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Synthesis Methodology for Mixed-topology Acoustic Wave Filters

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***Abstract*—Ladder topology is an excellent solution for filters based on AW technology, however, the required alternation of series and shunt resonators, or equivalently transmission zeros above and below the bandpass may impose some limitations to obtain greater out-of-band rejection levels. To overcome this limitation, external reactive elements may be used to improve the rejection level by altering the topology and generating an extra transmission zero due to parasitic effects. These elements are usually added to the already synthesized network causing a significant deterioration of the filter performance, requiring an optimization process to restore the in-band response. In this letter, a methodology for the synthesis of fully canonical filters with reactive elements based on a mixed-topology approach is presented. The proposed method combines in-line network with parallel-connected structures to generate ladder-like filters that provides a precise value of the reactive element. In this kind of networks the resonance frequencies of some resonators are not tied to any transmission zero of the filtering function. Thus, the method also allows a number of transmission zeros to be allocated above or below the bandpass, increasing the out-of-band rejection without compromising the feasibility of the filter.**

***Index Terms*—Acoustic wave technology, dangling resonator, ground-loop inductors, mixed-topology, parallel-connected, transversal networks.**

I. Introduction

In bandpass acoustic wave ladder filters, external elements like inductors and capacitors can be added to the network in order to achieve a better performance. Without a general method, these elements are not extracted during the synthesis process but added to the synthesized network afterwards. Consequently, the original filter response is degraded up to a certain extend. Recovering the original characteristics and maintaining the advantages introduced by the additional elements requires a time-consuming optimization process with a high computational cost.

There are some structures that have been proved to be useful for which a systematic synthesis method has not been yet developed, specifically, the one shown in Figure 1 is a filter with Ground-Loop Inductor (GLI) coupling that was published in the patent [1]. In this topology two shunt resonators are coupled to each other and connected to ground through a common inductor. Direct addition of reactive cross-couplings may cause a negative impact to the filters like a detune of the transmission zeros (TZs) and in-band return losses degradation. However, the reactive elements helps to introduce an additional TZ in a region far away of the passband without introducing a reflexion zero. The immediate effect is a significant improvement of the rejection level, attaining greater levels of isolation between bands in case of multiplexers. These effects can be seen clearly in Fig, 2 where two simulation cases are presented for illustration purpose. The S-parameters in Fig. 2(a) correspond to the simulation of a B25Tx ladder filter with 7 TZs, three of them below the passband and the rest are located above. In Fig. 2(b), it is presented the response of the same filter with a 0.15 nH inductor coupling resonators 2 and 4 to ground like in Fig. 1, this additional element produces the detuning of the TZs at each side of the passband. Those located above are moved toward the same frequency meanwhile those located below are move away from each other. It also can be noted that the aggregated inductor introduces a new TZ at 2.24 GHz, improving the rejection level in the OoB region above the passband more than 20dB. There is a slight degradation of the in-band return losses band but the obtained improvement in terms of rejection level is far superior.

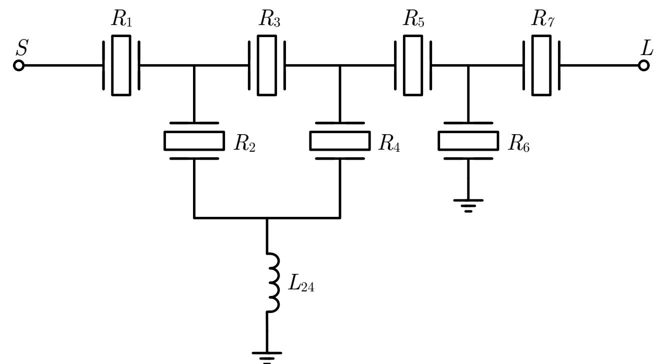

Fig. 1. Example of 7th-order filter with GLI cross-coupled inductor between resonators 2 and 4.

