Singlets, Cascaded Singlets, and the Nonresonating Node Model for Advanced Modular Design of Elliptic Filters

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***Abstract*—The singlet, which contains one resonator and generates one transmission zero, is introduced as the most basic building block for modular design of elliptic filters. Higher-order elliptic filters are designed by cascading singlets to generate the required transmission zeros. A novel model, the nonresonating node model (NRNM), which contains both resonating and nonresonating nodes is then introduced. The model allows a high level of modularity in the design of elliptic filters. Example filters are designed and measured to validate the model and the design approach.**

***Index Terms*—Bandpass filters, design, dual-mode filters, elliptic filters, resonator filters, synthesis.**

I. Introduction

ELLIPTIC and pseudo-elliptic filters offer optimal solutions to filtering structures with sharp cutoff skirts and low in-band insertion loss. To reduce the sensitivity of these filters to manufacturing tolerances, modular coupling schemes such as cascaded triplets and quadruplets are preferred [1].

The synthesis and design of these filters are based on models which consist of a network of interconnected nodes that are all ***resonating*** except for the nodes at the input and the output [2]–[4]. We show in this paper that such a model is unnecessarily restrictive and propose a new model, the nonresonating node model (NRNM), which involves both resonating and nonresonating nodes and is, therefore, more general.

In this paper, we introduce the most basic building block for modular design of elliptic filters. The building block, called singlet, contains one resonator and generates one transmission zero. Higher-order elliptic and pseudo-elliptic filters can be designed by cascading singlets and resonators.

II. Singlet

A singlet is a structure which contains one resonator and generates one transmission zero by bypassing the resonator as shown in Fig. 1. The synthesis of a singlet to yield a transmission zero at a prescribed frequency and an in-band return loss over a specified passband can be carried out using the technique presented in [5]. For example, the following coupling matrix yields a singlet response with a transmission zero at normalized frequency $\Omega = 8$ with an in-band return loss of 20 dB

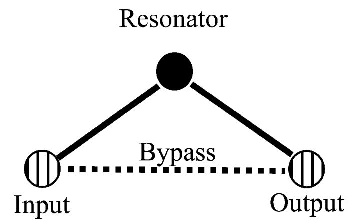

Fig. 1. Coupling and routing scheme of a singlet: one resonator with one transmission zero.

$$M = \begin{bmatrix} 0.0000 & 1.5376 & 0.4791 \\ 1.5376 & -3.0655 & 1.5376 \\ 0.4791 & 1.5376 & 0.0000 \end{bmatrix}. \quad (1)$$

To generate a transmission zero in the lower stop-band the bypass coupling and the frequency shift of the resonator must change sign.

Once the coupling matrix is known, the implementation of the coupling coefficients can be carried out following standard techniques [6].

III. Non-Resonating Node Model (NRNM)

We first consider a second-order filter with an in-band return loss of 20 dB and two transmission zeros at normalized frequencies $\Omega = -8$ and $\Omega = 8$. The emphasis is on modularity in order to guarantee reduced sensitivity to manufacturing tolerances.

In existing models, to get two transmission zeros out of two resonators, it is necessary to couple the source to the load [3]. However, by directly coupling the source and the load, the two transmission zeros become inter-dependent and cannot be easily controlled independently. This coupling scheme lacks modularity and flexibility.

A model in which the two transmission zeros can be controlled independently is shown in Fig. 2(a). The $\mathrm{K_{ij}}$'s are admittance inverters, the $\mathrm{B_i}$'s are constant reactances and s stands for a unit capacitance [4]. Note that the third node in this structure is connected to ground by only a constant reactance $\mathrm{jB_3}$, it is a **nonresonating** node (NRN). The port parameters of an NRN are simply those of a shunt admittance, they can be found in any textbook on electrical networks, e.g., [7]. The coupling and routing scheme corresponding to Fig. 2(a) is shown in Fig. 2(b). A straightforward analysis of this structure shows that it is indeed of second-order with two transmission zeros. An extremely

