[0005] Filtering relatively high frequency radio frequency signals and meeting stringent filtering specifications can be difficult. Accordingly, improved filters are desired to filter relatively high frequency signals and meet performance specifications.

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.

[0006a] In a first aspect, the present disclosure refers to a cascaded filter circuit for radio frequency filtering, the cascaded filter circuit comprising: a hybrid acoustic LC filter configured to filter a radio frequency signal, the hybrid acoustic LC filter including an acoustic resonator on an acoustic resonator die, a capacitor external to the acoustic resonator die, and an inductor external to the acoustic resonator die; a non-acoustic LC filter including an LC circuit; a second non-acoustic LC filter; and a switch configured to couple the hybrid acoustic LC filter and the non-acoustic LC filter in a first state, and to couple the hybrid acoustic LC filter and the second non-acoustic LC filter in a second state.

[0007] One example of this disclosure is a cascaded filter for radio frequency filtering. The cascaded filter includes a hybrid acoustic LC filter and a non-acoustic LC filter cascaded with the hybrid acoustic LC filter. The hybrid acoustic LC filter is configured to filter a radio frequency signal. The hybrid acoustic LC filter includes a first acoustic resonator on an acoustic resonator die, a second acoustic resonator, a capacitor external to the acoustic resonator die, and an inductor external to the acoustic resonator die. The non-acoustic LC filter includes an LC circuit.

[0008] The hybrid acoustic LC filter further can further include a second inductor in parallel with the second acoustic resonator, in which the second acoustic resonator is arranged as a shunt resonator in series with the inductor.

[0009] The first acoustic resonator and the second acoustic resonator can be shunt resonators. The capacitor and the inductor can be arranged as an LC tank coupled between the first acoustic resonator and the second acoustic resonator.

[0010] The first acoustic resonator can be coupled to a node in a signal path between the LC circuit and both the inductor and the capacitor.

[0011] The first acoustic resonator and the second acoustic resonator can be bulk acoustic wave resonators. For example, the first acoustic resonator and the second acoustic resonator can be film bulk acoustic wave resonators.

[0012] The LC circuit of the non-acoustic LC filter can include integrated passive devices on an integrated passive device die. The inductor of the hybrid acoustic LC filter can be a surface mount inductor. The inductor of the hybrid acoustic LC filter can include a

conductive trace of a substrate. The integrated passive devices can include an LC shunt circuit and a series LC resonant circuit.

[0013] The LC circuit of the non-acoustic LC filter can include a series LC resonant circuit and an LC shunt circuit. The series LC resonant circuit can include a parallel LC circuit. The LC shunt circuit can includes a series LC circuit. The LC circuit of the non-acoustic LC filter can further include a second shunt series LC circuit.

[0014] A passband of the cascaded filter can be set by the non-acoustic LC filter. The first acoustic resonator can be arranged to provide rejection at a frequency band outside of the passband. A lower bound of the passband can be at least 3 gigahertz. The passband can spans from at least 3.3 gigahertz to 4.2 gigahertz.

[0015] Another aspect of this disclosure is a multiplexer that includes a first filter coupled to a common node and a second filter coupled to the common node. The first filter is configured to filter a radio frequency signal. The first filter includes a hybrid acoustic LC filter and a non-acoustic LC filter cascaded with the hybrid acoustic LC filter. The hybrid acoustic LC filter includes a first acoustic resonator on an acoustic resonator die, a second acoustic resonator, a capacitor external to the acoustic resonator die, and an inductor external to the acoustic resonator die.

[0016] The multiplexer can further includes a third filter coupled to the common node. The second filter can include a second hybrid acoustic LC filter. The second filter can include a second non-acoustic LC filter.

[0017] Another example of this disclosure is a wireless communication device that includes an antenna and a radio frequency front end in communication with the antenna. The radio frequency front end includes a filter configured to filter a radio frequency signal for transmission via the antenna. The filter includes a hybrid acoustic LC filter and a non-acoustic LC filter cascaded with the hybrid acoustic LC filter. The hybrid acoustic LC filter includes acoustic resonators on an acoustic resonator die, a capacitor external to the acoustic resonator die, and an inductor external to the acoustic resonator die.

[0018] The wireless communication device can be a mobile phone.

