Synthesis Procedure for Ladder Acoustic Wave Filters Starting in Series Resonators

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***Abstract*— This work provides a new procedure to synthesize acoustic wave ladder filters starting with series resonators. The novelty of this method relies in a new synthesis methodology to extract a series inductance in filter configurations starting in series resonators. As a matter of fact, this new synthesis provides solutions with a reduced value of the electrostatic capacitance, thereby giving resonators with smaller size.**

Keywords—Synthesis of Filters, Acoustic Wave filters.

I. Introduction

Nowadays, the number of filters embedded in a handset device is increasing by the evolution of the new wireless standards, i. e. 5G, and Internet of Things (IoT) [1][2]. Moreover, the increasing in the number of wireless smart devices in the society is setting higher capacity requirements and, consequently, the appearing of new frequency bands, along with requirements for reduced power consumption. All together is becoming a difficult task for the industry, who is constantly struggling to find mechanisms that allow coexistence between different radio systems and the embedding of those ones in a single device.

Filtering stages play a significant role into the RF chain of any communication system, being the component taking a major part of the layout. In handset wireless devices, electro-acoustic technology fills this demand by providing high performance compact filters. The filtering function still takes a major part of the layout mostly for the increasing number of filters in a single device, so there is an actual need of reducing the size devoted for every single filtering stage in the Radio Frequency Front End module.

The motivation and objective of this work is to help into that direction by providing a new synthesis methodology for acoustic wave ladder filters starting in series resonator which results in more suitable configurations with reduction of the filter area. Previous synthesis methods force to extract a shunt input inductance when the filter configuration starts with a series resonator [3], which in some cases is impractical in real developments. The novelty of this method relies in a new synthesis methodology to extract a series inductance in filter configurations starting in series resonators.

Section II recalls the synthesis methodology of the starting-shunt-inductance synthesis approach [3] and explains and compares the new synthesis approach starting with series inductance. Moreover, in the end of this section, an advanced configuration is presented where the filter itself does not need any matching element to properly work, since the effect of the input and output series inductance is absorbed by the input and output resonator, respectively. Section III shows a comparison of the performance of the three topologies in terms of size of the resonators, values of the external components and electrical response. Finally, section IV shows the concluding remarks of this work.

II. Synthesis Procedure

A. *Starting-Shunt-Inductance Approach*

The synthesis procedure is based on the conventional element extraction method from a set of characteristic polynomials that define a Chebyshev response up to the obtaining of a ladder network configuration. The process is already explained in [3] but mainly, the impedance of the whole circuit is obtained with the characteristic polynomials as

$$Z_T(s) = \frac{E(s)+F(s)/\varepsilon_R}{E(s)-F(s)/\varepsilon_R} \quad (1)$$

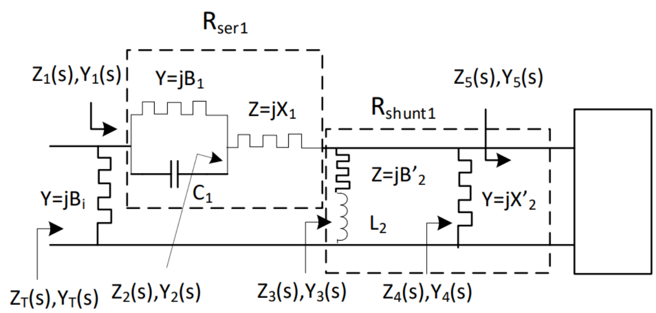

Fig. 1. Element extraction procedure of an acoustic ladder filter starting in series resonator in the lowpass prototype.

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Then, a set of elements of the lowpass prototype are extracted from this input impedance that make up the configuration of an acoustic wave ladder filter (Fig. 1). When the ladder configuration starts with a resonator in series, the first element to extract is a shunt susceptance jB_i which is intended to create a remaining admittance that exhibits a transmission zero in the parallel frequency of the first series resonator.

