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(54) **ACOUSTIC RESONATOR FILTER SYSTEM**

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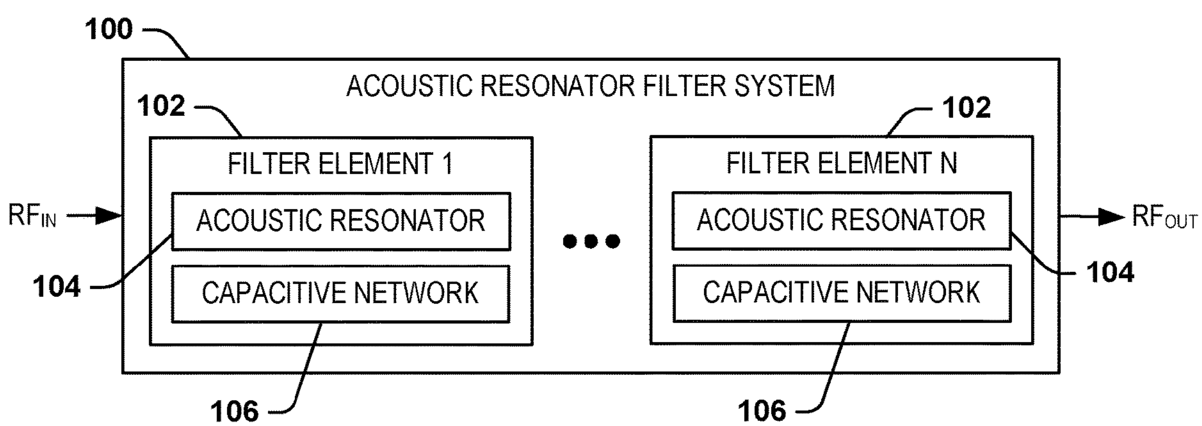
(57) **ABSTRACT**

One example includes an acoustic resonator filter system. The system includes a filter element arranged between a low-voltage rail and a filter-path node through which an RF input signal propagates to provide a filtered RF output signal. The filter element includes an acoustic resonator and a capacitive network arranged in parallel with the acoustic resonator.



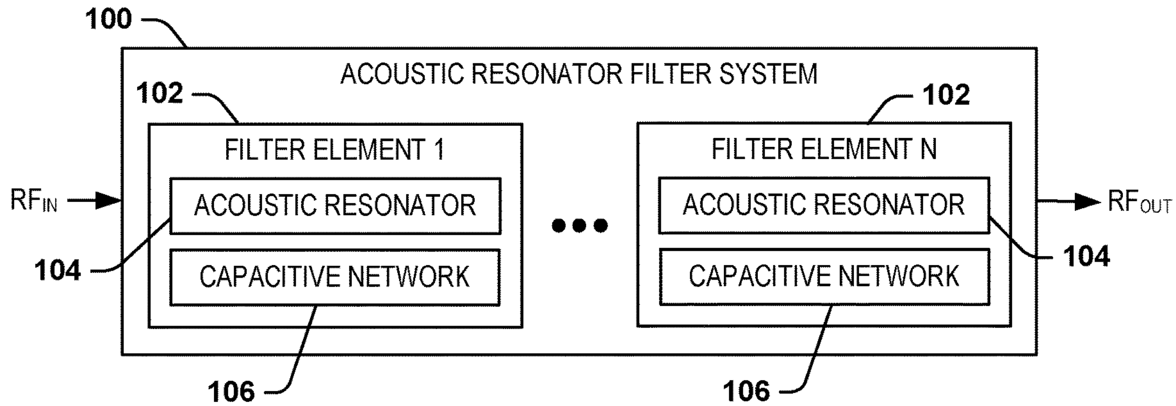

100
ACOUSTIC RESONATOR FILTER SYSTEM
102
FILTER ELEMENT 1
ACOUSTIC RESONATOR
CAPACITIVE NETWORK
102
FILTER ELEMENT N
ACOUSTIC RESONATOR
CAPACITIVE NETWORK
RFIN
RFOUT
104
104
106
106