[0018a] In a second aspect, the present disclosure refers to a cascaded filter circuit for radio frequency filtering, the cascaded filter circuit comprising: a hybrid acoustic LC filter configured to filter a radio frequency signal, the hybrid acoustic LC filter including an

acoustic resonator on an acoustic resonator die, a capacitor external to the acoustic resonator die, and an inductor external to the acoustic resonator die; a non-acoustic LC filter including an LC circuit; a second hybrid acoustic LC filter; and a switch configured to couple the hybrid acoustic LC filter and the non-acoustic LC filter in a first state, and to couple the second hybrid acoustic LC filter and the non-acoustic LC filter in a second state.

[0019] Another example of this disclosure is a cascaded filter circuit for radio frequency filtering that includes a hybrid acoustic LC filter, a non-acoustic LC filter including

[0026] A passband of a cascaded filter that includes the non-acoustic LC filter and the hybrid acoustic LC filter can be set by the non-acoustic LC filter. A lower bound of the passband can be at least 3 gigahertz.

[0027] In a third aspect, this disclosure refers to a method of filtering a radio frequency signal. The method includes coupling, with a switch, a hybrid acoustic LC filter and a non-acoustic LC filter. The hybrid acoustic LC filter includes an acoustic resonator on an acoustic resonator die, a capacitor external to the acoustic resonator die, and an inductor external to the acoustic resonator die. The method also includes filtering a radio frequency signal while the hybrid acoustic LC filter and the non-acoustic filter are coupled together. The filtering includes providing, using the acoustic resonator of the hybrid acoustic LC filter, rejection outside of a passband of a filter that includes the hybrid acoustic LC filter and the non-acoustic LC filter.

[0028] The method can further include decoupling, with the switch, the hybrid acoustic LC filter from the non-acoustic LC filter; and coupling, with the switch, the hybrid acoustic LC filter and a second non acoustic LC filter. The method can further include providing, with a power amplifier, the radio frequency signal to the non-acoustic LC filter; and amplifying, with a low noise amplifier, a filtered signal provided by the second non-acoustic filter.

[0029] The filtering can include providing, using the acoustic resonator of the hybrid acoustic LC filter, rejection outside of a passband of a filter that includes the hybrid acoustic LC filter and the non-acoustic LC filter.

[0030] The radio frequency signal can have a frequency in a range from 3 gigahertz to 5 gigahertz.

[0031] Another aspect of this disclosure is a wireless communication device that includes an antenna and a radio frequency front end in communication with the antenna. The radio frequency front end includes a filter configured to filter a radio frequency signal for transmission via the antenna. The filter includes a hybrid acoustic LC filter, a non-acoustic LC filter, and a switch configured to selectively couple the hybrid acoustic LC filter and the non-acoustic LC filter. The hybrid acoustic LC filter includes an acoustic resonator on an acoustic resonator die and an LC component external to the acoustic resonator die.

[0032] The wireless communication device can be a mobile phone.

[0033] Another aspect of this disclosure is a parallel hybrid acoustic passive filter that includes a first sub-filter and a second sub-filter coupled in parallel with the first sub-

filter. The first sub-filter includes a first acoustic resonator and a first non-acoustic passive component. The second sub-filter includes a second acoustic resonator and a second non-acoustic passive component. The first sub-filter and the second sub-filter are together arranged to filter a radio frequency signal.

[0034] The first sub-filter and the second sub-filter can be together arranged as a band pass filter having a passband. A frequency response of the parallel hybrid acoustic passive filter can have a first sub-passband corresponding to the first sub-filter, a second sub-passband corresponding to the second sub-filter, and a notch at a notch frequency between the first sub-passband and a second sub-passband.

[0035] The first sub-filter and the second sub-filter can be together arranged as a band stop filter having a stop band. The band stop filter can have a notch in the stop band.

[0036] The first sub-filter can includes bulk acoustic wave resonators that include the acoustic resonator.

[0037] The first non-acoustic passive component can include a first inductor and a second inductor, in which the first inductor is in parallel with the acoustic resonator, and in which the acoustic resonator is arranged as a shunt resonator that is in series with the second inductor.

[0038] The first sub-filter can further include an additional acoustic resonator, in which the first acoustic resonator and the additional acoustic resonator are shunt resonators, and in which the first non-acoustic passive component includes a capacitor and an inductor arranged as an LC tank coupled between the first acoustic resonator and the additional acoustic resonator.

