A Hybrid Ladder Filter with Enlarged Bandwidth by Using Acoustic-Wave-Lumped-Element Resonators

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***Summary*—In this paper, a new class of hybrid filters with enlarged bandwidth while keeping the steepness of the transition is proposed. The proposed hybrid filter is a ladder structure, with an acoustic wave lumped element resonator (AWLR) connected in each branch. The AWLR, which can break the limit of the electromechanical coupling coefficient (k_t^2) of conventional acoustic wave (AW) resonators, is made up of an AW resonator and two lumped elements simultaneously connected in series and shunt. The roles of the two lumped elements are to change the resonant frequency and the anti-resonant frequency of the AW resonator, which subsequently increases bandwidth or enhances the steepness of the hybrid filter. Simulation results show that the fractional bandwidth of the proposed hybrid filter is 6.0% (1.1k_t^2), which is about 2.1 times larger than the one obtained in traditional acoustic filters.**

Keywords—band-pass filters; electromechanical coupling coefficient; hybrid filters; SAW filters; surface acoustic wave resonators; wide bandwidth

I. Introduction

In modern handsets for cellular communication, a great number of radio frequency (RF) filters are being used. Typically, surface acoustic wave (SAW) and bulk acoustic wave (BAW) filters as acoustic wave filters are most extensively used due to their low insertion loss (IL), high shirt selectivity, and compact size. Their operation function is principally determined by the piezoelectric property of materials. However, the proliferation of 5G communications has an urgent requirement for acoustic filters with wider bandwidth to fulfill faster data transmission, which is a tremendous challenge for acoustic filters since the fractional bandwidth (FBW) is limited by the electromechanical coupling coefficient (k_t^2) of the piezoelectric substrate, and the value of the FBW is typically between 0.4k_t^2 -0.8k_t^2 [1-2].

In order to enhance the bandwidth, researchers are paying more attention to achieve a higher value of k_t^2 and new materials are being evaluated. On the other hand, the hybrid technology by using Acoustic-Wave-Lumped-Element Resonators (AWLRs) is proposed to enhance the bandwidth in Ref [3-9]. However, a trade-off relationship exists between the enlarged bandwidth and the steepness of the transition. The steepness of the transition is limited by the lumped resonators in series [3-5,9] and only the series or parallel resonant frequency is changed by lumped elements in AWLRs [6-8].

In this paper, a robust method is proposed to enhance the bandwidth of AW filters while keeping the steepness of the transition. Lumped elements are simultaneously connected in series and shunt for changing the resonant frequency and the anti-resonant frequency of the AW resonator, which subsequently increases the bandwidth or enhances the steepness of the filter. The resonators with a single resonant frequency are used to design the ladder-type hybrid filters, which means higher reliability for mass production owing to improved robustness to manufacturing and assembly tolerances. The Advanced Design System (ADS) and High Frequency Structure Simulator (HFSS) software is used to simulate the hybrid filter and parasitic parameters of the printed circuit board (PCB), respectively.

II. Hybrid Resonator Foundations

The proposed hybrid filter is based on a ladder structure which is made up of the new class of AWLRs module. The AWLR circuit details of two lumped elements and an acoustic wave (AW) resonator which is typically represented by the Butterworth Van-Dyke (BVD) model [see Fig.1(a)] are depicted in Fig.1(b). The electrical impedance of an AW resonator based on the BVD model can be simplified and expressed by (1) [10].

$$Z = \frac{(f^2 - f_s^2)}{sC_0(f^2 - f_p^2)} \tag{1}$$

Where $s = j\omega$, f_s and f_p are the series resonant frequency and parallel resonant frequency, respectively.

