

and BAW solidly mounted resonators (SMRs). In BAW resonators, acoustic waves propagate in a bulk of a piezoelectric layer.

5 **[0005]** BAW resonators can have non-linearities at high power levels. For example, BAW resonators can generate second harmonic power emissions (H2) when filtering signals at high power levels. Reducing and/or eliminating H2 is generally desirable.

SUMMARY

[0006] The innovations described in the claims each have several aspects, no single one of which is solely responsible for its desirable attributes. Without limiting the scope of the claims, some prominent features of this disclosure will now be briefly described.

10 **[0007]** One aspect of this disclosure is an acoustic wave filter with second harmonic emission suppression. The acoustic wave filter includes a first pair of bulk acoustic wave resonators in anti-series with each other, a second pair of bulk acoustic wave resonators in anti-series with each other, and a capacitor. The first pair of bulk acoustic wave resonators includes a first bulk acoustic wave resonator and a second bulk acoustic wave resonator. The
15 second pair of bulk acoustic wave resonators is in parallel with the first pair of bulk acoustic wave resonators. The second pair of bulk acoustic wave resonators has reverse electrode polarization relative to the first pair of bulk acoustic wave resonators. The capacitor is connected to a common electrode of the first bulk acoustic wave resonator and the second bulk acoustic wave resonator. The capacitor is configured to compensate for a mismatch in parasitic
20 capacitance between the first pair of bulk acoustic wave resonators and the second pair of bulk acoustic wave resonators. The acoustic wave filter is configured to filter a radio frequency signal.

[0008] The acoustic wave filter can include a plurality of additional acoustic wave resonators. All other acoustic wave resonators of the acoustic wave filter can be coupled to an
25 antenna node by way of the first and second pairs of bulk acoustic wave resonators. The plurality of additional acoustic wave resonators can include a pair of shunt resonators in anti-parallel with each other in a filter stage. The plurality of additional acoustic wave resonators can include a pair of series bulk acoustic wave resonators in anti-series with each other in a filter stage. The acoustic wave filter can include a second capacitor connected to a

common electrode of the pair of series bulk acoustic wave resonators. The plurality of additional acoustic wave resonators can be bulk acoustic wave resonators.

[0009] The first and second bulk acoustic wave resonators can be series bulk acoustic wave resonators.

5 **[0010]** The acoustic wave filter can be a transmit filter.

[0011] The acoustic wave filter can be included in a multiplexer that includes at least one additional acoustic wave filter connected to the acoustic wave filter at a common node.

10 **[0012]** The capacitor can have a capacitance in a range from 0.03 picofarad to 0.2 picofarad. The capacitor can be an interdigital transducer electrode capacitor. The capacitor can be a resonator capacitor. The capacitor can be a near metal capacitor. The capacitor can be a metal insulator metal capacitor.

15 **[0013]** The acoustic wave filter can include a pair of shunt bulk acoustic wave resonators in anti-series with each other and a second capacitor connected to a common electrode of the pair of shunt bulk acoustic wave resonators.

20 **[0014]** Another aspect of this disclosure is a radio frequency module that includes an acoustic wave filter, radio frequency circuitry coupled to the acoustic wave filter, and a package structure enclosing the acoustic wave filter and the radio frequency circuitry. The acoustic wave filter includes a first pair of bulk acoustic wave resonators in anti-series with each other, a second pair of bulk acoustic wave resonators in anti-series with each other and having reverse electrode polarization relative to the first pair of bulk acoustic wave resonators, and a capacitor connected to a common electrode of a first bulk acoustic wave resonator and a second bulk acoustic wave resonator of the first pair of bulk acoustic wave resonators.

[0015] The radio frequency circuitry can include a switch and/or a power amplifier.

25 **[0016]** The acoustic wave filter is included in a multiplexer. The multiplexer can include a second filter connected to the acoustic wave filter at a common node.

30 **[0017]** Another aspect of this disclosure is method of radio frequency signal processing with second harmonic emission suppression. The method includes amplifying a radio frequency signal and filtering the radio frequency signal with an acoustic wave filter. The acoustic wave filter includes a first pair of bulk acoustic wave resonators in anti-series with each other, a second pair of bulk acoustic wave resonators in anti-series with each other

and having reverse electrode polarization relative to the first pair of bulk acoustic wave resonators, and a capacitor connected to a common electrode of a first bulk acoustic wave resonator and a second bulk acoustic wave resonator of the first pair of bulk acoustic wave resonators, the capacitor compensating for a mismatch in parasitic capacitance between the first pair of bulk acoustic wave resonators and the second pair of bulk acoustic wave resonators to provide second harmonic emission suppression.

