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Investigations of a New Design Concept for Wide-Band Hybrid Ladder Filters

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***Abstract*—In this paper, a new design concept for wide-band hybrid ladder filters is investigated. The concept enables manipulation of the fixed behavior and limited electromechanical coupling coefficient (k_{eff}^2) of acoustic-wave resonators by additional lumped-element resonators. This hybrid approach allows for resonance spreading of single acoustic-wave resonators, which corresponds to an increased k_{eff}^2. An illustration of the concept is given, as well as an example for the application to wide-band filter design. Measurements of one of two proposed basic structures show an effective increase of k_{eff}^2 by a factor of more than 4, demonstrating that the concept is feasible in practice.**

I. Introduction

Modern handsets for mobile communication include a high number of radio frequency (RF) filters. These filters are required to separate between different frequency domains (e.g. LTE, WiFi, Bluetooth), as well as various supported frequency bands. This results in increasing complexity of the RF front-ends and puts high demands on the employed filters [1].

In the frequency range up to 6 GHz, acoustic-wave resonators (AWRs) are the dominating technology for filter purposes. Their operation is based on the piezoelectric effect, which makes their behavior dependent on the employed materials [2]. Depending on the exploited wave mode and its excitation, they may be subdivided into surface acoustic-wave (SAW) and bulk acoustic-wave (BAW) type, usually used for different frequency ranges. Acoustic-wave resonators and filters exhibit very high quality factors [3], but their bandwidth is limited by material properties. One main characteristic is the electro-mechanical coupling coefficient (EMCC) k_{eff}^2. For state-of-the-art resonators using Aluminum Nitrate (AlN) as piezoelectric material, it is in the range of 7 %. The achievable bandwidth (FBW) of filters made of these resonators is in the order of (0.4 .. 0.8) k_{eff}^2 [4]. This means that for wide-band filter applications, either new materials with higher EMCC have to be employed, or new architectures or concepts have to be developed.

Classic filter theory, on the other side, is based only on inductors and capacitors to realize a specified transfer function. These filters are theoretically unlimited in bandwidth, but they offer only low quality [5] and their realizability depends on technologically feasible component values.

In this paper, a hybrid resonator concept is presented that may be used for hybrid filter design. It is based on combinations of AWRs and lumped-element LC resonators (LCRs). Due to the spreading of resonance frequencies that is hereby possible in a theoretically arbitrary manner, the concept proves feasible for wide-band filter design. A prototype demonstrating the concept is shown, including measurement results.

II. Acoustic-Wave Resonator Fundamentals

An acoustic-wave resonator is an electromechanical component that uses a piezoelectric material layer for the transformation between electrical and mechanical (acoustic) waves. Depending on the acoustic wave mode, different types of AWRs have evolved. SAW resonators make use of surface acoustic waves, whereas BAW resonators depend on bulk acoustic waves [6], [7]. The resonance and anti-resonance frequencies are defined by either spacing of inter-digital transducer fingers (SAW) or thickness of the piezoelectric layer (BAW), respectively.

A. Equivalent Circuit Model

An effective description of acoustic-wave resonators from circuit design perspective is the modified Butterworth-van-Dyke (BVD) model [8]. It describes the electrical behavior at the ports of the resonator by a dipole of equivalent circuit elements. In Fig. 1, the BVD model of a lossless resonator is shown, as well as a common network transformation thereof with equal electrical properties but different element values. Equations for this network transformation can be found in [9], [10].

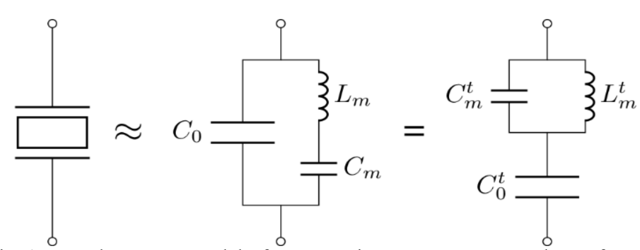


Fig. 1. Lossless BVD model of an acoustic-wave resonator and transformed equivalent circuit

For the greatest part of the frequency range, the resonator's behavior is dominated by its static capacitance C_0. It is the only reactive element of the BVD model that physically exists. In the case of BAW resonators, it is simply defined by the plate capacitance, whereas for SAW resonators it is the capacitance between the inter-digital transducer fingers. A series resonance

(f_r) is created by the reactive elements of the motional branch (L_m, C_m), where the resonator admittance reaches a maximum. Together with the parallel capacitance C_0, a parallel resonance, or anti-resonance (f_{ar}), is created, where the resonator admittance is minimum.