B. Starting-Series-Inductance Approach

This section outlines the steps to go from the conventional configuration with shunt inductance (section II.A) to the one starting with a series inductance. This is to go from Fig. 2a to Fig. 2b. Considering that the series reactance jX_p is equal in both circuits, the condition of equivalent circuits is achieved by equating the impedance of both circuits $Z_{IN\_a} = Z_{IN\_a2}$.

If we inspect the circuits, we end up with the following set of equations:

$$\begin{gathered} Z_{IN\_a} = \frac{1}{j\Omega C_{LP}+jB_{LP}} + \frac{1}{1-jB_i} \\ Re(Z_{IN\_a}) = \frac{1}{1+B_i^2} \\ Im(Z_{IN\_a}) = \frac{-1}{\Omega C_{LP}+B_{LP}} + \frac{B_i^2}{1+B_i^2} \end{gathered} \tag{2}$$

$$\begin{gathered} Z_{IN\_a2} = \frac{1}{j\Omega C_{LP\_2}+jB_{LP\_2}} + 1 + \frac{j}{B_{i2}} \\ Re(Z_{IN\_a2}) = 1 \\ Im(Z_{IN\_a2}) = \frac{-1}{\Omega C_{LP\_2}+B_{LP\_2}} + \frac{1}{B_{i2}} \end{gathered} \tag{3}$$

Looking at the real part of both impedances and by considering that both circuits must have the same source impedance (1 Ohm in the lowpass prototype), the source impedance of the circuit of Fig. 2b (Z_i) needs to be scaled by $\frac{1}{1+B_i^2}$. In order to keep the same ratio between currents and voltages at each node of the circuit, so perfect matching condition over the network, all the impedances of the resonators need to be scaled by the same value, which in turns give rise to a new set of equations:

$$\begin{gathered} Re(Z_{IN\_a2}) = \frac{1}{1+B_i^2} \\ Im(Z_{IN\_a2}) = \frac{-1}{\Omega C_{LP_2}(1+B_i^2)+B_{LP_2}(1+B_i^2)} + \frac{1}{B_{i2}(1+B_i^2)} \end{gathered} \tag{4}$$

Now, if we equate the imaginary part of both impedances from (2) and (4), the values of the equivalent network of Fig. 2b are found out as

$$C_{LP\_2} = \frac{C_{LP}}{(1+B_i^2)} \tag{5}$$

$$B_{LP\_2} = \frac{B_{LP}}{(1+B_i^2)} \tag{6}$$

$$B_{i2} = \frac{1}{B_i} \tag{7}$$

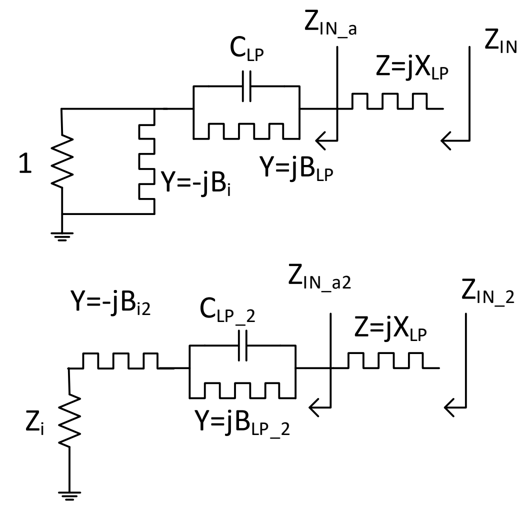

Fig. 2. Lowpass equivalent circuits of starting-series-resonator ladder topology: (a) shunt susceptance and series lowpass BVD resonator and (b) series susceptance and series lowpass BVD resonator.

C. No-Matching Elements Approach

This section provides a new filter configuration where no matching elements are needed. We start from the lowpass prototype of II.b, then, the effect of the matching series susceptance at either input or output (B_{i2}) is integrated into the series reactance of the input and output resonators (X_{LP}). So, the new series reactance of the resonators is given by

$$Z' = j\left(X_{LP} + \frac{1}{B_{i2}}\right) \tag{9}$$

As a result of the absorption, the input and output series resonators present a larger coupling coefficient, as it could be appreciated in Fig. 3.

