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(54) ENHANCING ISOLATION IN HYBRID-BASED RADIO FREQUENCY DUPLEXERS AND MULTIPLEXERS

(71) Applicant: **Abtum Inc.**, Irvine, CA (US)

(72) Inventor: **Sam Mandegaran**, Pasadena, CA (US)

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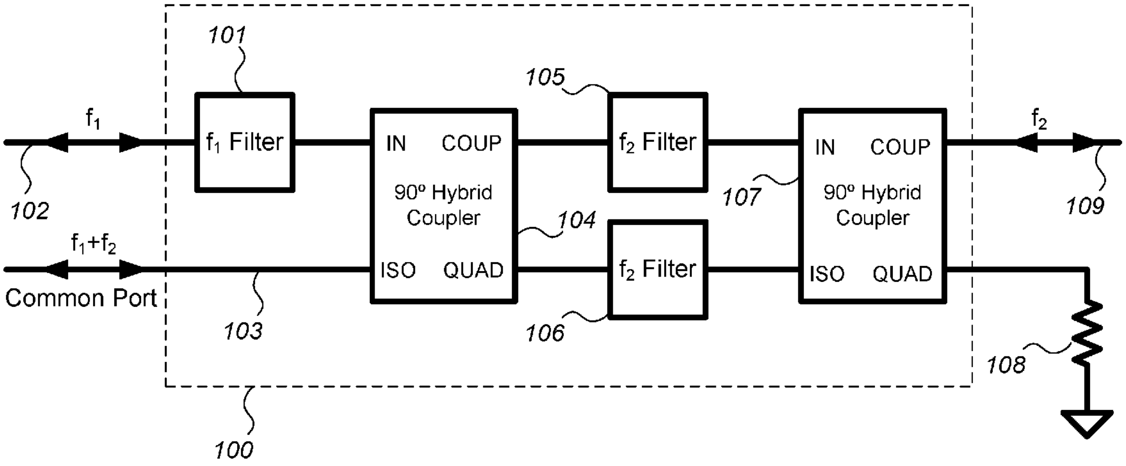
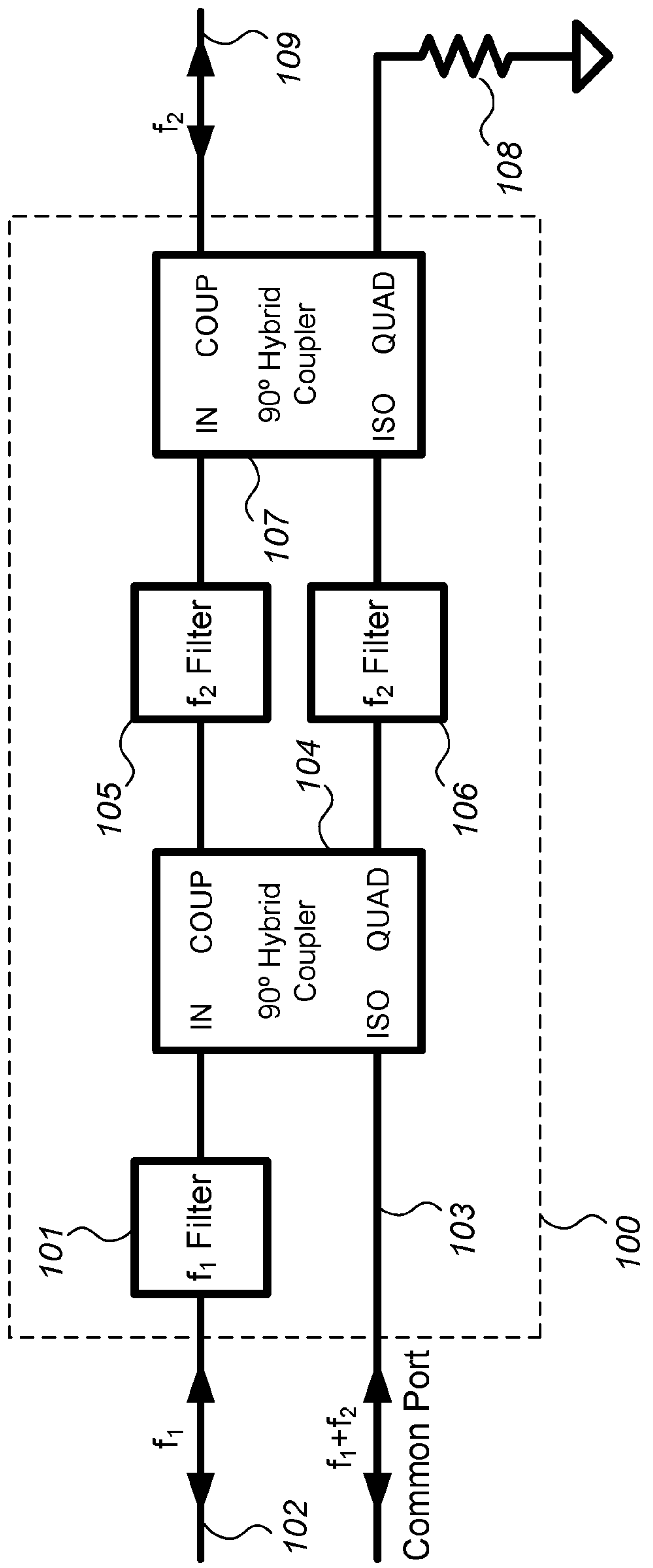
(52) **U.S. Cl.**

CPC ***H03H 7/465*** (2013.01); ***H04L 5/14*** (2013.01); ***H01P 5/18*** (2013.01)

(57) ABSTRACT

A radio frequency (RF) duplexer may comprise quadrature hybrid couplers and RF filters. The isolation and insertion loss of such RF duplexer, often limited by practical imperfections such as component mismatches and layout asymmetries, may be improved by including capacitors in the RF duplexer. A tunable or reconfigurable RF duplexer with high isolation and low insertion loss, under all desired settings, may be realized by adding tunable capacitors to the tunable RF duplexer which includes the quadrature hybrid couplers and tunable RF filters.

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102
f_1+f_2
Common Port
101
f_1 Filter
103
100
IN
COUP
90° Hybrid Coupler
ISO
QUAD
104
105
f_2 Filter
106
f_2 Filter
IN
COUP
90° Hybrid Coupler
ISO
QUAD
107
f_2
109
108

FIG. 1

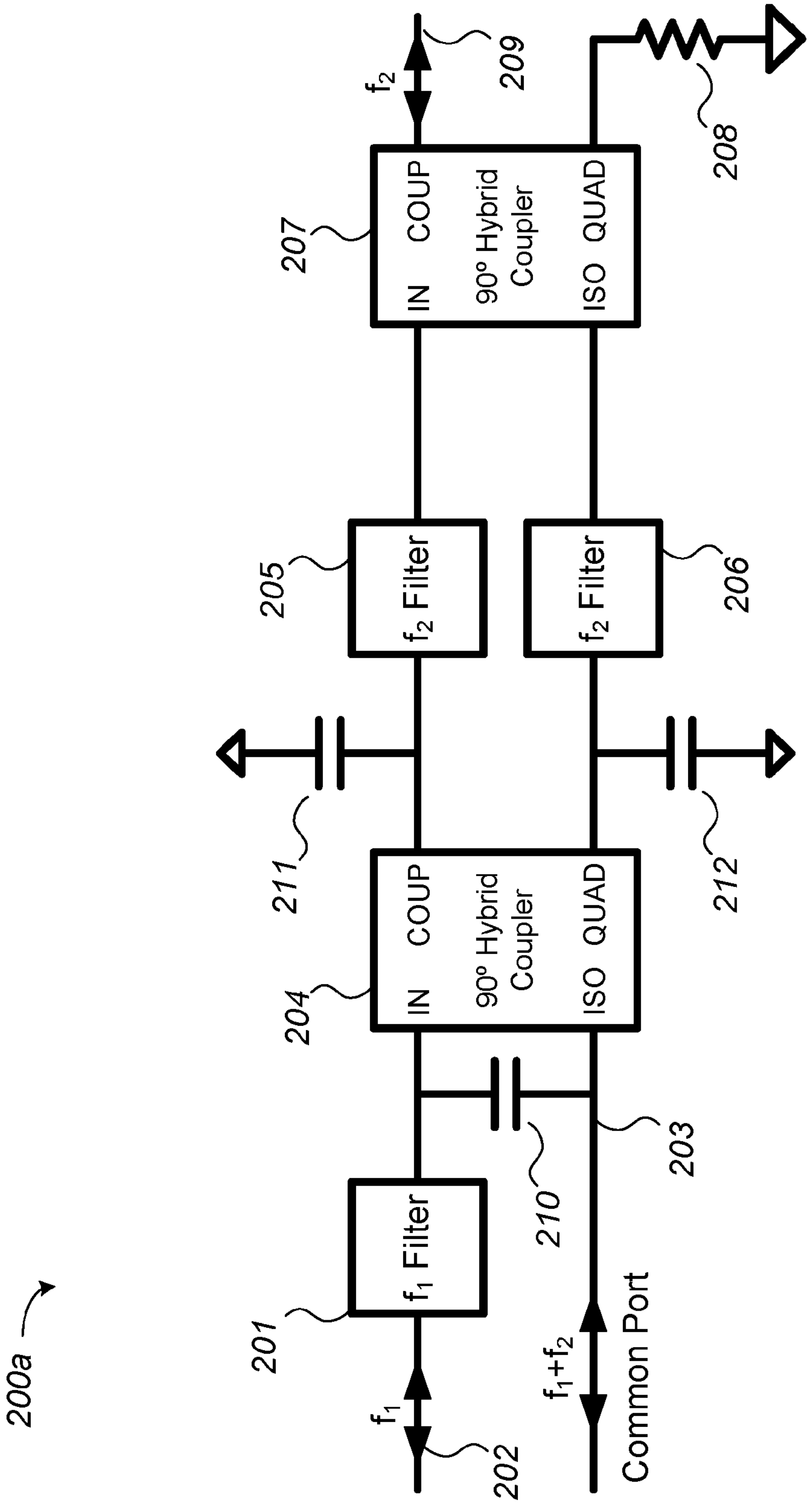
200a
201
f_1 Filter
f_1
202
f_1+f_2
Common Port
210
203
204
IN
COUP
90° Hybrid Coupler
ISO
QUAD
211
212
205
f_2 Filter
206
f_2 Filter
207
IN
COUP
90° Hybrid Coupler
ISO
QUAD
f_2
209
208