FIG. 1

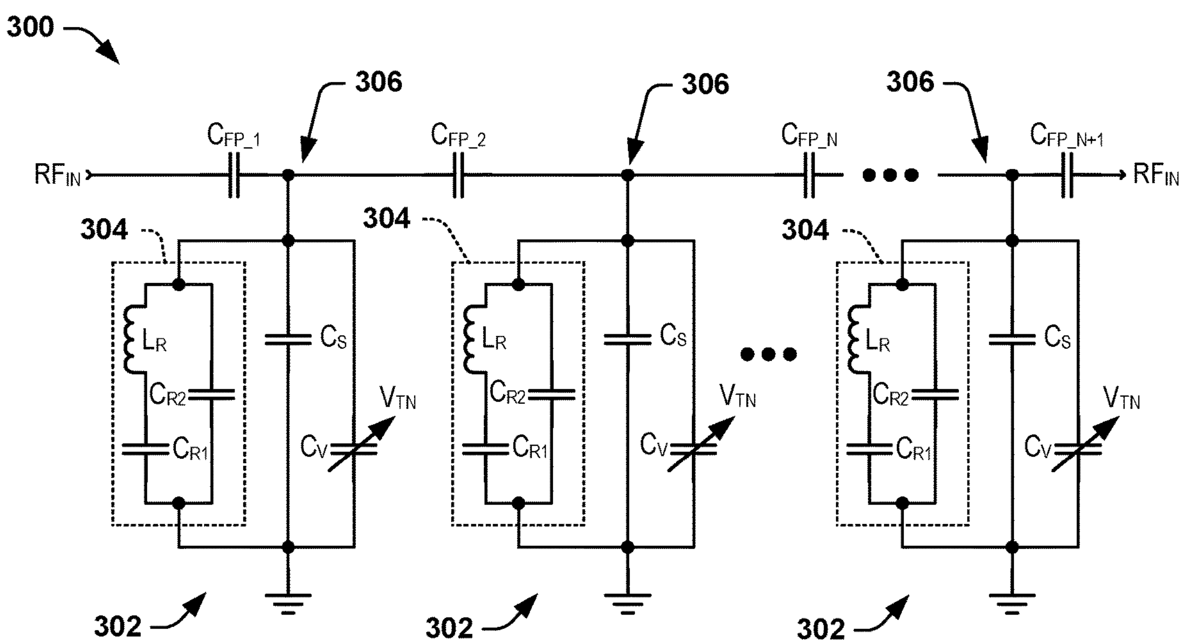

300
306
306
306
CFP_1
CFP_2
CFP_N
CFP_N+1
RFIN
RFIN
304
304
304
LR
CR2
CR1
CS
VTN
CV
302
302
302

FIG. 3

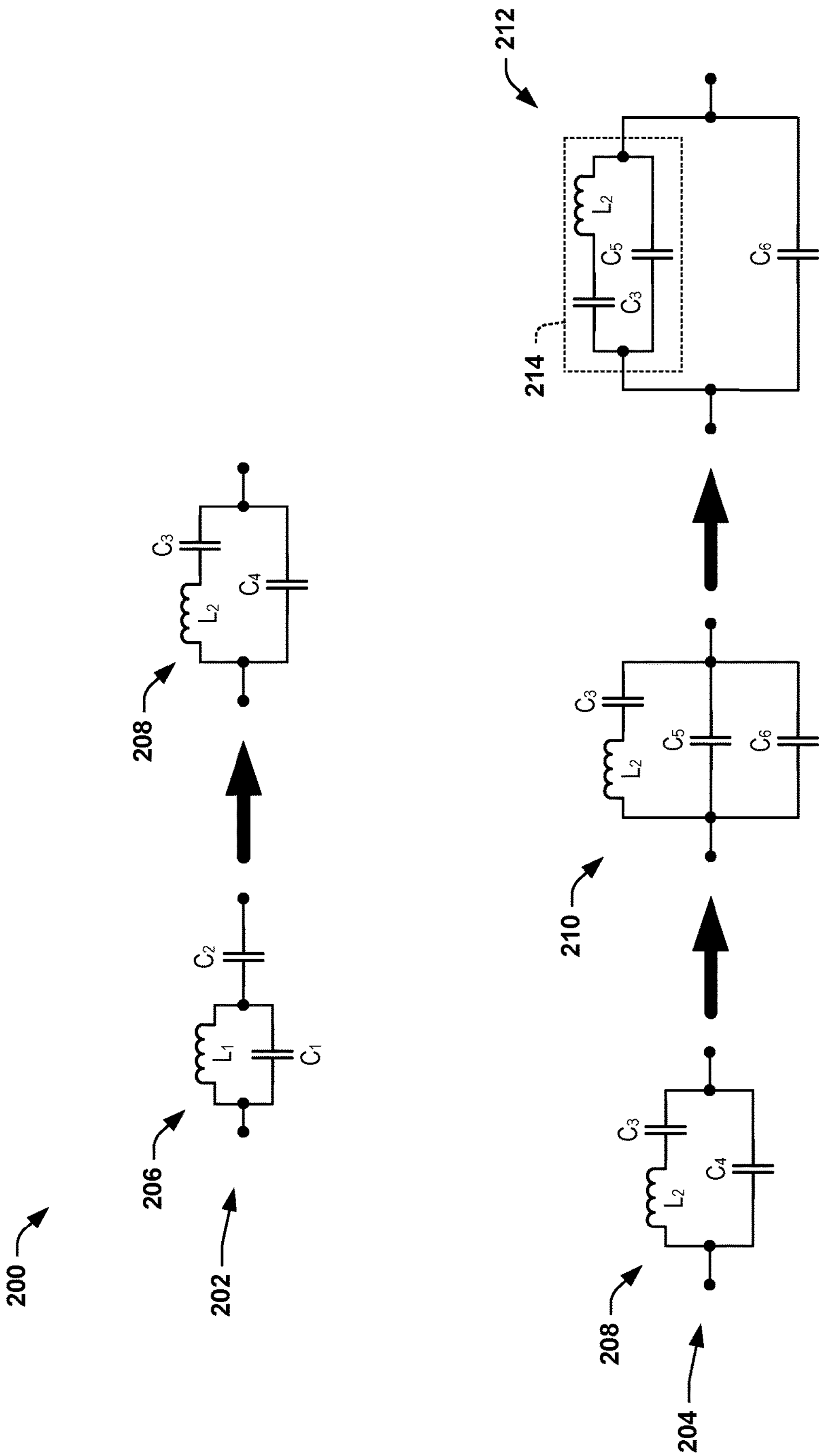

200
202
206
L1
C1
C2
208
L2
C3
C4
204
208
L2
C3
C4
210
L2
C3
C5
C6
212
214
L2
C5
C3
C6

FIG. 2

ACOUSTIC RESONATOR FILTER SYSTEM

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims priority from U.S. Provisional Patent Application No. 63/321085, filed 17 Mar. 2022, which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

[0002] The present disclosure relates generally to communications, and specifically to an acoustic resonator filter.

BACKGROUND

[0003] Resonator circuits are implemented in a variety of different types of applications, such as to filter ranges of frequencies. A variety of different types of resonators exist. One such type of resonator is an acoustic resonator that implements acoustic waves on an integrated circuit (IC). Acoustic resonators include bulk acoustic wave (BAW) resonators and standing acoustic wave (SAW) resonators. Acoustic wave resonators are designed to provide confinement of the acoustic energy in the resonator to increase quality factor (Q) of the resonator. As an example, conventional acoustic resonators can provide for effective filtering in a narrow band about a center frequency (e.g., +/− approximately 5 dB).

[0004] One example includes an acoustic resonator filter system. The system includes a filter element arranged between a low-voltage rail and a filter-path node through which an RF input signal propagates to provide a filtered RF output signal. The filter element includes an acoustic resonator and a capacitive network arranged in parallel with the acoustic resonator.

[0005] Another example includes an acoustic resonator filter system. The system includes a plurality of filter elements. Each of the filter elements can be arranged between a low-voltage rail and one of a plurality of filter-path nodes through which an RF input signal propagates to provide a filtered RF output signal. The acoustic resonator filter system is arranged as a resonator tank network. Each of the filter elements includes an acoustic resonator and a capacitive network arranged in parallel with the acoustic resonator.

[0006] Another example includes an integrated circuit (IC) that includes an acoustic resonator filter system. The system includes a plurality of filter elements. Each of the filter elements can be arranged between a low-voltage rail and one of a plurality of filter-path nodes through which an RF input signal propagates to provide a filtered RF output signal. The acoustic resonator filter system is arranged as a resonator tank network. Each of the filter elements includes an acoustic resonator and a capacitive network arranged in parallel with the acoustic resonator.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. **1** illustrates an example block diagram of an acoustic resonator filter system.