The aim of this paper is to take advantage of the capabilities of synthesis techniques to define a systematic procedure to obtain the exact lowpass prototype network ready to implement the GLI structure in a general way. The synthesis proposed in

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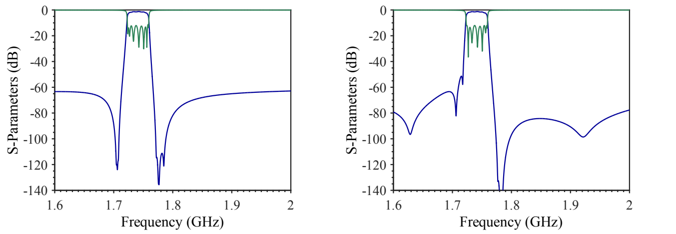


(a) (b)

Fig. 2. S-parameters of a (a) plain ladder filter and the same filter with a GLI (b) between resonators 2 and 4.

this work is based on mixed-topology filters, highly useful to obtain a sophisticated transmission response like the presented in Fig. 2.

For the synthesis of this mixed-topology filters, some general methods have been already developed in [2], [3]. In both works, a higher level of flexibility of the filter topology definition is introduced. Nevertheless, these improvements are limited to the implementation of structures exclusively made of resonators and ideal couplings or classic ladder filters, and none of them exploit the use external reactive elements to implement those cross-couplings from the synthesis point of view. In more recent works like [4], [5] it has been proposed a mixed-topology synthesis method that combines parallel-connected and in-line networks in which some of prescribed TZs of the filtering function are disassociated from the resonance frequencies of the resonators. This characteristic provides a more flexible assignation of TZs to the resonators, allowing the maximization of an arbitrary number of TZs above or below the bandpass.

This helps to overcome the main restriction of AW ladder filters, alternation of series and shunt resonators or equivalently, TZs above and below the bandpass. This features, combined to addition of the GLI, becomes very useful to achieve higher out-of-band rejection levels and steeper roll-off at the same time.

II. Synthesis Procedure of Mixed-Topologies

The synthesis procedure is based on [4], [5]. To illustrate process, a 5th-order filter with a GLI between resonators 2 and 4 like the filter shown in Fig. 3 will be described. As already mentioned, the proposed procedure combines transversal networks and the extracted-pole technique to create mixed-topology fully canonical filters with dangling resonators based on the generalized Chebyshev filtering function. The resulting topology can be described in the scenario depicted in Fig. 4 where three sections can be recognized. The outer sections corresponds to in-line structures and the central section is a parallel-connected subnetwork. The dangling resonators [6] shown in the figure are made of a constant susceptance b_i connected through and admittance inverter J_{ri} to a Non-Resonating Node (NRN) implemented by a FIR B_i and they are coupled to each other through admittance inverters J_i.

The extraction procedure starts from source and load, moving in further until reaching the transversal section. To convert

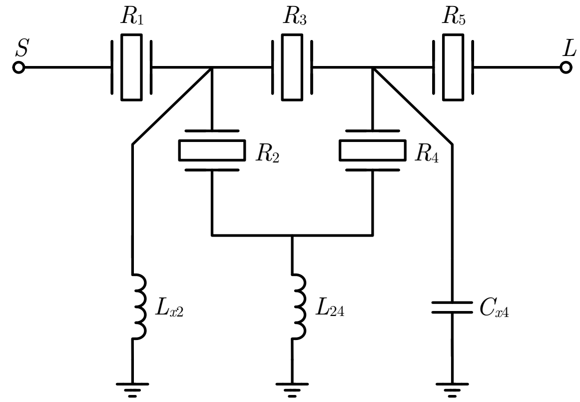


Fig. 3. Scheme of the 5th-order filter with a GLI in resonators 2 and 4.