The distance between the series and anti-resonance frequency is an important figure when using AWRs for filter applications, since the overall achievable bandwidth mostly depends on it. The effective electro-mechanical coupling factor k_{eff}^2 can be expressed as a function of the resonant frequencies by [11], [12]:

$$k_{eff}^2 = \frac{\pi^2}{4} \frac{f_r}{f_{ar}} \frac{f_{ar}-f_r}{f_{ar}} \approx \frac{\pi^2}{4} \frac{f_{ar}-f_r}{f_{ar}} \qquad (1)$$

The element values of the BVD model depend on material properties (especially of the piezoelectric layer) and other conditions such as targeted operation frequency and resonator type. They are constant and are related to each other by physical size, resonance frequencies and the EMCC.

III. Hybrid Resonator Concept

In this section the new hybrid resonator concept is presented that can be used for hybrid filter design. The principle of the concept is to shift either the series resonance to a lower frequency or the anti-resonance to a higher frequency. The concept is described in detail in [13]. In contrast to similar concepts adding only one element such as the "AWLR" [14], no parasitic resonances are introduced. The resonance shift is accomplished by adding LC resonators to the AWR in special configurations. That means, instead of adding only inductors that are able to shift resonance frequencies, too, an additional capacitor is required. A good overview of the impact of single lumped elements on the AWR resonances' behavior can be found in [16].

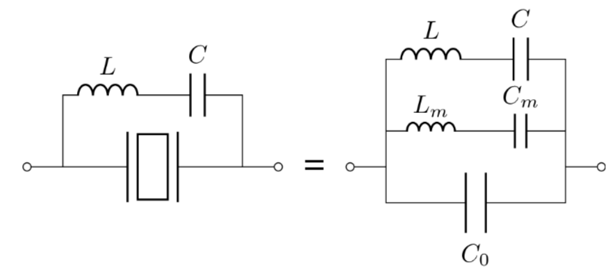
A. Resonance Shift by Additional LC Resonators

The investigation of this paper is based on a special kind of resonance shift. Given the fact that adding one element will always alter one of the resonance frequencies and introduce an additional one, two special cases of adding two elements to the resonator are presented. These two cases are:

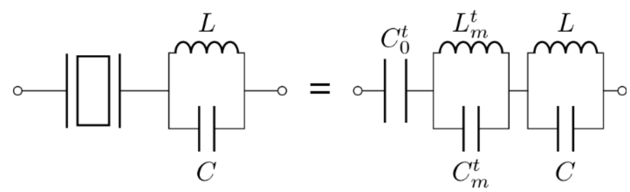
1. Connecting an LC series resonator in parallel to an AWR, both comprising the same series resonance;
2. Connecting an LC parallel resonator in series to an AWR, both comprising the same parallel resonance.

The two cases are depicted in Fig. 2, including their equivalent circuits.

In that way, the properties of the overall created dipole are modified in such a way that only one resonance is shifted in frequency, but the other one will remain the same and no parasitic resonance is introduced. For case 1, the new parallel resonance is at a higher frequency than that of the AWR only. This is due to the fact, that the series LC resonator behaves like an inductor at frequencies higher than its resonance, causing similar operation like the "AWLR" in this range, while it behaves capacitive in the lower frequency range up to the resonance, thus not introducing a parasitic resonance. In case 2,



(a) Equivalent circuit representation of case 1



(b) Equivalent circuit representation of case 2

Fig. 2. Two cases of presented AWR manipulation and their equivalent circuit model

the new series resonance is at a lower frequency than that of the AWR only. This is because at frequencies up to the LC resonance, the LCR exhibits inductive behavior (basically a series L, see [16]), while at higher frequencies, it is capacitive and therefore no parasitic resonance is introduced in this range.

The resonance shift in both cases can also be described by the equivalent circuit model as shown in Fig. 2 on the right [13]. For case 1, when the LC resonator exhibits the same resonance frequency as the motional branch of the AWR, these two branches can be effectively combined into one single series resonator, consisting of a smaller L and a higher capacitor (the parallel combination of the respective elements). This results in a higher effective C_m, leading to a higher k_{eff}^2. On the other hand, for case 2, the series connection of the parallel resonators at the same resonance can theoretically be combined into one single resonator consisting of a larger inductor and a smaller capacitor (the series connection of the respective elements), which also leads to a higher k_{eff}^2. The effective resonance spread in both cases depends on the values of the added L and C. The only limit is the realizability of the added component values.

