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Mandegaran

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(54) **REFLECTION-BASED RADIO-FREQUENCY MULTIPLEXERS**

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(51) **Int. Cl.**

H04W 4/00	(2018.01)
H04B 1/00	(2006.01)
H04W 72/04	(2009.01)

(52) **U.S. Cl.**
CPC ***H04B 1/005*** (2013.01); ***H04B 1/0057*** (2013.01); *H04W 72/0453* (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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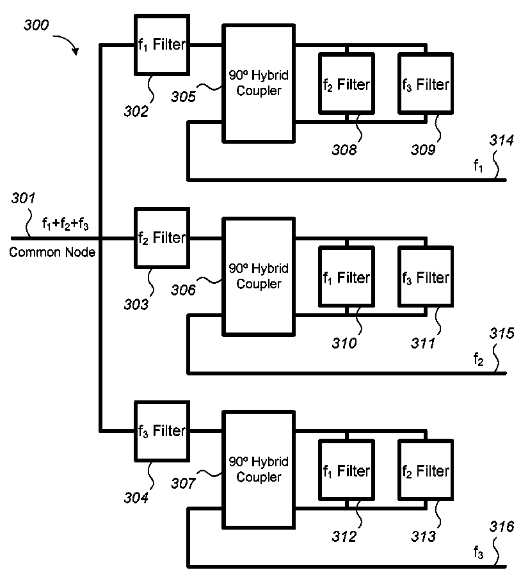
(57) **ABSTRACT**

A radio frequency multiplexer, which supports a plurality of frequency bands, comprises a common node, a plurality of single band nodes, and a plurality of parallel branches. Each of the plurality of parallel branches is designated to one of the plurality of frequency bands and connects the common node and one of the plurality of single band nodes. A particular branch of the parallel branches may comprises a filter for a desired frequency band that passes through the particular branch, a quadrature hybrid coupler coupled to the filter, and a set of one or more other filters for one or more other frequency bands in the plurality of frequency bands respectively. The set of one or more other filters is coupled to the quadrature hybrid coupler for rejecting the one or more other frequency bands by the particular branch.

20 Claims, 8 Drawing Sheets



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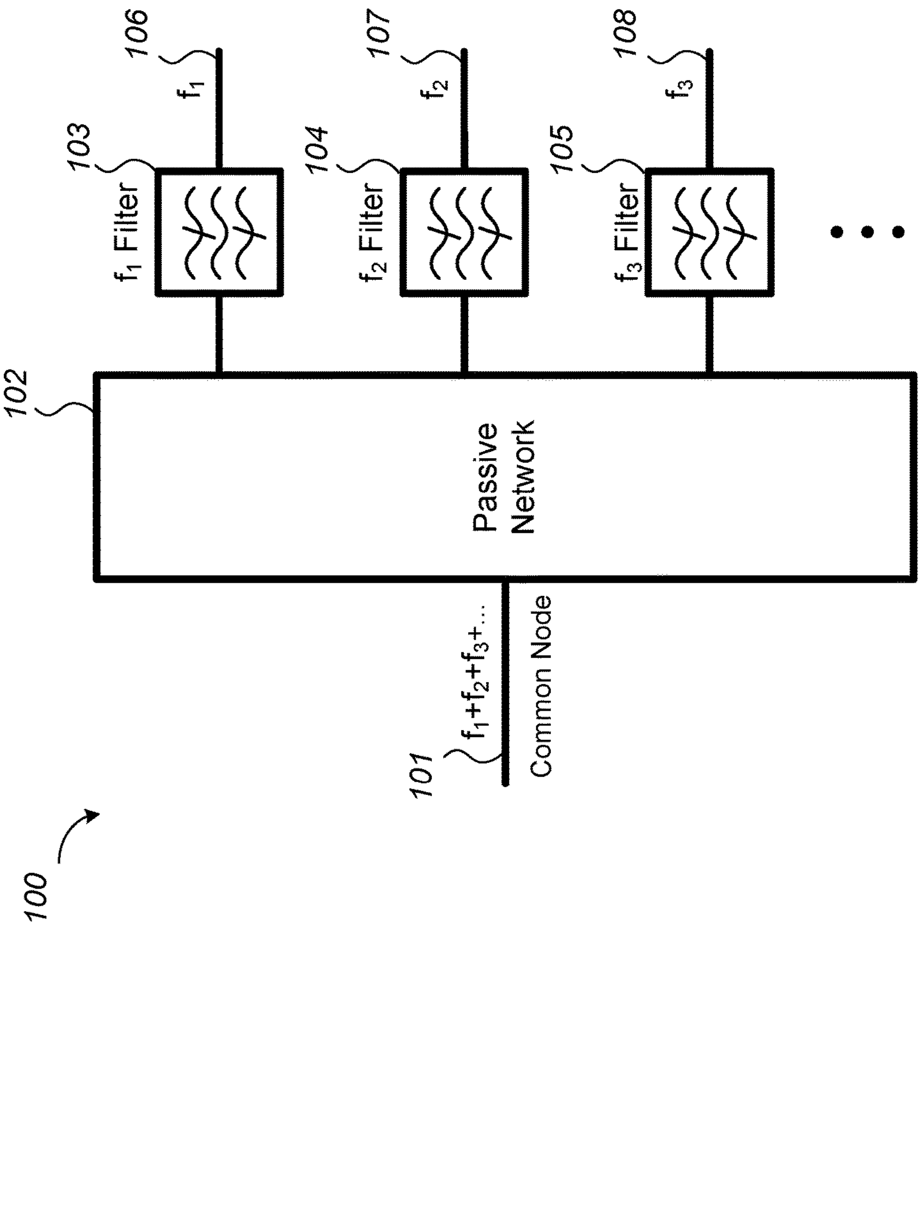

100
101
102
103
104
105
106
107
108
Passive Network
f_1 Filter
f_2 Filter
f_3 Filter
f_1
f_2
f_3
$f_1+f_2+f_3+\ldots$
Common Node