FIG. 2A

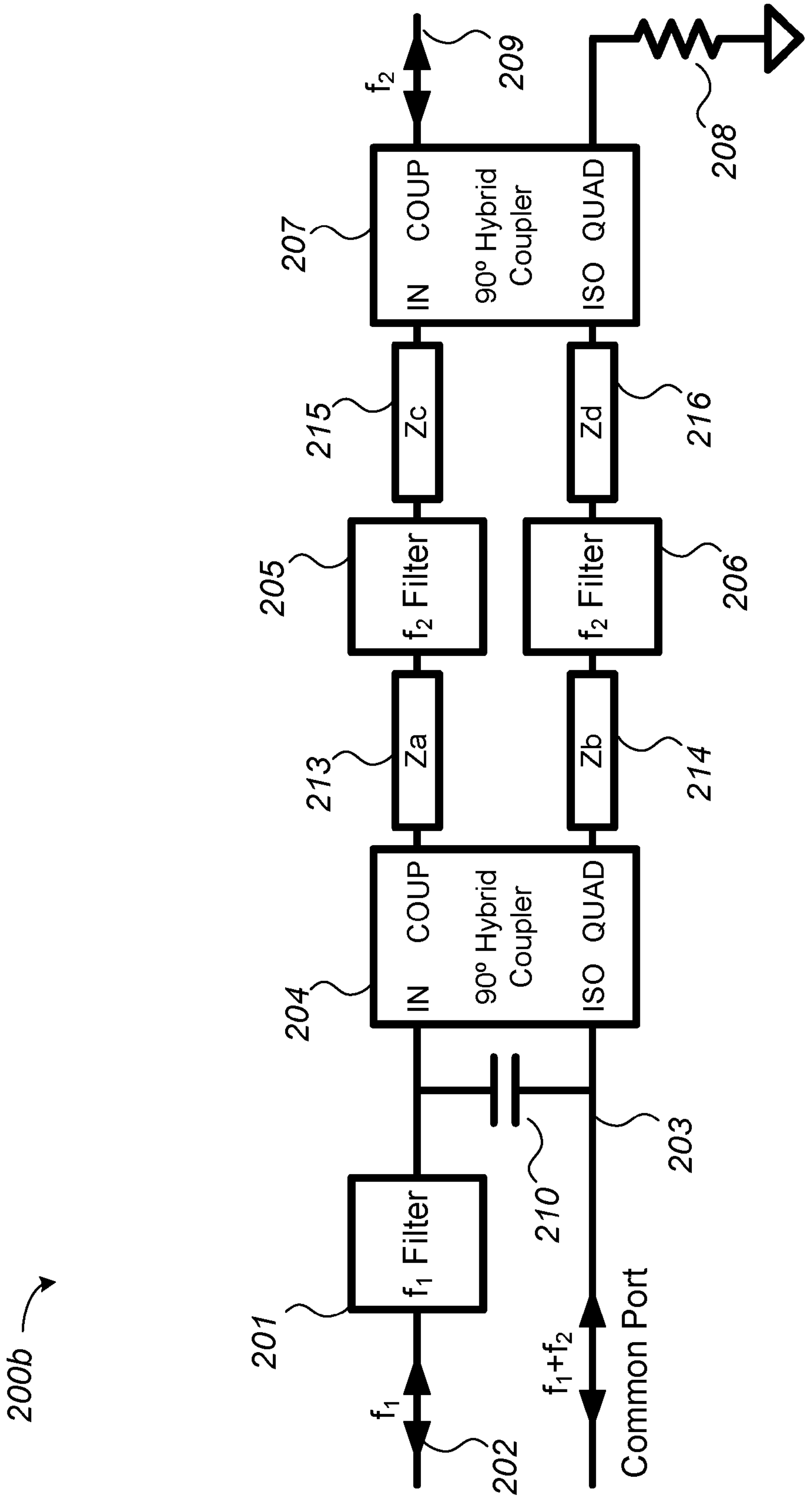
200b
f_1
202
201
f_1 Filter
210
203
f_1+f_2
Common Port
204
IN
COUP
90° Hybrid Coupler
ISO
QUAD
213
Za
214
Zb
205
f_2 Filter
206
f_2 Filter
215
Zc
216
Zd
207
IN
COUP
90° Hybrid Coupler
ISO
QUAD
f_2
209
208

FIG. 2B

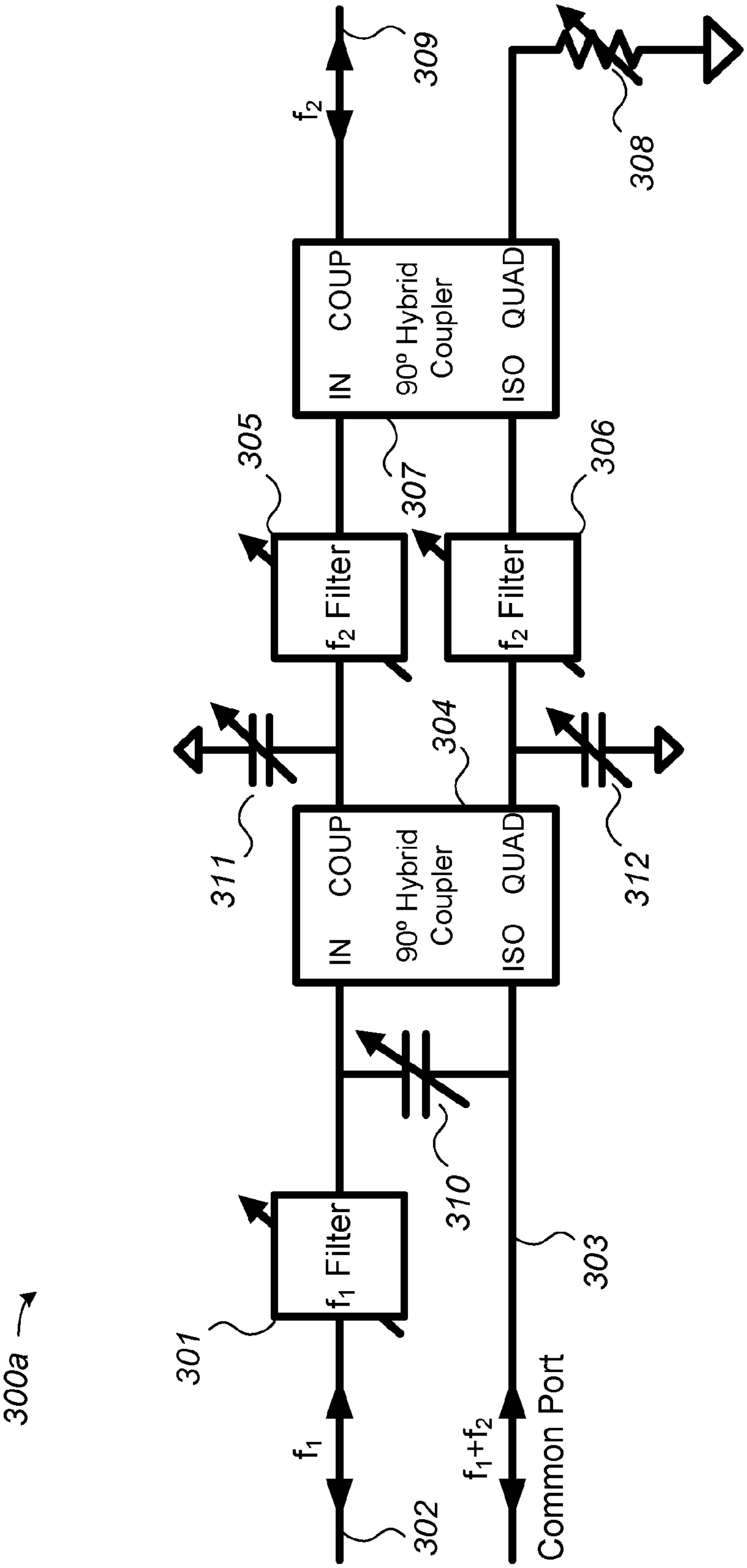
300a
302
f_1
301
f_1 Filter
Common Port
f_1+f_2
303
310
IN
COUP
90° Hybrid Coupler
ISO
QUAD
304
311
312
f_2 Filter
305
f_2 Filter
306
307
IN
COUP
90° Hybrid Coupler
ISO
QUAD
f_2
309
308

