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(54) **SYSTEM AND METHOD FOR COUPLED RESONATOR FILTERING**

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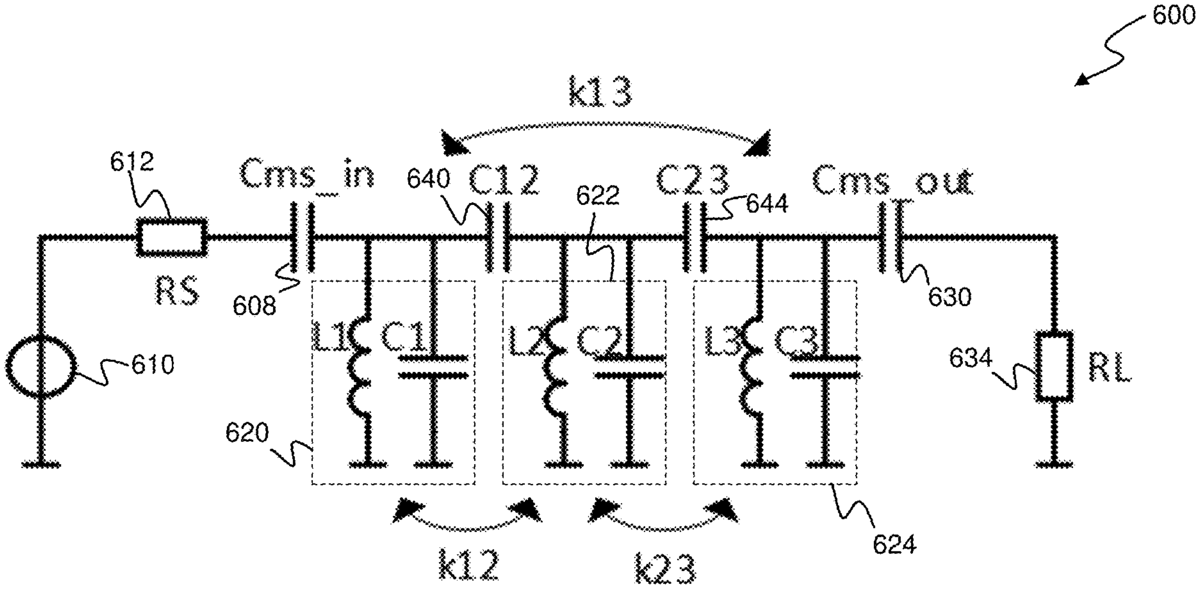
H03H 9/205	(2006.01)
H03H 9/54	(2006.01)

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

CPC ***H03H 9/605*** (2013.01); ***H03H 9/205*** (2013.01); ***H03H 9/542*** (2013.01); *H03K 17/6872* (2013.01)

(57) **ABSTRACT**

A coupled resonator filter including a first parallel resonator including a first capacitance connected in parallel with a first inductance. The filter includes a second parallel resonator including a second capacitance connected in parallel with a second inductance and a third parallel resonator including a third capacitance connected in parallel with a third inductance. Magnetic coupling between the first inductance and the second inductance, between the second inductance and the third inductance, and between the first inductance the third inductance occurs in accordance with first, second and third coupling factors, respectively. A frequency response of the coupled resonator filter includes a notch when values of the first coupling factor, the second coupling factor and the third coupling factor satisfy predetermined conditions.