FIG. 1

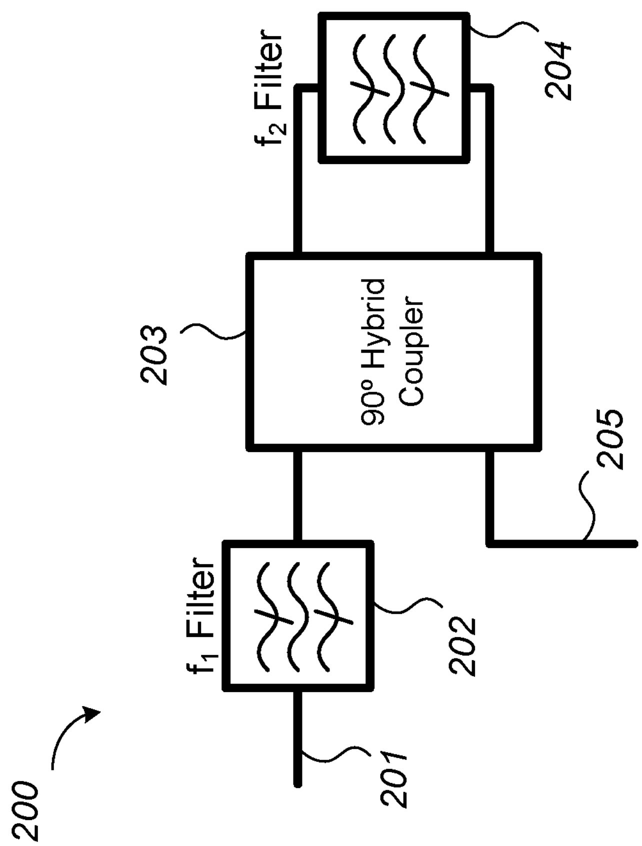

FIG. 2

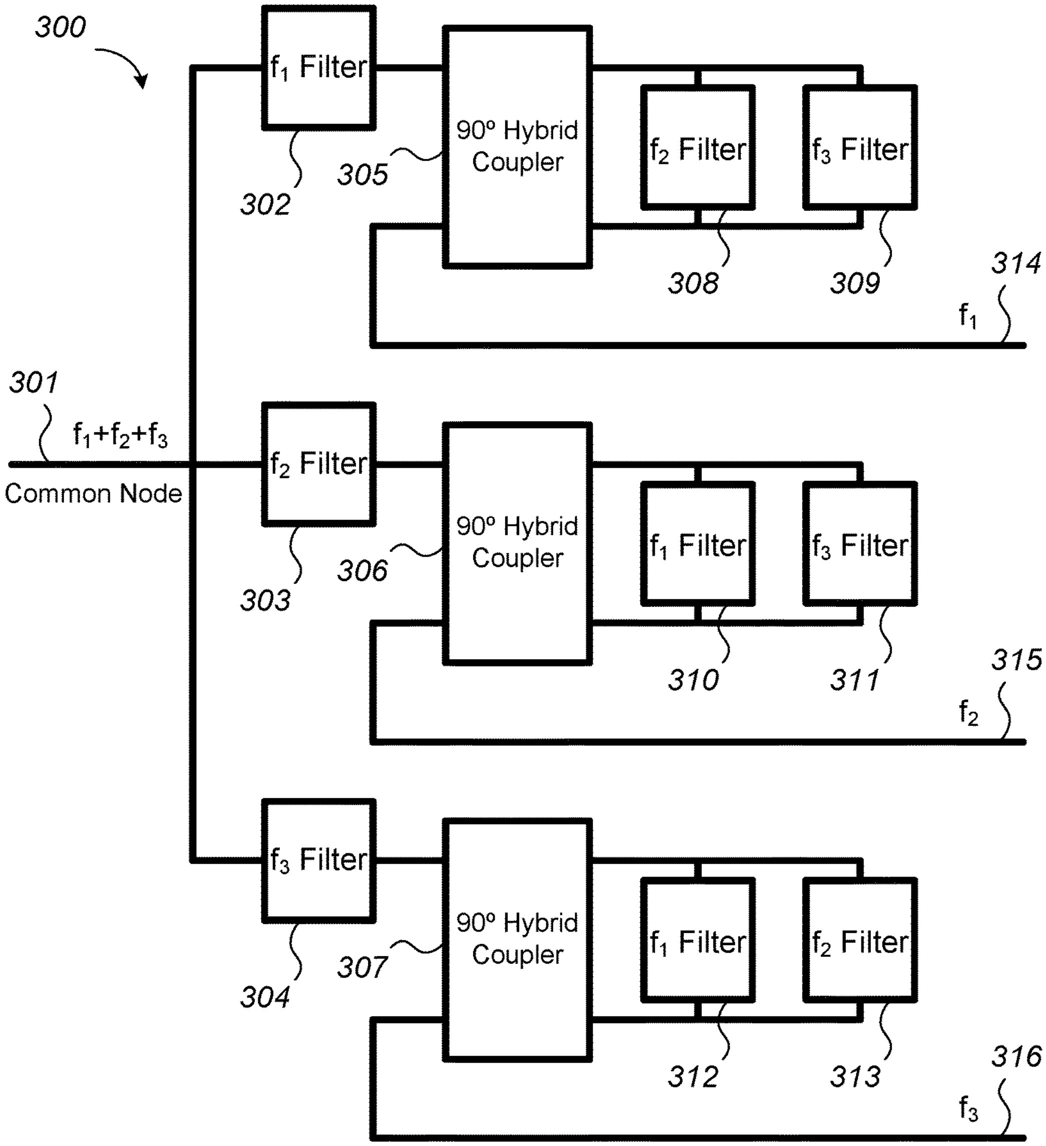
300
301
$f_1+f_2+f_3$
Common Node
f_1 Filter
302
f_2 Filter
303
f_3 Filter
304
90° Hybrid Coupler
305
306
307
f_2 Filter
f_3 Filter
f_1 Filter
f_3 Filter
f_1 Filter
f_2 Filter
308
309
310
311
312
313
314
315
316
f_1
f_2
f_3

FIG. 3

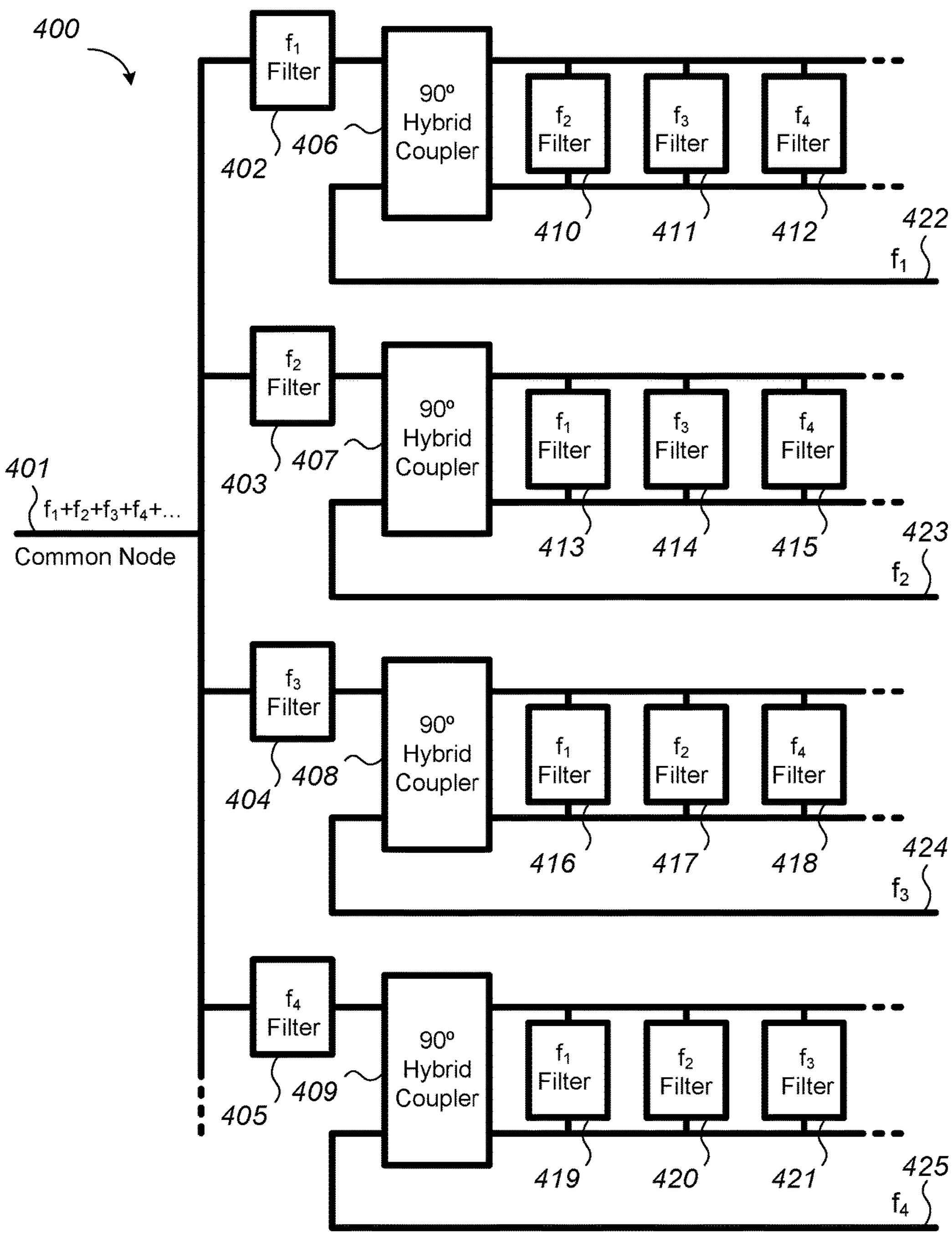
400
401
f1+f2+f3+f4+...
Common Node
f1 Filter
f2 Filter
f3 Filter
f4 Filter
90º Hybrid Coupler
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420
421
422
423
424
425
f1
f2
f3
f4