FIG. 3A

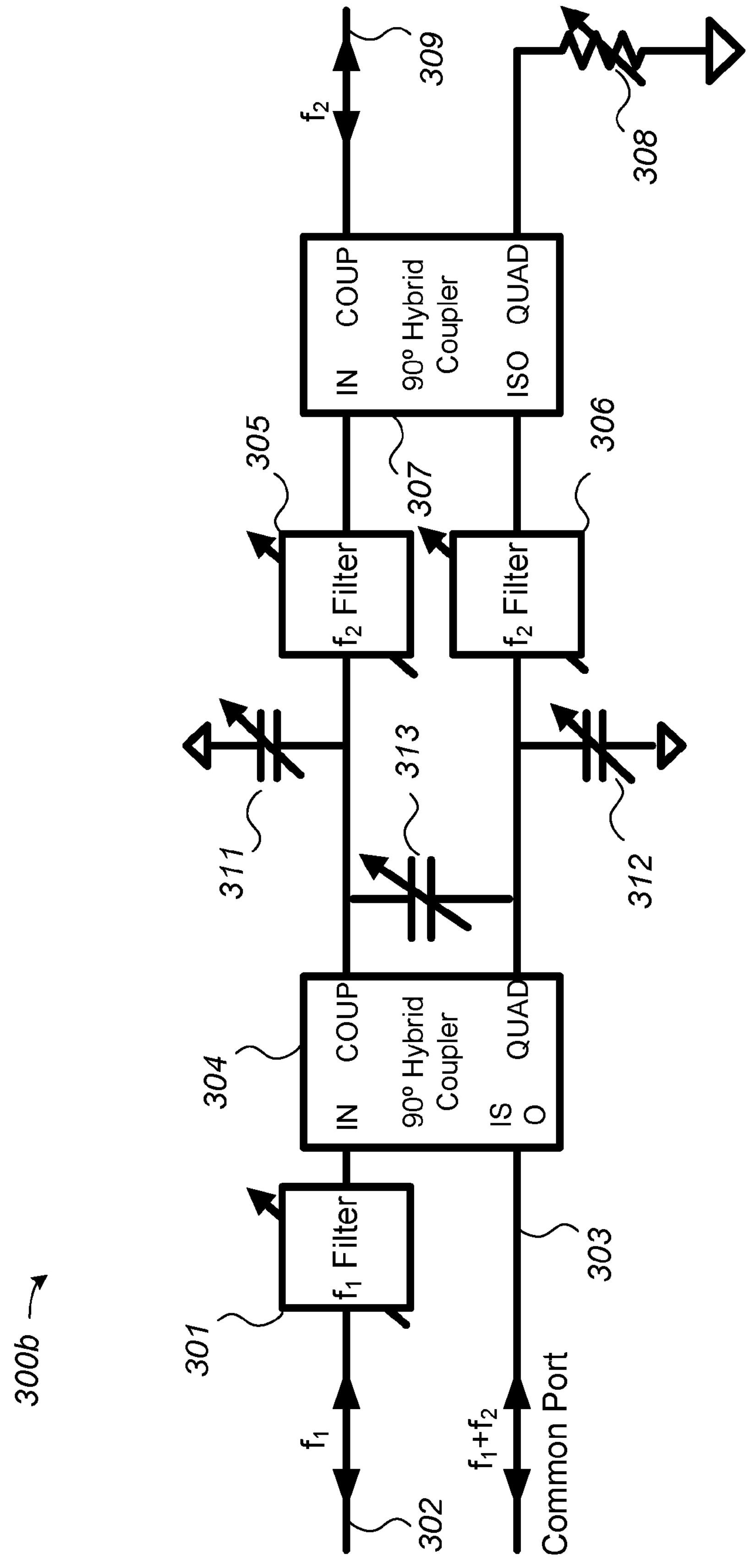
300b
301
302
f_1
f_1+f_2
Common Port
303
f_1 Filter
304
IN
COUP
90° Hybrid Coupler
IS O
QUAD
311
313
312
f_2 Filter
305
f_2 Filter
306
307
IN
COUP
90° Hybrid Coupler
ISO
QUAD
f_2
309
308

FIG. 3B

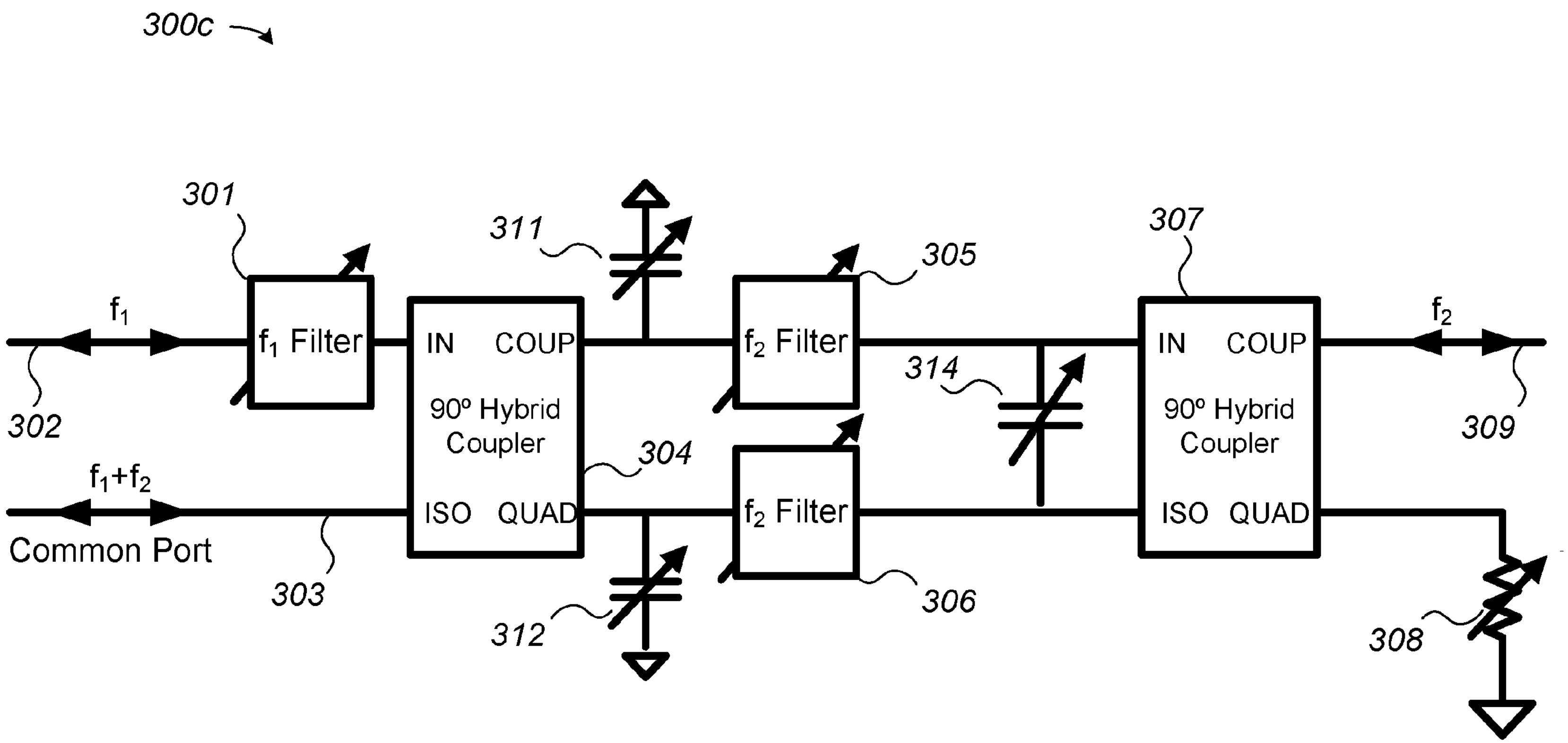
300c
301
311
305
307
f_1
f_1 Filter
IN
COUP
90° Hybrid Coupler
ISO
QUAD
f_2 Filter
314
IN
COUP
90° Hybrid Coupler
ISO
QUAD
f_2
302
304
f_2 Filter
309
f_1+f_2
Common Port
303
312
306
308

FIG. 3C

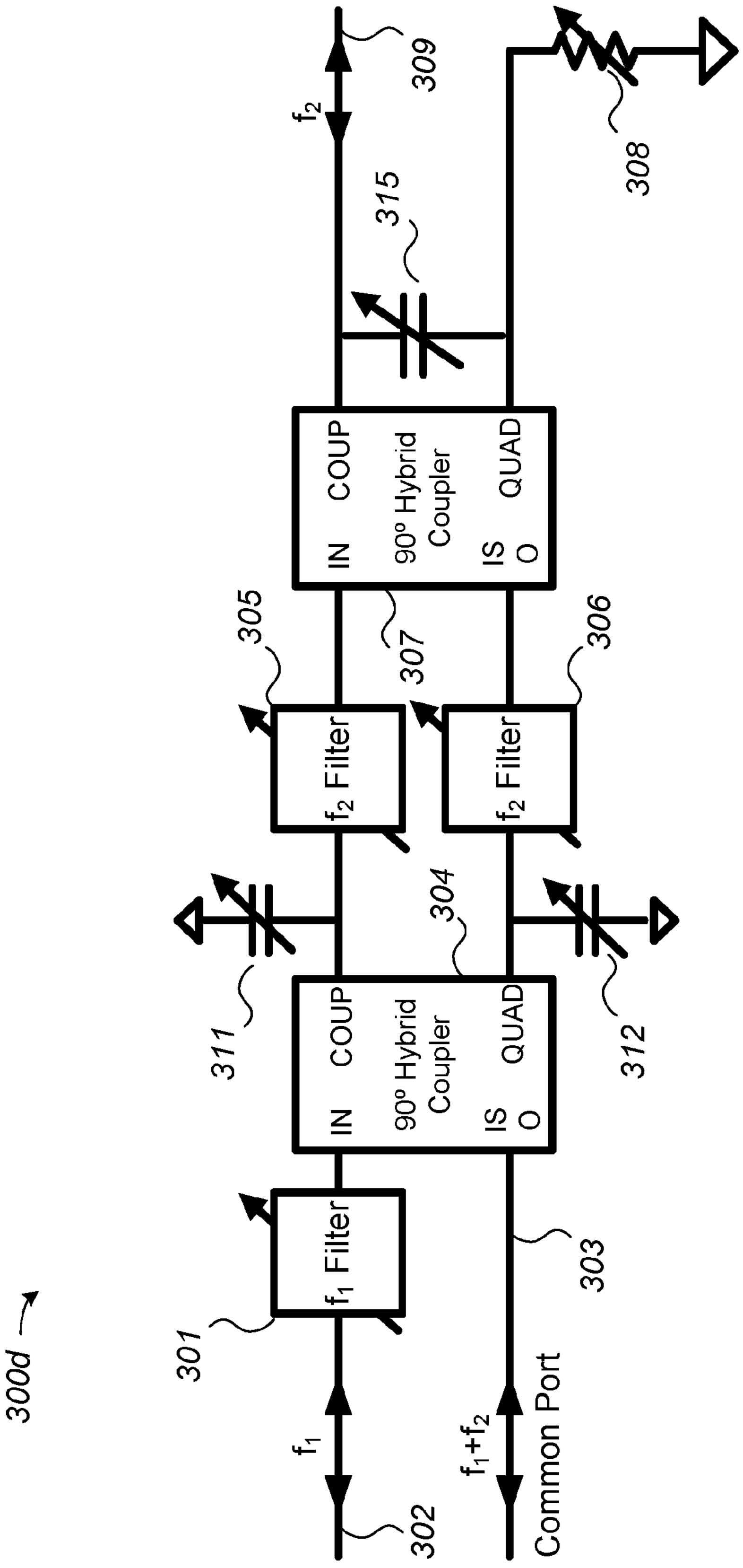
300d
f1
302
301
f1 Filter
f1+f2
Common Port
303
311
90° Hybrid Coupler
IN
COUP
IS O
QUAD
304
312
f2 Filter
305
f2 Filter
306
307
90° Hybrid Coupler
IN
COUP
IS O
QUAD
315
f2
309
308