[0018] Another aspect of this disclosure is an acoustic wave filter with second harmonic emission suppression. The acoustic wave filter includes a first pair of bulk acoustic wave resonators in anti-series with each other in a filter stage and a second pair of bulk acoustic wave resonators in anti-series with each other in another filter stage. The second pair of bulk acoustic wave resonators have reverse electrode polarization relative to the first pair of bulk acoustic wave resonators. The first pair of bulk acoustic wave resonators is series with the second pair of bulk acoustic wave resonators. The acoustic wave filter is configured to filter a radio frequency signal.

[0019] The acoustic wave filter can include comprising a capacitor connected to a common electrode of the first pair of bulk acoustic wave resonators. The capacitor can cause second harmonic emissions to be reduced. The capacitor can have a capacitance in a range from 0.03 picofarad to 0.2 picofarad. The acoustic wave filter can include a second capacitor connected to a common electrode of the second pair of bulk acoustic wave resonators.

[0020] The acoustic wave filter can include a third pair of bulk acoustic wave resonators in anti-series with each other. The first pair of bulk acoustic wave resonators can be in series with the third pair of bulk acoustic wave resonators. The first pair of bulk acoustic wave resonators and the third pair of bulk acoustic wave resonators can have a common electrode polarization.

[0021] The acoustic wave filter can include a pair of shunt bulk acoustic wave resonators in anti-parallel with each other in a shunt filter stage. The acoustic wave filter can include an inductor in series with one shunt bulk acoustic wave resonator of the pair of shunt bulk acoustic wave resonators. The acoustic wave filter can include a capacitor in series with one shunt bulk acoustic wave resonator of the pair of shunt bulk acoustic wave resonators.

[0022] The acoustic wave filter can include a plurality of series bulk acoustic wave resonators coupled between the first pair of bulk acoustic wave resonators and the second pair of bulk acoustic wave resonators.

5 **[0023]** The acoustic wave filter can include a third pair of bulk acoustic wave resonators in anti-parallel with each other and a passive impedance element in series with one bulk acoustic wave resonator of the third pair, in which the third pair of bulk acoustic wave resonators is in series with the first pair of bulk acoustic wave resonators.

10 **[0024]** The first pair of bulk acoustic wave resonators can be in a first series filter stage of the acoustic wave filter form an antenna node. All other acoustic wave resonators of the acoustic wave filter can be coupled to an antenna node by way of the first pair of bulk acoustic wave resonators.

[0025] The acoustic wave filter can be a transmit filter.

15 **[0026]** The acoustic wave filter can be included in a multiplexer that includes at least one additional acoustic wave filter connected to the acoustic wave filter at a common node.

[0027] The acoustic wave filter can include a pair of shunt bulk acoustic wave resonators in anti-series with each other. The acoustic wave filter can include a second capacitor connected to a common electrode of the pair of shunt bulk acoustic wave resonators.

20 **[0028]** Another aspect of this disclosure is an acoustic wave filter with second harmonic emission suppression. The acoustic wave filter includes a first bulk acoustic wave resonator, a second bulk acoustic wave resonator in anti-parallel with the first bulk acoustic wave resonator, and a passive impedance element in series with the first bulk acoustic wave resonator. The passive impedance element is configured to cause to an imbalance in resonant frequency between the first and second bulk acoustic wave resonators to be reduced. The
25 acoustic wave filter is configured to filter a radio frequency signal.

[0029] The passive impedance element can be a capacitor. The passive impedance element can be an inductor.

30 **[0030]** The first and second bulk acoustic wave resonators can be series resonators. The first and second bulk acoustic wave resonators can be included in a first series stage of the acoustic wave filter from an antenna node. The acoustic wave filter can be a transmit filter.

[0031] The first and second bulk acoustic wave resonators can be shunt resonators. The acoustic wave filter can be included in a multiplexer. The first and second bulk acoustic wave resonators can be included in a first shunt stage of the acoustic wave filter from a common node of the multiplexer. The acoustic wave filter can be a receive filter.

5 **[0032]** The acoustic wave filter can include a plurality of additional bulk acoustic wave resonators.

[0033] Another aspect of this disclosure is a multiplexer with second harmonic emission suppression. The multiplexer includes a first acoustic wave filter and a second acoustic wave filter coupled to the first acoustic wave filter at a common node. The first
10 acoustic wave filter includes a first bulk acoustic wave resonator, a second bulk acoustic wave resonator in anti-parallel with the first bulk acoustic wave resonator, and a passive impedance element in series with the first bulk acoustic wave resonator. The passive impedance element is configured to cause to an imbalance in resonant frequency between the first and second bulk acoustic wave resonators to be reduced.

15 **[0034]** The passive impedance element can be a capacitor. The passive impedance element can be an inductor.