FIG. 4

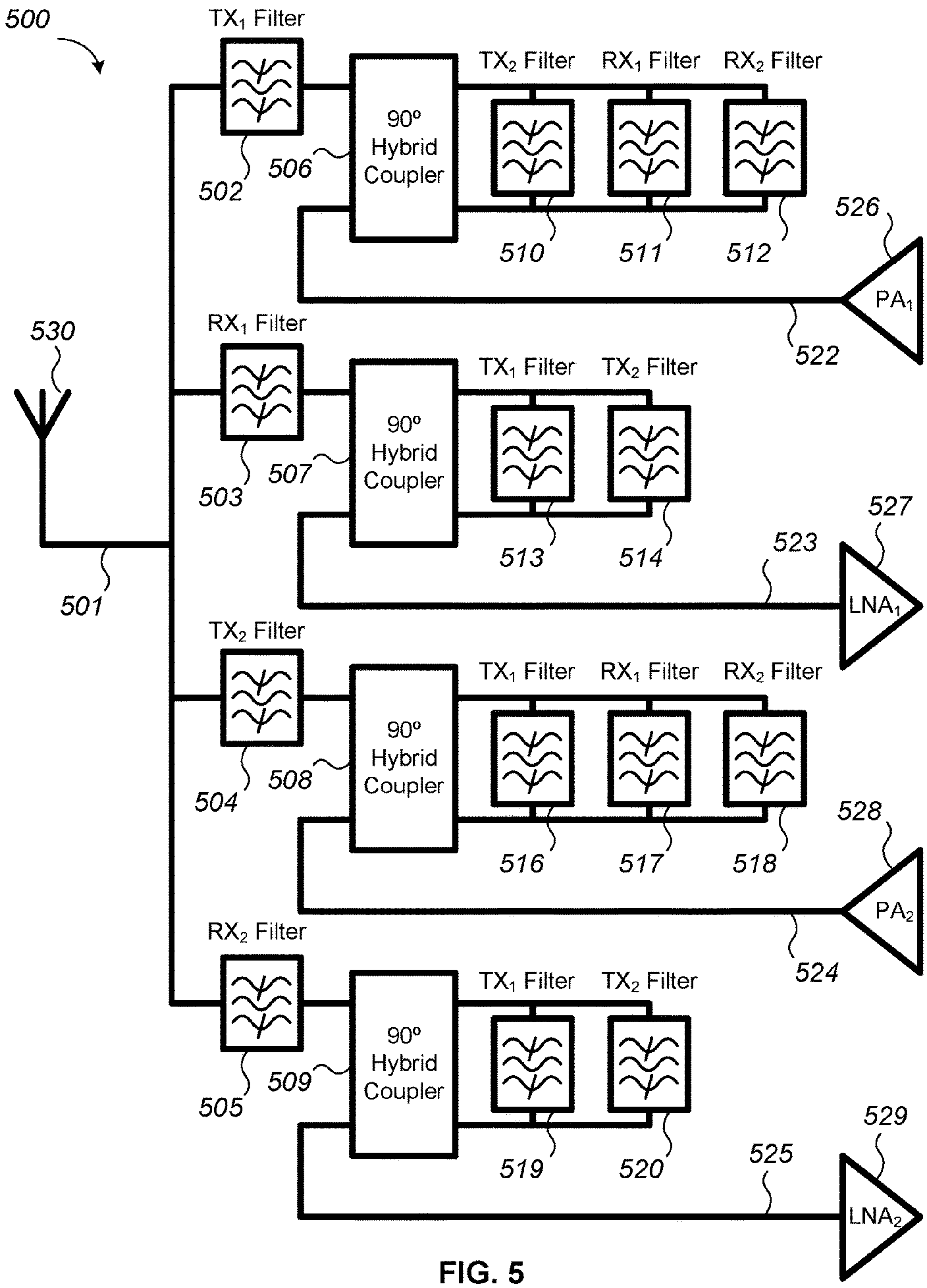
500
530
501
TX1 Filter
502
506
90º Hybrid Coupler
TX2 Filter
RX1 Filter
RX2 Filter
510
511
512
526
PA1
522
RX1 Filter
503
507
90º Hybrid Coupler
TX1 Filter
TX2 Filter
513
514
523
527
LNA1
TX2 Filter
504
508
90º Hybrid Coupler
TX1 Filter
RX1 Filter
RX2 Filter
516
517
518
528
PA2
524
RX2 Filter
505
509
90º Hybrid Coupler
TX1 Filter
TX2 Filter
519
520
525
529
LNA2

