-mode resonators. The resulting response of the coupling matrix (Fig. 4a) shows four reflection and four transmission zeros which are obtained using source/load coupling. The coupling matrix for this type of filter is found as

$$M = \begin{bmatrix} 0 & 0.77 & 0 & 0 & 0 & 0.073 \\ 0.77 & 0 & 0.99 & 0 & -0.72 & 0 \\ 0 & 0.99 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.99 & 0 \\ 0 & -0.72 & 0 & 0.99 & 0 & 0.77 \\ 0.073 & 0 & 0 & 0 & 0.77 & 0 \end{bmatrix} \quad (2)$$

with a center frequency at 3 GHz and four percent bandwidth in each passband. The results simulated with Ansoft Designer® are illustrated in Fig. 4b. The insertion loss within the passbands is less than 2.5 dB, and the return loss is better than 15dB. In addition and as an improvement over the coupling matrix response, the quasi-dual-mode structure achieves 30 dB attenuation between the two passbands and in the stopbands to the left and right.



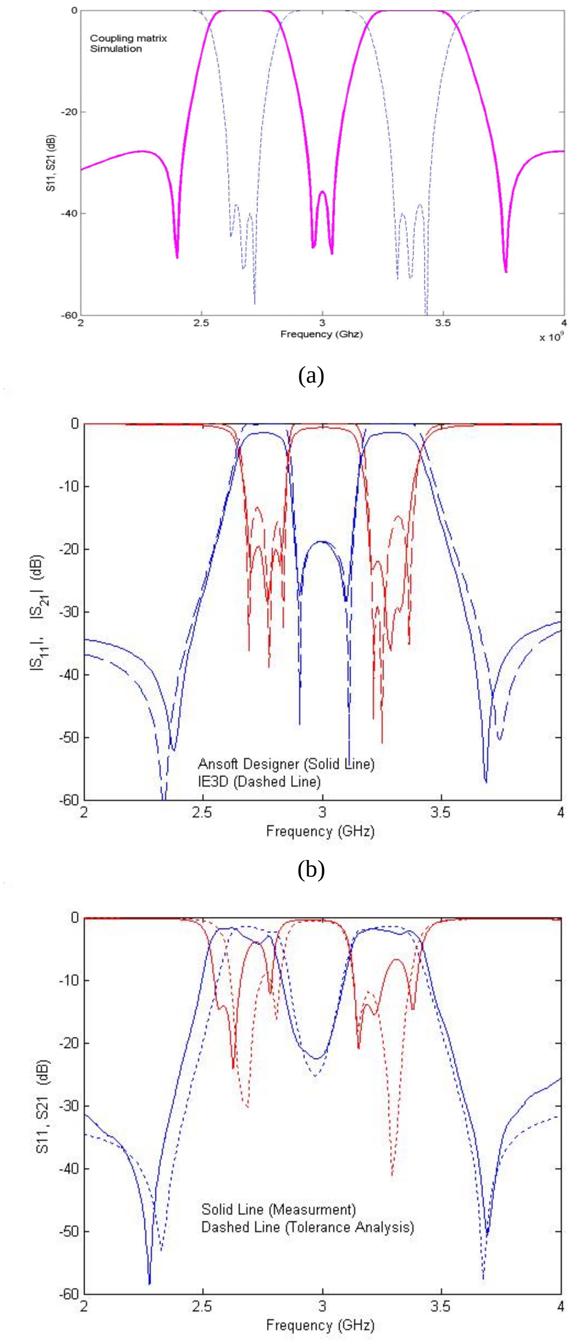
(a)

(b)

Fig. 4. Responses of four-pole dual-band filter using quasi-dual-mode resonators: (a) coupling matrix, (b) Ansoft Designer.

In order to improve selectivity around each passband, a six-pole cross-coupled dual-band filter with hairpin resonators is designed with a center frequency at 3 GHz, five percent bandwidth in each of the passbands and transmission zeros at 2.4, 2.9, 3.1 and 3.7 GHz. The substrate is RT6006 as in previous examples. After applying the theory outlined in Section II, the following coupling matrix is obtained:

$$M = \begin{bmatrix} 0 & 0.9055 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.9055 & 0 & 0.7992 & 0.5812 & 0 & 0 & -0.1777 & 0 \\ 0 & 0.7992 & 0 & 0 & 0 & 0.0065 & 0 & 0 \\ 0 & 0.5812 & 0 & 0 & 0.9924 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.9924 & 0 & 0 & 0.5812 & 0 \\ 0 & 0 & 0.0065 & 0 & 0 & 0 & 0.7992 & 0 \\ 0 & -0.1777 & 0 & 0 & 0.5812 & 0.7992 & 0 & 0.9055 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.9055 & 0 \end{bmatrix} \quad (3)$$



(a)

(b)

(c)

Fig. 5. Responses of six-pole dual-band filter using hairpin resonators: (a) coupling matrix, (b) IE3D (lossless) and Ansoft Designer (including losses), (c) measurements and tolerance analysis.

Figs. 5a and 5b show the simulated responses from the coupling matrix and two EM-based software packages, respectively. Good agreement is observed. Slight differences between Ansoft Designer$^{\circledR}$ and IE3D$^{\circledR}$ results have been observed previously [12] and are attributed to the different approaches of the method-of-moments implementation in both packages. The measurements in Fig. 5c confirm the design in principle but fail to reproduce the two transmission zeros between the passbands. This is attributed to the manufacturing tolerances, which were originally specified to be within 10 μm but turned out to be 25 μm and even slightly above. Therefore, a tolerance analysis was performed which is also shown in Fig. 5c. This analysis confirms the disappearance of the two transmission zeros, thus validating the design in principle. Of course, the cross couplings that create transmission zeros between passbands are sensitive to fabrication tolerances which are recommended to be in the order of 10 μm for similar designs. Fig. 6 shows a photograph of the prototype on RT6006 substrate. The six individual hairpin resonators are clearly visible.

