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All-Pass Based Filter Design Using BAW Resonators

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***Abstract*—The integration of multiple bands and higher power standards lead to enhanced interference problems and make higher attenuation levels in next-gen RF-Front-Ends necessary. This paper introduces an all-pass based BAW filter design concept for notch, band-stop and band-pass filter topologies to indicate the possibilities and the impact of key parameters like material electromechanical coupling factor k^2_{eff}, piezoelectric material quality factor Q_m and inductor losses Q_L. This work outlines the concept and design aspects. Also various examples will be proposed to show the main benefits of this approach.**

***Keywords*—BAW filter, BAW resonator, all-pass network, acoustic wave filter**

I. Introduction

BAW filter enjoy a high market interest due to the challenging mobile communication standards. Multiple frequency bands and higher power standards lead to enhanced interference problems and make higher attenuation levels necessary [1]. Furthermore, the upcoming 5G NR bands n77, n78 and n79 have wide frequency bands and are difficult to realize with conventional ladder/lattice topologies based on poly-crystalline AlN-BAW resonators [2]. Therefore, new filter circuits (e.g. transversal filter circuits [3], LC BAW hybrid filter [4]), alternative acoustic wave resonators [5] and high coupling piezoelectric materials [6] dominate the current research efforts. Despite these needs relatively little work has been published to develop an all-pass network (APN) based LC BAW bybrid filter [7].

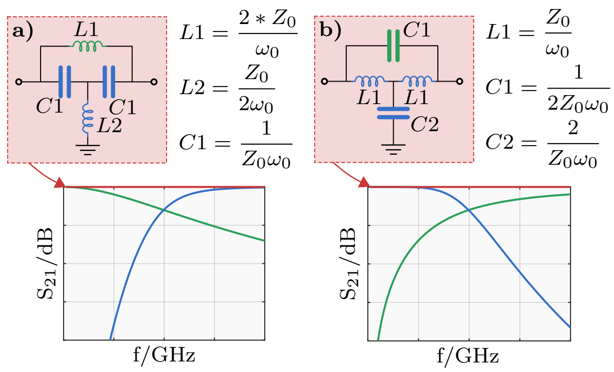

Fig. 1. Passive bridged-T networks in a) series-C configuration and b) series-L configuration. The respective equations describe the conditions for an all-pass characteristics (see red line) [8].

II. Theory & Concept

Usually filters are categorized in low-pass, high-pass, band-pass and band-stop filter. However, a fifth filter class can be added: the all-pass filter. In signal processing circuits, an all-pass network (APN) is applied to allow signals at any frequency to pass, but change their phase relationship. Beneath the use of active all-pass circuits, passive topologies are known [8]. In this work, passive bridged-T all-pass networks are used to implement APN BAW hybrid filter for RF applications.

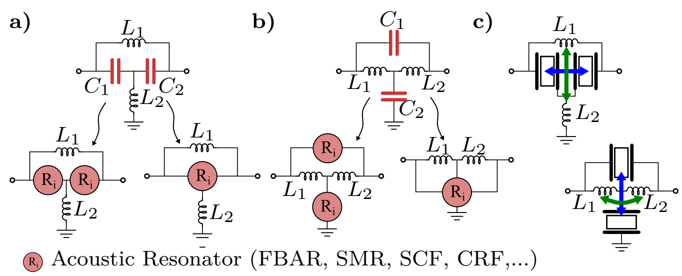

Fig. 2. Principle of an APN BAW hybrid filter: a) Series-C configuration; b) Series-L configuration; c) Examples with capacitors replaced by BAW resonators with or without acosutic coupling (blue arrow) and with or without inductive coupling (green arrow).

A. Passive LC All-Pass Circuits

For passive all-pass circuits various topologies are known. The most commonly used ones are the bridged T-section topology in series-C or series-L configuration [8]. Their ideal response and the respective formulas for all-pass characteristic are depicted in Fig. 1. Generally, the circuits are rather trivial and no detailed analysis is proposed here. By adopting APNs for phase shifter design, wideband frequency responses for return loss and insertion loss can be achieved [8]. In addition, the mutual coupling of the APN's inductors can help to meet the required filter specifications and should be always considered as a design parameter. As can be seen in the following sections, some filter characteristics could also benefit from a detuned all-pass network. All in all, this approach can be assigned to the LC BAW hybrid filter category, which combines the well discussed classic filter theory of LC lumped components and the high-Q characteristics of BAW resonators.

B. Bridged-T All-Pass BAW Filter Methodologies

The principle of creating an all-pass based hybrid BAW filter circuitry is to replace the capacitance in the previously mentioned passive APNs by the characteristic capacitance of BAW resonators (see Fig. 2 a) to c)). This way, the natural capacitive behavior of the BAW resonators allows to maintain the overall all-pass characteristics far from resonance.