[0039] The second non-acoustic passive component can include an integrated passive device.

[0040] The first sub-filter and the second sub-filter can have different passbands. A lower bound of a passband of the parallel hybrid acoustic passive filter can be at least 2 gigahertz.

[0041] Another example of this disclosure is a multiplexer with a parallel hybrid acoustic passive filter. The multiplexer includes a first filter coupled to a common node and a second filter coupled to the common node. The first filter is configured to filter a radio

frequency signal. The first filter includes a first sub-filter in parallel with a second sub-filter. The first sub-filter includes a first acoustic resonator and a first non-acoustic passive component. The second sub-filter includes a second acoustic resonator and a second non acoustic passive component.

[0042] The first filter can be a band pass filter. A frequency response of the first filter can have a first sub-passband corresponding to the first sub-filter, a second sub-passband corresponding to the second sub-filter, and a notch at a notch frequency between the first sub-passband and a second sub-passband. The second filter can be a band stop filter.

[0043] The first filter can be a band stop filter having a stop band and a notch in the stop band.

[0044] The second filter can include another acoustic resonator and another non-acoustic passive component.

[0045] The first filter can have a first passband, the second filter can have a second passband, and the first passband can have a lower edge that is at a higher frequency than an upper edge of the second passband.

[0046] The multiplexer can further include a third filter coupled to the common node.

[0047] The multiplexer can further include a shared filter in series between the first filter and the common node, in which the shared filter is also in series between the second filter and the common node. The shared filter can be a high pass filter.

[0048] Another example of this disclosure is a wireless communication device that includes a radio frequency front end an antenna in communication with the radio frequency front end. The radio frequency front end includes a filter configured to filter a radio frequency signal. The filter includes a first sub-filter in parallel with a second sub filter. The first sub-filter includes a first acoustic resonator and a first non-acoustic passive component. The second sub-filter includes a second acoustic resonator and a second non acoustic passive component.

[0049] Another example of this disclosure is a multiplexer with a hybrid acoustic passive filter. The multiplexer includes a plurality of filters configured to filter respective radio frequency signals, a shared filter coupled between each of the plurality of filters and a

common node, and a radio frequency filter coupled to the common node. Each filter of the plurality of filters has a different passband. At least a first filter of the plurality of filters includes acoustic resonators and a non-acoustic passive component.

[0050] The plurality of filters can includes the first filter, a second filter, and a third filter. The first filter can be a first band pass filter having a first passband. The second filter can be a second band pass filter having a second passband. The third filter can be a band stop filter having a stop band that includes the first passband and the second passband.

[0051] The shared filter can be a high pass filter. The radio frequency filter can be a low pass filter.

[0052] The shared filter can be a non-acoustic LC filter. The shared filter can include second acoustic resonators and an LC component.

[0053] The non-acoustic passive component can include an inductor arranged in parallel with a first acoustic resonator of the acoustic resonators.

[0054] The acoustic resonators can be embodied on an acoustic resonator die. The non-acoustic passive component can include an inductor external to the acoustic resonator die and a capacitor external to the acoustic resonator die.

[0055] A second filter of the plurality of filter can include second acoustic resonators and a second non-acoustic passive component. The first filter can have a first passband and the second filter can have a second passband. The first and second passbands can both be within a frequency range from 2 gigahertz to 5 gigahertz. The first and second passbands can both be within a frequency range from 2 gigahertz to 3 gigahertz.

[0056] The multiplexer can be arranged as a quadplexer.

[0057] Another example of this disclosure is wireless communication device that includes an antenna and a multiplexer in communication with the antenna. The multiplexer includes a plurality of filters configured to filter respective radio frequency signals, a shared filter coupled between each of the plurality of filters and a common node, and a radio frequency filter coupled to the common node. The plurality of filters includes a first filter that includes acoustic resonators and a non-acoustic passive component.

[0058] A second filter of the plurality of filter can include second acoustic resonators and a second non-acoustic passive component. The wireless communication

device can be configured to support a carrier aggregation at the common node. The carrier aggregation can includes a first carrier and a second carrier, in which the first carrier is within a first passband of the first filter, and in which the second carrier is outside of the first passband and a second passband of the second filter.