FIG. 3D

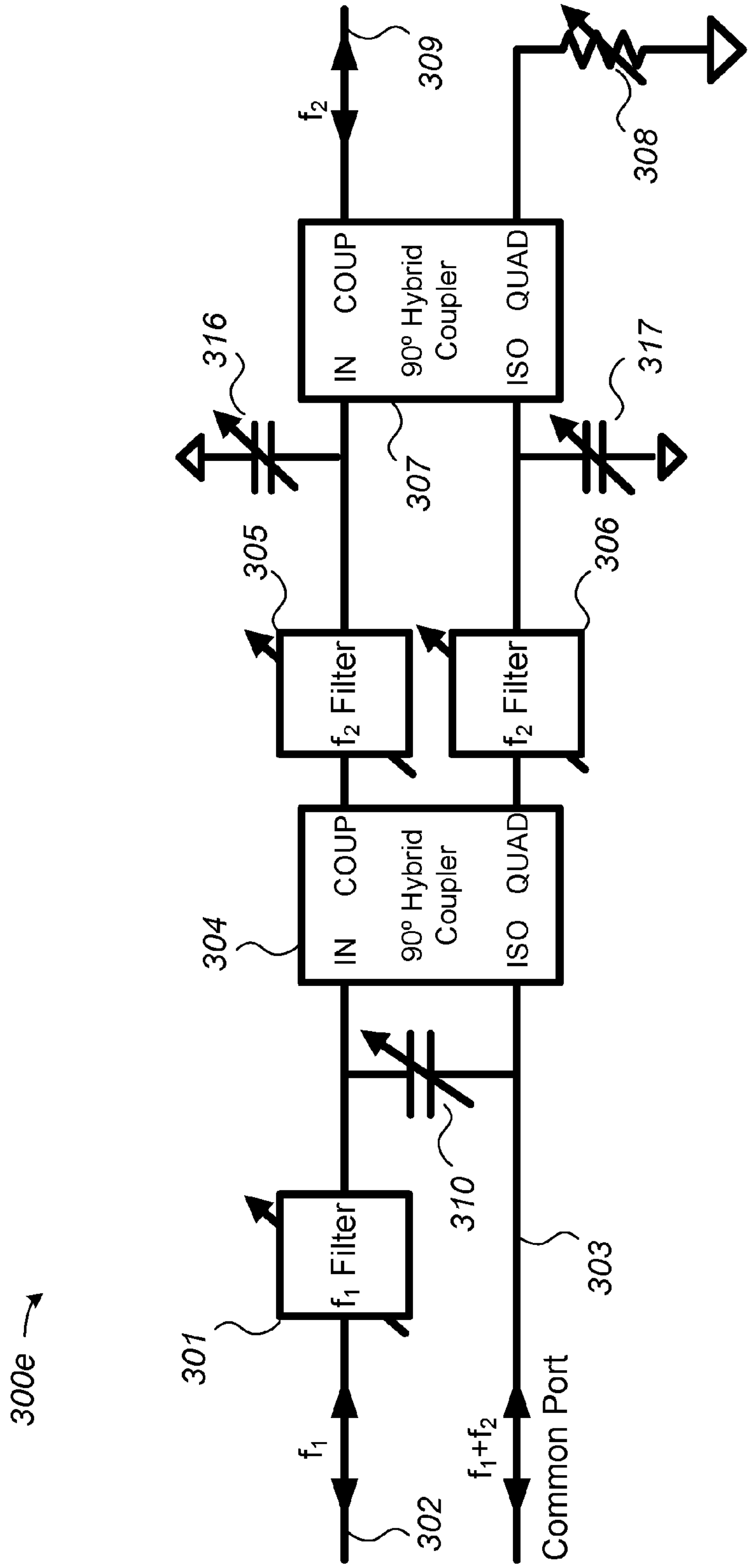
300e
301
f_1 Filter
f_1
302
f_1+f_2
Common Port
303
310
304
IN
COUP
90° Hybrid Coupler
ISO
QUAD
305
f_2 Filter
306
f_2 Filter
316
317
307
IN
COUP
90° Hybrid Coupler
ISO
QUAD
f_2
309
308

FIG. 3E

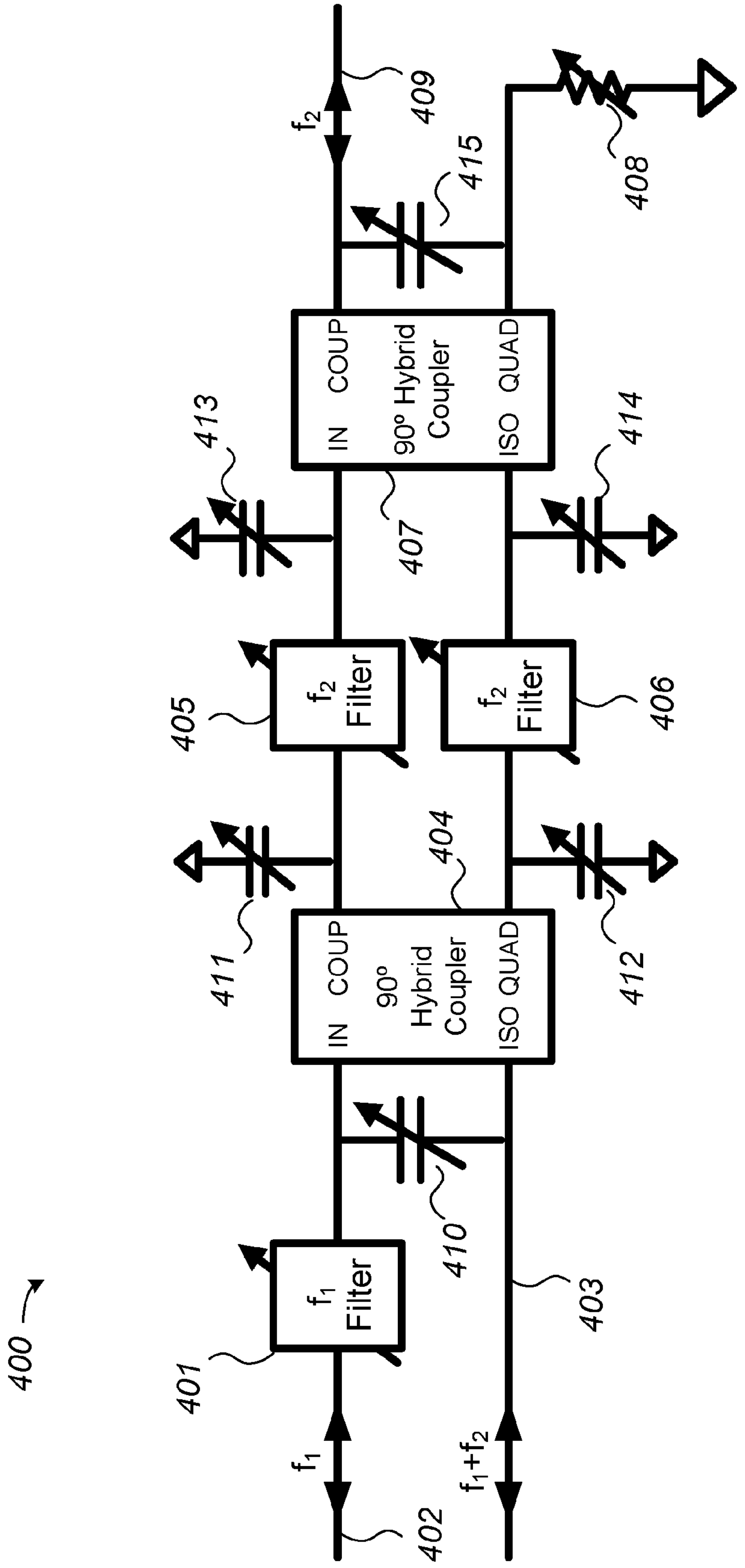
400
401
f_1 Filter
f_1
402
f_1+f_2
403
410
IN
COUP
90° Hybrid Coupler
ISO
QUAD
404
411
412
405
f_2 Filter
406
f_2 Filter
413
414
407
IN
COUP
90° Hybrid Coupler
ISO
QUAD
415
f_2
409
408