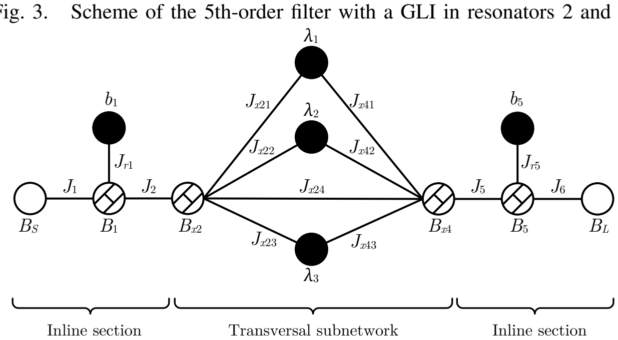


Fig. 4. Lowpass prototype nodal scheme of a 5th-order mixed-topology fully canonical filter.

the transversal network, some reconfiguration will be carried out after the rest of the filter parameters have been extracted following a sequence similar the proposed in [4]. Once the network is fully extracted, a circuital transformation process is carried out to generated a FIR in the parallel-connected structure that represents the coupling inductor.

A. Inline Sections

The extraction of the elements is carried out successively from the ABCD transfer matrix of the network matrix [7], [8], requiring N recursive steps to be completed, where N is the number of resonators to be extracted. The ABCD matrix is related to the characteristic polynomials of a generalized Chebyshev class of filtering function $P(s)$, $F_{11}(s)$, $F_{22}(s)$ and $E(s)$. Beginning from the source node and using the general scheme in Fig. 4, the extraction process is carried out as usual until resonator 1, obtaining B_s, J_1, b_1, J_{r1}. Next, part of the B_1 is extracted by means of partial extractions, evaluating the ABCD polynomials to one of the TZs set not assigned to the inline sections as follows:

$$B_i = \alpha \frac{D(s_i)}{B(s_i)} \tag{1}$$

where s_i is the value of the normalized TZ used for the evaluation of the polynomials $D(s)$ and $B(s)$ of the ABCD transfer matrix at that stage of the extraction process. The variable α is the setting factor for the reactance portion assigned to B_1 that has to be a positive number. This is necessary to achieve the proper phase accommodation between in-line and transversal sections. The non-extracted fraction will be assigned to the NRN with value B_{x2} at the input of the transversal network later on. Finally, the adjacent admittance inverter J_2 is extracted.

Now, the synthesis proceeds from load node. Once the extraction procedure reaches the resonator 5 after successive iterations, the parameters B_5 and J_5 have to be extracted by partial extractions, assigning only a part of the value to B_5 using (1), and leaving the remaining quantity to the transversal network. The later is implemented based on the approach employed to synthesize its coupling matrix for fully-canonical filters described in [9].

B. Transversal Section

In this stage of the synthesis process, the remaining ABCD matrix is converted to an admittance matrix $[Y_{rem}]$ with the classical conversion equations for the two-port networks. The latter can be expressed in terms of its residues by partial fraction expansions:

$$Y_{rem} = j\begin{bmatrix} B_{x2} & J_{x24} \\ J_{x24} & B_{x4} \end{bmatrix} + \sum_{i=1}^{3} \frac{1}{(s-j\lambda_i)} \begin{bmatrix} r_{11i} & r_{12i} \\ r_{21i} & r_{22i} \end{bmatrix} \quad (2)$$

where the order of the sub-network is three, the number of resonators not extracted yet.

The coupling matrix of the sub-network can be obtained by synthesis, yielding the nodal scheme of the central section in Fig. 4. Usually, transversal network input and output phase is zero. In this case the sub-network is part of a more complex structure and they take a different phase values, to accommodate the central section of the filter, the aforementioned terms B_{x2} and B_{x4} cannot be null, otherwise, the in-line and transversal sub-networks would not match. They can be obtained as frequency invariant reactances at infinity as follows:

$$jB_{x2} = \lim_{s\to\infty} \frac{Y_{11n}(s)}{Y_d(s)} \quad (3)$$

$$jB_{x4} = \lim_{s\to\infty} \frac{Y_{22n}(s)}{Y_d(s)} \quad (4)$$

To implement the final lowpass prototype, the transversal sub-network must be transformed to a parallel-connected configuration. With this aim, it must be split in two branches, upper and lower, in order to deal with two fully-canonical networks. The upper branch will implement the resonator 3 and the lower branch will implement resonators 2 and 4 and B_{24}, the FIR that represents the coupling inductor L_{24}.