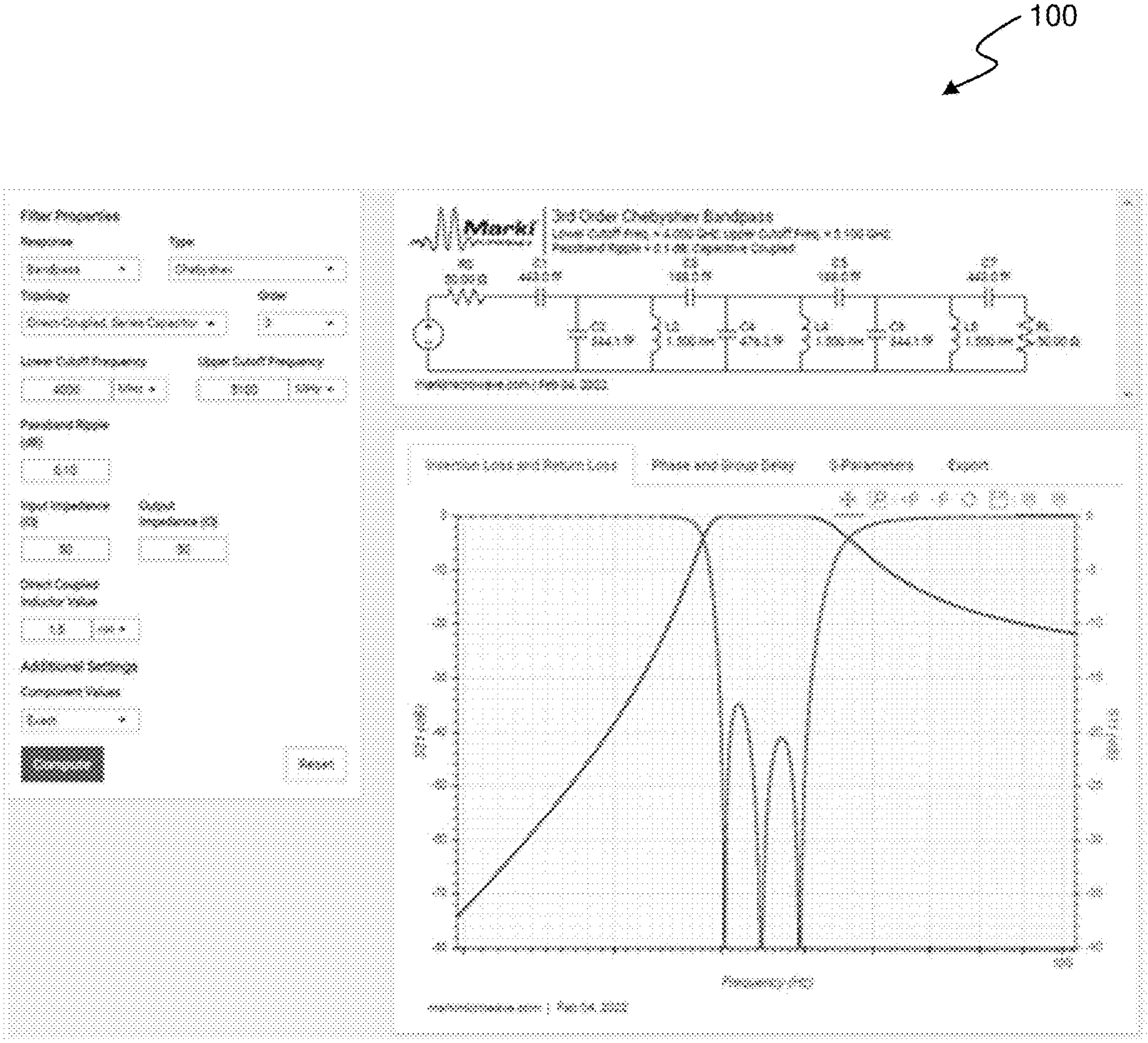


FIG. 1
Prior Art

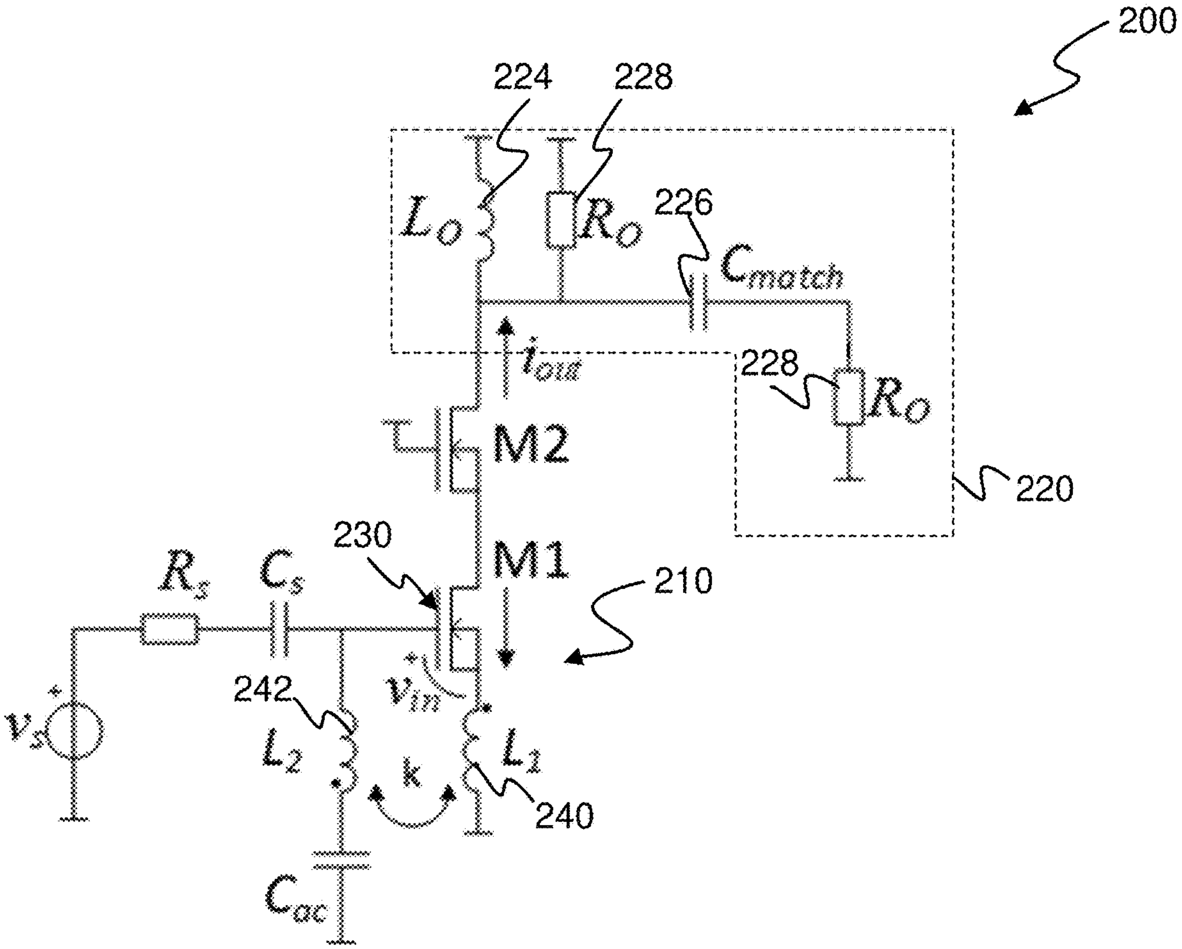


FIG. 2
Prior Art

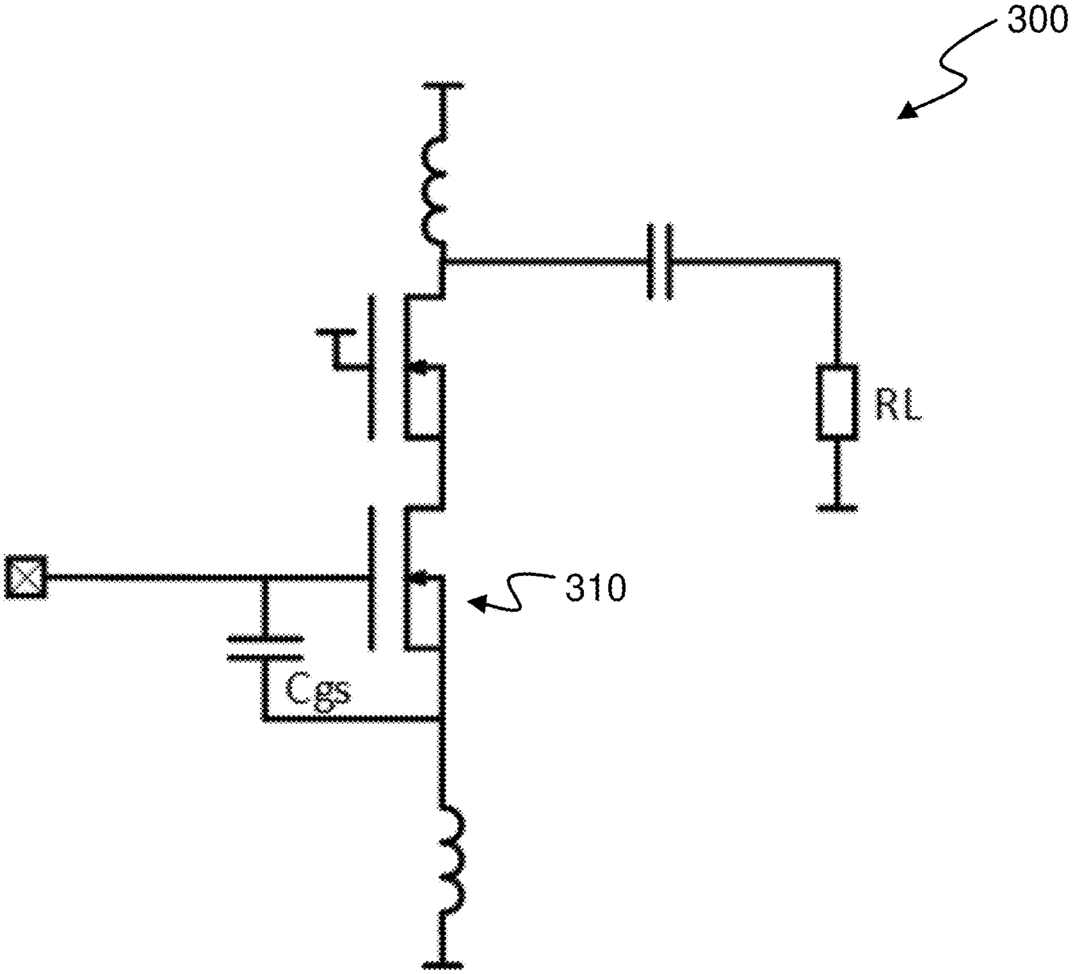


FIG. 3
Prior Art

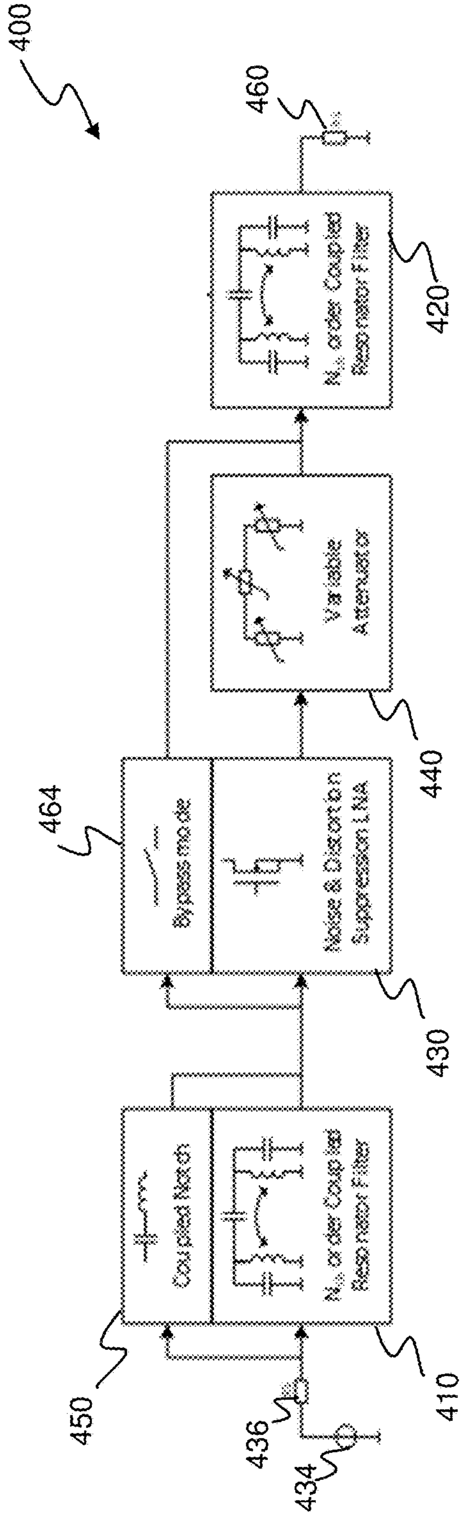

400
450
Coupled Notch
Nth order Coupled Resonator Filter
410
434
436
464
Bypass mode
Noise & Distortion Suppression LNA
430
Variable Attenuator
440
Nth order Coupled Resonator Filter
420
460

