Uniform electro-acoustic coupling in ladder acoustic wave filters

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***Abstract*- This work outlines the synthesis procedure for the development of ladder acoustic wave (AW) filters with uniform electro-acoustic coupling. This approach prevents the need to include external components in a final filter configuration and therefore provides a simpler and valuable network from the application point of view. The paper presents the initial synthesis process and complements it with an iterative and formulated process to obtain a ladder network with prescribed electro-acoustic coupling. The process has been fully proved with a fabricated order 2 filter.**

I. INTRODUCTION

Although the filter synthesis can lead to series and shunt resonators with different electro-acoustic coefficients, the fabrication stage often imposes restrictions regarding the electro-acoustic coupling. It is sometimes difficult to achieve high coupling coefficients and the coupling coefficient is usually fixed for all the resonators of a given set. Furthermore, achieving a uniform electro-acoustic coupling in the synthesis process prevents the need to include external lumped components in charge of artificially modifying the coupling coefficient of the individual resonators. These lumped components introduce undesirable additional losses and imply larger footprints.

To achieve a specific coupling coefficient across all resonators of a ladder filter in either series or shunt configuration, the position of the transmission zeros (TZs) can be conveniently adjusted, without missing the rejection specifications of the targeted filter. The pre-selection of the TZs positions is not arbitrary, since each transmission zero is governed by a specific resonator. Consequently, by manipulating the position of a specific transmission zero and the position of the resonator into the ladder configuration [1], the coupling coefficient of the corresponding resonator can be fine-tuned. Additionally, owing to the element extraction theory [1], when extracting the last resonator of the low-pass prototype of the filter in the synthesis stage, the designer has the flexibility of selecting the value of the reactance or susceptance element of the last BVD resonator. Hence, although this procedure is not disclosed in the current paper, this element can also be modified to establish the desired coupling coefficient at the last BVD resonator.

II. BASIC CONCEPTS ON LADDER AW FILTERS

In contrast to conventional resonators, AW resonators exhibit a pole/zero response, that is, they account for two resonance frequencies: the series and the shunt resonant frequency. This behaviour can be simply described by the Butterworth-Van Dyke model (BVD) [2], which accepts the two equivalent circuits shown in Fig. 1 for both SAW (Surface Acoustic Wave) and BAW (Bulk Acoustic Wave) technologies. The choice of the circuit depends on the resonator being extracted. In the element extraction approach for ladder filters, the circuit comprising L_s, C_s and C_p is used to represent the shunt resonators, while the circuit involving L_2, C_2 and C_3 is employed for series resonators.

The pole/zero response characteristic allows ladder filters constructed with acoustic resonators to achieve sharper filter responses without requiring the inclusion of cross-coupling effects. However, AW filters in ladder configuration impose some limitations on the transmission response, such as the number of transmission zeros and the sideband position of these zeros.

- Lower sideband transmission zeros arise from the series resonant frequencies of shunt resonators (f_s^{shu}). Hence, the number of shunt resonators determines the number of TZs in the lower sideband of the response (see brown box in Fig. 2).
- The upper sideband transmission zeros correspond to the shunt resonant or anti-resonant frequencies of series resonators (f_p^{ser}). As a result, the number of series resonators determines the number of TZs in the upper sideband of the response (see blue box in Fig. 2).
- Finally, the in-band response of the filter is determined by the anti-resonant frequencies of shunt resonators (f_p^{shu}) and the series resonant frequencies of series resonators (f_s^{ser}). When evaluating the filter at frequencies close to the anti-resonance of shunt resonators and the series resonance of series resonators, the filter acts as a pass-through, allowing the signal to pass from the input to the output port (see red box in Fig. 2).