The eigenvalues of the transversal sub-network cannot be associated to upper or lower branches arbitrarily. They can be categorized in odd and even modes by arranging them in descending value order. According to [7], there must be complementary pairs of eigenvalues and their associated residues within each branch in case of having an even number of eigenvalues. That is, if an odd eigenvalue and its couplings are selected to be part of one group, there must be an even eigenvalue in the same group.

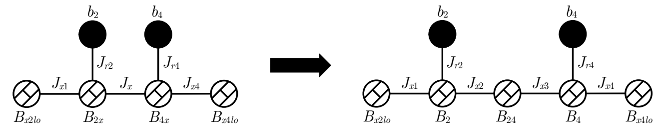


Fig. 5. Lower branch scheme after the extraction (left) and the equivalent scheme with the FIR B_{24} generated by circuit transformation (right).

Together with the eigenvalues, the input-to-output coupling J_{x24} plays a major role in the definition of the resonant frequency of the resonators in both branches. Every resonator implements TZs at finite frequencies. As previously commented, both sub-networks are fully canonical, so they require a direct input-to-output path at each branch. A good follow-up strategy to assign a specific value of J_{x24} to each split, is to compute it from the desired resonant normalized frequencies. Using the equations in [10] that relates the trisection to the dangling configuration, the equation of the coupling can be defined, for the upper and lower branches J_{x24up} and J_{x24lo} respectively, as:

$$J_{x24up} = -\frac{J_{x2i}J_{x4i}}{(b_i - \lambda_i)} \quad (5)$$

$$J_{x24lo} = J_{x24} - J_{x24up} \quad (6)$$

where b_i represents the resonance frequencies which are implemented by the resonators in the upper branch, and λ_i the eigenvalues that will be used to form it. The rest of TZs and eigenvalues are assigned to the lower branch.

After distributing the admittance matrix between both the sub-matrices $[Y_{up}]$, $[Y_{lo}]$ are formed and turned into ABCD matrices $ABCD_{up}$ and $ABCD_{lo}$, respectively. Then, they can be extracted as in-line networks using the same process as described for the outer sections of the filter. The resonance frequencies of the resonators at each branch is determined by the roots of polynomials $P_{up}(s)$ and $P_{lo}(s)$. It has to be pointed out that within the parallel-connected sub-network, the TZs are implemented by the whole structure and not as the individual contribution of each resonator. Therefore, their resonance frequencies may not meet the prescribed TZs anymore.

The lower branch scheme is a 2th-order fully canonical network of in-line dangling resonators as depicted in Fig. 5. The FIR is created from B_{x2}, B_{x4} and J_x through a circuital transformation, yielding the final sub-network. Finally, both upper and lower branches are merged together and joint to the rest of the network to form the whole filter.

III. Illustrative Example

In this section, an 5th-order example is presented to validate the method described in this document. During the extraction process, the values of admittance inverters J_i can be set to a common value. For the sake of simplicity, they will be ± 1 along the main path. The lowpass transmission zeros are $\Omega_{tz} = \{2.5,\ 4,\ 2,\ -2.2,\ 1.6\}$ and RL = 20 dB. Taking advantage of the method, 4 TZs are located above the passband and single one is below (see Fig. 7(a)). The GLI is coupling resonators 2 and 4 yielding the scheme in Fig. 6. The FIRs B_1 and B_5, are

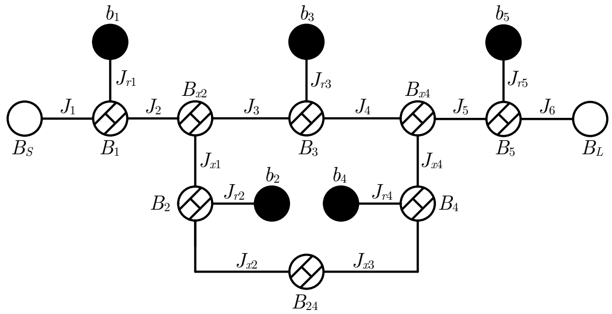


Fig. 6. Scheme of the 5th-order filter with a GLI in resonators 2 and 4.

calculated using $\alpha = \{1.4,\ 0.4\}$ for the NRN of the resonators 1 and 5, respectively.