FIG. 4A

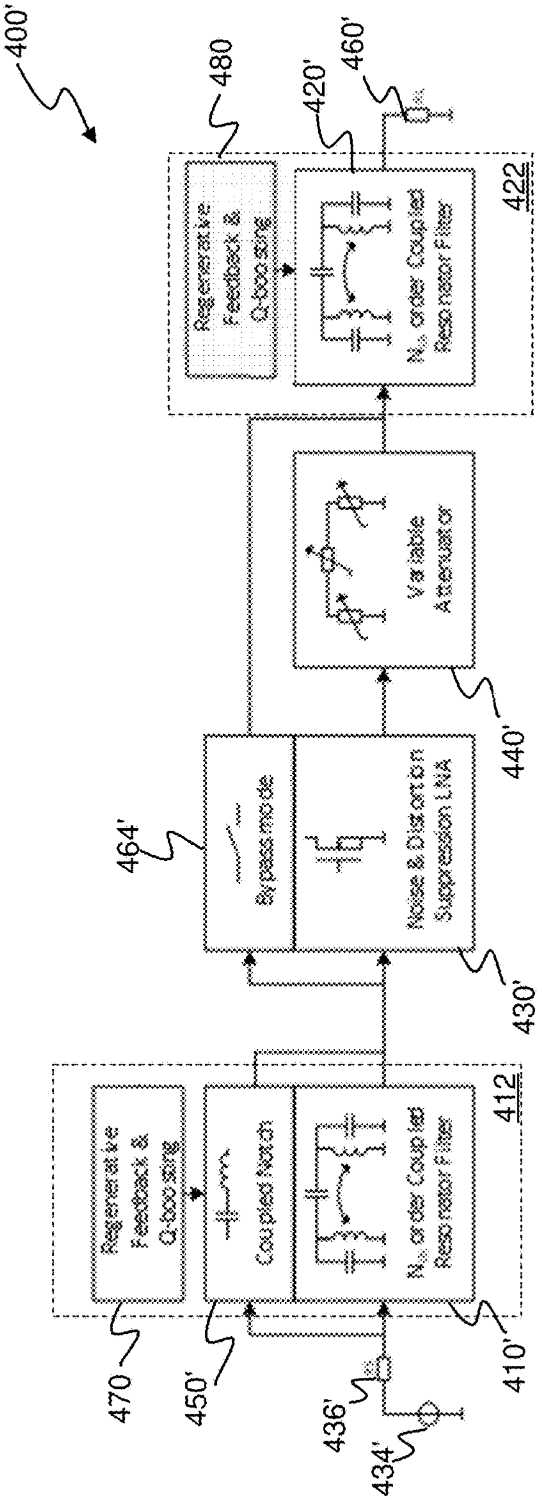

400'
470
Regenerative Feedback & Q-boosting
450'
Coupled Notch
Nth order Coupled Resonator Filter
410'
412
434'
436'
464'
Bypass mode
Noise & Distortion Suppression LNA
430'
Variable Attenuator
440'
480
Regenerative Feedback & Q-boosting
Nth order Coupled Resonator Filter
420'
422
460'

FIG. 4B

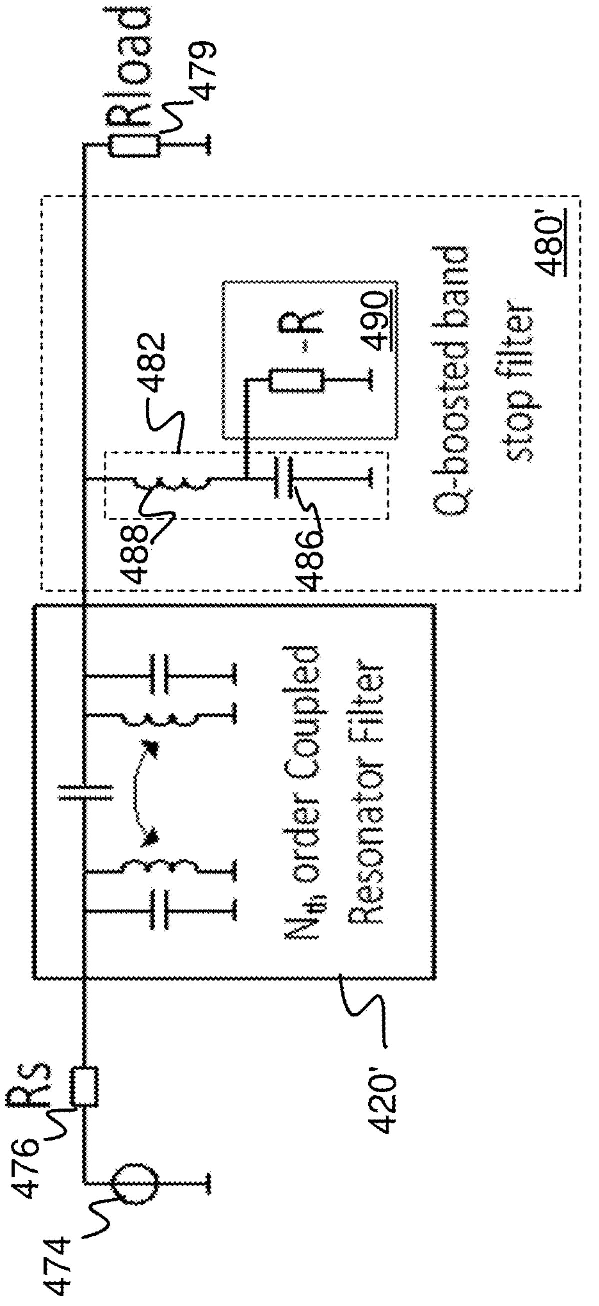

Rload
479
Q-boosted band stop filter
480'
-R
490
482
488
486
Nth order Coupled Resonator Filter
Rs
476
474
420'