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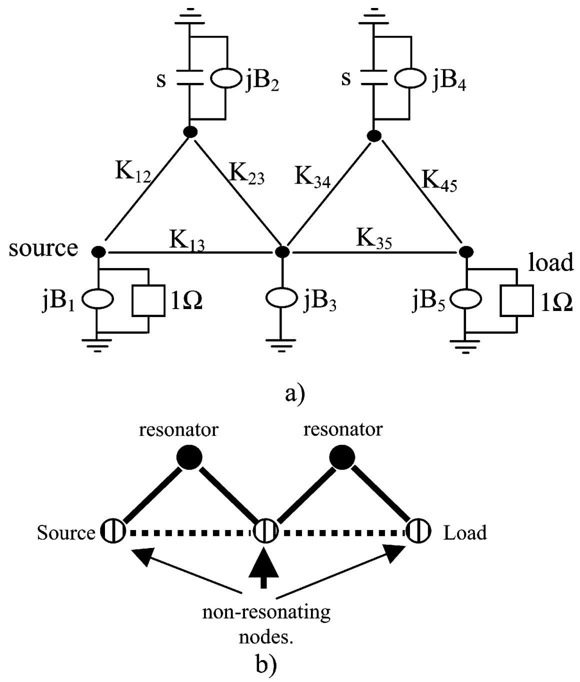

Fig. 2. Nonresonating node model (NRNM) of two cascaded singlets. (a) Equivalent low-pass network and (b) coupling and routing scheme.

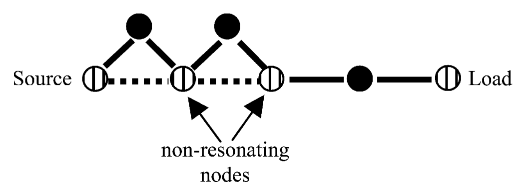

Fig. 3. Nonresonating node model (NRNM) of a third-order filter with two cascaded singlets and one additional resonator. Dark disks: resonators; patterned disks: nonresonating nodes.

important feature of this model is its modularity. Each "triangle" generates and completely controls its own transmission zero.

The model shown in Fig. 2(a) can be extended to elliptic filters of arbitrary orders by cascading as many singlets as needed. Additional poles at infinity, if present, can be generated by adding directly coupled resonators in cascade. For example, the coupling and routing scheme of a filter of order 3 with two transmission zeros at finite frequencies is shown in Fig. 3.

We refer to the model shown in this figure as the NRNM. Note that the NRNM may contain an arbitrary number of nonresonating nodes (NRNs) to better control the signal flow, especially the stop-band of the filter. Only two NRNs are used in Fig. 3.

IV. Results and Validation

Two singlets were cascaded to design the previously specified second-order elliptic filter. The coupling and routing scheme is that of Fig. 2(b).

A coupling matrix for this structure can be extracted using the technique in [5] with proper extension to handle NRN's. A possible solution is given by

$$M = \begin{bmatrix} 0.0000 & 1.3166 & 0.1500 & 0.0000 & 0.0000 \\ 1.3166 & -0.1855 & -0.9328 & 0.0000 & 0.0000 \\ 0.1500 & 0.9328 & -0.9841 & 1.6230 & 0.2572 \\ 0.0000 & 0.0000 & 1.6230 & -3.2457 & 0.7534 \\ 0.0000 & 0.0000 & 0.2572 & 0.7534 & 0.0000 \end{bmatrix}. \quad (2)$$