A typical design flow would start with the lumped components of the chosen passive all-pass network. Here, one has to consider that the capacitance values have to be physically feasible for BAW technology. Finally, the BAW resonators have to be designed to meet the needed capacitances of the LC circuit. The respective design variables are the resonators active area and the piezoelectric layer thickness. At this point, also the BAW resonance has to be included in the layer stack design to get the desired filter characteristics.

Another aspect that can be used in the APN BAW filter design flow is to use different resonance frequencies by mechanically loading one of the BAW resonators in the APN. This allows the use of basic ladder filter concepts in the filter design of the APN network.

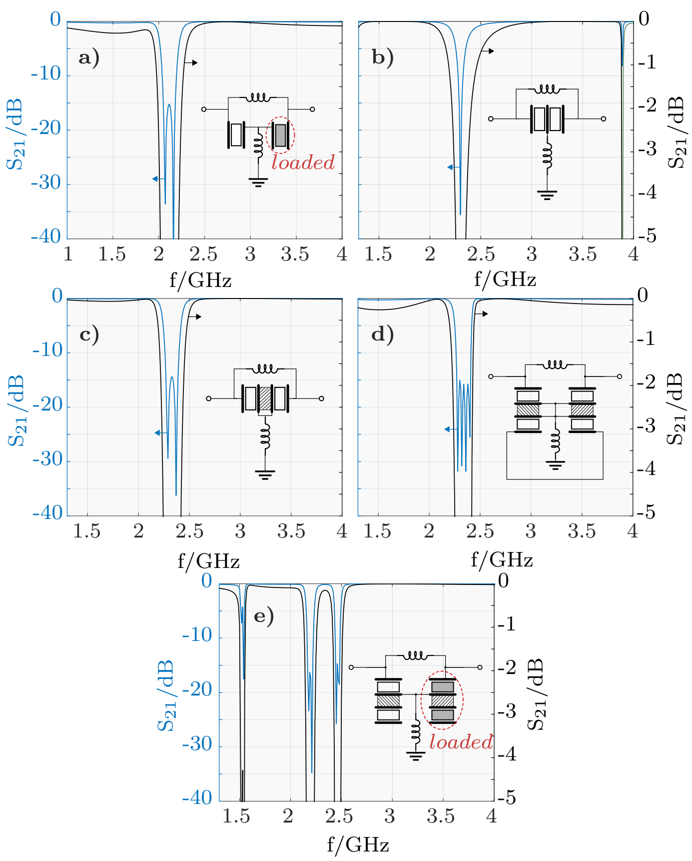

Fig. 3. Exemplary APN BAW notch filter circuits and their respective transmission response: a) Band-stop filter with resonators of FBAR/SMR-type; b) Notch filter with a stacked crystal filter; c) Band-stop filter with one coupled resonator filter; d) Band-stop filter with two coupled resonator filter; e) Dual-Notch filter with two coupled resonator filter.

To get the needed capacitance or avoid physically limits of BAW technology, series and parallel combinations of BAW resonators can be used as a replacement for the APNs capacitors. Indeed, one isn't restricted to the use of single BAW resonators of the FBAR or SMR type. Also the use of acoustically coupled BAW resonators like stacked crystal filter (SCF) and coupled resonator filter (CRF) can be of great interest for APN based filter circuitries. Lastly, an APN based BAW filter can consist of more than one stage or even can be combined with ladder/lattice BAW filter stages.

III. All-Pass Based BAW Filter Circuits

This section shows some fundamental topologies, which indicate the possibilities of the proposed concept. For demonstration purposes, the one-dimensional Mason model is used to represent FBARs, SCFs or CRFs. The acoustic resonators are simulated with AlN ($k^2_{eff} = 0.065$ and material quality factor $Q_m = 1500$). For the notch or band-stop filter examples, the series-C configuration APN is used. The band-pass filter characteristic is achieved by a detuned series-L configuration.

A. Notch & Band-Stop Filter Circuits

The application for notch filters is one of the preferred applications of the APN based Hybrid-Circuits. At first, an all-pass characteristic has to be defined by the APN. BAW resonators are then used to replace the capacitors of the circuits. As a result, a highly selective suppression at the resonance frequencies of the BAW resonators is achieved. A simple approach is to use two physically and electrically equal resonators. However, a wider bandwidth is usually desired. In this case, one of the resonators can be mechanically loaded to shift its resonance frequency without changing its capacitance. This way a second notch is created. An example shows Fig. 3 a).