FIG. 4C

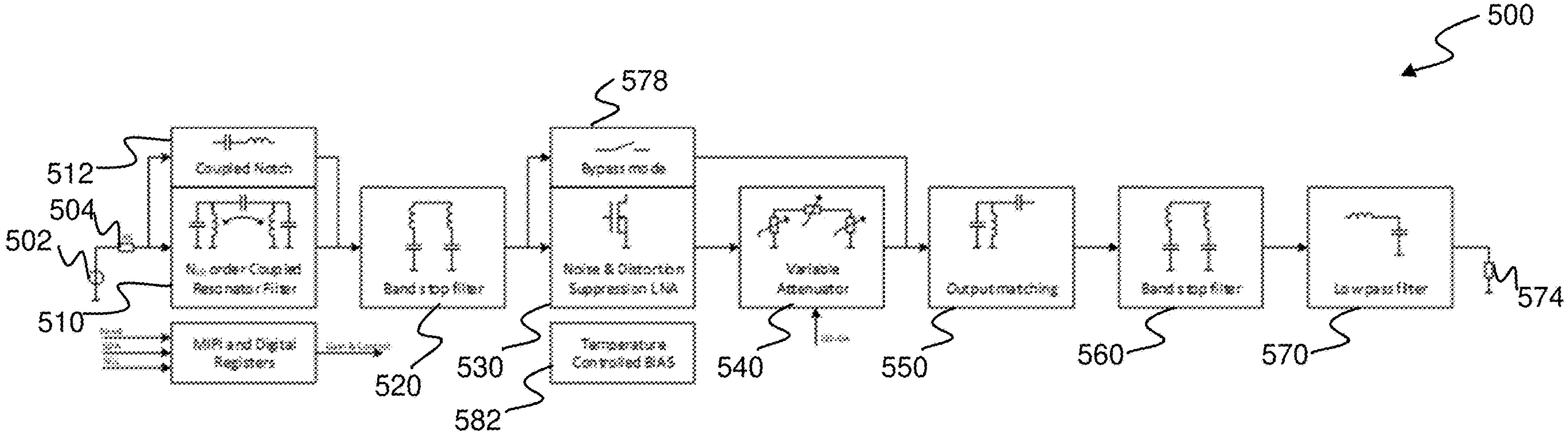

500
578
512
504
502
510
Coupled Notch
Nth order Coupled Resonator Filter
MIPI and Digital Registers
Band stop filter
520
Bypass mode
Noise & Distortion Suppression LNA
Temperature Controlled BIAS
530
582
Variable Attenuator
540
Output matching
550
Band stop filter
560
Low pass filter
570
574

FIG. 5A

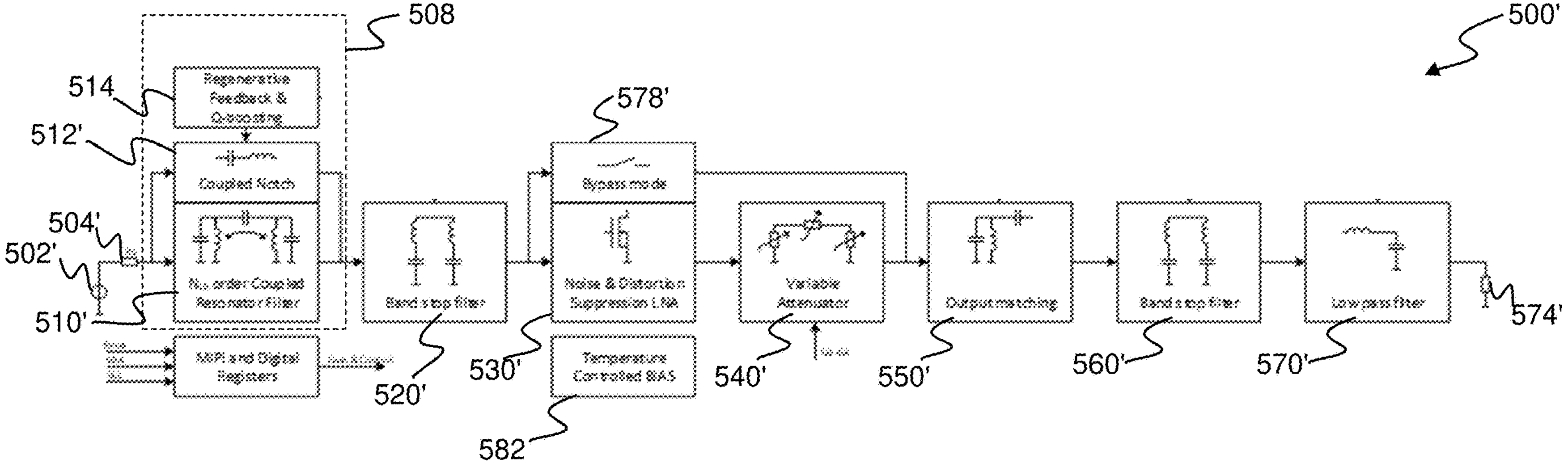

500'
508
514
Regenerative Feedback & Qmhancing
512'
Coupled Notch
504'
502'
Nth order Coupled Resonator Filter
510'
MIPI and Digital Registers
Band stop filter
520'
578'
Bypass mode
Noise & Distortion Suppression LNA
530'
Temperature Controlled BIAS
582
Variable Attenuator
540'
Output matching
550'
Band stop filter
560'
Low pass filter
570'
574'