FIG. 4

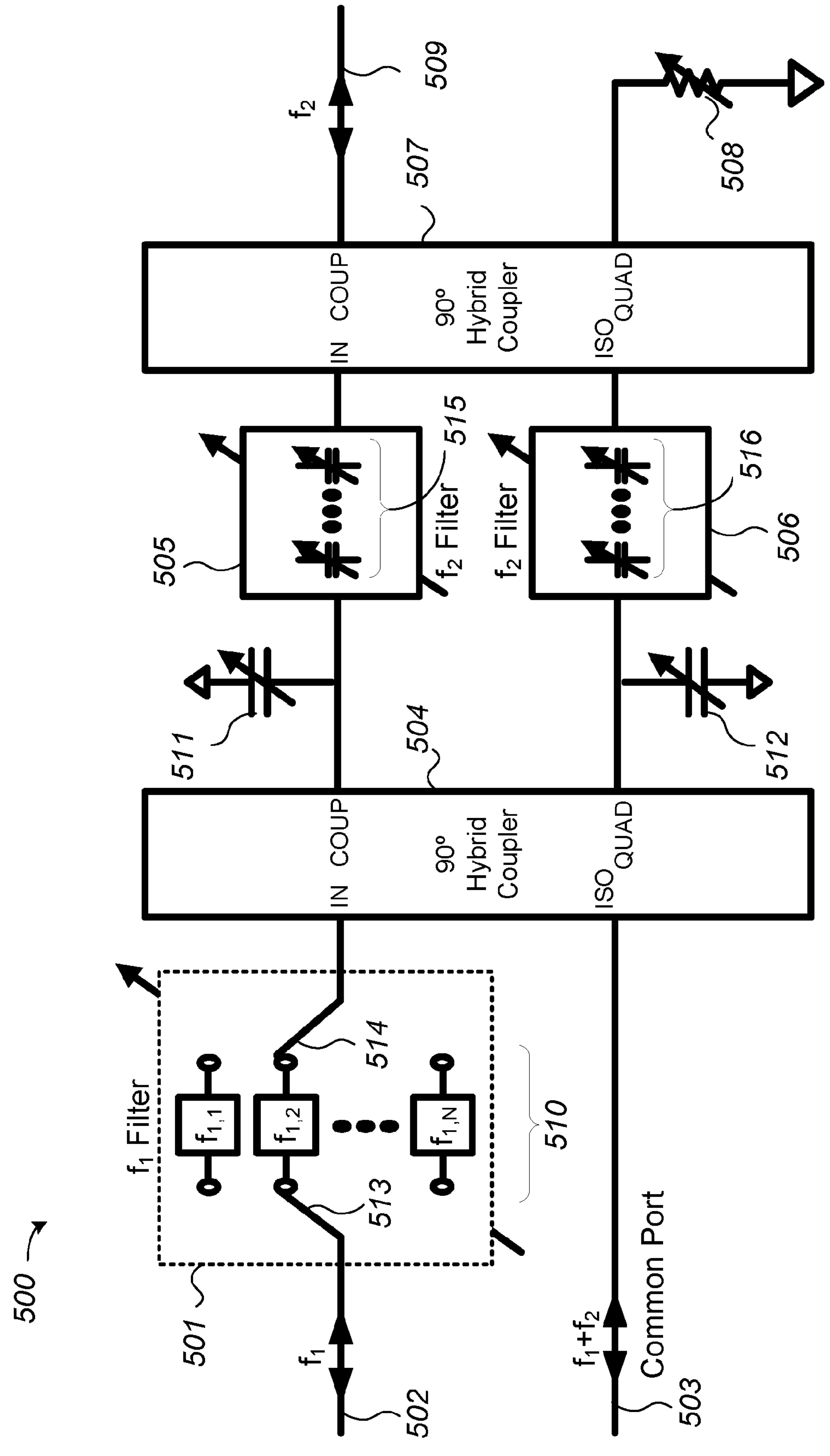
500
501
f_1 Filter
$f_{1,1}$
$f_{1,2}$
$f_{1,N}$
510
513
514
f_1
502
f_1+f_2
Common Port
503
IN
COUP
ISO
QUAD
90° Hybrid Coupler
504
511
512
505
f_2 Filter
515
f_2 Filter
516
506
IN
COUP
ISO
QUAD
90° Hybrid Coupler
507
f_2
509
508

FIG. 5

ENHANCING ISOLATION IN HYBRID-BASED RADIO FREQUENCY DUPLEXERS AND MULTIPLEXERS

CROSS-REFERENCE TO RELATED APPLICATIONS/INCORPORATION BY REFERENCE

[0001] This patent application makes reference to, claims priority to, and claims benefit from U.S. Provisional Application No. 62/397,727, filed on Sep. 21, 2016.

FIELD OF THE DISCLOSURE

[0002] Certain embodiments of the present disclosure relate to radio frequency (RF) duplexers that may be used in wireless communication systems, for example. More specifically, certain embodiments of the disclosure relate to a method and system for enhancing isolation in hybrid-based RF duplexers and multiplexers.

BACKGROUND OF THE DISCLOSURE

[0003] Existing methods and systems for enhancing isolation in hybrid-based RF duplexers and multiplexers can be costly, cumbersome and inefficient. Further limitations and disadvantages of conventional and traditional approaches will become apparent to one of skill in the art, through comparison of such systems with the present disclosure as set forth in the remainder of the present application with reference to the drawings.

BRIEF SUMMARY OF THE DISCLOSURE

[0004] A system and/or method for enhancing isolation in hybrid-based radio frequency (RF) duplexers and multiplexers, substantially as shown in and/or described in connection with at least one of the figures, as set forth more completely in the claims.

[0005] Various advantages, aspects and novel features of the present disclosure, as well as details of an illustrated embodiment thereof, will be more fully understood from the following description and drawings.

BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

[0006] The drawings are of illustrative embodiments. They do not illustrate all embodiments. Other embodiments may be used in addition or instead. Details that may be apparent or unnecessary may be omitted to save space or for more effective illustration. Some embodiments may be practiced with additional components or steps and/or without all of the components or steps that are illustrated. When the same numeral appears in different drawings, it refers to the same or like components or steps.

[0007] FIG. **1** illustrates a schematic of an embodiment of an RF duplexer according to the present disclosure.

[0008] FIGS. **2**A-**2**B illustrate block diagrams of embodiments of the RF duplexer according to the present disclosure.

[0009] FIGS. **3**A-**3**E illustrate block diagrams of embodiments of the RF duplexers according to the present disclosure.

[0010] FIG. **4** illustrates a block diagram of an embodiment of the RF duplexer according to the present disclosure.

[0011] FIG. **5** illustrates a block diagram of an embodiment of the RF duplexer according to the present disclosure.

DETAILED DESCRIPTION OF THE DISCLOSURE

[0012] As utilized herein the terms “circuit” and “circuitry” refer to physical electronic components (i.e., hardware) and any software and/or firmware (“code”) which may configure the hardware, be executed by the hardware, and/or otherwise be associated with the hardware. As utilized herein, “and/or” means any one or more of the items in the list joined by “and/or”. As an example, “x and/or y” means any element of the three-element set {(x), (y), (x, y)}. As another example, “x, y, and/or z” means any element of the seven-element set {(x), (y), (z), (x, y), (x, z), (y, z), (x, y, z)}. As utilized herein, the term “exemplary” means serving as a non-limiting example, instance, or illustration. As utilized herein, the terms “e.g.” and “for example” set off lists of one or more non-limiting examples, instances, or illustrations.

[0013] The components, steps, features, objects, benefits and advantages which have been discussed are merely illustrative. None of them, nor the discussions relating to them, are intended to limit the scope of protection in any way. Numerous other embodiments are also contemplated. These include embodiments which have fewer, additional, and/or different components, steps, features, objects, benefits and advantages. These also include embodiments in which the components and/or steps are arranged and/or ordered differently.

[0014] Unless otherwise stated, all measurements, values, ratings, positions, magnitudes, sizes, and other specifications that are set forth in this specification, including in the claims that follow, are approximate, not exact. They are intended to have a reasonable range that is consistent with the functions to which they relate and with what is customary in the art to which they pertain.

[0015] All articles, patents, patent applications, and other publications that have been cited in this disclosure are incorporated herein by reference.

[0016] The phrase “means for” when used in a claim is intended to and should be interpreted to embrace the corresponding structures and materials that have been described and their equivalents. Similarly, the phrase “step for” when used in a claim is intended to and should be interpreted to embrace the corresponding acts that have been described and their equivalents. The absence of these phrases from a claim means that the claim is not intended to and should not be interpreted to be limited to these corresponding structures, materials, or acts, or to their equivalents.

[0017] Relational terms such as “first” and “second” and the like may be used solely to distinguish one entity or action from another, without necessarily requiring or implying any actual relationship or order between them. The terms “comprises,” “comprising,” and any other variation thereof when used in connection with a list of elements in the specification or claims are intended to indicate that the list is not exclusive and that other elements may be included. Similarly, an element preceded by an “a” or an “an” does not, without further constraints, preclude the existence of additional elements of the identical type.

[0018] Illustrative embodiments are now described. Other embodiments may be used in addition or instead. Details that may be apparent to a person of ordinary skill in the art may have been omitted. Some embodiments may be practiced with additional components or steps and/or without all of the components or steps that are described.

[0019] Some embodiments according to the present disclosure provide RF duplexers and RF multiplexers that can be used in wireless communication systems including, for example, those that support Frequency Division Duplexing (FDD), multi-channel or multi-band communications, and carrier aggregation.

[0020] Some embodiments according to the present disclosure provide RF duplexers and RF multiplexers that are characterized by one or more of the following: a low insertion loss from each port to the common port, high port-to-port isolation, high linearity, an ability to handle large signals (power handling), a compact size, manufacturability, and a low cost.

[0021] Some embodiments according to the present disclosure contemplate that requirements for RF duplexers and RF multiplexers have become more stringent in light of new communication standards where frequency bands are closer to each other; the need to support multiple standards in one platform; cost- and footprint-sensitive platforms such as smartphones; and co-existing communication systems where multiple communication transmitters and receivers work simultaneously.

[0022] Due to linearity, noise, and power handling requirements, some embodiments according to the present disclosure contemplate using passive RF duplexers and RF multiplexers for some applications. Due to the selectivity and isolation requirements, some embodiments according to the present disclosure contemplate using high-order filters that employ high quality factor (Q) components in the RF duplexer and the RF multiplexer.

[0023] Some embodiments according to the present disclosure solve one or more of the following problems: high-Q components can be costly; components can be larger to increase their Q; and tunable components provide lower Q compared to non-tunable counterparts.

[0024] Some embodiments according to the present disclosure contemplate using various technologies to realize RF duplexers and RF multiplexers. For instance, handheld consumer wireless devices can use acoustic technologies such as Surface Acoustic Wave (SAW) and Bulk Acoustic Wave (BAW) technologies to realize RF duplexers and RF multiplexers. These technologies offer high-Q, compact RF resonators suitable for filters, duplexers, and multiplexers with limited, yet sufficient, power handling capabilities for handheld devices. Commercial wireless infrastructure platforms such as base stations, repeaters, access points, and routers may use either acoustic or dielectric resonators (e.g., air cavity or ceramic resonators) to realize highly-selective, low-loss, linear RF filters, RF duplexers, and RF multiplexers with higher isolation and power handling requirements.