FIG. 5

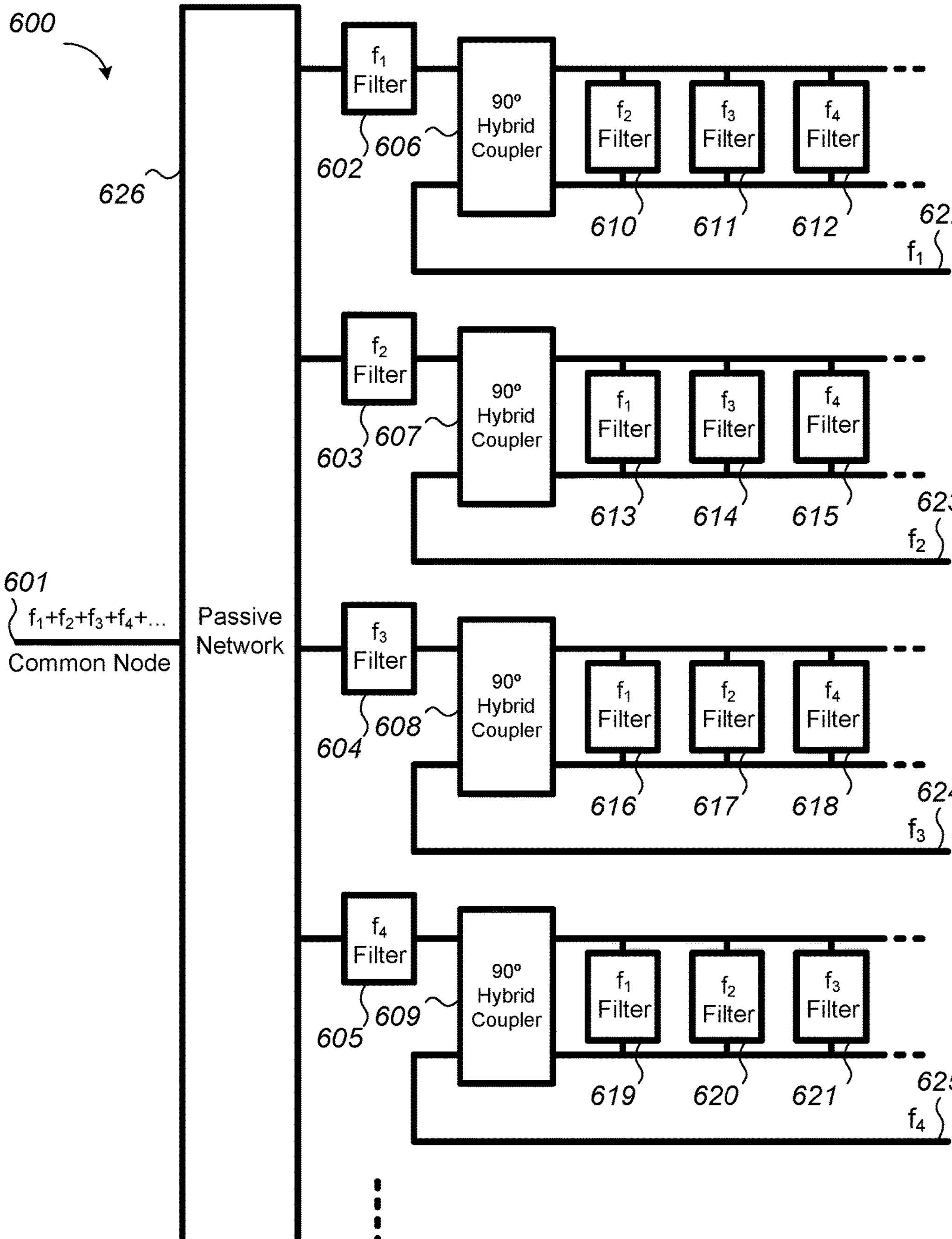
600
601
$f_1+f_2+f_3+f_4+$...
Common Node
Passive Network
626
f_1 Filter
602
606
90° Hybrid Coupler
f_2 Filter
f_3 Filter
f_4 Filter
610
611
612
622
f_1
f_2 Filter
603
607
90° Hybrid Coupler
f_1 Filter
f_3 Filter
f_4 Filter
613
614
615
623
f_2
f_3 Filter
604
608
90° Hybrid Coupler
f_1 Filter
f_2 Filter
f_4 Filter
616
617
618
624
f_3
f_4 Filter
605
609
90° Hybrid Coupler
f_1 Filter
f_2 Filter
f_3 Filter
619
620
621
625
f_4

FIG. 6

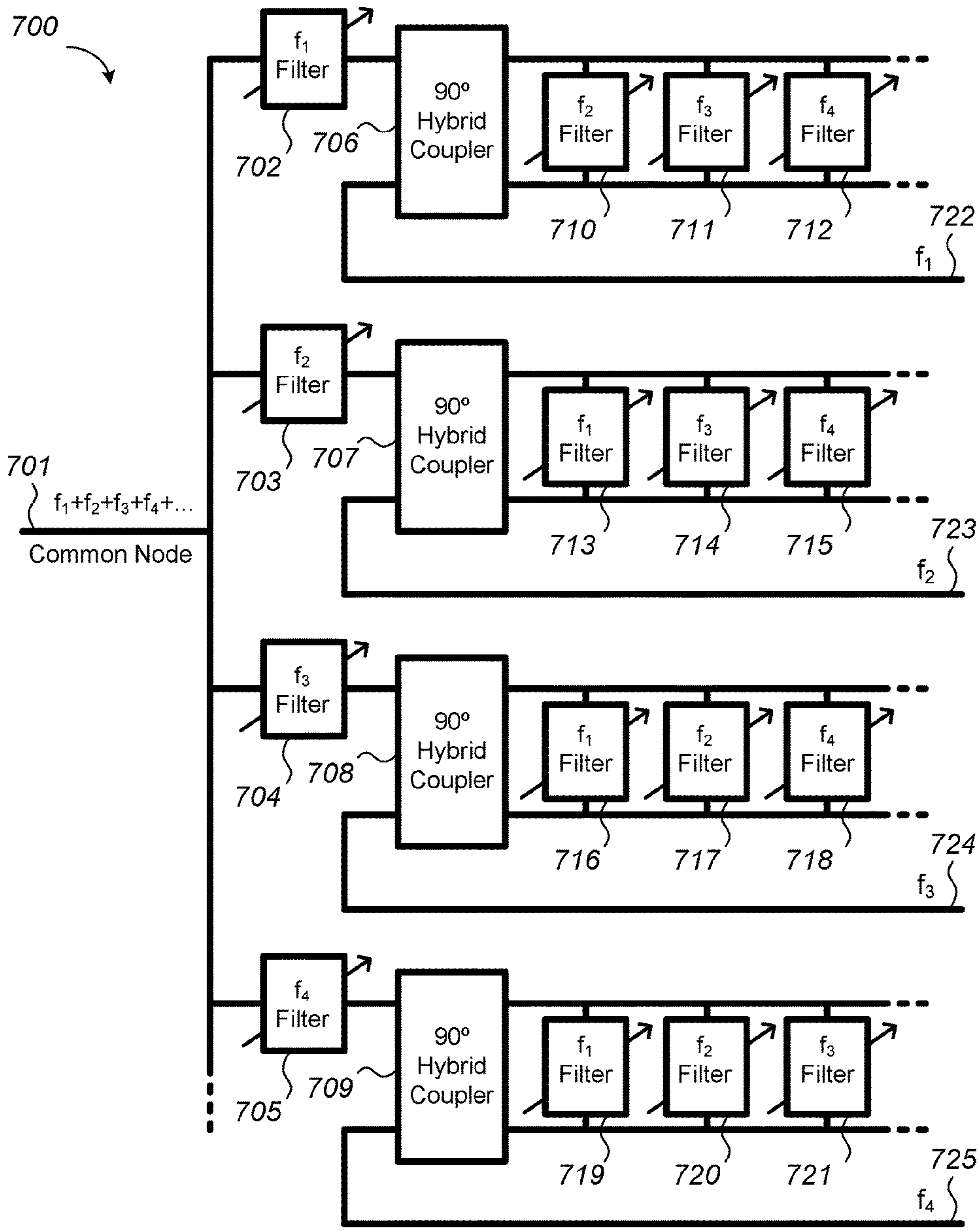
700
701
f1+f2+f3+f4+…
Common Node
f1 Filter
f2 Filter
f3 Filter
f4 Filter
90º Hybrid Coupler
702
703
704
705
706
707
708
709
710
711
712
713
714
715
716
717
718
719
720
721
722
723
724
725
f1
f2
f3
f4