FIG. 5B

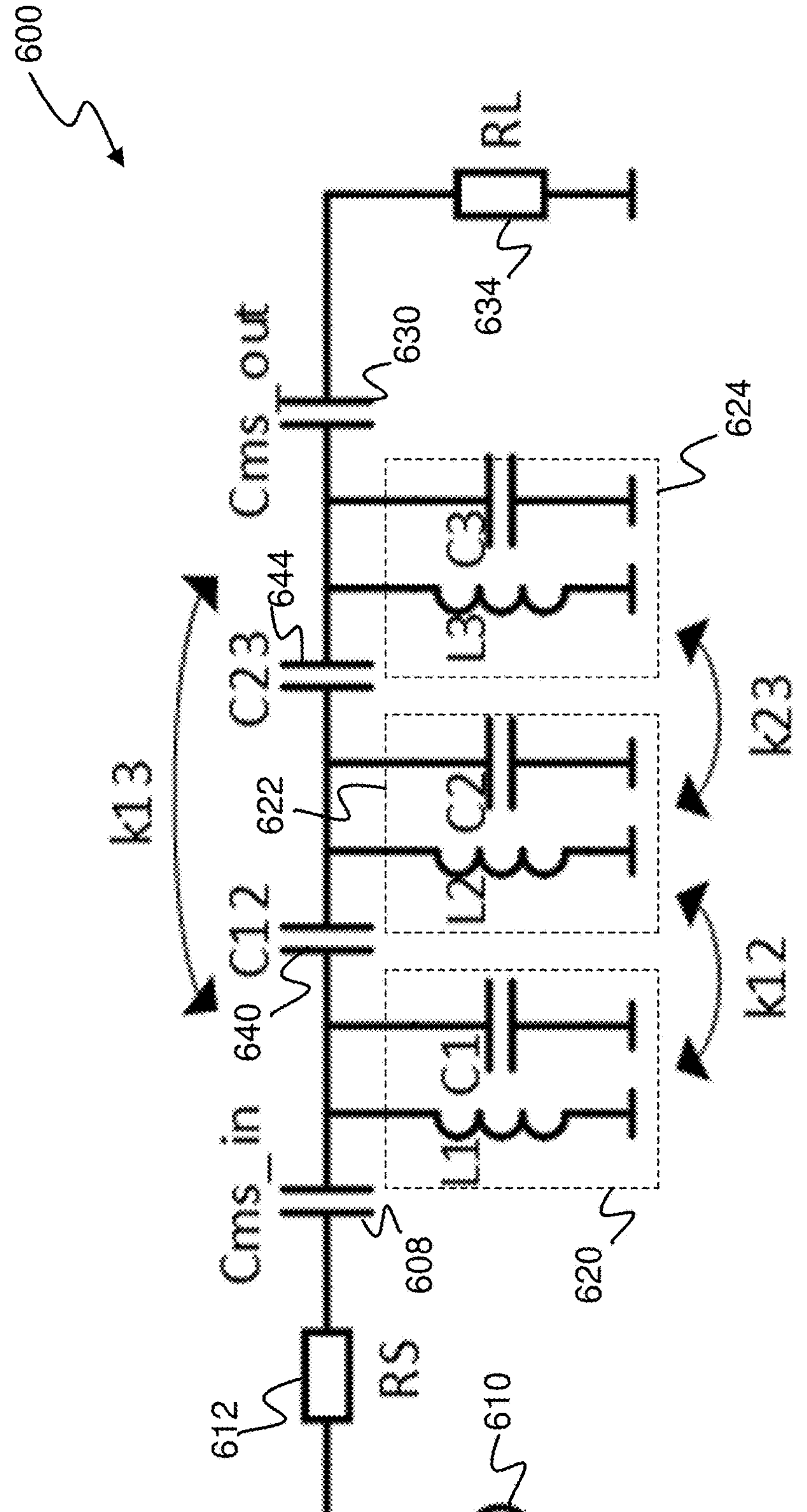

600
RL
634
Cms_out
630
624
C23
644
L3
C3
k13
k23
C2
L2
622
C12
640
k12
C1
L1
Cms_in
608
620
RS
612
610