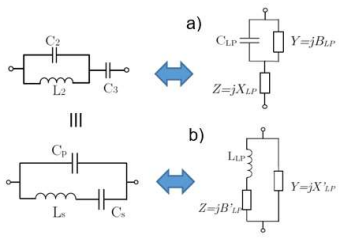

Fig. 1. Band-pass BVD circuits (left) and equivalent low-pass prototypes (right) [1]

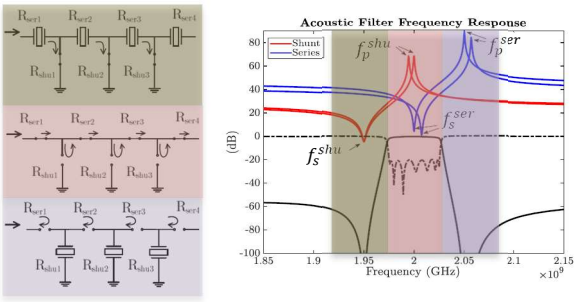

Fig. 2. 7th order ladder filter behavior ($f_0 = 2\ GHz, BW = 80\ MHz$) [1]

Given that each TZ is associated with a single resonator, the coupling coefficient can be individually adjusted for each resonator in the following way:

- If the coupling coefficient (k_e^2) of a shunt resonator is smaller than the target coupling coefficient ($k_{e_{target}}^2$), its series resonant frequency (f_s) is moved down (resulting in larger values of C_s and L_s). Conversely, if the coupling coefficient is higher than the target value, its series resonant frequency is increased (resulting in smaller values of C_s and L_s).
- If the coupling coefficient of a series resonator is smaller than the target coupling coefficient, its anti-resonant frequency (f_p) is increased (resulting in smaller values of C_2 and L_2). Conversely, if the coupling coefficient is higher than the target value, its anti-resonant frequency is moved down (resulting in larger values of C_2 and L_2).

As outlined in the next section, the position of the resonant frequency corresponding to the transmission zero to be tuned can be directly computed using the well-known electro-acoustic coupling equation [1], which relates the electro-acoustic coefficient and the two resonant frequencies of the resonator. Therefore, by prescribing a target electro-acoustic coupling and by keeping the other resonant frequency fixed, the position of the TZ for a given resonator can be easily figured out. However, the computed TZ will need to be fine-tuned due to the nature of the element extraction procedure, as it will be explained in the following section.

Directly modifying C_s and L_s to adjust the series resonance frequencies of shunt resonators or modifying C_2 and L_2 to adjust the anti-resonance frequencies of series resonators, is not feasible. Given that such modifications would be done in the band-pass circuit, they would cause the filter to deviate from its intended Chebyshev behavior. Therefore, to maintain a Chebyshev response in the final band-pass filter, it is necessary to recalculate the Chebyshev polynomials shifting the positions of the upper sideband zeros (f_p of the series resonators) or the lower sideband zeros (f_s of the shunt resonators). Hence, an iterative approach must be adopted to adjust the coupling coefficient of each resonator of the network individually. Whenever an anti-resonant frequency (for series resonators) or a series resonant frequency (for shunt resonators) is modified, the polynomials are recalculated, and the low-pass prototype is extracted again by following the element extraction process detailed in [1]. Subsequently, the band-pass circuit is obtained by applying the low-pass to band-pass transformation also described in [1], and the coupling coefficient of the target resonator is reevaluated.

III. Iterative Algorithm

The flow diagram in Fig. 3 aims to describe the main steps to follow to find the TZ values that lead to the same coupling coefficient across all the resonators of the AW ladder network.