The transversal network element values are calculated yielding $J_{x2i} = \{-0.6354,\ 0.5494, -0.1533\}$, $J_{x4i} = \{0.1695,\ 0.4634,\ 0.5133\}$, $\lambda_i = \{-1.1681, -0.095,\ 1.0386\}$ and $J_{x24} = -0.0178$. The upper branch resonator is desired to resonate at $\Omega_3 = 2$ using λ_1, J_{x21} and J_{x41}. Therefore, using (5) and (6), the input-to-output coupling for each branch is $J_{24up} = 0.034$, $J_{24lo} = -0.0518$. The rest of parameters are assigned to the lower branch. After synthesizing separately both branches they are merged together, the FIRs connecting the central section to the in-lines sections are $Bx2 = -1.1962$ and $Bx4 = 1.0638$ and the FIR $B_{24} = -0.8835$ The rest of the filter paremeters is listed in Table I.

The impedance denormalization and the frequency transformation has been done for B42Tx band following the procedure used in [11], yielding the response in Fig. 7. The coupling inductor value is $L_{24} = 2.57$ nH, it can be noted that the main effect is the introduction of an extra TZ in the lower side of the band at 3.008 GHz without adding a reflexion zero. The parasitic TZ increases the isolation level more than 20 dB in comparison with the lowpass response. The static capacitance of the resonators are C_{0i}[pF]= $\{0.3,\ 0.19,\ 0.01,\ 0.14,\ 2.5\}$ and the resonance frequencies are f_{ri}[GHz]= $\{3.61,\ 3.62,\ 3.39,\ 3.57,\ 3.43\}$.

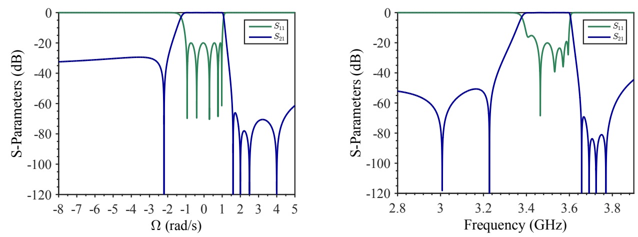
After the bandpass transformation, the FIRs B_{x2}, B_{x4} have to be implemented as an inductor and a capacitor, respectively. They are necessary to obtain a fully synthesized network. Due to the low impact on the filter performance, their physical implementation is usually omitted when the inductor is introduced without the synthesis method proposed in this work as was shown in Fig. 1. This helps to reduce the network complexity, and their negative impact can be minimized by optimization. In this example the reactive elements are $L_{x2} = 1.9$ nH and $C_{x4} = 0.97$ pF.

IV. Conclusions

This paper provides a robust mathematical procedure for synthesizing ladder-like filters with a ground-loop inductor coupling between two shunt resonators. The technique is based on the use of in-line network along with parallel-connected structures. The networks obtained provides the exact parameters for the lowpass structure ready for a direct bandpass transformation. The presented topology not only introduces reactive elements but also provides flexibility to allocate more transmission zeros above or below the passband than classic ladder filter. Through an illustrative example the method has been proved and shows the capability to be used in acoustic wave technology.

TABLE I
Lowpass Elements of the Synthesized 5th-Order Filter.

Parameters	B_k	b_k	J_{rk}
Res1	-3.2653	-2.5	2.0672
Res2	-5.1303	-2.5304	2.5435
Res3	-110.2152	-2	18.686
Res4	-6.9199	-2	3.0344
Res5	-0.3501	-1.6	0.8943
B_S	-0.4585		
B_L	-0.928		



(a) (b)

Fig. 7. S-parameters of (a) the lowpass response of the 5th-order filter and (b) the bandpass response.

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