As mentioned in the previous section, also SCF and CRF components can be used. They help to reduce the footprint of the BAW circuit. Some examples with SCF or CRF structures are illustrated in Fig. 3 b) to e). The multiple symmetric and asymmetric resonance modes in the acoustically coupled resonators allow the design of numerous variants. Beneath the implementation of notch/band-stop filter with SCFs and CRFs also dual notch filter are possible (see Fig. 3 e)). However, the design of APN BAW filter with acoustically coupled resonators faces an increased complexity. The reasons are the additional design parameters like acoustic coupling and interdependent design of the acoustically coupled resonators.

B. Band-Pass Filter Circuits

An band-pass like behavior can be achieved, if the APN is detuned with the LC component relations creating a notch characteristic at desired frequencies. After the replacement of the capacitors with properly designed BAW resonators, further notches can be added and an local pass-band characteristic can be formed. Fig. 4 shows exemplary the band-pass characteristic (solid blue line) formed by a detuned APN (dashed black line) and two BAW resonators shifted in frequency.

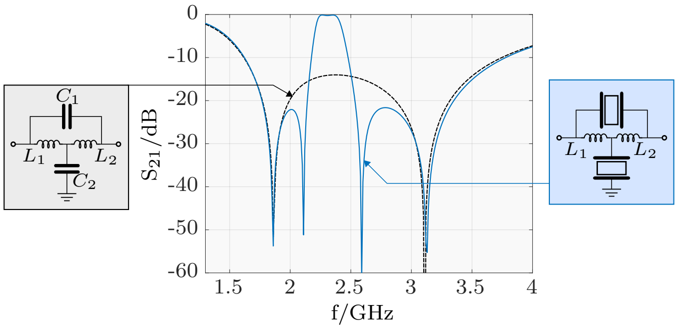

Fig. 4. Exemplary APN based BAW filter with band-pass characteristic. The dashed black line illustrates detuned APN transmission response without BAW resonators and the solid blue line depicts the resulting band-pass characteristic of the detuned APN with the capacitors replaced by properly designed BAW resonators.

Although a high rejection near the pass-band can be observed, suppression far from pass-band is very low. This is due to the still present all-pass characteristic of the APN BAW circuit far from its resonances. If a higher out-of-band rejection is needed, one has to add another filter stage or further lumped elements to the circuit.

C. Basic Design Parameter Dependencies

Due to the numerous topology variants and the complex parameter dependencies the analysis focus of the design parameters is reduced to the topology of the series-C APN based band-stop filter of Fig. 3 a). The studied key parameters are: the intrinsic electromechanical coupling factor k^2_{eff}, piezoelectric material quality factor Q_m and inductor losses Q_L. The ideal case and starting point of every parameter study is depicted in Fig. 5 a) with $k^2_{eff} = 0.065$, $Q_m = 1500$ and $Q_L = 100$. The respective parameter variations are $Q_m = 1500$, 1000, 500, 250 and 100 in Fig. 5 b) and $Q_L = 1500$, 100, 50, 30, 20 and 10 in Fig. 5 c). Since new materials like AlScN with higher electromechanical coupling are of great interest in today's acoustic resonator research, also the intrinsic material coupling is varied (see Fig. 5 d)). The respective values are $k^2_{eff} = 0.065$, 0.09, 0.12 and 0.15.

1) Inductor performance: For the filter circuits the required inductor values vary between 0.5 nH and 5 nH for frequencies up to 6 GHz. The usually low Q-factor of inductors and the required space for integration belong to the main drawbacks of the APN based filter design. However, as can be seen in Fig. 5 c), even low Q-factors lead to reasonable insertion loss.

2) BAW resonator performance: The BAW resonator key parameters Q-factor and effective electromechanical coupling also determine the limits of the proposed hybrid filter design. A higher effective electromechanical coupling for example, helps like in ladder filter design to realize wider bandwidths (see Fig. 5 d)). Hence, the proposed filter design approach would benefit drastically from new materials like AlScN even with moderate Sc concentrations up to 20at.-%.

Usually, the material Q-factor was found to be lower for higher Sc concentrations and a decreasing material Q-factor should be considered. In Fig. 5 c) the Q_m-factor was varied from 1500 down to 100, which is a rather low value for BAW technology. However, the resonators Q-factor hardly changed the filter performance in the applied models. Even for small resonator Q-factors acceptable notch filter characteristics are possible.