The inner loop, represented by the green arrows in Fig. 3, is responsible for achieving the desired/target coupling coefficient at the current resonator of the network within an acceptable error range. To accomplish this, the position of the transmission zero is calculated while keeping the other resonant frequency fixed. It is important to recall that the TZ corresponds to the value of f_p if it is a series resonator and to the value of f_s if it is a shunt resonator. By manipulating the electro-acoustic coupling formula of [1], the equation for calculating the approximate value of the shunt and series resonant frequencies can be derived given the coupling coefficient and the other resonant frequency, as shown in (1) and (2), respectively.

$$f_p \cong \frac{f_s}{1 - \frac{4}{\pi^2} \cdot k_{e_{target}}^2 \left(1 + \frac{4}{\pi^2} \cdot k_{e_{target}}^2\right)} \tag{1}$$

$$f_s \cong f_p \left[1 - \frac{4}{\pi^2} \cdot k_{e_{target}}^2 \left(1 + \frac{4}{\pi^2} \cdot k_{e_{target}}^2\right)\right] \tag{2}$$

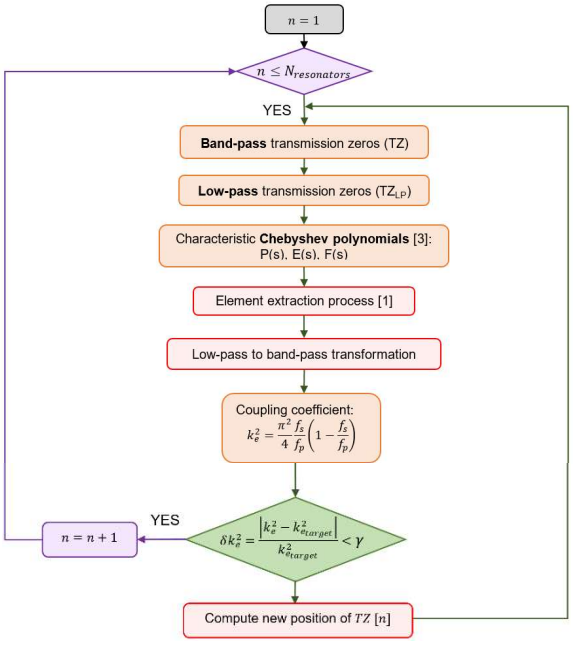

Fig. 3. Flow diagram to achieve a uniform coupling coefficient

However, the computed value of f_s or f_p (depending on whether the resonator is in shunt or series configuration, respectively) needs to be fine-tuned since the element extraction process operates with the BVD models in the low-pass domain [4]. Hence, modifying the position of one resonant frequency in the low-pass domain, which occurs when modifying the position of the TZ, also affects the other low-pass resonant frequency. The formulas for the low-pass series (Ω_s) and low-pass shunt (Ω_p) resonant frequencies for the equivalent circuits a) and b) of Fig. 1 correspond to (3) and (4), respectively. Equation (3) shows that the low-pass series resonant frequency in series resonators depends on the low-

pass anti-resonant frequency, while (4) shows that the low-pass anti-resonant frequency in shunt resonators, depends on the low-pass series resonant frequency.

$$\Omega_p = -\frac{B_{LP}}{C_{LP}}, \qquad \Omega_s = \frac{1}{C_{LP}X_{LP}} - \frac{B_{LP}}{C_{LP}} = \frac{1}{C_{LP}X_{LP}} + \Omega_{\mathrm{p}} \quad (3)$$

$$\Omega_s = -\frac{B'_{LP}}{L_{LP}}, \qquad \Omega_p = \frac{1}{L_{LP}X'_{LP}} - \frac{B'_{LP}}{L_{LP}} = \frac{1}{L_{LP}X'_{LP}} + \Omega_{\mathrm{s}} \quad (4)$$

Because of this, an optimization process is performed in subsequent iterations by comparing the current coupling coefficient (k_e^2) to the target coupling coefficient ($k_{e_{target}}^2$) for the resonator. If $k_e^2 < k_{e_{target}}^2$ and the resonator is in shunt configuration, or if $k_e^2 > k_{e_{target}}^2$ and the resonator is in series configuration, the corresponding TZ of the resonator is decreased by small quantity (Δf). Otherwise, if $k_e^2 > k_{e_{target}}^2$ and the resonator is in shunt configuration, or if $k_e^2 < k_{e_{target}}^2$ and the resonator is in series configuration, the TZ is increased by Δf. The loop terminates whenever the relative error between the current value and the target value is smaller than a specific threshold (γ).