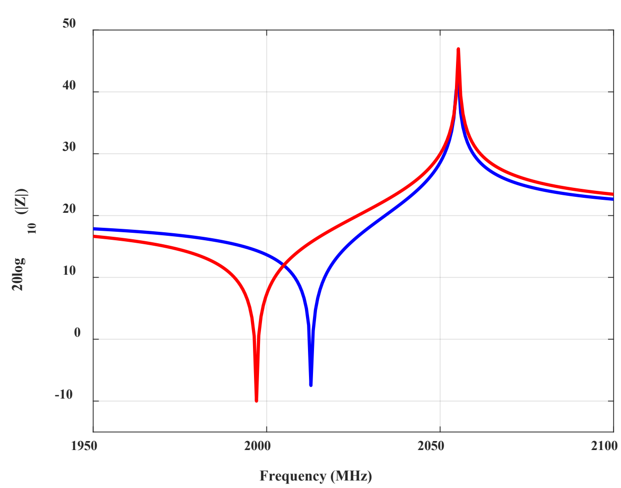

Fig. 3. Electrical impedance of the input and output resonators at (blue) series inductance approach at input and output and (orange) without external elements.

III. ANALYSIS OF THE PERFORMANCE

This section provides a comparison of the three configurations that have been shown in section II for a filter centered at 2 GHz with bandwidth of 60 MHz. The three topologies are depicted in Fig. 4.

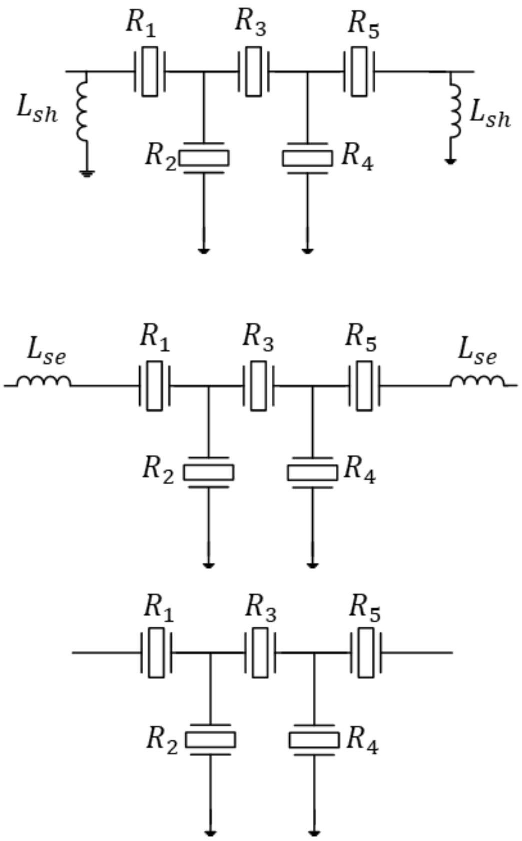

Fig. 4. 5th order filter topologies for the three approaches of Section II: (a) Starting-Shunt-Inductance Approach, (b) Starting-Series-Inductance Approach and (c) No-Matching Elements Approach.

The results depicted at Table 1 show that the approaches II.b and II.c always provide resonators with a lower value of electrostatic capacitance. Note that this reduction occurs at the very beginning of the synthesis, in the lowpass prototype, where the impedances of the resonators are scaled by the term $1 + B_i^2$, as (5) and (6) show. This is an important aspect, since the footprint of the devices with this configuration would be smaller. Moreover, the value of the series external matching inductances in approach of Section II.b are smaller than the shunt ones present in approach of Section II.a. Having matching elements with a reduced value is also more convenient since they facilitate their integration all together in the laminate of the device.