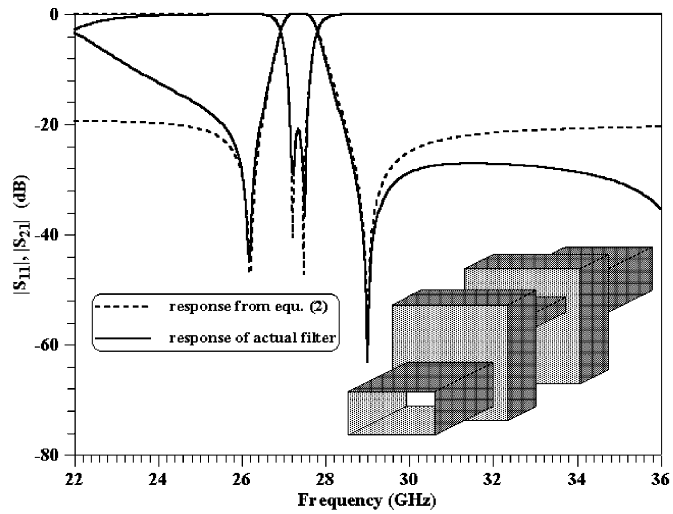

Fig. 4. Transmission and reflection coefficient of two cascaded singlets yielding a symmetric response. Solid lines: full wave (CIET), dashed lines: coupling matrix (2).

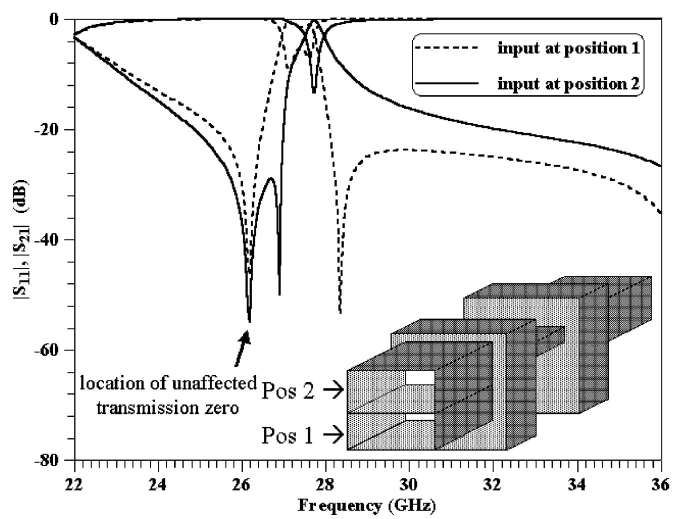

Fig. 5. Effect of moving the input coupling aperture of two cascaded singlets. One transmission zero remains unaffected.

It is very important to keep in mind that the third diagonal element is not only constant but does **not** contribute a frequency term when the scattering parameters are evaluated. The normalized frequency does not appear in the third diagonal element of the matrix [A] in equation (4) in [5].

The TM_{110}—mode resonance of a rectangular cavity is used to implement the two resonators. The bypass coupling of each resonator exploits the propagating but nonresonating TE_{10} of each cavity. A capacitive iris, in which the TE_{10} mode is propagating but **nonresonating**, is placed between the two cavities. The actual design of the structure is not detailed here for lack of space.

The response of the designed filter is shown in Fig. 4 as the solid line. The dashed lines show the response of the coupling matrix in (2). It is very clear that the two results agree very well in the vicinity of the passband. The differences over a wider frequency range are attributed to parasitic effects.

To confirm the modularity of the design, the position of the input aperture was moved up and down without changing any

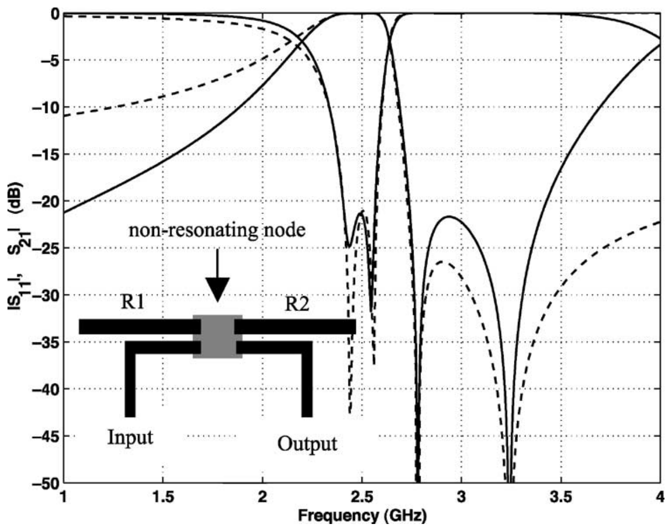

Fig. 6. Reflection and transmission coefficients of two cascaded singlets in two-layer microstrip technology. Solid lines: full-wave (IE3D), dashed lines: coupling matrix.