[0025] Some embodiments according to the present disclosure support multiple frequency bands and wireless standards within the same platform (either handheld or infrastructure systems). Some embodiments according to the present disclosure provide reconfigurable or tunable radio frequency components such as filters, duplexers, and multiplexers, for example.

[0026] Some embodiments according to the present disclosure provide piezoelectric material that can be used to realize compact high-Q resonators. Crystal resonators can provide spectrally-pure oscillators. SAW resonators can provide compact low-loss selective RF filters and duplexers as well as oscillators. Further, BAW resonators can be used to construct high-performance RF filters and duplexers as well as oscillators. Ceramic resonators and micro-electro-mechanical system (MEMS) resonators with high quality factor can be used in frequency generation as well as filtering applications.

[0027] In some embodiments according to the present disclosure, RF SAW filters and RF duplexers can be used in wireless communications such as cellular phones, wireless local area network (WLAN) transceivers, global positioning system (GPS) receivers, cordless phones, wireless phones, mobile phones, smartphones, tablets, laptops, and so forth. RF SAW filters can be used as band-select filters, image-reject filters, intermediate frequency (IF) filters, transmitter noise or spur reduction filters, and so forth. An exemplary smartphone can have several SAW resonators, SAW filters, and SAW duplexers to support various communication systems and standards.

[0028] Some embodiments according to the present disclosure contemplate that BAW resonators can have a lower loss (or a higher Q) or are more compact, especially at higher frequencies, when compared with SAW resonators. RF filters and duplexers that use BAW resonators may benefit from a lower insertion loss, or a higher selectivity, or a smaller form factor when compared with RF filters and duplexers that use SAW resonators, especially at higher frequencies. Thin film bulk acoustic resonators (FBARs) are exemplary examples of BAW resonators.

[0029] Wireless communication standards designate many different operational frequency bands to support the increase in the overall wireless capacity and reach. For instance, cellular phone standards may include RF frequency bands that range from approximately 700 MHz to approximately 4000 MHz. Furthermore, in order to increase the overall wireless capacity, the frequency spacing between adjacent frequency bands or channels within the same application or different applications may be reduced. This may be done, for instance, by reducing the guard bands in the wireless standard or by placing the transmit and receive frequency bands in an FDD scheme closer to each other. As a result, some embodiments of the present disclosure provide RF filters and duplexers with higher selectivity. More selective RF filters and duplexers that utilize a given component or technology (e.g., SAW, BAW, etc.) might incur more in-band insertion loss. The higher RF filter or duplexer insertion loss may reduce the wireless receiver noise figure and sensitivity, increase the wireless transmitter power consumption or reduce the transmitted power, and/or deteriorate the overall performance of a communication system.

[0030] In commercial systems, some embodiments of the present disclosure contemplate that the choice of technology may depend on the technical performance, such as power consumption as well as economic and business considerations such as cost, size, and time to market. For instance, while one technology may offer a better performance compared with another technology, it may not be adopted for a commercial system that is cost sensitive. In the case of RF filters and duplexers, it may be desirable to use a technology that provides the lowest-cost and/or most-compact solution, as long as a predetermined performance criterion is met. In other words, a more expensive or larger solution may not be adopted, even if it offers a better performance as compared with an alternative solution that meets an acceptable performance level at a lower cost and/or size. For instance, while RF filters and duplexers that use BAW resonators may offer lower loss compared with RF filters and duplexers that use SAW resonators for a given set of specifications, the higher relative cost of BAW technology, as well as its relatively smaller number of suppliers, may disfavor their usage in certain applications and standards. Other considerations may include, for example, the ease of integration with the rest of the components in a communication system. For instance, there may be performance, business, or economic advantages to integrate RF filters and duplexers with low noise amplifiers (LNAs), power amplifiers (PAs), transmit/receive (T/R) or band-select switches, impedance matching networks, etc. A wireless communication device, such as a smartphone, can include a number of SAW filters and duplexers as well as a number of BAW filter and duplexers. Each SAW or BAW filter or duplexer may be used for a specific communication application, standard, or frequency band.

[0031] Some embodiments according to the present disclosure provide architectural solutions that enable realization of highly-selective, low-loss RF duplexers with high-isolation between transmit and receive bands. Specifically, some embodiments according to the present disclosure provide a lower cost or more compact technology within an innovative architecture that satisfies a comparable or better specification compared to what can be achieved using a more expensive or less compact technology. Exemplary embodiments might include replacing BAW duplexers with SAW duplexers using an innovative architecture, or replacing ceramic or cavity duplexers with BAW duplexers using an innovative architecture.

[0032] An exemplary method for designing acoustic resonator based filters and duplexers begins by deciding upon the number of resonators to be used which can depend on the required stopband rejection for the filters or the required isolation for the duplexers. The larger the number of resonators used in filter design, the larger may be the order of the filter and the sharper may be the filter roll-off around passband. Sharper filter roll-off may provide higher stopband rejection. Similarly, the number of resonators used in the transmit (TX) and receive (RX) filters of the duplexer may determine the total isolation from TX to RX. The larger the order of the TX and RX filters (e.g., the larger the number of resonators used in the filters), the larger may be the amount of isolation between TX and RX. Due to the limited quality factor of the acoustic resonators, the insertion loss in the filter and duplexer may be directly proportional to the number of the resonators used. In other words, the larger the order of the filter and the TX and RX filter, the larger may be the loss of the filter and duplexer, respectively. Some embodiments according to the present disclosure contemplate overcoming this insertion loss and isolation or stopband rejection tradeoff by incorporating hybrid couplers in the design of the filters and duplexers.

[0033] FIG. **1** shows a simplified block diagram schematic of an embodiment of an RF duplexer **100** according to the present disclosure. The RF duplexer **100** includes a common port **103** and two single-frequency ports **102** and **109**. An f_1 filter **101** has a passband at frequency band f_1. f_2 filters **105** and **106** are similar and have passbands at frequency band f_2 and stopbands that include frequency band f_1. In an ideal structure, ports **102** and **109** are completely isolated due to symmetry. The transfer function between ports **109** and **103** follows that of the f_2 filters **105** and **106**. The transfer function between ports **102** and **103** follows that of the f_1 filter **101** multiplied by the input reflection coefficient of f_2 filters **105** and **106**. In an exemplary design, the input reflection coefficient of f_2 filters **105** and **106** is close to one outside of f_1 passband including f_2. Hence, in an exemplary design, the insertion loss between ports **102** and **103**, within the f_1 filter passband, is equal or approximately equal to the insertion loss f_1 filter **101**.

[0034] There are several non-idealities associated with the design of the RF duplexer **100** in FIG. **1**. Some of these non-idealities and their effects on the RF duplexer **100** are described herein.

[0035] Practical quadrature hybrid couplers, such as quadrature hybrid couplers **104** and **107**, demonstrate amplitude and phase mismatches at their ports. The scattering parameters of an ideal symmetric quadrature hybrid coupler may be expressed as

$$[S] = \frac{-1}{\sqrt{2}}\begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix}. \tag{1}$$

In such an ideal hybrid coupler, the insertion loss from port one to the through and coupled ports is −3 dB, i.e., $|S_{21}|=|S_{31}|=1/\sqrt{2}$, and the phase difference in the transfer functions between ports one and two, and ports one and three is 90°, i.e., $\angle S_{21}-\angle S_{31}=90°$. However, in practice, neither condition holds; in other words, in a practical realization of a hybrid coupler, $|S_{21}|\neq|S_{31}|$ and $\angle S_{21}-\angle S_{31}\neq 90°$; these are referred to as amplitude mismatch and phase mismatch.

[0036] Another non-ideality of a quadrature hybrid coupler is the non-zero isolation between the otherwise ideally isolated ports. In an ideal duplexer described above, ports **2** and **3** are fully isolated as shown by $S_{23}=S_{32}=0$. However, in a practical RF duplexer, the isolation is often non-zero. Due to the non-zero isolation, the isolation deteriorates between ports **102** and **109**. The insertion loss also deteriorates between ports **102** and **103**, and between ports **103** and **109**. For instance, due to non-zero isolation in the quadrature hybrid coupler **107**, some of the signal at the port **109** might be lost in a termination **108** as opposed to reaching the common port **103**. This provides higher insertion loss between ports **103** and **109**. For instance, due to the non-zero isolation in the quadrature hybrid coupler **104**, some of the f_2 signal component from the common port **103** may be leaked to the port **102** (e.g., only seeing attenuation of f_1 filter); this can translate into less isolation between the ports **102** and **109**.

[0037] In practice, the f_2 filters **105** and **106** are not identical. Specifically, the input-output transfer functions as well as input reflection coefficients of f_2 filters **105** and **106** are not identical.

[0038] The combined effect of the amplitude and phase mismatch in the quadrature hybrid couplers **104** and **107**, the non-zero isolation in the quadrature hybrid couplers **104** and **107**, and the non-identical response of f_2 filters **105** and **106** may cause asymmetries in the RF duplexer **100**. As such, ports **102** and **109** might not be completely isolated anymore. High isolation is desired in RF duplexers. For instance, the desired isolation between transmit and receive ports of a commercial RF duplexer for certain handheld devices may be over 50 dB, whereas the same specification for an infrastructure base station device may be over 75 dB.

[0039] Some embodiments according to the present disclosure provide solutions that increase the isolation and maintain a low insertion loss in the duplexer **100** under practical scenarios including, for example, the amplitude and phase mismatch in the quadrature hybrid couplers **104** and **107**, the non-zero isolation of the quadrature hybrid couplers **104**, **107**, and/or the non-identical response of f_2 filters **105** and **106**.