Fig. 5 shows the In-Band performance of the three approaches, where all circuits behave almost identical. Instead, Fig, 6 shows the out-of-band (OoB) response, there is a degradation in the attenuation of the approach of Section II.b at the frequencies around 4 GHz, which coincides with the inherent resonant frequency created by the external series inductance and the electrostatic capacitance of the input and output resonators.

Table 1. Electrical parameters of the three filter configurations.

	R_1&R_5	R_2&R_4	R_3
Starting-Shunt-Inductance Approach (Sect. II.a)			
$C_0\ (pF)$	1.068	4. 99	0.682
$f_s\ (GHz)$	2.012	1.94	2
K_{eff} (%)	4.9	6.63	4.9
$L_{sh}\ (nH)$	7.28		
Starting-Series-Inductance Approach (Sect. II.b)			
$C_0\ (pF)$	0.8233	3.84	0.52
$f_s\ (GHz)$	2.012	1.94	2
K_{eff} (%)	4.9	6.63	4.9
$L_{se}\ (nH)$	2.12		
No-Matching Elements Approach (Sect. II.c)			
$C_0\ (pF)$	0.8234	3.84	0.52
$f_s\ (GHz)$	1.997	1.94	2
K_{eff} (%)	6.6	6.63	6.6

IV. CONCLUSIONS

The nature of the presented synthesis procedure allows to achieve filter configurations with a reduction on the size of the resonator. Little differences are observed between the previous approach, mostly in the OoB rejection, but it allows to achieve more compact solutions since the area of the resonators is smaller and the external matching elements that require are smaller or needless.

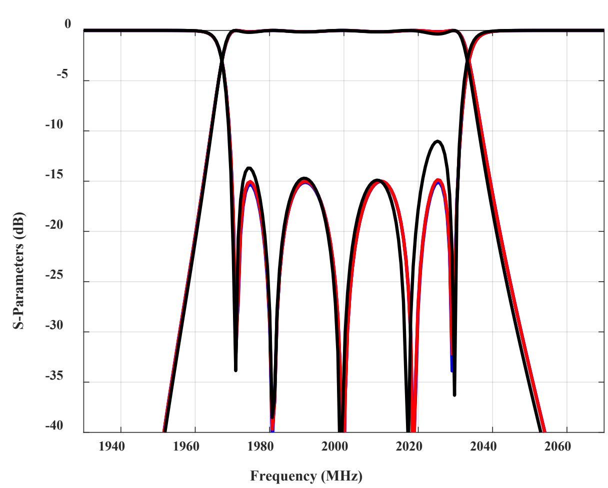

Fig. 5. In-Band response the three approaches of Section II: (blue) Starting-Shunt-Inductance Approach, (red) Starting-Series-Inductance Approach and (black) No-Matching Elements Approach.

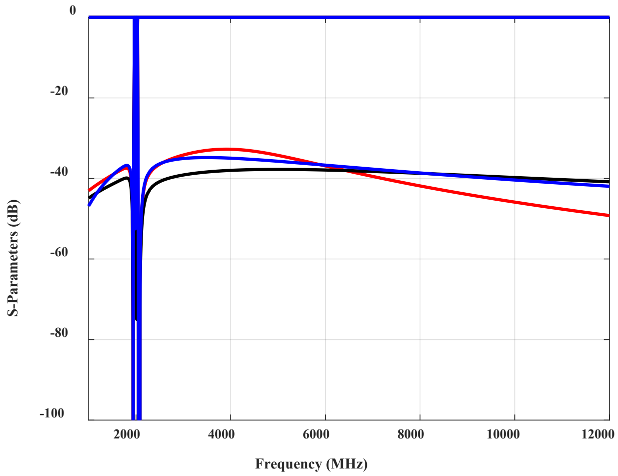

Fig. 6. Broadband response the three approaches of Section II: (blue) Starting-Shunt-Inductance Approach, (red) Starting-Series-Inductance Approach and (black) No-Matching Elements Approach.

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