FIG. 6

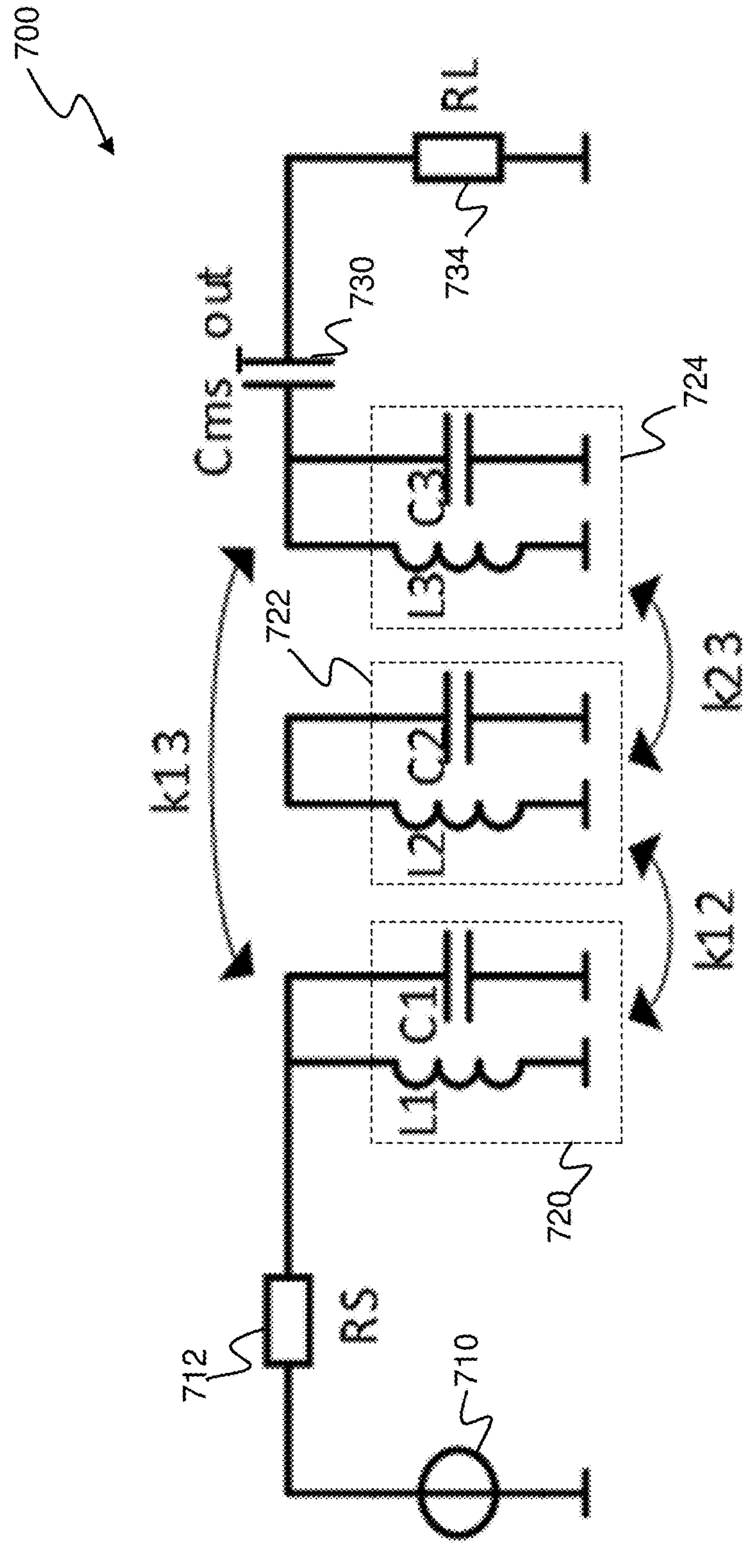

700
RL
734
Cms_out
730
724
C3
L3
722
k13
k23
C2
L2
k12
C1
L1
720
RS
712
710

FIG. 7