[0035] The first and second bulk acoustic wave resonators can be series resonators. The first acoustic wave filter can be a transmit filter. The first and second bulk acoustic wave resonators can be included in a first series stage of the first acoustic wave filter from the
20 common node.

[0036] The first and second bulk acoustic wave resonators can be shunt resonators. The first acoustic wave filter can be a receive filter. The second acoustic wave filter can be a transmit filter. The first and second bulk acoustic wave resonators can be in a first shunt stage of the first acoustic wave filter from the common node.

25 **[0036a]** Another aspect of this disclosure is a radio frequency module that includes an acoustic wave filter, radio frequency circuitry coupled to the acoustic wave filter, and a package structure enclosing the acoustic wave filter and the radio frequency circuitry. The acoustic wave filter includes a first pair of bulk acoustic wave resonators in anti-series with each other and a second pair of bulk acoustic wave resonators in anti-series with each other.
30 The second pair of bulk acoustic wave resonators having reverse electrode polarization relative to the first pair of bulk acoustic wave resonators. The first pair of bulk acoustic wave resonators

is in series with and in a different filter stage than the second pair of bulk acoustic wave resonators.

[0036b] Another aspect of this disclosure is a wireless communication device that includes a radio frequency front end including an acoustic wave filter configured to filter a
5 radio frequency signal and an antenna configured to transmit the radio frequency signal. The acoustic wave filter includes a first pair of bulk acoustic wave resonators in anti-series with each other and a second pair of bulk acoustic wave resonators in anti-series with each other. The second pair of bulk acoustic wave resonators having reverse electrode polarization relative to the first pair of bulk acoustic wave resonators. The first pair of bulk acoustic wave resonators
10 is in series with and in a different filter stage than the second pair of bulk acoustic wave resonators.

[0036c] Another aspect of this disclosure is a method of radio frequency signal processing with second harmonic emission suppression. The method includes amplifying a radio frequency signal and filtering the radio frequency signal with an acoustic wave filter to
15 suppress second harmonic emissions. The acoustic wave filter includes a first bulk acoustic wave resonator, a second bulk acoustic wave resonator in anti-parallel with the first bulk acoustic wave resonator, and a passive impedance element in series with the first bulk acoustic wave resonator.

[0037] An example of this disclosure is a multiplexer that includes an acoustic
20 wave filter in accordance with any suitable principles and advantages disclosed herein and a second filter connected to the acoustic wave filter at a common node.

[0038] Another example of this disclosure is a radio frequency module that includes an acoustic wave filter in accordance with any suitable principles and advantages disclosed herein, radio frequency circuitry, and a package structure enclosing the acoustic wave
25 filter and the radio frequency circuitry.

[0039] Another example of this disclosure is a wireless communication device that includes a radio frequency front end including an acoustic wave filter in accordance with any suitable principles and advantages disclosed herein; and an antenna configured to transmit the radio frequency signal filtered by the acoustic wave filter.

5 [0040] Another example of this disclosure is a method of radio frequency signal processing with second harmonic emission suppression. The method includes amplifying a radio frequency signal and filtering the radio frequency signal with an acoustic wave filter in accordance with any suitable principles and advantages disclosed herein.

10 [0041] For purposes of summarizing the disclosure, certain aspects, advantages and novel features of the innovations have been described herein. It is to be understood that not necessarily all such advantages may be achieved in accordance with any particular embodiment. Thus, the innovations may be embodied or carried out in a manner that achieves or optimizes one advantage or group of advantages as taught herein without necessarily achieving other advantages as may be taught or suggested herein.

15 BRIEF DESCRIPTION OF THE DRAWINGS

[0042] Embodiments of this disclosure will now be described, by way of non-limiting example, with reference to the accompanying drawings.

[0043] Figure 1A is a schematic diagram of a series bulk acoustic wave resonator implemented by two bulk acoustic wave resonators in anti-series.

20 [0044] Figure 1B is a schematic diagram of a shunt bulk acoustic wave resonator implemented by two bulk acoustic wave resonators in anti-parallel.

[0045] Figure 1C is a schematic diagram of a bulk acoustic wave resonator implemented by two pairs of bulk acoustic wave resonators in parallel, where each pair of bulk acoustic wave resonators includes two bulk acoustic wave resonators in anti-series.

25 [0046] Figure 2 is a schematic diagram of a bulk acoustic wave filter that includes series and shunt resonator splits.

[0047] Figure 3A is a schematic diagram of a bulk acoustic wave filter that includes a quad resonator split with a balancing capacitor according to an embodiment.

30 [0048] Figure 3B is a schematic diagram of a bulk acoustic wave filter that includes a quad resonator split with a balancing capacitor according to an embodiment.