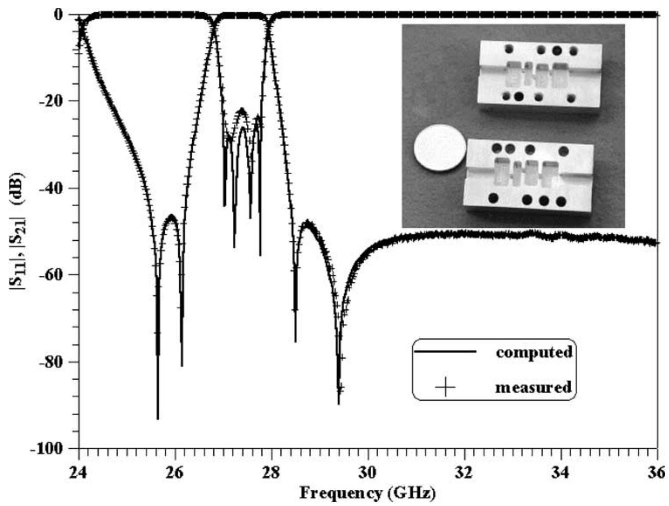

Fig. 7. Measured (+) and simulated (−) response of a fourth-order elliptic filter implemented by cascading four singlets in TM_{110}-mode rectangular cavities.

other parameters in the structure. This displacement changes the coupling from the source to resonator 1 but does not affect the bypass coupling to the NRN since the field distribution of the TE_{10} does not depend on y whereas that of TM_{11} is an odd function of y with respect to the center of the cross section of the cavity. (Here, y is the coordinate along the small dimension of the cross section of the waveguides).

The results of this numerical experiment are shown in Fig. 5. It is evident that one of the transmission zeros **remains unaffected** while the second one is even moved to the other side of the passband. The two transmission zeros are independently controlled; they cannot be the result of the source-load coupling of the existing models.

Fig. 6 shows the reflection and transmission coefficients of a two-layer filter in microstrip technology. The nonresonating node is implemented as a small conducting plate whose resonant frequency is very large compared to the center frequency of the filter. The two resonators are microstrip lines which are half a wavelength long at the center frequency of the filter. The feeding microstrip lines are edge coupled to the two resonators. The input and output as well as the two resonators are coupled to the nonresonating node which is between the microstrips and the ground plane. A top view of the layout of the filter is shown in the inset of Fig. 6. The filter was designed using the commercial package IE3D of Zeland Software. Its response agrees well with that of an extracted NRNM coupling matrix (not shown) in the vicinity of the passband and the transmission zeros. The low frequency deviation between the two results is partly due to the NRN.

The next example is a fourth-order elliptic filter with four transmission zeros implemented using TM_{110}-mode cavities (inset of Fig. 7) as in the two cascaded singlets discussed before. The simulated (μWave Wizard) and measured responses of the filter are shown in Fig. 7. The two results agree very well. The measured insertion loss is less than 0.4 dB over a 700-MHz bandwidth.

V. Conclusion

A novel model for modular design of advanced elliptic and pseudo-elliptic filters is presented. The singlet is introduced as the most basic building block for modular design of elliptic and pseudo-elliptic filters. The NRNM is introduced to accurately model cascaded singlets and increase the flexibility and modularity of elliptic filter design. Example filters based on this model were designed and their responses are shown to agree with measurement. Naturally, nonresonating nodes may be added to other filtering networks, they are not limited to the case of cascaded singlets.

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