In ladder filters, as opposed to transversal filters, it is not possible to achieve a very small coupling coefficient because it would result in the transmission zeros falling within the operating band. To prevent this, whenever the transmission zeros are shifted towards the pass-band edges, the iteration process terminates, even if the target coupling coefficient has not been attained.

The outer loop, depicted by the purple arrows in Fig. 3, traverses through all the resonators to fine-tune the transmission zero of each resonator, aiming to achieve the prescribed target coupling coefficient at each resonator. The term "$N_{resonators}$" represents the total number of resonators in the network, and "n" is used as an index to identify the resonator currently being adjusted for its coupling coefficient.

Although not explicitly depicted in Fig. 3, it is feasible to establish a uniform coupling coefficient solely among the series or shunt resonators. This can be achieved by excluding in the loop all the resonators in either the series or shunt configuration, resulting in an increment of the index "n" in steps of two. Another important aspect to consider is that the iterative algorithm adjusts the coupling coefficient of all the resonators, including the last one, only when the network has absorbed the lumped components of the matching network [5]. If the lumped components are present, the coupling coefficient of the last resonator is fixed without needing to adjust its associated TZ. This is because the synthesis process can fix a specific coupling coefficient in the last resonator thanks to the freedom in selecting the value of the X_{LP} or X'_{LP} component of the last series or shunt resonator, respectively.

The whole process of adjusting the TZ for all the resonators of the network should be repeated L iterations to establish a uniform coupling coefficient across all resonators. The reason for this is that adjusting the coupling coefficient of subsequent resonators affects the coupling coefficient of preceding resonators. This is because whenever the position of a transmission zero is modified, the Chebyshev polynomials are regenerated. Consequently, the input impedance of the filter is altered, leading to changes in the extracted element values. The required number of iterations to achieve convergence to a desired coupling coefficient at each resonator depends on the acceptable error level. Therefore, it is essential to strike a balance between the number of iterations (L) and the tolerable relative error (γ).

IV. Simulation and Measurement

To validate the algorithm explained in the previous section, it has been synthesized a 2nd order TC-SAW ladder filter exhibiting a uniform coupling coefficient of 8%. The manufactured test filter has been designed with a central frequency of 843 MHz, a bandwidth of 30 MHz and a return loss level of 15 dB. The filter has been manufactured as an on-wafer tester filter to evaluate a given technology which cannot be disclosed for confidential reasons.

Fig. 4 displays the S-parameters of the synthesized order 2 (O2) filter with an arbitrary position of the TZs to illustrate how the response changes and the TZs are moved after setting a uniform coupling of 8%. The TZs are initially located at 770 MHz and 900 MHz (see Fig. 4) and the coupling coefficients of the series and shunt resonators are 14% and 19 %, respectively. After applying the iterative algorithm, the new positions of the transmission zeros are shifted so that the coupling coefficient of all the resonators is 8% (see Fig. 5). From the synthesized BVDs, the dimensions and geometry for each SAW resonator of the real filter have been extracted using the COM (Coupling of Modes) model [6]. This is a widely-used modelling approach to simulate the response of SAW devices by extracting a set of parameters based on either experimental data or numerical calculations. Fig. 5 demonstrates how the measured (black and green solid traces), the COM (red and blue solid traces) and the synthesized BVD (cyan and magenta dashed traces) filter using the iterative algorithm with a prescribed uniform coupling of 8% show a very good agreement. The insertion and return losses at the measured filter's central frequency are 0.36 dB and 20.33 dB, respectively.