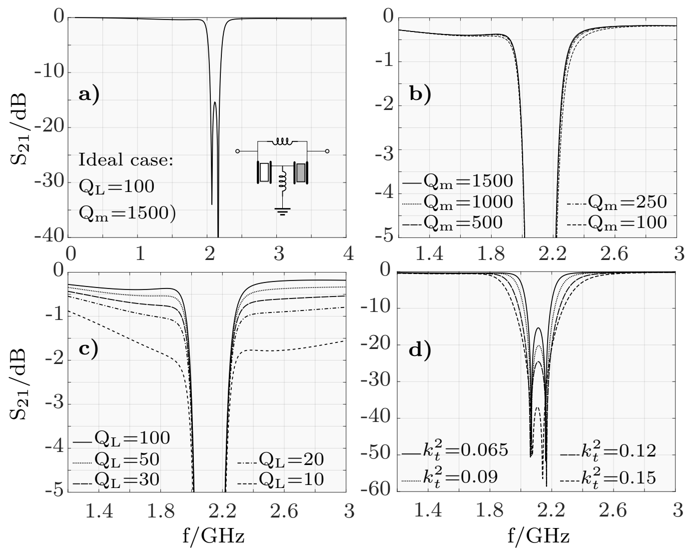

Fig. 5. Parameter study of the series-C APN based band-stop filter with FBARs: a) Ideal case simulation with $k^2_{eff} = 0.065$, $Q_m = 1500$) and Q_L=100; b) Simulation of piezoelectric material Q dependency with $Q_m = 1500$, 1000, 500, 250 and 100; c) Simulation of inductor Q impact with $Q_L = 1500$, 100, 50, 30, 20 and 10; d) Simulation of electromechanical coupling with $k^2_{eff} = 0.065$, 0.09, 0.12 and 0.15.

Finally, it was found, that the parameter relations concluded from the series-C band-stop filter also can be transferred to the series-L APN BAW filter circuits.

IV. Application Example - Band n79

The upcoming 5G mobile communication standard will include new frequency bands in the 3 GHz to 6 GHz range. One of these new bands is band n79 with a very large relative bandwidth from 4.4 GHz to 5 GHz. In this section an APN based circuit is modeled exemplary to meet the pass-band requirements of band n79. Here, the circuit consists of two series-L APN BAW filter stages. Thus, four BAW resonators with equal layer stack, material properties and piezoelectric layer thickness are used. The BAW resonators differ only in the active area size and mechanical loading of the top electrode. Furthermore, the electromechanical coupling is $k^2_{eff} = 0.11$, which is a reasonable value for moderate Sc concentrations around 15 at.-% Sc. To include the usually lower Q-factor for AlScN with high Sc concentrations the material Q-factor is reduced to $Q_m = 500$. The final circuit and the respective transmission response is given in Fig. 6. Furthermore, for the sake of completeness an ideal BAW ladder topology and ideal inverse 3rd order LC Chebyshev filter are included for comparison purposes.

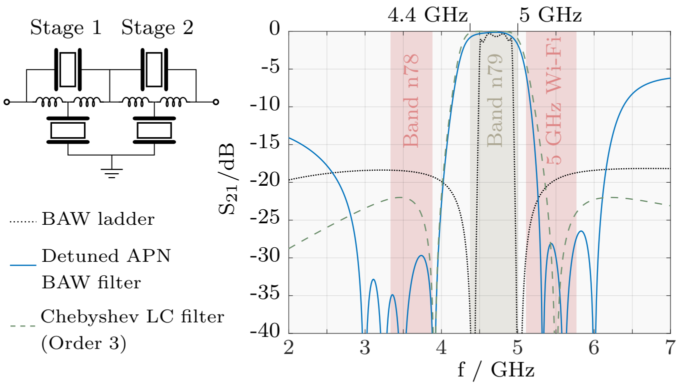

Fig. 6. Exemplary n79 filter circuit with a 2-stage series-L APN BAW filter.

Another challenge of the n79 band, apart from its wide relative bandwidth, are the co-existence requirements with band n78 and the 5 GHz Wi-Fi frequencies. Especially the Wi-Fi leads to high selectivity needs, which might be solved by the addition of another notch stage. However, the simple circuit example illustrates the benefits of the proposed APN BAW hybrid filter concept compared to classical filter circuits.

Conclusion & Outlook

We introduced an all-pass based filter design concept for BAW resonators to create high rejection notches in the overall all-pass response. Notch, band-stop and band-pass filter topology studies have been performed to explore the possibilities and to investigate the impact of key parameters. The limiting factor of the proposed circuits are the inductor's Q-factors. Consequently, their usually high losses and the required space for integration belongs to the main drawbacks of this concept. Nevertheless, without novel high coupling materials or sufficient acoustic alternatives to BAW resonators, high quality and highly integrated inductors might be a key requirement for next-generation BAW filter technology. Therefore, the development of integration concepts to combine BAW technology, inductors and CMOS dies for RF-path switching could become the major development challenge for APN-based BAW filters. Future research topics include the design and physical implementation to validate the findings and practical issues.

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