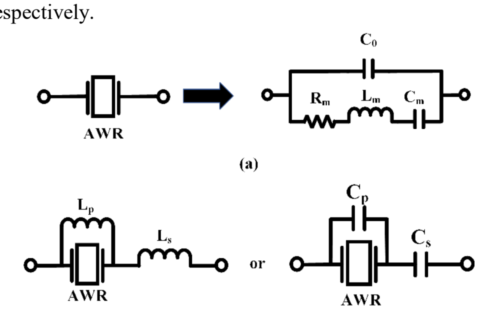

Fig. 1. Proposed AWLR circuit. (a) the BVD model of an acoustic wave

resonator. (b) the circuit of the AWLR.

By adding series and parallel inductors, the series resonant frequency (f_s) and parallel resonant frequency (f_p) can be changed to enhance the bandwidth of the hybrid filter, which is deduced by (2-5), and the results are shown in Fig.2. The formulas (2-3) and (4-5) represent the value of the f_s and f_p after adding a series or parallel inductor, respectively. The inductor L is the additional series or parallel inductor, which just affects the f_s or f_p. Moreover, the value of the inductor L is inversely proportional to f_s or f_p.

$$f_s = \frac{1}{2\pi}\sqrt{\frac{(C_m L_m + C_0 L + C_m L) \pm \sqrt{(C_m L_m + C_0 L + C_m L)^2 - 4C_0 C_m L_m L}}{2C_0 C_m L_m L}} \quad (2)$$

$$f_p = \frac{1}{2\pi}\sqrt{\frac{C_0 + C_m}{C_m L_m C_0}} \quad (3)$$

$$f_s = \frac{1}{2\pi}\sqrt{\frac{1}{C_m L_m}} \quad (4)$$

$$f_p = \frac{1}{2\pi}\sqrt{\frac{(C_0 L + C_m L + C_m L_m) \pm \sqrt{(C_m L_m + C_0 L + C_m L)^2 - 4C_0 C_m L_m L}}{2C_0 C_m L_m L}} \quad (5)$$

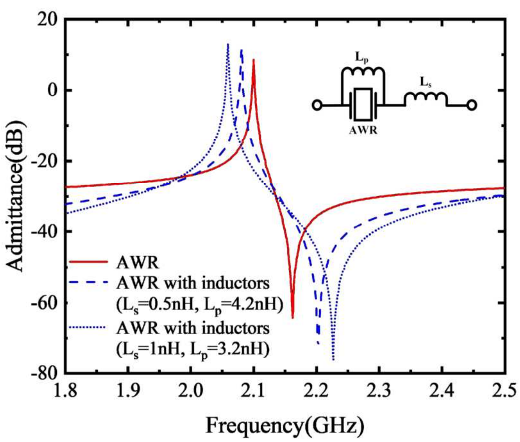

Fig. 2. Admittance response of the AWR with inductors.

By adding series and parallel capacitors, the f_s and f_p can be changed to improve the steepness of the hybrid filter, which is deduced by (6-9), and the results are shown in Fig.3. The formulas (6-7) and (8-9) represent the value of the f_s and f_p after adding a series or parallel capacitor, respectively. The capacitor C is the additional series or parallel capacitor, which just affects the f_s or f_p. Furthermore, the value of the capacitor C is inversely proportional to f_s or f_p.

$$f_s = \frac{1}{2\pi}\sqrt{\frac{C_m + C_0 + C}{CC_m L_m + C_0 C_m L_m}} \quad (6)$$

$$f_p = \frac{1}{2\pi}\sqrt{\frac{C_0 + C_m}{C_m L_m C_0}} \quad (7)$$

$$f_s = \frac{1}{2\pi}\sqrt{\frac{1}{C_m L_m}} \quad (8)$$

$$f_p = \frac{1}{2\pi}\sqrt{\frac{C_0 + C_m + C}{L_m C_m (C + C_0)}} \quad (9)$$

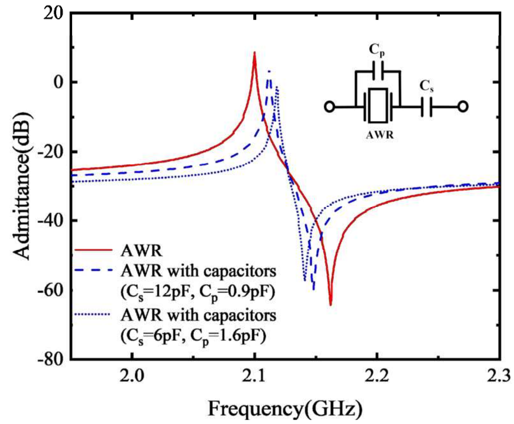

Fig. 3. Admittance response of the AWR with capacitors.