[0008] FIG. **2** illustrates an example diagram of dipole transforms of filter elements.

[0009] FIG. **3** illustrates an example diagram of an acoustic resonator filter system.

DETAILED DESCRIPTION

[0010] The present disclosure relates generally to communications, and specifically to an acoustic resonator filter system. The acoustic resonator filter system can be implemented in any of a variety of communications systems, such as in a transmit and/or a receive path of a wireless transceiver, or in a variety of variable filter applications. The acoustic resonator filter system includes a plurality of filter elements that each include an acoustic resonator and a capacitive network. As an example, the acoustic resonator can be configured as a combined overtone resonator (COR), a bulk acoustic wave (BAW) resonator, or another type of acoustic resonator. As another example, the capacitive network can include at least one capacitor provided in parallel with the acoustic resonator. For example, the capacitor(s) can include a fixed capacitor and a variable capacitor (varactor), such as a barium strontium titanate (BST) varactor, configured to provide a variable capacitance.

[0011] As an example, the filter elements can each be arranged between one of a plurality of filter-path nodes and a low-voltage rail (e.g., ground). Therefore, the acoustic resonator filter system can be arranged as a resonator tank network. As an example, each of the filter-path nodes can be coupled by a plurality of filter-path capacitors. The physical characteristics of the acoustic resonators, the capacitance of the capacitive network, and the capacitance of the filter-path capacitors can be arranged to tune the filter characteristics of the acoustic resonator filter system. Therefore, an RF input signal that is provided through a signal path that includes each of the filter-path nodes and the filter-path capacitors can be provided as an RF output signal that is filtered by the acoustic resonator filter system. Based on the arrangement of the filter elements that include an acoustic resonator and a capacitive network in parallel, the acoustic resonator filter system can achieve a significantly larger bandwidth (e.g., up to 25%) relative to a typical acoustic resonator filter. The arrangement of the acoustic resonator filter system as a resonator tank network with respect to the filter elements can thus provide for a significantly improved filter system than a typical filter that includes acoustic resonators in a ladder network.

[0012] FIG. **1** illustrates an example block diagram of an acoustic resonator filter system **100**. The acoustic resonator filter system can be implemented in any of a variety of communications systems, such as in a transmit and/or a receive path of a wireless transceiver, or as a filter block for a larger selective filter system. As described herein, the acoustic resonator filter system can provide pass-band filtering of a radio frequency (RF) input signal, demonstrated in the example of FIG. **1** as a signal RF_{IN}. As an example, the acoustic resonator filter system **100** can be fabricated in an integrated circuit (IC).

[0013] The acoustic resonator filter system **100** includes a plurality N of filter elements **102**. Each of the filter elements **102** includes an acoustic resonator **104** and a capacitive network **106**. As an example, the acoustic resonator **104** can be configured as a combined overtone resonator (COR), a bulk acoustic wave (BAW) resonator, or any of a variety of other types of acoustic resonators. The capacitive network **106** can be arranged in parallel with the acoustic resonator **104**. The arrangement and characteristics of the acoustic resonator **104** and capacitive network **106** in each of the filter elements can provide for a pass-band of the respective one of the filter elements **102** that can provide for a large bandwidth (e.g., up to approximately 25%) of the pass-band provided by the respective filter element **102**. Thus, the RF input signal RF_{IN} can be filtered at the respective pass-band and provided as an RF output signal RF_{OUT}.

[0014] As an example, the filter elements **102** can each be arranged between one of a plurality of filter-path nodes and a low-voltage rail (e.g., ground). Therefore, the acoustic resonator filter system **100** can be arranged as a resonator tank network. As an example, each of the filter-path nodes can be coupled by a plurality of filter-path capacitors. The physical characteristics of the acoustic resonators **104** and the capacitance values of the capacitive networks **106** of the respective filter elements **102** can be set to tune the filter characteristics of the acoustic resonator filter system **100**. The arrangement of the acoustic resonator filter system **100** as a resonator tank network with respect to the filter elements **102** can thus provide for a significantly improved filter system than a typical filter system that includes acoustic resonators in a ladder network.

[0015] FIG. **2** illustrates an example diagram **200** of dipole transforms of filter elements. The diagram **200** demonstrates a first dipole transform **202** and a second dipole transform **204**. The dipole transforms **202** and **204** can correspond to the formation of a filter element, such as one of the filter elements **102** of the example of FIG. **1**. Therefore, reference is to be made to the example of FIG. **1** in the following description of the example of FIG. **2**.