Fig. 3 shows an example of the resulting resonator admittance curves for the two spreading techniques for a general 2 GHz resonator. The admittance curve of the pure AWR is plotted for comparison.

By these resonator configurations, the spacing between series and parallel resonance can be widened arbitrarily by shifting one of the respective resonance frequencies. In other words, k_{eff}^2 of any AWR can be increased without introducing parasitic resonances, which would be the case when adding only one inductor.

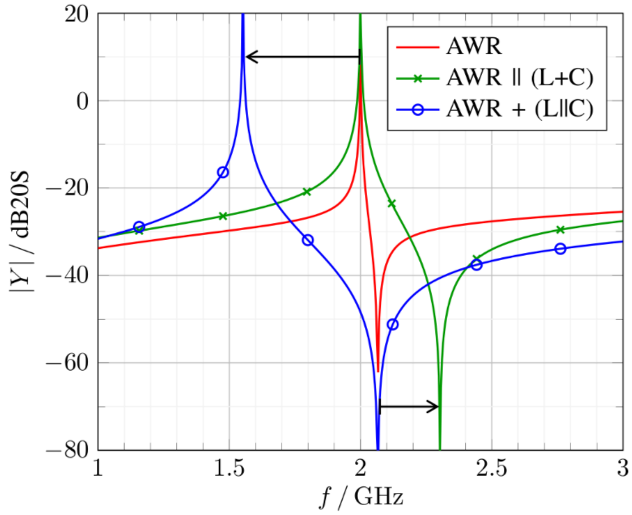


Fig. 3. AWR resonance spreading by shifting either series or parallel resonance (blue or green, resp.)

IV. Application to Filter Design

With the proposed concept it is possible to build resonators with effectively wide-spread resonance frequencies. Considering that the coupling factor of every AWR can be increased arbitrarily, it is therefore possible to use these composite resonators for wide-band filter design.

The principle of the concept can be inverted, so that instead of adding LC resonators to AWRs, a circuit is designed assuming availability of high-k_{eff}^2 resonators. Then, these high-k_{eff}^2 resonators are realized by conventional low-k_{eff}^2 AWRs and added LC circuitry. This means that every conventional ladder filter can in theory be realized by acoustic-wave resonators and added LC resonators [13].

A. Application Example of a Hybrid High-k_{eff}^2 Resonator

For demonstration purpose, a discrete test structure for measurements has been built to verify the design principle in practice. It represents the AWR manipulation of case 2 and therefore realizes the structure shown in Fig. 2b. A photograph of the PCB with mounted components is shown in Fig. 4.

The employed resonator has a static capacitance of $C_0 = 2.9$ pF, a series resonance at $f_r = 1.71$ GHz and an anti-resonance at $f_{ar} = 1.76$ GHz. According to (1), this corresponds to a k_{eff}^2 of 6.8 %. The resonator is bonded directly to the PCB and the bond wires have impact on resonator behavior. They effectively contribute to a shift of the series resonance and introduce a parasitic series resonance at higher frequencies as shown in Fig. 5. To reduce the effect, the resonator was placed in a cavity on the PCB. The effect is, however, still observable but it can be completely de-embedded by using bond wire models extracted from the measurement results, so that the original effect of only the added LC resonator can be seen.

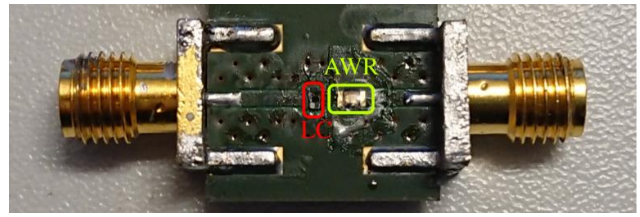


Fig. 4. Photograph of the PCB with mounted components

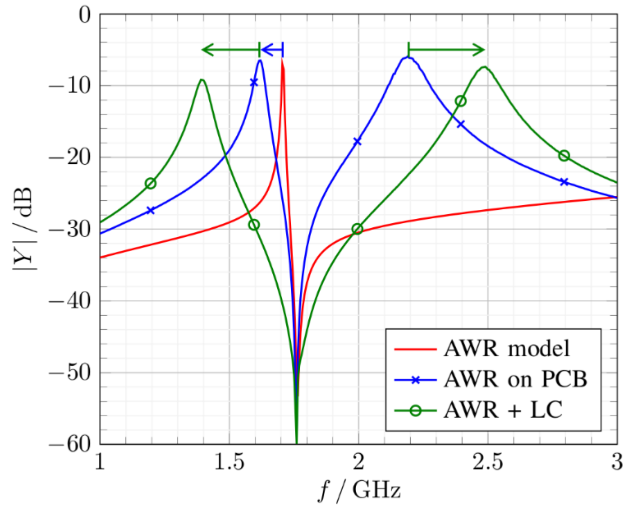


Fig. 5. Comparison of the admittance magnitude of several structures: simple AWR model (red), AWR bonded on PCB (blue), AWR + PLC structure (green); bond wire effect not de-embedded