III. Application To Filter Design

With the proposed AWLR concept, it is possible to build a hybrid ladder filter with enlarged bandwidth. An example filter has been designed and the schematic of the proposed hybrid filter is shown in Fig.4(a). The inductors can enhance the bandwidth, and the capacitors and ladder structure can improve the steepness. The quality factors of the inductors and capacitors are 30 and 400, respectively. A commercially available resonator is considered and the electrical parameters of the employed resonator are from Ref. [6]. The electromechanical coupling coefficient k_t^2 is 5.6% (k_t^2 =1-w_s^2/w_p^2). The simulation results of the proposed hybrid filter compared with the traditional acoustic filter are shown in Fig.5, which has the same k_t^2 in resonators. The FBW of the proposed hybrid filter is 6.94% (1.24k_t^2), which is about 2.4 times larger than the one obtained in traditional acoustic filters.

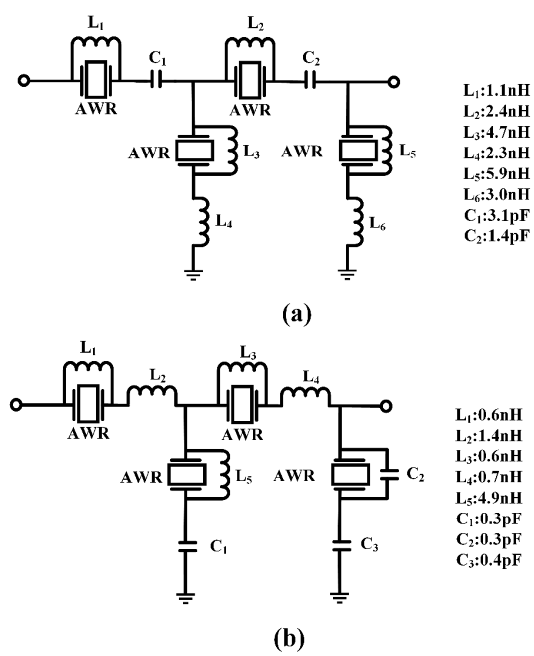

Fig. 4. Topology of the proposed hybrid filter. (a) the schematic of the proposed hybrid filter. (b) the schematic of the modified circuit.

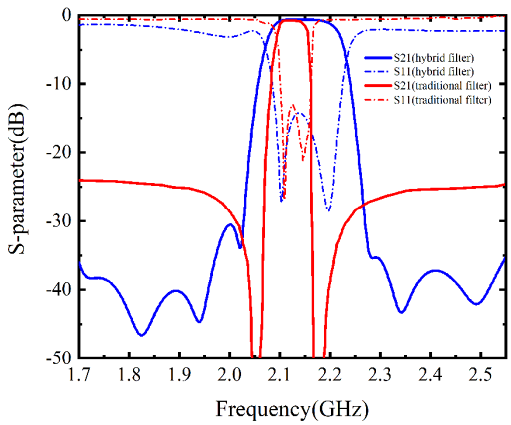

Fig. 5. Comparisons of the frequency response between the proposed hybrid filter and the traditional acoustic filter.

An electromagnetic co-simulation based optimization technique is implemented to enhance the simulated accuracy of the proposed hybrid filter. The optimization flow chart is illustrated in Fig.6. The ADS and HFSS software is used to simulate the hybrid filter and parasitic parameters of the printed circuit board (PCB), respectively. Considering the influence of parasitic parameters of the PCB, the proposed filter circuit is modified, shown in Fig.4(b). The filter layout is shown in Fig.7.