[0040] FIG. **2**A shows an embodiment of an RF duplexer **200***a* according to the present disclosure. The exemplary RF duplexer **200***a* adds capacitors **210**, **211**, and **212** to the RF duplexer **100** of FIG. **1**. In some embodiments, only one or two of the aforementioned three capacitors **210**, **211**, and **212** are used. In other words, not all the three capacitors are needed to achieve a desired performance. For instance, some embodiments provide that the capacitor **210** is used without capacitors **211** and **212** to achieve a desired configuration and performance.

[0041] Any or all of capacitors **210**, **211**, and **212** may be realized within a package or a printed circuit board that includes the duplexer components so that it does not add to the overall cost or footprint. For instance, some or part of any of these capacitors **210**, **211**, and **212** may be realized through the capacitance of the interconnect lines.

[0042] In an exemplary embodiment, the capacitor **210** provides intentional coupling across the two hybrid ports that are otherwise meant to be isolated. This intentional coupling, when properly designed, can cancel out the effect of inherent unwanted coupling between these ports so that the overall duplexer isolation between ports **202** and **209** is enhanced. Some embodiments contemplate that a single capacitor **210** can enhance the duplexer isolation between ports **202** and **209** due to poor isolation in either of the quadrature hybrid couplers **204** or **207**. In other exemplary embodiments, capacitor **210** can be placed on either side of the quadrature hybrid coupler **204** or on either side of the quadrature hybrid coupler **207**.

[0043] Some embodiments provide that capacitors **211** and **212** can improve duplexer performance, especially the isolation between ports **202** and **209**, in the presence of non-idealities, especially asymmetry caused by amplitude and phase mismatches in the quadrature hybrid couplers **204** and **207**, and by the mismatch between f_2 filters **205** and **206**. In some embodiments, the capacitors **211** and **212** can be placed on either side of the quadrature hybrid coupler **204** or on either side of the quadrature hybrid coupler **207**. The values for the capacitors **211** and **212** may be different or the same. In some embodiments, only one of capacitors **211** and **212** is used to achieve a desired set of specifications.

[0044] Some embodiments contemplate that the value of the terminating impedance **208** provides another degree of freedom to enable high isolation between **202** and **209** ports. The impedance **208**, ideally set to the terminating impedance of all the other ports at 50 Ω, for example, may have to be different in a practical design due to the aforementioned non-idealities as well as the impedance mismatches at any of the ports. In a practical design, the impedance **208** may have both resistive and reactive components, for example.

[0045] FIG. **2**B shows another embodiment of the RF duplexer **200***b* according to the present disclosure. The exemplary RF Duplexer **200***b* uses transmission lines **213**, **214**, **215**, and **216** instead of capacitors **211** and **212**. Not all the transmission lines are needed in all implementations. Some or all of these transmission lines could have different impedances Za, Zb, Zc, Zd and lengths. The characteristic impedance and length of each transmission line may be set so that any of these transmission lines behaves like a capacitor or an inductor. The characteristic impedance and length of these transmission lines **211**, **212**, **213**, **214** can be set to increase the isolation between ports **202** and **209** in the RF duplexer **200***b*. These transmission lines **211**, **212**, **213**, **214** may be realized in various forms including, but not limited to, microstrips, coplanar striplines, coplanar waveguides, coaxial lines, etc. on any substrate including, but not limited to, printed circuit boards (PCB), ceramic substrates, etc.

[0046] FIG. **3**A shows another embodiment of the RF duplexer **300***a* according to the present disclosure. The RF duplexer **300***a* provides for capacitors **310**, **311**, and **312** (e.g., tunable or reconfigurable capacitors) to be added to form a tunable or reconfigurable RF duplexer based, in part, on the design of the RF duplexer **100** of FIG. **1**, where the f_1 filter **301** and/or the f_2 filters **305** and **306** are realized as tunable or reconfigurable filters. Any tunable or reconfigurable filter may be used in this scheme. In one embodiment, each tunable filter may comprise several fixed-frequency filters and one or more switches that select one of the fixed-frequency filters at a given time. In another embodiment, each tunable filter may comprise tunable components such as tunable capacitors or switched capacitors. The tunable filters **301**, **305**, **306** may comprise only passive elements, only active elements (e.g., components), or some combination of passive and active elements. Some embodiments provide that the tunable filters **301**, **305**, **306** are controlled through electrical stimuli. However, the internal mechanisms that make the filters tunable may be electrical, magnetic, electromagnetic, mechanical, chemical, etc. Quadrature hybrid couplers **304** and **307** may be fixed or tunable or reconfigurable in such a design. Tunable or reconfigurable RF duplexer **300***a* may enable realization of multi-band, multi-mode, multi-standard, or multi-function wireless communication systems. Specifically, the tunable or reconfigurable RF duplexer **300***a* may be realized at a lower cost or smaller form factor or with higher performance when compared with other solutions such as those requiring switching among multiple fixed RF duplexers. Satisfying low insertion loss and high isolation in the design of a tunable RF duplexer is more challenging when compared to a fixed RF duplexer design. This is due to the low quality factor of tunable components that are used in the tunable or reconfigurable filters. The non-idealities such as the amplitude and phase mismatch in the quadrature hybrid couplers **304** and **307**, the non-zero isolation in the quadrature hybrid couplers **304** and **307**, and the mismatch between the f_2 filters **305** and **306** are frequency dependent.

[0047] Furthermore, duplexer specifications including, for example, frequency bands f_1 and f_2, and insertion loss and isolation requirements may be different across different settings in a tunable/reconfigurable RF duplexer. In short, fixed values for capacitors **310**, **311**, and **312** might not be sufficient to satisfy the desired RF duplexer specifications for all the settings. Therefore, in a tunable or reconfigurable

RF duplexer **300***a*, tunable or variable capacitors **310**, **311**, and **312** may be used. The values for the capacitors **310**, **311**, **312** can be selected to satisfy the RF duplexer specification across all the settings (e.g., different frequency bands of interest). Similar to the previous exemplary embodiment described above with respect to FIG. **2**, not all the capacitors **310**, **311**, **312** may be necessary in a design. Furthermore, it might not be necessary that all of the capacitors **310**, **311**, **312** be tunable or variable. In some embodiments, any type of variable or tunable capacitor such as switched capacitors, varactors, etc. may be used. The tuning mechanism may be based on changing the dielectric constant of a capacitor, such as those using ferroelectric effects in materials such as Barium Strontium Titanate (BST); changing the distance or effective overlap of the capacitance plates; and/or changing the width of a depletion region or carrier density across or in a semiconductor junction, etc. Following the same discussions (e.g., the frequency dependency of the non-idealities), the terminating resistance **308** may also be tunable as shown in FIG. **3**A. The control signals for any of the capacitors **310**, **311**, and **312** may be different or similar to each other, different or similar to control signals for any of the filters **301**, **305**, and **306**, and different or similar to the control signal for the terminating impedance **308**. However, the control signals for all the tunable components (e.g., filters, capacitors, and/or impedances) can be changed in tandem (e.g., concurrently, sequentially, etc.) to achieve the desired performance across all the tunable or reconfigurable duplexer settings.

[0048] FIGS. **3**B-**3**D show other embodiments of the RF duplexer according to the present disclosure. The RF duplexers **300***b*-**300***d* provide that capacitors **313**, **314**, and **315** are placed across different sides of either of the quadrature hybrid couplers **304** and **307**. As stated before, some embodiments contemplate that not all capacitors are needed in a particular design; likewise, not all capacitors have to be tunable or reconfigurable in a particular design.

[0049] FIG. **3**E shows another embodiment of the RF duplexer **300***e* according to the present disclosure. Unlike capacitors **311**, **312** described above with respect to the RF duplexer **300***a* shown in FIG. **3**A, RF duplexer **300***e* provides capacitors **316** and **317** at a different quadrature hybrid coupler, such as the quadrature hybrid coupler **307**. Some embodiments provide that the tunable parallel capacitor across the quadrature hybrid coupler, such as the capacitor **310**, may be placed across any side of either of the quadrature hybrid couplers **304**, **307**. Furthermore, the tunable parallel capacitors to ground (e.g., electrical ground, chassis ground, circuit ground, etc.), such as the capacitors **316**, **317**, may be placed at either side of either of the quadrature hybrid couplers **304**, **307**.

[0050] FIG. **4** shows another embodiment of the RF duplexer **400** according to the present disclosure. The RF duplexer **400** provides capacitors **410**-**415** (e.g., tunable or reconfigurable capacitors) as part of a tunable or reconfigurable RF duplexer. A tunable impedance **408** may also be included in the tunable or reconfigurable RF duplexer **400**. In an exemplary embodiment, the tunable or reconfigurable RF duplexer **400** is configured to enhance the performance, for example, to enhance the isolation between ports **402** and **409**, and/or reduce the insertion loss between ports **403** and **402**, and between ports **403** and **409**, in the presence of various non-idealities such as the frequency dependent amplitude and phase mismatch or the limited isolation in the quadrature hybrid couplers **404**, **407**, the frequency dependent mismatch between f_2 filters **405** and **406**, etc.

[0051] FIG. **5** shows another embodiment of the RF duplexer **500** according to the present disclosure. The RF duplexer **500** provides a tunable or reconfigurable RF duplexer. Referring to FIG. **5**, tunable f_1 filter **501** is realized as a bank of fixed-frequency filters **510**, with corresponding frequency bands $f_{1,1}, f_{1,2}, \ldots, f_{1,N}$, and a pair of switches **513**, **514** to select one of the fixed-frequency filters **510** when appropriate. These fixed-frequency filters **510** may be constructed using various technologies such as, for example, surface acoustic wave (SAW) components, bulk acoustic wave (BAW) components, lumped circuit components, transmission lines and waveguides, dielectric or air cavity resonators, etc. Tunable f_2 filters **505** and **506** may include tunable capacitors such as varactors or switched capacitors that enable tunability or reconfigurability in their responses. These tunable f_2 filters **505** and **506** may include other components such as inductors, capacitors, and transmission lines, and may include components that operate based on electromagnetic or acoustic principles. Tunable capacitors **511** and **512** may enable maintaining high isolation between ports **502** and **509** in the presence of various non-idealities such as amplitude and phase mismatches in the quadrature hybrid couplers **504** and **507**, mismatches between f_2 filters **505** and **506**, mismatches in the layout, etc.