[0016] The first dipole transform **202** demonstrates a first resonator dipole **206**. The first resonator dipole **206** includes an inductor L_1 in parallel with a capacitor C_1, with the parallel arrangement of the inductor L_1 and the capacitor C_1 in series with a capacitor C_2. The first dipole transform **202** demonstrates a second resonator dipole **208** that is equivalent to the first resonator dipole **206**. The second resonator dipole **208** includes an inductor L_2 in series with a capacitor C_3, with the series arrangement of the inductor L_2 and the capacitor C_3 in parallel with a capacitor C_4. For example, the equivalency between the first and second resonator dipoles **208** and **210** can be based on an approximately same performance over frequency (e.g., including poles and zeroes) based on tuning the values of the inductors L_1 and L_2, as well as the capacitors C_1 through C_4.

[0017] The second dipole transform **204** demonstrates the second resonator dipole **208**, and a third resonator dipole **210** that is approximately equivalent to the second resonator dipole **208**. The third resonator dipole **210** is arranged similar to the second dipole **208**, but the capacitor C_4 is split into a parallel set of capacitors C_5 and C_6. Similar to as described above in the second dipole transform **204**, the equivalency between the second and third resonator dipoles **208** and **210** can correspond to a nominal performance over frequency (e.g., including poles and zeroes) based on tuning the values of the inductors L_1 and L_2, as well as the capacitors C_1, C_5, and C_6. However, by tuning the capacitance values of the parallel set of capacitors C_5 and C_6, the bandwidth of the third resonator dipole **210** can be tuned to a much larger percentage about the frequency pole than by implementing the capacitor C_4 alone.

[0018] The second dipole transform **204** also demonstrates a fourth resonator dipole **212** that is approximately equivalent to the third resonator dipole **210**. The fourth resonator dipole **212** is arranged similar to the third dipole **210**, but the capacitor C_5 is arranged in parallel with the series arrangement of the inductor L_2 and the capacitor C_5. The arrangement of the inductor L_2 and the capacitors C_2 and C_5 can thus correspond to an acoustic resonator dipole equivalent circuit, demonstrated at **214**. The arrangement of the acoustic resonator dipole **214** can be representative of operational characteristics of the associated acoustic resonator. For example, the inductance value of the inductor L_2, the capacitance value of the capacitor C_3, and the capacitance value of the capacitor C_5 can be based on physical characteristics (e.g., substrate dimensions) of the associated acoustic resonator.

[0019] Therefore, similar to as described above regarding the third resonator dipole **210**, by incorporating the capacitor C_6 in parallel with an acoustic resonator (e.g., the acoustic resonator dipole **214**), the associated fourth dipole **212** can achieve a bandwidth having a significantly larger percentage about the associated frequency pole the acoustic resonator dipole **214** alone. Accordingly, the fourth resonator dipole **212** can be implemented as a filter element in an acoustic resonator filter system, such as the acoustic resonator filter system **100** in the example of FIG. **1**, to provide significantly greater performance than a conventional filter system that implements acoustic resonators.

[0020] FIG. **3** illustrates an example diagram of an acoustic resonator filter system **300**. The acoustic resonator filter system **300** can correspond to the acoustic resonator filter system **100** in the example of FIG. **1**. Therefore, reference is to be made to the example of FIG. **1** in the following description of the example of FIG. **3**.

[0021] The acoustic resonator filter system **300** includes a plurality N of filter elements **302**, where N is a positive integer. Each of the filter elements **302** includes an acoustic resonator **304**, a capacitor C_S, and another capacitor C_V arranged in parallel. The filter elements **302** can be arranged similar to the fourth resonator dipole **212** in the example of FIG. **2**, such that the parallel arrangement of the capacitors C_S and C_V can correspond to the capacitor C_6. In the example of FIG. **3**, the capacitor is demonstrated as a variable capacitor (varactor), such that a voltage V_{TN} could be provided to set the capacitance of the capacitor C_V. Alternatively, the capacitor C_V could have a fixed capacitance, or the capacitors C_S and C_V could be combined into a single equivalent capacitance (e.g., similar to the capacitor C_6).