[0059] Another example of this disclosure is a multiplexer with hybrid acoustic passive filters. The multiplexer includes a plurality of filters including a first filter and a second filter having different radio frequency passbands, a shared high pass filter coupled between each of the plurality of filters and a common node, and a low pass filter coupled to the common node. The first filter includes first acoustic resonators and a first LC circuit. The second filter includes second acoustic resonators and a second LC circuit.

[0060] The plurality of filters can further include a band stop filter having a stop band that includes the passbands of the first and second filters.

[0061] Another example of this disclosure is a hybrid acoustic LC filter with harmonic suppression. The hybrid acoustic LC filter includes a hybrid passive/acoustic filter configured to filter a radio frequency signal and a non-acoustic LC filter cascaded with the hybrid passive/acoustic filter. The hybrid passive/acoustic filter includes acoustic resonators and a non-acoustic passive component. The non-acoustic LC filter is configured to suppress a harmonic of the radio frequency signal.

[0062] The non-acoustic LC filter can be a notch filter. A frequency response of the notch filter can have a notch corresponding to a second harmonic of the radio frequency signal. A frequency response of the notch filter can have two notches corresponding to different harmonics of the radio frequency signal.

[0063] The non-acoustic LC filter can be a low pass filter.

[0064] The non-acoustic LC filter can include integrated passive devices of an integrated passive device die.

[0065] The acoustic resonators can include bulk acoustic wave resonators.

[0066] The non-acoustic passive component can include a first inductor and a second inductor. The acoustic resonators can include a first shunt acoustic resonator arranged in series with the first inductor and in parallel with the second inductor.

[0067] The acoustic resonators can include a first shunt acoustic resonator and a second shunt acoustic resonator. The non-acoustic passive component can include an LC tank coupled between the first shunt acoustic resonator and the second shunt acoustic resonator.

[0068] Another example of this disclosure is a multiplexer that includes a first filter configured to filter a radio frequency signal and a second filter coupled to the first filter at a common node. The first filter includes a hybrid passive/acoustic filter and a non-acoustic LC filter cascaded with the hybrid passive/acoustic filter. The hybrid passive/acoustic filter includes acoustic resonators and a non-acoustic passive component. The non-acoustic LC filter is configured to suppress a harmonic of the radio frequency signal.

[0069] The second filter can include second acoustic resonators and a second non-acoustic passive component. The first filter can be a mid-band filter and the second filter can be a high band filter. The multiplexer can further include a low band filter coupled to the first filter and the second filter at the common node.

[0070] The non-acoustic LC filter can include integrated passive devices of an integrated passive device die.

[0071] The non-acoustic passive component can include a first inductor and a second inductor. The acoustic resonators can include a first shunt acoustic resonator arranged in series with the first inductor and in parallel with the second inductor.

[0072] The acoustic resonators can include a first shunt acoustic resonator and a second shunt acoustic resonator. The non-acoustic passive component can include an LC tank coupled between the first shunt acoustic resonator and the second shunt acoustic resonator.

[0073] The acoustic resonators can include bulk acoustic wave resonators.

[0074] Another example of this disclosure is a wireless communication device that includes radio frequency front end and an antenna in communication with the radio frequency front end. The radio frequency front end includes a filter configured to filter a radio frequency signal. The filter includes a hybrid passive/acoustic filter and an LC filter cascaded with the hybrid passive/acoustic filter. The hybrid passive/acoustic filter includes acoustic resonators and a non-acoustic passive component. The non-acoustic LC filter is

WHAT IS CLAIMED IS:

1. A cascaded filter circuit for radio frequency filtering, the cascaded filter circuit comprising:

a hybrid acoustic LC filter configured to filter a radio frequency signal, the hybrid acoustic LC filter including an acoustic resonator on an acoustic resonator die, a capacitor external to the acoustic resonator die, and an inductor external to the acoustic resonator die;

a non-acoustic LC filter including an LC circuit;

a second non-acoustic LC filter; and

a switch configured to couple the hybrid acoustic LC filter and the non-acoustic LC filter in a first state, and to couple the hybrid acoustic LC filter and the second non-acoustic LC filter in a second state.