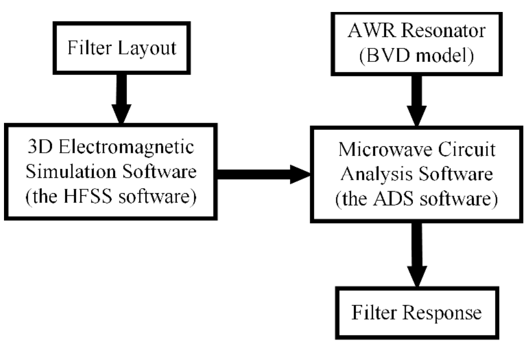

Fig. 6. Electromagnetic co-simulation based optimization flow chart.

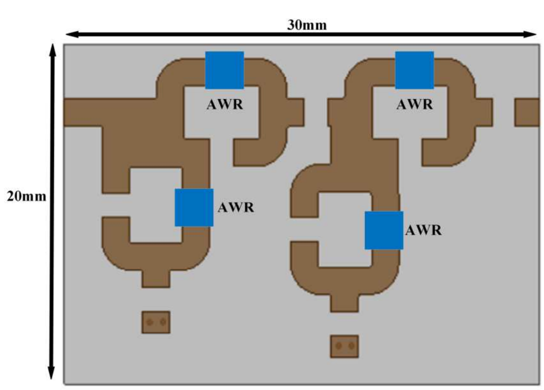

Fig. 7. Filter circuit board layout.

The co-simulation result of the proposed hybrid filter is shown in Fig.8. The FBW of the proposed hybrid filter is 6.0% ($1.1k_t^2$), which is about 2.1 times larger than the one obtained in traditional acoustic filters. The shape factor (SF), which is defined as the 30-dB bandwidth divided by the 3-dB bandwidth, of the proposed hybrid filter is 2.0. However, the values of the SF reported in Ref. [3, 4, 7, 9] reach up to 4.1-9.9, which indicates a remarkably steeper response achieved in this work. A similar SF is acquired in Ref. [6, 8]. However, the out-of-band rejection and the ripple of bandpass are 22dB and 2dB in Ref. [6], respectively. For the FBW in Ref. [8], it is merely $0.56k_t^2$. In addition, the insertion loss, the return loss, and the 3dB bandwidth achieved for the proposed hybrid filter are 0.6dB, below 11.4dB, and 129MHz, respectively.

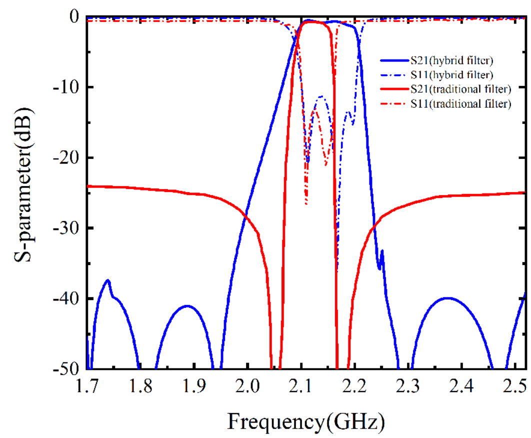

Fig. 8. Co-simulation result of the proposed hybrid filter.

IV. Conclusions

In this work, a theoretical approach to the realization of a hybrid filter with wide bandwidth has been demonstrated. The proposed hybrid filter is based on a ladder structure made up of the new class of the AWLR module, which has two lumped elements and an acoustic wave (AW) resonator. Two lumped elements are simultaneously connected in series and shunt for changing the resonant frequency and the anti-resonant frequency, which increases bandwidth or enhances steepness. The simulation results show that the FBW of the proposed hybrid filter is 6.0% ($1.1k_t^2$), which is about 2.1 times larger than the one obtained in traditional acoustic filters. The SF of the proposed hybrid filter is 2.0. These investigation results demonstrate that the proposed method can be used to design a hybrid filter with enlarged bandwidth, keeping the steepness of the transition.

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