FIG. 7

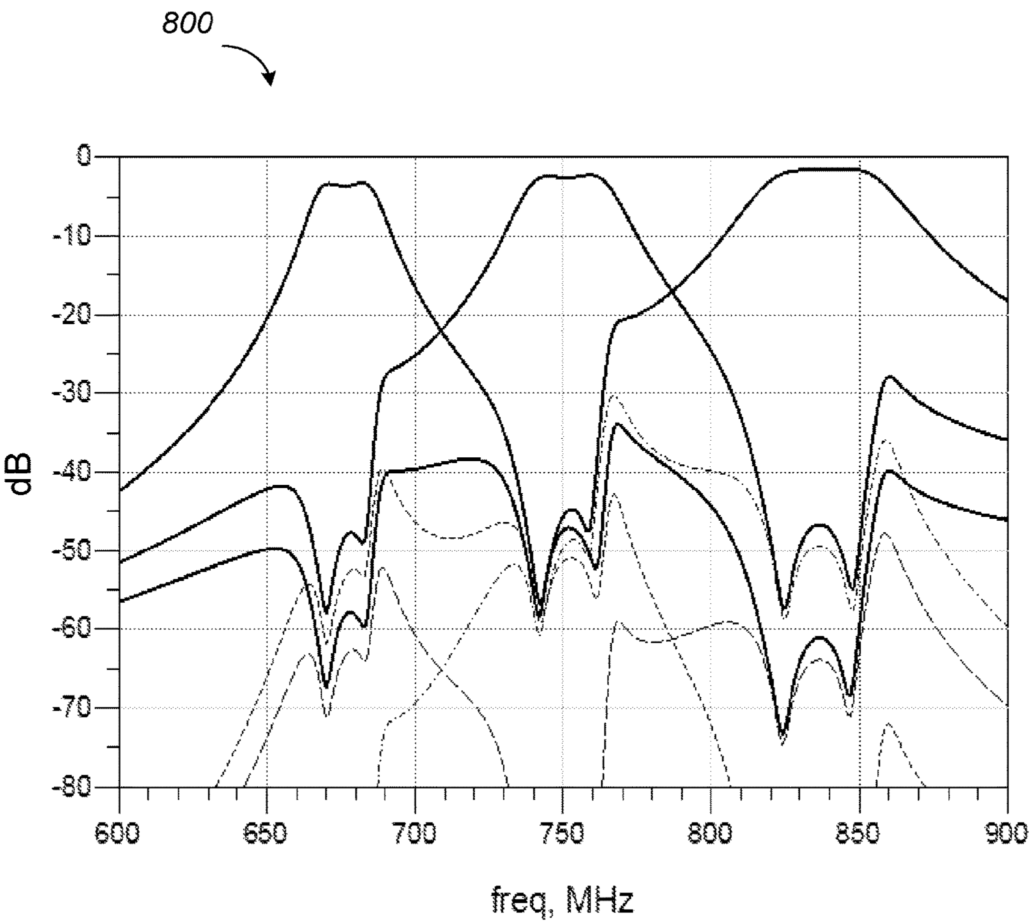
800
0
-10
-20
-30
-40
-50
-60
-70
-80
dB
600
650
700
750
800
850
900
freq, MHz

FIG. 8

REFLECTION-BASED RADIO-FREQUENCY MULTIPLEXERS

CROSS-REFERENCE TO RELATED APPLICATIONS/INCORPORATION BY REFERENCE

This patent application makes reference to, claims priority to, and claims benefit from U.S. Provisional Application Ser. No. 62/237,891, filed on Oct. 6, 2015.

The above-referenced application is hereby incorporated herein by reference in its entirety.

FIELD OF THE DISCLOSURE

Certain embodiments of the disclosure relate to electromagnetic components, integrated circuits, and/or wireless communication devices and systems. More specifically, certain embodiments of the disclosure relate to a method and system for reflection-based radio frequency (RF) multiplexers.

BACKGROUND OF THE DISCLOSURE

In communications, in order to correctly receive a desired signal, the desired signal is separated from many other signals that are present on the same medium. This is applicable to wired communication systems and/or wireless communication systems. In the case of wireless communication systems, for example, the task of separating the desired signal from other signals can be a substantial challenge since it might not be known what other signals are present in the air which may interfere with receive circuitry. Further, the transmitter may also interfere with the receive circuitry since the transmitter sits on the same system as the receive circuitry and may operate at the same or a very close frequency to that of the desired receive signal. There are many techniques to isolate a receiver from a transmitter.

As demand for higher bandwidths and better connectivity continues to grow, interest in carrier aggregation has increased. In carrier aggregation, a wireless device may receive the desired information at different frequency bands (or channels) and/or may transmit the information at different frequency bands (or channels).

The requirements for RF filters and multiplexers have become more stringent in light of new communication standards where information channels and frequency bands are closer to each other; new communication devices such as smartphones where the footprint and cost of all components must be very small as more components are needed in support of multiple standards and applications; and co-existing communication systems where multiple communication transmitters and receivers work simultaneously.

Linearity, noise, and power handling requirements might lead to utilization of passive RF filters and multiplexers in many applications. The performance of passive RF filters may be limited by the quality factor (Q) of the components that are used in their realization. The filter selectivity as well as passband requirement may lead to a filter topology and filter order. For a given RF filter topology and order, insertion loss may reduce with the increase of component Q.

Various technologies can be used to realize passive RF filters and duplexers. For instance, capacitors, inductors, or transmission lines can be used to realize passive RF filters and duplexers. Electromagnetic resonators, including waveguide, air cavity, dielectric, and ceramic resonators, can also be used to realize passive filters and duplexers. The quality factor of such components is proportional to their overall physical size. As such, it has been difficult to realize compact low-loss selective passive RF filters and duplexers using electromagnetic components and resonators.

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

A system and/or method for reflection-based radio frequency (RF) 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.

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

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.

FIG. **1** illustrates an embodiment of an RF multiplexer according to the present disclosure.

FIG. **2** illustrates an embodiment of a reflection-type filter according to the present disclosure.

FIG. **3** illustrates an embodiment of a multiplexer that supports three frequency bands according to the present disclosure.

FIG. **4** illustrates an embodiment of a multiplexer that supports four or more frequency bands according to the present disclosure.

FIG. **5** illustrates an application for an example multiplexer that supports four frequency bands in the front end of a wireless communication system according to the present disclosure.

FIG. **6** illustrates an embodiment of multiplexer that supports four or more frequency bands according to the present disclosure.

FIG. **7** illustrates an embodiment of a tunable multiplexer that supports four or more frequency bands according to the present disclosure.

FIG. **8** is a graph showing the frequency response of an example RF multiplexer according to the present disclosure.

DETAILED DESCRIPTION OF THE DISCLOSURE

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.

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.

In some embodiments of the present disclosure, a component that separates different frequency bands is called a multiplexer. An RF multiplexer, in its simplest form, is a 1×N passive network including 1 nominal input and N nominal output ports (N is a positive integer) where each output corresponds to a specific frequency band. In other words, the transfer function from the input to each of the N outputs resembles a filter tuned to a specific frequency band. Furthermore, it is often desirable that the output ports of the multiplexer are isolated. In other words, the transfer functions from each of the output ports to every other output port should have a small magnitude at the frequency bands corresponding to those two ports.

Some embodiments of the present disclosure provide 1×N RF multiplexers that include RF band-pass filters (BPF) with distinct passband frequencies that are connected to a common port using a passive network or a number of passive networks. The passive network or networks can ensure proper impedance at all frequency bands of interest and may assist in enhancing the frequency response.

In some embodiments of the present disclosure, an input port of an RF multiplexer may correspond to an antenna interface and the output ports may correspond to receive or transmit frequency bands.

In some embodiments of the present disclosure, a duplexer may be considered a multiplexer with N=2. In other words, a duplexer is a three-port device. In an exemplary example, a duplexer can be configured to achieve good isolation between the transmitter and the receiver by using a pair of quadrature hybrid couplers (QHC) along with filters for the desirable bands. A duplexer can be used, for example, in wireless communication systems supporting frequency division duplexing (FDD).

In some embodiments of the present disclosure, piezoelectric material can be used to realize compact high-Q resonators. Surface acoustic wave (SAW) resonators can provide compact low-loss selective RF filters and duplexers. Further, bulk acoustic wave (BAW) resonators can be used to construct high-performance RF filters and duplexers. Micro-electro-mechanical system (MEMS) resonators with high quality factor can also be used in filtering applications.