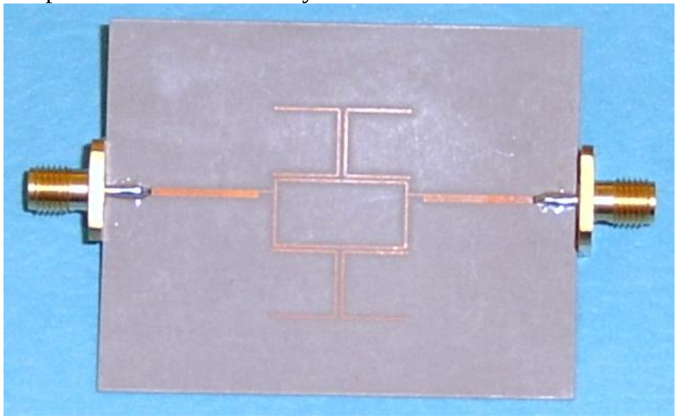
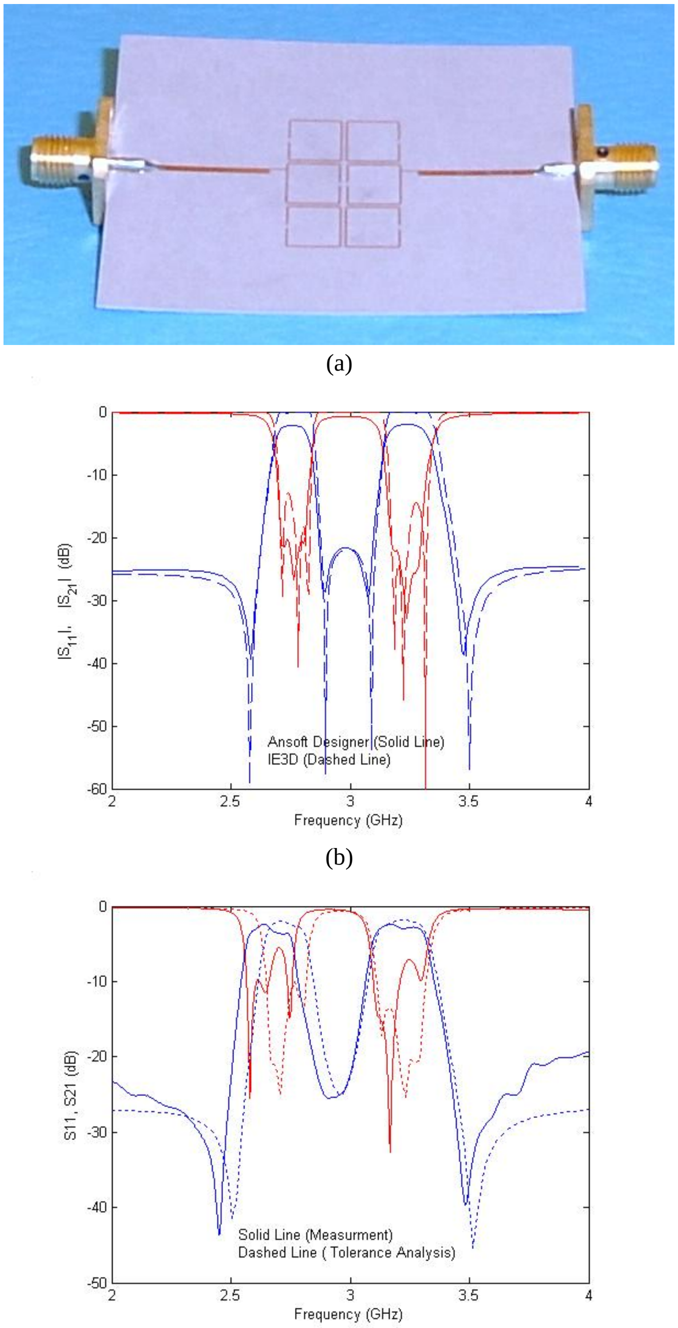


Fig. 6. Photograph of the prototype six-pole dual-mode filter using hairpin resonators.

The last example is a six-pole dual-band cross-coupled filter using open-loop resonators. The topology of the coupling matrix equals that of (3) with only slightly changes in the matrix elements. A photograph of his dual-band filter prototype is depicted in Fig. 7a. It is noted that the design is more compact than that of the previous example (Fig. 6). Fig. 7b demonstrates good agreement between the simulation results of Ansoft Designer$^{\circledR}$ and IE3D$^{\circledR}$. Similar to the results of Fig. 5, the measurements presented in Fig. 7c fail to reproduce the two transmission zeros between the passbands. However, reasonable agreement with measurements is again observed once the effects of fabrication tolerances, which are shown in Fig. 7c for comparison, are taken into account.

V. CONCLUSIONS

The new coupling-matrix approach for uni-planar dual-band and triple-band filters presents a viable alternative to current multiband design techniques. Of special advantage are the specification of the coupling topology and the enforcement of coupling coefficients during the design stages. The results demonstrate the feasibility of the technique for hairpin, open-loop and quasi-dual-mode resonator configurations. The designs presented are verified by commercially available field solvers and, in principle, by measurements.



(a)

(b)

(c)

Fig. 7. Six-pole dual-band filter using open-loop resonators: (a) photograph, (b) IE3D (lossless) and Ansoft Designer (including losses) results, (c) measurements and tolerance analysis.

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