Fig. 5 shows the admittance curves of several structures. The pure resonator behavior is compared to the resonator bonded on the PCB, showing the impact of the bond wires, and to a hybrid structure with an additional parallel LC tank in series to the resonator (Fig. 2b). The additional frequency shift of the LC resonator without adding additional parasitic resonances can be observed. Furthermore, it is shown that the LC tank is even able to reduce the parasitic bond wire impact at higher frequencies.

In Fig. 6 the behavior of the pure resonator and one resonator with added LC elements is shown for a variation of the capacitor value where the effect of the bond wires was de-embedded. Two important things can be derived from this measurement. First, the behavior with bond wires excluded is indeed the same as of a resonator with shifted series resonance (higher k_{eff}^2). This proves the concept to be applicable in real-world scenarios. Second, it shows that when the LC resonance frequency does not exactly match the corresponding AWR resonance, this does not change the overall behavior significantly. Obviously, the behavior around the LC resonance is a bit different than expected, but this can actually lead to a second notch close to the passband when applied to filter circuits as e.g. mentioned in [13]. This can result in better stopband suppression and/or can eventually relax accuracy constraints of the L and C components. The effect of the bond wires can be de-embedded but it is significant. It is therefore favorable to remove them for real filter applications. This can e.g. be accomplished by integrating the lumped elements with the AWR in a single chip.

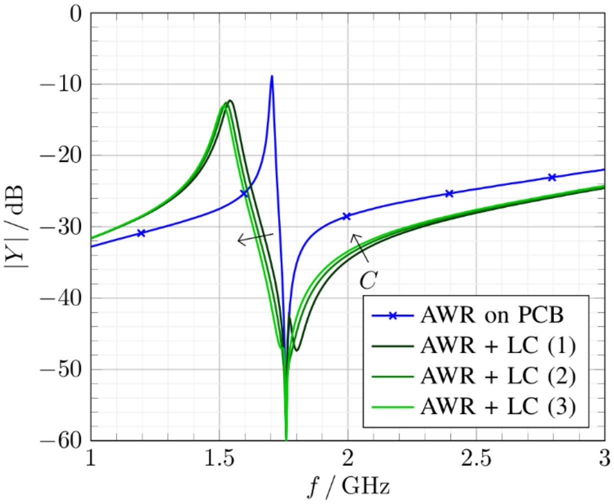


Fig. 6. Comparison of the admittance magnitude of several structures: AWR bonded on PCB (blue), AWR + PLC structure with a sweep of C (green); bond wire effect is de-embedded

The de-embedded structure behaves like a single resonator with its series resonance at f_r = 1.53 GHz and its anti-resonance at f_{ar} = 1.76 GHz. This corresponds to a k_{eff}^2 of 28 %, i.e. the original value of k_{eff}^2 was more than quadrupled.

V. Conclusion

In this paper, a concept has been presented that can be used for wide-band filter design in traditional ladder-type structures, combining AWRs and other passive elements. It is based on an effective increase of the EMCC (k_{eff}^2) of the AWRs, overcoming a substantial limit of state-of-the-art AWR-based filters. This is achieved by adding lumped LC resonators to the AWRs in special configurations comprising similar series or anti-resonance, respectively. Theoretical investigation of the concept is based on the BVD model of the AWRs.

Measurements of one of two types of hybrid resonator structure have been presented, demonstrating the concept to be realizable in practice. Variations of element values have been considered and analyzed. It can be concluded that their impact is tolerable under certain circumstances and that it can, in contrast, even result in beneficial characteristics.

It is believed that this concept will prove useful for future investigations of hybrid filter topologies. Especially regarding future technologies, a potential integration of the LC resonators together with the AWRs on the same chip might lead to well-performing wide-band RF filters in a small form factor. While it is still favorable to remove bond wires from the design, it has been shown that the proposed concept can also minimize bond wire impact.

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