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

Some embodiments of the present disclosure provide resonators (e.g., BAW resonators) that have lower loss (or higher Q) or are more compact, especially at higher frequencies, compared with SAW resonators, for example. Therefore, RF filters and duplexers that use BAW resonators can have lower insertion loss, or higher selectivity, or smaller form factor compared with those that utilize SAW resonators, especially at higher frequencies. Thin film bulk acoustic resonators (FBAR) and bulk acoustic wave solidly mounted resonator (BAW SMR) are exemplary examples of BAW resonators.

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 might 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 leads to the lower cost and/or more 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 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 multiplexers that use BAW resonators may offer lower loss compared with RF filters and multiplexers 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, might 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 for integrating RF filters and multiplexers 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 multiplexers as well as a number of BAW filters and duplexers. Each SAW filter or BAW filter or duplexer may be used for a specific communication application, standard, or frequency band.

Some embodiments of the present disclosure provide architectural solutions that enable realization of highly-selective, low-loss multiplexers with high-isolation between the ports. Some embodiments of the present disclosure use 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 multiplexers with SAW multiplexers using an innovative architecture, or replacing ceramic or cavity multiplexers with BAW multiplexers using an innovative architecture.

Some embodiments of the present disclosure provide architectural solutions that enable realization of tunable, reconfigurable, and/or programmable RF multiplexers that can satisfy the requirements of multi-standard communication systems.

Some embodiments of the present disclosure provide reflection-type filters that can use an elegant method to produce desired filter responses using filters and quadrature hybrid couplers (QHCs), such as disclosed in U.S. Pat. Nos. 4,694,266, 5,781,084, 8,013,690, and 8,749,321, which are hereby incorporated herein by reference in their entirety. In an exemplary example, high quality band-stop filters (BSF) can be implemented using a low-loss quadrature hybrid and a low-loss selective band-pass filters (BPF) realized with high-quality-factor SAW resonators.

In wireless communication, it is often desirable to receive and transmit, or operate at two frequency bands, at the same time using one antenna. To accomplish this, some embodiments provide that circuitry is used to send most of the incoming signal from the antenna to the receiver, and send most of the outgoing signal from the transmitter to the antenna, while maintaining high isolation between the transmit and receive paths. Two circuitry options include circulators and/or duplexers.

Some embodiments provide for receiving and transmitting simultaneously over more than two frequency bands. Just like the case for two frequency bands, it is desirable to have low insertion loss from and to the antenna for each frequency band while maintaining high isolation between frequency bands.

Some embodiments provide a novel multiplexer for three or more frequency bands that are used concurrently. Some embodiments provide that QHCs and filters are used to separate multiple frequencies. An advantage of some embodiments is that some embodiments are modular and scalable in the number of frequency bands. Accordingly, more frequency bands can be supported without significant degradation in performance. Another advantage of some embodiments is that some embodiments enable low-cost compact multiplexers for commercial wireless communication systems in support of carrier aggregation, multi-standard, multi-band, and multi-mode operation. Yet another advantage of some embodiments is that some embodiments enable low-cost compact tunable frequency multiplexers that meet the requirements of commercial wireless communication standards. Another advantage of some embodiments is that some embodiments relax the requirements for filters and associated components in a multiplexer.

FIG. **1** illustrates an exemplary realization of an RF multiplexer **100** including filters **103**, **104**, **105**, . . . specific to the desired frequency bands f_1, f_2, f_3, . . . that are coupled to a common node **101** through a passive network **102**. The passive network **102** provides proper impedance matching at the desired frequencies to the common node **101**. It may also provide additional filtering and port-to-port isolation. In order to satisfy the stringent port-to-port isolation requirement in the RF multiplexer **100**, filters **103**, **104**, **105**, . . . are typically extremely selective. These filters are high-order filters; they have several poles and zeros in their transfer functions to ensure high selectivity. To maintain a low insertion loss, these selective filters use high quality factor components in their realizations. Filter technologies that offer high quality factor components can be expensive or can have a large footprint. Tunable RF multiplexers are desirable in support of multi-band, multi-standard, software-defined, and cognitive wireless schemes. In the realization of FIG. **1**, RF filters **103**, **104**, **105**, . . . may be tunable. Unfortunately, typical tunable components might not have the high quality factors that are required to keep the insertion loss below acceptable levels in highly selective filters. It is therefore desirable that some embodiments enable realizations of tunable RF multiplexers with low cost technologies (e.g., commercially available low cost technologies).

FIG. **2** illustrates an exemplary realization of a reflection-type filter **200**. The signal entering through node **201** passes through a band-pass filter **202** with a nominal passband frequency f_1 (f_1 band-pass filter **202**). The filtered signal then enters a QHC **203** and is then split into two signals that differ by 90 degrees in phase from each other. A portion of the signal in frequency band f_1 reflects off of an f_2 band-pass filter **204** which causes its polarity to invert, re-enter the QHC **203**, recombine constructively, and exit at node **205**. A portion of the split signal that is within another frequency band f_2 passes through the f_2 band-pass filter **204** and re-enters the QHC **203** in the opposite nodes it entered the f_2 band-pass filter **204** and combines constructively to exit to top left node to f_1 band-pass filter **202**. Because the portion of the signal that is centered at frequency band f_2 is not sent to the node **205**, the circuitry **200** is effectively further filtering the f_2 portion of the signal. In other words, the combination of the QHC **203** and the f_2 band-pass filter **204** creates a band-stop filter at frequency band f_2. The entire structure **200** including the f_1 band-pass filter **201**, the QHC **203**, and the f_2 band-pass filter **204** provides band-pass filtering at frequency band f_1 and band-stop filtering at frequency band f_2. For instance, the f_1 band-pass filter **202** may be tuned to a frequency band of interest while the f_2 band-pass filter **204** may be tuned to a frequency band where there is an undesired signal (blocker, jammer, self-interference, etc.). The stopband provided by the QHC **203** and the f_2 band-pass filter **204** may reduce the selectivity requirement of f_1 band-pass filter **202**. Specifically, the filter order, hence the insertion loss, of f_1 band-pass filter **202** may be reduced for the same filter technology and component quality factors.

FIG. **3** illustrates an embodiment of a multiplexer according to the present disclosure. This scheme is a multiplexer **300** in support of three frequency bands, f_1, f_2, and f_3; as such, it may also be referred to as a triplexer. The triplexer **300** includes three parallel branches that share a common node **301**. Each branch provides band-pass filtering at one desired frequency band while it provides band-stop filtering at the other two desired frequency bands. For instance, including an f_1 band-pass filter **302**, a QHC **305**, and a parallel connection (e.g., a parallel electrical circuit arrangement) of an f_2 band-pass filter **308** and an f_3 band-pass filters **309**, an exemplary top branch of the triplexer **300** offers band-pass filtering at frequency band f_1 and band-stop filtering at frequency band f_2 and frequency band f_3 between the common node **301** and an f_1 node **314**. In comparison to the RF multiplexer of FIG. **1**, this scheme offers higher port-to-port isolation at all the desired frequency bands because of the creation of stopbands. Therefore, the selectivity requirements of f_1, f_2, and f_3 filters are relaxed. For instance, these filters now can be realized as low-order filters with fewer components resulting in a lower insertion loss, a smaller footprint, and a lower cost. One or more of these filters may be tunable resulting in a tunable RF multiplexer. The filters in FIG. **3** are shown as band-pass filters, but can also be other types of filters such as low-pass or high-pass. As long as the filter passes the desired frequency band, it can be used. These filters need not be limited to a single passband. In each parallel branch, the number and specification of the parallel filters resulting in a band-stop response (e.g., filters **308** and **309** in the top path) may depend on the port-to-port isolation requirement and other factors. Different parallel paths need not have the same number of such filters. The type and order of the f_1 filter, f_2 filter, and f_3 filter need not be the same, and can depend on the specifications of the triplexer. Furthermore, f_1 filters **302**, **310**, and **312** need not be the same. Likewise, f_2 filters **303**, **308**, **313** need not be same; f_3 filters **304**, **309**, and **311** need not be the same either. QHCs **305**, **306**, and **307** need not be identical; each QHC may be designed in conjunction with the filters that connect to it for a desired performance.