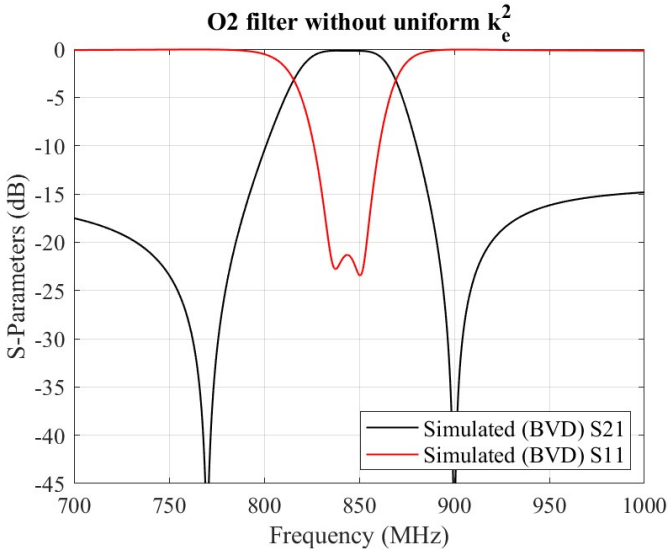

Fig. 4. O2 filter without uniform k_e^2

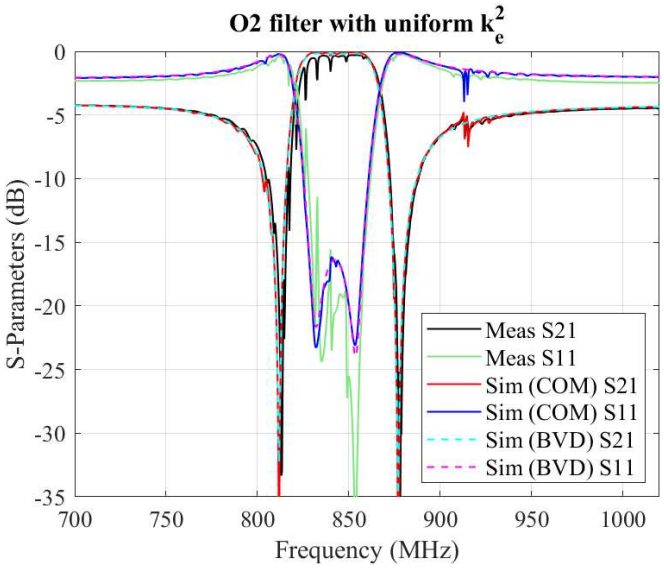

Fig. 5. O2 filter with uniform k_e^2 of 8 %

Table I presents the BVD parameters of the resonators for the two synthesized filters (with and without setting the uniform coupling coefficient of 8%).

TABLE I. Band-pass BVD parameters of the 2nd -order simulated filters.

2nd–order filter parameters	Ideal BVD components		
	L_s (nH)	C_s (pF)	C_p (pF)
Series BVD ($k_e^2 = 14\%$)	184.55	0.1919	1.45
Shunt BVD ($k_e^2 = 19\%$)	17.95	2.38	12.17
Series BVD ($k_e^2 = 8\%$)	154.13	0.229	3.195
Shunt BVD ($k_e^2 = 8\%$)	148.4	0.259	3.941

V. CONCLUSIONS

The algorithm described in this paper uses the flexibility of pre-selecting the position of transmission zeros to adjust a specific coupling coefficient in either shunt resonators, series resonators, or both series and shunt resonators of a ladder filter. Small coupling coefficients may not be achievable in some cases given that the electro-acoustic coupling is directly related to filter bandwidth.

It is worth mentioning that the computational time required to achieve a uniform coupling coefficient with a 2% relative error in a 10th order ladder filter only takes a few seconds if using this algorithm. Hence, this process can be systematically applied to a large bench of networks, eliminating the need for manual tuning of the transmission zeros by a filter designer. Naturally, this would only provide a good starting point for the final design of a more complex filter, where an optimization process will be unavoidable due to the technological complexity of the AW filters that are finally developed for the market. Furthermore, other strategies could be applied, if necessary, to ensure that the filter fulfils the rejection criteria.

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