[0052] In some embodiments, the proper settings (e.g., desired settings) for the tunable capacitors **511** and **512** may be the same or different for different settings in the tunable or reconfigurable RF duplexer **500**. The proper settings for tunable capacitors **511** and **512**, along with those for tunable capacitors **515**, **516** in the tunable f_2 filters **505** and **506**, may be determined during assembly and testing of the RF duplexer **500**. These settings may be stored in a memory (e.g., a non-transitory memory) for future use. The proper values for the tunable capacitors **511** and **512** may be determined through determination on duplexer performance metrics such as isolation or insertion loss.

[0053] In some embodiments, the proper settings for tunable capacitors **511** and **512**, along with those for tunable capacitors **515**, **516** in the tunable f_2 filters **505** and **506**, may be determined by a wireless communication device that utilizes the RF duplexer **500**. The control signals for the tunable f_1 filter **501**, or the tunable f_2 filters **505** and **506**, or the tunable capacitors **511** and **512** may be analog or digital signals. An analog control signal may be supplied through a digital-to-analog converter (DAC). The digital control signals, once determined, may be stored in a memory or register to be recalled later as needed.

[0054] Some embodiments of the RF duplexers according to the present disclosure may be used in handheld portable devices supporting wireless communications such as a mobile phones, cellular phones, smartphones, tablets, laptops, smartwatches, etc. Some embodiments of the RF duplexers according to the present disclosure may be used in devices supporting the wireless communication infrastructure such as base stations (including macro-, micro-, pico-, and femto-base stations), repeaters, etc. Some embodiments of the RF duplexers according to the present disclosure may enable compact multiband, multi-standard wireless communication devices, wireless communication devices that support carrier aggregation, and wireless communication devices that support frequency division duplexing (FDD).

[0055] Other embodiments of the disclosure may provide a non-transitory computer readable medium and/or storage medium, and/or a non-transitory machine readable medium and/or storage medium, having stored thereon, a machine code and/or a computer program having at least one code section executable by a machine and/or a computer, thereby causing the machine and/or computer to perform some or all of the steps as described herein for enhancing isolation in hybrid-based RF duplexers and multiplexers.

[0056] Accordingly, aspects of the present disclosure may be realized in hardware, software, or a combination of hardware and software. The present disclosure may be realized in a centralized fashion in at least one computer system or in a distributed fashion where different elements are spread across several interconnected computer systems. Any kind of computer system or other apparatus adapted for carrying out the methods described herein is suited. A combination of hardware and software may be a general-purpose computer system with a computer program that, when being loaded and executed, controls the computer system such that it carries out the methods described herein.

[0057] Aspects of the present disclosure may also be embedded in a computer program product, which comprises all the features enabling the implementation of the methods described herein, and which when loaded in a computer system is able to carry out these methods. Computer program in the present context means any expression, in any language, code or notation, of a set of instructions intended to cause a system having an information processing capability to perform a particular function either directly or after either or both of the following: a) conversion to another language, code or notation; b) reproduction in a different material form.

[0058] While the present disclosure has been described with reference to certain embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the scope of the present disclosure. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the present disclosure without departing from its scope. Therefore, it is intended that the present disclosure not be limited to the particular embodiment disclosed, but that the present disclosure will include all embodiments falling within the scope of the appended claims.

[0059] The scope of protection is limited solely by the claims that now follow. That scope is intended and should be interpreted to be as broad as is consistent with the ordinary meaning of the language that is used in the claims when interpreted in light of this specification and the prosecution history that follows, except where specific meanings have been set forth, and to encompass all structural and functional equivalents.

What is claimed is:

1. A radio frequency duplexer, comprising:
a first port;
a second port;
a third port;
two or more quadrature hybrid couplers;
two or more filters;
a terminating impedance; and
a capacitor,
wherein:
the two or more filters are coupled to the two or more quadrature hybrid couplers,
the terminating impedance is coupled to a port of one of the two or more quadrature hybrid couplers, and
the capacitor is connected across one of the two or more quadrature hybrid couplers.

2. The radio frequency duplexer of claim **1**, wherein the capacitor and the two or more quadrature hybrid couplers are configured to improve isolation or an insertion loss of the radio frequency duplexer.

3. The radio frequency duplexer of claim **1**, wherein one or more of the two or more filters, the terminating impedance, and the capacitor are tunable or reconfigurable.

4. The radio frequency duplexer of claim **1**, comprising:
at least one more capacitor coupled between a port of one of the two or more quadrature hybrid couplers and a ground, wherein the at least one more capacitor and the two or more quadrature hybrid couplers are configured to further enhance isolation or an insertion loss of the radio frequency duplexer.

5. The radio frequency duplexer of claim **4**, wherein the at least one more capacitor is tunable or reconfigurable.

6. The radio frequency duplexer of claim **1**, wherein the two or more quadrature hybrid couplers, the two or more filters, the terminating impedance, and the capacitor are integrated in a single package.

7. The radio frequency duplexer of claim **1**, wherein the radio frequency duplexer is included in a multi-standard communication system or a multi-band communication system.

8. The radio frequency duplexer of claim **1**, wherein the radio frequency duplexer is included in a device that supports wireless communications.

9. A tunable radio frequency duplexer, comprising:
a first port;
a second port;
a third port;
a first quadrature hybrid coupler;
a second quadrature hybrid coupler;
a first tunable radio frequency filter;
a second tunable radio frequency filter;
a third tunable radio frequency filters;
a terminating impedance;
a first tunable capacitor; and
a second tunable capacitor,
wherein:
the third tunable radio frequency filter is similarly structured as the second radio frequency tunable filter,
a first terminal and a second terminal of the first tunable radio frequency filter are respectively coupled to the first port and a first terminal of the first quadrature hybrid coupler,
a first terminal and a second terminal of the second tunable radio frequency filter are respectively coupled to a second terminal of the first quadrature hybrid coupler and a first terminal of the second quadrature hybrid coupler,
a first terminal and a second terminal of the third tunable radio frequency filter are respectively coupled to a third terminal of the first quadrature hybrid coupler and a fourth terminal of the second quadrature hybrid coupler, respectively,

the terminating impedance is coupled to a third terminal of the second quadrature hybrid coupler,

a second terminal of the second quadrature hybrid coupler is coupled to the second port,

a fourth terminal of the first quadrature hybrid coupler is coupled to the third port,

a first terminal of the first tunable capacitor is coupled to the first terminal of the first quadrature hybrid coupler, or the second terminal of the first quadrature hybrid coupler, or the first terminal of the second quadrature hybrid, or the second terminal of the second quadrature hybrid coupler,

a second terminal of the first tunable capacitor is coupled to a ground,

a first terminal of the second tunable capacitor is coupled to the third terminal of the first quadrature hybrid coupler, or the fourth terminal of the first quadrature hybrid coupler, or the third terminal of the second quadrature hybrid coupler, or the fourth terminal of the second quadrature hybrid coupler, and

a second terminal of the second tunable capacitor is coupled to a ground.

10. The tunable radio frequency duplexer of claim **9**, wherein the first tunable capacitor and the second tunable capacitor are configured to improve isolation between the first port and the second port.

11. The tunable radio frequency duplexer of claim **9**, comprising:

a third tunable capacitor,

wherein:

a first terminal of the third tunable capacitor is coupled to the first terminal of the first quadrature hybrid coupler, or the second terminal of the first quadrature hybrid coupler, or the first terminal of the second quadrature hybrid, or the second terminal of the second quadrature hybrid coupler, and

a second terminal of the third tunable capacitor is coupled to the fourth terminal of the first quadrature hybrid coupler, or the third terminal of the first quadrature hybrid coupler, or the fourth terminal of the second quadrature hybrid coupler, or the third terminal of the second quadrature hybrid coupler, respectively.

12. The tunable radio frequency duplexer of claim **9**, wherein the first radio frequency tunable filters, the second radio frequency tunable filter, the third radio frequency tunable filter, the first tunable capacitor, and the second tunable capacitor are controlled to improve performance of the tunable radio frequency duplexer.

13. The tunable radio frequency duplexer of claim **9**, wherein the first radio frequency tunable filters, the second radio frequency tunable filter, the third radio frequency tunable filter, the first tunable capacitor, and the second tunable capacitor are controlled to improve isolation or an insertion loss of the tunable radio frequency duplexer for one or more frequency bands.

14. The tunable radio frequency duplexer of claim **9**, wherein one or more of the first tunable radio frequency filter, the second tunable radio frequency filter, the third radio frequency tunable filter, the first tunable capacitor and the second tunable capacitor are controlled by analog control signals through a digital-to-analog (DAC) converter.

15. The tunable radio frequency duplexer of claim **9**, wherein one or more of the first tunable radio frequency filter, the second tunable radio frequency filter, the third radio frequency tunable filter, the first tunable capacitor and the second tunable capacitor are controlled by digital control signals.

16. The tunable radio frequency duplexer of claim **9**, wherein the tunable radio frequency duplexer is included in a multi-standard wireless communication system or a multi-band wireless communication system.

17. The tunable radio frequency duplexer of claim **9**, wherein the tunable radio frequency duplexer is included in a cellular phone or a handheld wireless communication device.

18. A radio frequency duplexer, comprising:

a first port;

a second port;

a third port;

two or more quadrature hybrid couplers;

two or more filters;

a terminating impedance; and

one or more transmission lines,

wherein:

the two or more filters are coupled to the two or more quadrature hybrid couplers,

the terminating impedance is coupled to a port of one of the two or more quadrature hybrid couplers, and

each of the one or more transmission lines connects one of the two or more filters to a port of one of the two or more quadrature hybrid couplers.

19. The radio frequency duplexer of claim **18**, wherein the characteristic impedance and length of the one or more transmission lines are configured to improve isolation or an insertion loss of the radio frequency duplexer.

20. The radio frequency duplexer of claim **18**, wherein the radio frequency duplexer is included in a multi-standard communication system or a multi-band communication system.

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