In an exemplary passive filter, the input reflection coefficient (S_{11}) and the input-output transfer function (S_{21}) are related. For instance, within the passband of a passive filter where S_{21} is ideally close to 1, the input reflection coefficient

S_{11} is ideally close to zero. In other words, the filter is impedance matched at the input at its passband. Likewise, within the stopbands of a passive filter where S_{21} is ideally close to zero, the input reflection coefficient is close to one. In other words, the filter reflects the signals at its input outside of its passband (within its stopband). Given that filters **302**, **303**, and **304** nominally have non-overlapping passbands, their inputs can be tied to each other at a common node **301** without undesired loading effects. For instance, at frequency band f_1, only the input impedance of f_1 filter **302** is impedance matched while the inputs of f_2 filter **303** and f_3 filter **304** act as reflectors. This ensures that the power of the input signal at frequency band f_1 is primarily delivered to the first (top) branch. As discussed before, the residual signal power at frequency band f_1 that enters the other two branches due to the f_1 filter **302** imperfections (e.g., due to realization of a low order or tunable filter) can be further attenuated by the band-stop filters formed by the combination of QHC **306** and f_1 filter **310** before reaching output **315**, and by the combination of QHC **307** and f_1 filter **312** before reaching output **316**. Passive components may be added to the common node **301** to improve the input impedance matching at the frequency bands of interest. In fact, in practice, some embodiments contemplate the co-design of the filters **302**, **303**, and **304**, along with possible additional input impedance matching circuitry, to ensure an optimal response.

FIG. **4** illustrates an embodiment of a multiplexer according to the present disclosure. This scheme is a multiplexer **400** in support of four or more frequency bands, f_1, f_2, f_3, f_4. The RF multiplexer **400** includes four or more parallel branches that share a common node **401**. Each branch provides band-pass filtering at one desired frequency band while it provides band-stop filtering at the other desired frequency bands. For instance, including an f_1 band-pass filter **402**, a QHC **406**, and a parallel connection of an f_2 band-pass filter **410**, an f_3 band-pass filter **411**, an f_4 band-pass filter **412** . . . , an exemplary top branch of the multiplexer **400** offers band-pass filtering at f_1 and band-stop filtering at f_2, f_3, f_4 . . . , between the common node **401** and an f_1 node **422**. In comparison to the RF multiplexer **100** of FIG. **1**, this scheme offers higher port-to-port isolation at all the desired frequency bands because of the creation of stopbands. Therefore, the selectivity requirements of f_1, f_2, f_3, f_4 . . . filters are relaxed. For instance, these filters now can be realized as low-order filters with fewer components resulting in a lower insertion loss, a smaller footprint, and a lower cost. One or more of these filters may be tunable resulting in a tunable RF multiplexer. The filters in FIG. **4** are shown as band-pass filters, but can also be other types of filters such as low-pass or high-pass. As long as the filter passes the desired frequency band, it can be used. These filters need not be limited to a single passband. In each parallel branch, the number and specification of the parallel filters resulting in a band-stop response (e.g., filters **410**, **411**, **412** . . . in the top path) may depend on the port-to-port isolation requirement and other factors. Different parallel paths need not have the same number of such filters. The type and order of the f_1 filter, f_2 filter, f_3 filter, f_4 filter . . . need not be the same, and can depend on the specifications of the multiplexer. Furthermore, f_1 filters **402**, **413**, **416**, **419**, . . . need not be the same. Likewise, f_2 filters **403**, **410**, **417**, **420**, . . . need not be same; f_3 filters **404**, **411**, **414**, **421**, . . . need not be the same; f_4 filters **405**, **412**, **415**, **418**, . . . need not be the same. QHCs **306**, **307**, **308**, **309**, . . . need not be identical; each QHC may be designed in conjunction with the filters that connect to it for a desired performance. The previous discussions about input impedance matching at the common node **301** in FIG. **3** apply similarly to the input impedance matching at common node **401** in FIG. **4**.

FIG. **5** illustrates an example application for an exemplary RF multiplexer **500** in a front end of a wireless communication system that supports two transmit and two receive frequency bands. In this example, the common node **501** is coupled to an antenna **530**. There might be additional components provided to improve impedance matching at the common node **501**. Branches **522** and **524** correspond to transmit frequency bands and are coupled to transmitting power amplifiers (PA) **526** and **528**, respectively, representing two transmit paths. In some embodiments, both branches **522** and **524**, corresponding to transmit frequency bands, may be coupled to the same transmitting power amplifier. Branches **523** and **525** correspond to receive frequency bands and are coupled to receiving low noise amplifiers (LNA) **527** and **529**, respectively, representing two receive paths. In some embodiments, both branches **523** and **525**, corresponding to receive frequency bands, may be coupled to the same receiving low noise amplifier. As discussed before and explicitly shown in FIG. **5**, not all filters are necessary in an application. For instance, in this exemplary example, since isolation from transmit signal is advantageous in most wireless systems, every branch may include the transmit filters in the reflection section (filters **510**, **513**, **514**, **516**, **519**, **520**). However, in this exemplary example, there is no need to further reject the other receive band in the receive branches. As such, the reflection sections of the receive paths include TX filters and do not include RX filters.

FIG. **6** illustrates an embodiment of a multiplexer according to the present disclosure. This scheme is a multiplexer **600** in support of four or more frequency bands, f_1, f_2, f_3, f_4 . . . The RF multiplexer **600** includes four or more parallel branches that are coupled to a common node **601** through a passive network **626**. The passive network **626** may provide proper impedance matching and additional filtering. Each of the parallel branches provides band-pass filtering at one desired frequency band while providing band-stop filtering at the other desired frequency bands. For instance, including an f_1 band-pass filter **602**, a QHC **606**, and a parallel connection of an f_2 band-pass filter **610**, an f_3 band-pass filter **611**, an f_4 band-pass filter **612** . . . , the top branch of the multiplexer **600** provides band-pass filtering at frequency band f_1 and band-stop filtering at frequency bands f_2, f_3, f_4 . . . between the common node **601** and an f_1 node **622**. In comparison to the RF multiplexer **100** of FIG. **1**, this scheme provides higher port-to-port isolation at all the desired frequency bands because of the creation of stopbands. Therefore, the selectivity requirements of f_1, f_2, f_3, f_4 . . . filters are relaxed. For instance, these filters now can be realized as low-order filters with fewer components resulting in a lower insertion loss, a smaller footprint, and a lower cost. One or more of these filters may be tunable resulting in a tunable RF multiplexer. The filters in FIG. **6** are shown as band-pass filters, but could be other types of filters such as low-pass or high-pass. As long as the filter passes the desired frequency band, it can be used. These filters need not be limited to a single passband. In each parallel branch, the number and specification of the parallel filters resulting in a band-stop response (e.g., filters **610**, **611**, **612** . . . in the top path) may depend on the port-to-port isolation requirement and other factors. Different parallel paths need not have the same number of such filters. The type and order of the f_1 filter, f_2 filter, f_3 filter, f_4 filter . . . need not be the same, and can depend on the specifications of the multiplexer. Furthermore, f_1 filters **602**, **613**, **616**, **619**, . . . need not be the same. Likewise, f_2 filters **603**, **610**, **617**, **620**, . . . need not be same; f_3 filters **604**, **611**, **614**, **621**, . . . need not be the same; f_4 filters **605**, **612**, **615**, **618**, . . . need not be the same, ... QHCs **606**, **607**, **608**, **609**, . . . need not be identical; each QHC may be designed in conjunction with the filters that connect to it for a desired performance.