2. The cascaded filter circuit of claim 1 wherein the non-acoustic LC filter is a transmit filter and the second non-acoustic LC filter is a receive filter.

3. The cascaded filter circuit of claim 1 wherein the hybrid acoustic LC filter further includes a second inductor in parallel with the acoustic resonator, and the acoustic resonator is arranged as a shunt resonator in series with the inductor.

4. The cascaded filter circuit of claim 1 wherein the hybrid acoustic LC filter further includes a second acoustic resonator, the first acoustic resonator and the second acoustic resonator are shunt resonators, and the capacitor and the inductor are arranged as an LC tank between the acoustic resonator and the second acoustic resonator.

5. The cascaded filter circuit of claim 4 wherein the hybrid acoustic LC filter further includes a second inductor in series with the first acoustic resonator and a third inductor in series with the second acoustic resonator.

6. The cascaded filter circuit of claim 1 wherein the acoustic resonator is a bulk acoustic wave resonator.

7. The cascaded filter circuit of claim 1 wherein the LC circuit of the non-acoustic LC filter includes integrated passive devices of an integrated passive device die.

8. The cascaded filter circuit of claim 7 wherein the inductor of the hybrid acoustic LC filter is a surface mount inductor.

9. The cascaded filter circuit of claim 7 wherein the inductor of the hybrid acoustic LC filter includes a conductive trace of a substrate.

10. The cascaded filter circuit of claim 1 wherein a passband of a cascaded filter that includes the non-acoustic LC filter and the hybrid acoustic LC filter is set by the non-acoustic LC filter.

11. The cascaded filter circuit of claim 10 wherein a lower bound of the passband is at least 3 gigahertz.

12. A cascaded filter circuit for radio frequency filtering, the cascaded filter circuit comprising:

a hybrid acoustic LC filter configured to filter a radio frequency signal, the hybrid acoustic LC filter including an acoustic resonator on an acoustic resonator die, a capacitor external to the acoustic resonator die, and an inductor external to the acoustic resonator die;

a non-acoustic LC filter including an LC circuit;

a second hybrid acoustic LC filter; and

a switch configured to couple the hybrid acoustic LC filter and the non-acoustic LC filter in a first state, and to couple the second hybrid acoustic LC filter and the non-acoustic LC filter in a second state.

13. The cascaded filter circuit of claim 12 wherein the hybrid acoustic LC filter further includes a second inductor in parallel with the acoustic resonator, and the acoustic resonator is arranged as a shunt resonator in series with the inductor.

14. The cascaded filter circuit of claim 12 wherein the hybrid acoustic LC filter further includes a second acoustic resonator, the first acoustic resonator and the second acoustic resonator are shunt resonators, and the capacitor and the inductor are arranged as an LC tank between the acoustic resonator and the second acoustic resonator.

15. The cascaded filter circuit of claim 14 wherein the hybrid acoustic LC filter further includes a second inductor in series with the first acoustic resonator and a third inductor in series with the second acoustic resonator

16. The cascaded filter circuit of claim 12 wherein a passband of the non-acoustic LC filter cascaded with the hybrid acoustic LC filter is set by the non-acoustic LC filter.

17. A method of filtering a radio frequency signal, the method comprising:

coupling, with a switch, a hybrid acoustic LC filter and a non-acoustic LC filter, the hybrid acoustic LC filter including an acoustic resonator on an acoustic resonator die, a capacitor external to the acoustic resonator die, and an inductor external to the acoustic resonator die; and

while the hybrid acoustic LC filter and the non-acoustic filter are coupled together, filtering a radio frequency signal,

the filtering including providing, using the acoustic resonator of the hybrid acoustic LC filter, rejection outside of a passband of a filter that includes the hybrid acoustic LC filter and the non-acoustic LC filter.

18. The method of claim 17 further comprising:

decoupling, with the switch, the hybrid acoustic LC filter from the non-acoustic LC filter; and

coupling, with the switch, the hybrid acoustic LC filter and a second non-acoustic LC filter.

19. The method of claim 18 further comprising:

providing, with a power amplifier, the radio frequency signal to the non-acoustic LC filter; and

amplifying, with a low noise amplifier, a filtered signal provided by the second non-acoustic filter.

20. The method of claim 17 wherein the radio frequency signal has a frequency in a range from 3 gigahertz to 5 gigahertz.