[0022] The acoustic resonator **304** is demonstrated in the example of FIG. **3** as an acoustic resonator dipole including a first capacitor C_{R1} and an inductor L_R arranged in series, with the series arrangement of the first capacitor C_{R1} and the inductor L_R being arranged in parallel with a second capacitor C_{R2}. The acoustic resonator **304** is therefore arranged similar to the acoustic resonator dipole **214** in the example of FIG. **2**. The arrangement of the acoustic resonator **304** can be representative of operational characteristics of the acoustic resonator **304**. For example, the values of the first capacitor C_{R1}, the second capacitor C_{R2}, and the inductor L_R can be based on physical characteristics (e.g., substrate dimensions) of the acoustic resonator **304**. The filter elements **302** can be arranged in a symmetrical manner with respect to the first, last, and intermediate filter elements **302** to provide appropriate impedance matching and filter matching characteristics.

[0023] As an example, the acoustic resonator **304** can be configured as a COR (e.g., an aluminum nitride (AlN) COR). Therefore, the acoustic resonators **304** can exhibit a high quality factor (Q) at frequencies both above and below a given range of frequencies of the RF input signal RF_{IN}

(e.g., Ka-band). For example, the CORs can operate at a Q between approximately 400 and approximately 1000. Additionally, the acoustic resonators **304** configured as CORs can provide a shape factor selectivity of approximately 1.03 to provide significant out-of-band and interference rejection of the RF input signal RF_{IN}. Such a selectivity can achieve a rejection of approximately 60 dB at approximately 50 MHz on either side of a 3.5 GHz bandwidth, thus providing a significantly greater rejection characteristic of conventional acoustic resonator filters (e.g., exhibiting a selectivity of approximately 1.5).

[0024] The parallel arrangement of the acoustic resonator **304**, the capacitor C_S, and the capacitor C_V can provide for significantly improved filter characteristics over conventional filters. For example, the split capacitance provided by the capacitors C_S and C_V in parallel with the acoustic resonator **304** can provide for the ability to tune of the filter element **302** over a broad frequency range with minimal impact to quality factor Q and insertion loss. As an example, the capacitor C_V can be configured as a barium strontium titanate (BST) varactor, thus enabling a tuning range of approximately 33% with a loss tangent of approximately 0.006 and a quality factor Q of approximately 40 at a frequency of approximately 18 GHz. Therefore, the split capacitor arrangement of the capacitors C_S and C_V in parallel with the acoustic resonator **304** can provide for a large range of frequency tuning without providing performance degradation of the acoustic resonator filter system **300**.

[0025] In the example of FIG. **3**, each of the filter elements **302** is arranged between a filter-path node **306** and a low-voltage rail, demonstrated in the example of FIG. **3** as ground. Each of the filter-path nodes **306** interconnects a pair of filter-path capacitors, demonstrated in the example of FIG. **3** as capacitors C_{FP_1} through C_{FP_N+1} for the set of N filter elements. Therefore, the filter-path capacitors C_{FP_1} through C_{FP_N+1} number one greater in quantity than the N filter elements **302**. Therefore, the acoustic resonator filter system **300** is arranged as a resonator tank network to filter the RF input signal RF_{IN}. The RF input signal RF_{IN} is provided in a signal path through the filter-path capacitors C_{FP_1} through C_{FP_N+1} and the filter-path nodes **306** to provide the RF output signal RF_{OUT}. Therefore, based on the arrangement of the filter elements **302** between the filter-path capacitors C_{FP_1} through C_{FP_N+1}, the acoustic resonator filter system **300** is configured to provide one or more pass-bands (e.g., harmonically related passbands). As an example, a given pass-band of the acoustic resonator filter system **300** can have a bandwidth up to approximately 25%. By contrast, a conventional filter system that includes an acoustic resonator can have a bandwidth of less than 5%. Therefore, the acoustic resonator filter system **300** can provide a significant benefit over a typical filter system that includes an acoustic resonator.

[0026] What have been described above are examples of the present invention. It is, of course, not possible to describe every conceivable combination of components or methodologies for purposes of describing the present invention, but one of ordinary skill in the art will recognize that many further combinations and permutations of the present invention are possible. Accordingly, the present invention is intended to embrace all such alterations, modifications and variations that fall within the spirit and scope of the appended claims. Additionally, where the disclosure or claims recite "a," "an," "a first," or "another" element, or the equivalent thereof, it should be interpreted to include one or more than one such element, neither requiring nor excluding two or more such elements. As used herein, the term "includes" means includes but not limited to, and the term "including" means including but not limited to. The term "based on" means based at least in part on.