FIG. **7** illustrates an embodiment of a multiplexer according to the present disclosure. This scheme is a tunable multiplexer **700** in support of four or more frequency bands, f_1, f_2, f_3, f_4 . . . The tunable RF multiplexer **700** includes four or more parallel branches that share a common node **701**. Each branch provides tunable band-pass filtering at one desired frequency band while providing tunable band-stop filtering at the other desired frequency bands. For instance, including a tunable f_1 band-pass filter **702**, a QHC **706**, and a parallel connection of a tunable f_2 band-pass filter **710**, a tunable f_3 band-pass filter **711**, a tunable f_4 band-pass filter **712** . . . , the top branch of the multiplexer **700** provides tunable band-pass filtering at frequency band f_1 and tunable band-stop filtering at frequency bands f_2, f_3, f_4 . . . between the common node **701** and an f_1 node **722**. In comparison to the RF multiplexer **100** of FIG. **1**, this scheme offers higher port-to-port isolation at all the desired frequency bands because of the creation of stopbands. Therefore, the selectivity requirements of f_1, f_2, f_3, f_4 . . . filters are relaxed. For instance, these filters now can be realized as low-order filters with fewer components resulting in a lower insertion loss, a smaller footprint, and a lower cost. The filters in FIG. **7** are shown as band-pass filters, but could be other types of filters such as low-pass or high-pass. As long as the filter passes the desired frequency band, it can be used. These filters need not be limited to a single passband. In each parallel branch, the number and specification of the parallel filters resulting in a band-stop response (e.g., filters **710**, **711**, **712** . . . in the top path) may depend on the port-to-port isolation requirement and other factors. Different parallel paths need not have the same number of such filters. The type and order of the f_1 filter, f_2 filter, f_3 filter, f_4 filter . . . need not be the same, and can depend on the specifications of the multiplexer. Furthermore, f_1 filters **702**, **713**, **716**, **719**, . . . need not be the same. Likewise, f_2 filters **703**, **710**, **717**, **720**, . . . need not be same; f_3 filters **704**, **711**, **714**, **721**, . . . need not be the same; f_4 filters **705**, **712**, **715**, **718**, . . . need not be the same, ... QHCs **706**, **707**, **708**, **709**, . . . need not be identical; each QHC may be designed in conjunction with the filters that connect to it for a desired performance. While not explicitly shown, any or all of the QHCs may also be tunable. A passive network, fixed or tunable, may also be provided in a similar manner as shown in FIG. **6** to improve impedance matching or provide additional filtering.

FIG. **8** illustrates an example graph showing the frequency response of an embodiment of an RF multiplexer that supports three frequency bands. The graph **800** shows the S-parameters of the multiplexer. The solid lines are the signal transfer functions between the common port and every single band ports (e.g., transfer function between node **301** and nodes **314**, **315**, and **316** in FIG. **3**). Each transfer function has a passband at one frequency band and a large attenuation (stopband) at the other two frequency bands. The dotted and dashed lines are the transfer function between every single band ports (e.g., transfer function between pairs of nodes **314**, **315**, and **316** in FIG. **3**). Low insertion loss (in the passband) and high port-to-port isolation in the exemplary RF multiplexer are some of the architectural advantages of the present disclosure.

Some embodiments of the RF multiplexer according to the present disclosure may be used or included in hand-held portable or mobile devices supporting wireless communications such as a cell phone, a smartphone, a tablet, a laptop, a smartwatch, etc.

Some embodiments of the RF multiplexer according to the present disclosure may be used or included in devices supporting the wireless communication infrastructure such as base stations (e.g., macro-, micro-, pico-, and femto-base stations), repeaters, etc.

Some embodiments of the RF multiplexer, according to the present disclosure, enable compact multiband, multi-standard wireless communication devices, wireless communication devices that support carrier aggregation, and wireless communication devices that support frequency division duplexing.

Some embodiments of the RF multiplexer according to the present disclosure may be used or included in a multi-antenna communication system.

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 the steps as described herein for reflection-based RF multiplexers.

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 typical 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.

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.

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.

What is claimed is:

1. A radio frequency multiplexer supporting a plurality of frequency bands, comprising:
   a common node;
   a plurality of single band nodes;
   a plurality of parallel branches, wherein each parallel branch is dedicated to one of the plurality of frequency bands, wherein each parallel branch connects the common node and one of the plurality of single band nodes, and wherein a particular branch of the parallel branches comprises:
      a filter configured to pass a desired frequency band through the particular branch;
      a quadrature hybrid coupler coupled to the filter; and
      a set of one or more other filters corresponding to one or more other frequency bands of the plurality of frequency bands, wherein the set of one or more other filters and the quadrature hybrid coupler are coupled and configured to reject the one or more other frequency bands by the particular branch.

2. The radio frequency multiplexer of claim 1, comprising a passive network coupled to the common node and configured to further improve impedance matching.

3. The radio frequency multiplexer of claim 1, wherein the radio frequency multiplexer comprises a triplexer.

4. The radio frequency multiplexer of claim 1, wherein the filter and the one or more other filters comprise one or more band-pass filters.

5. The radio frequency multiplexer of claim 1, wherein one or more of the filter and the one or more other filters comprise one or more low-pass filters.

6. The radio frequency multiplexer of claim 1, wherein one or more of the filter and the one or more other filters comprise one or more high-pass filters.

7. The radio frequency multiplexer of claim 1, wherein one or more of the filter and the one or more other filters are tunable or reconfigurable.

8. The radio frequency multiplexer of claim 1, wherein one or more of the quadrature hybrid couplers are tunable or reconfigurable.

9. The radio frequency multiplexer of claim 1, wherein one or more of the filter and the one or more other filters comprise one or more surface acoustic wave (SAW) filters.

10. The radio frequency multiplexer of claim 1, wherein one or more of the filter and the one or more other filters comprise one or more bulk acoustic wave (BAW) filters.

11. The radio frequency multiplexer of claim 1, wherein the radio frequency multiplexer is included in a front end of a wireless communication system that supports carrier aggregation.

12. The radio frequency multiplexer of claim 1, wherein the radio frequency multiplexer is included in a front end of a wireless communication system that supports frequency division duplexing.

13. The radio frequency multiplexer of claim 1, wherein the radio frequency multiplexer is included in a front end of a multiband communication system.

14. The radio frequency multiplexer of claim 1, wherein the radio frequency multiplexer is included in a hand-held portable device that supports wireless communication.

15. The radio frequency multiplexer of claim 1, wherein the radio frequency multiplexer is included in a base station that supports a wireless communication infrastructure.

16. The radio frequency multiplexer of claim 1, wherein the radio frequency multiplexer is included in a repeater that supports a wireless communication infrastructure.

17. The radio frequency multiplexer of claim 1, wherein the particular branch is configured to correspond to a transmit frequency band.

18. The radio frequency multiplexer of claim 1, wherein one or more of the filter and the one or more other filters are realized in an acoustic domain.

19. The radio frequency multiplexer of claim 1, wherein the particular branch is configured to correspond to a receive frequency band.

20. The radio frequency multiplexer of claim 1, wherein the radio frequency multiplexer is included in a multi-antenna communication system.

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