What is claimed is:

1. An acoustic resonator filter system comprising a filter element arranged between a low-voltage rail and a filter-path node through which an RF input signal propagates to provide a filtered RF output signal, the filter element comprising:

an acoustic resonator; and

a capacitive network arranged in parallel with the acoustic resonator.

2. The system of claim **1**, wherein the capacitive network comprises:

a first capacitor arranged in parallel with the acoustic resonator; and

a second capacitor arranged in parallel with the acoustic resonator and the first capacitor.

3. The system of claim **2**, wherein the second capacitor is arranged as a varactor that is configured to provide a variable capacitance in response to a control voltage.

4. The system of claim **3**, wherein the varactor is arranged as a barium strontium titanate (BST) varactor.

5. The system of claim **1**, wherein the filter element is a first filter element of a plurality of filter elements, each of the filter elements being arranged between one of a plurality of filter-path nodes and the low-voltage rail, such that the acoustic resonator filter system is arranged as a resonator tank network.

6. The system of claim **5**, further comprising a plurality of filter-path capacitors, each of the filter-path capacitors being coupled between a pair of the filter-path nodes, such that the RF input signal propagate through each of the filter-path capacitors and each of the filter-path nodes.

7. The system of claim **1**, wherein the acoustic resonator comprises physical characteristics and wherein the capacitive network comprises a capacitance value, wherein the physical characteristics and the capacitance value are selected to set filter characteristics associated with the acoustic resonator filter system.

8. The system of claim **1**, wherein the acoustic resonator is arranged as a combined overtone resonator (COR).

9. An integrated circuit (IC) comprising the acoustic resonator filter system of claim **1**.

10. An acoustic resonator filter system comprising a plurality of filter elements, each of the filter elements being arranged between a low-voltage rail and one of a plurality of filter-path nodes through which an RF input signal propagates to provide a filtered RF output signal, such that the acoustic resonator filter system is arranged as a resonator tank network, each of the filter elements comprising:

an acoustic resonator; and

a capacitive network arranged in parallel with the acoustic resonator.

11. The system of claim **10**, wherein the capacitive network comprises:

a first capacitor arranged in parallel with the acoustic resonator; and

a second capacitor arranged in parallel with the acoustic resonator and the first capacitor.

12. The system of claim **11**, wherein the second capacitor is arranged as a varactor that is configured to provide a variable capacitance in response to a control voltage.

13. The system of claim **11**, further comprising a plurality of filter-path capacitors, each of the filter-path capacitors being coupled between a pair of the filter-path nodes, such that the RF input signal propagate through each of the filter-path capacitors and each of the filter-path nodes.

14. The system of claim **10**, wherein the acoustic resonator comprises physical characteristics and wherein the capacitive network comprises a capacitance value, wherein the physical characteristics and the capacitance value are selected to set filter characteristics associated with the acoustic resonator filter system.

15. An integrated circuit (IC) comprising the acoustic resonator filter system of claim **10**.

16. An integrated circuit (IC) comprising an acoustic resonator filter system, the acoustic resonator filter system comprising a plurality of filter elements, each of the filter elements being arranged between a low-voltage rail and one of a plurality of filter-path nodes through which an RF input signal propagates to provide a filtered RF output signal, such that the acoustic resonator filter system is arranged as a resonator tank network, each of the filter elements comprising:

an acoustic resonator; and

a capacitive network arranged in parallel with the acoustic resonator.

17. The IC of claim **16**, wherein the capacitive network comprises:

a first capacitor arranged in parallel with the acoustic resonator; and

a second capacitor arranged in parallel with the acoustic resonator and the first capacitor.

18. The IC of claim **17**, wherein the second capacitor is arranged as a varactor that is configured to provide a variable capacitance in response to a control voltage.

19. The IC of claim **16**, wherein the acoustic resonator comprises physical characteristics and wherein the capacitive network comprises a capacitance value, wherein the physical characteristics and the capacitance value are selected to set filter characteristics associated with the acoustic resonator filter system.

20. The IC of claim **16**, wherein the acoustic resonator is arranged as a combined overtone resonator (COR).

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