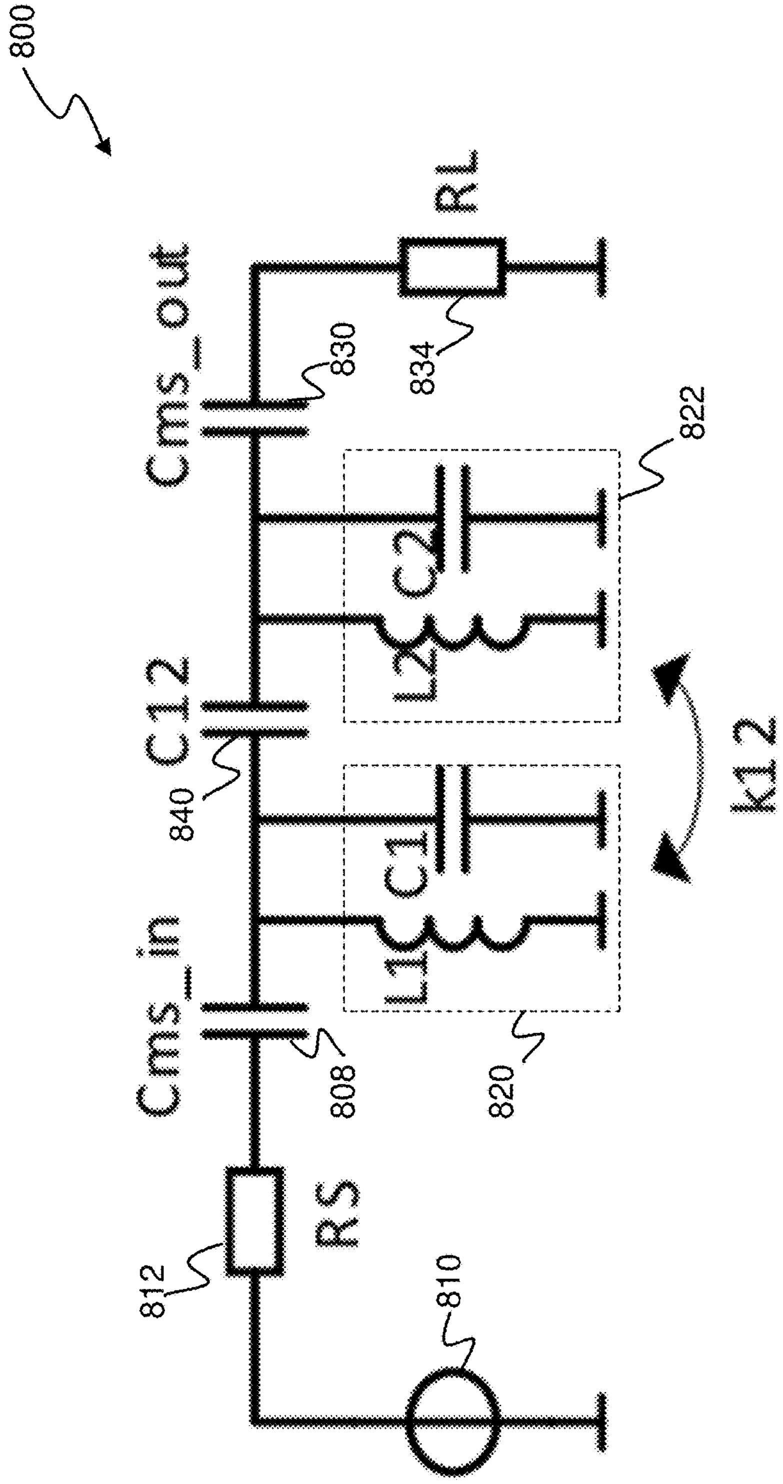

800
RL
Cms_out
830
834
822
C2
L2
C12
k12
840
C1
L1
Cms_in
808
820
RS
812
810

FIG. 8

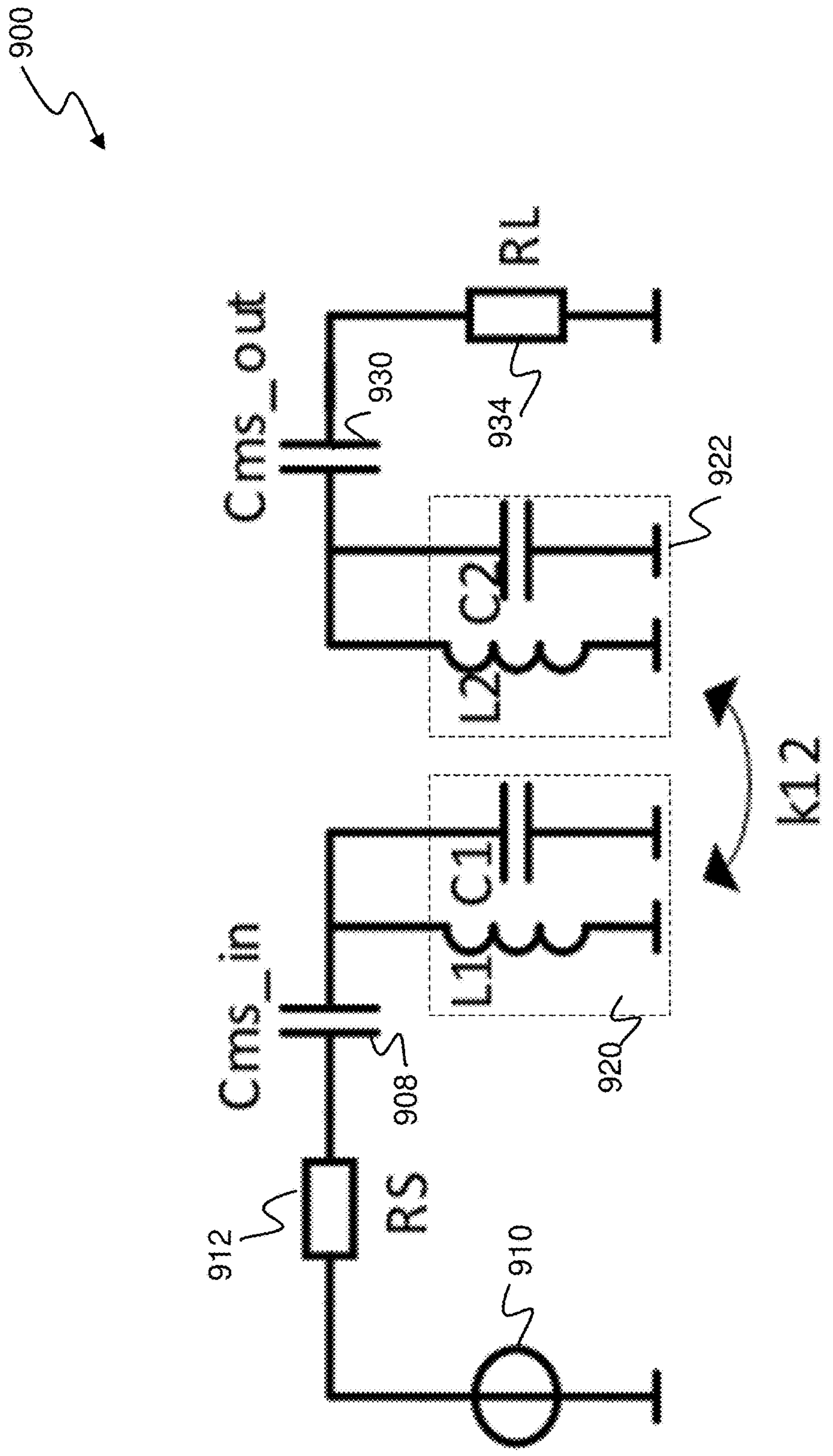
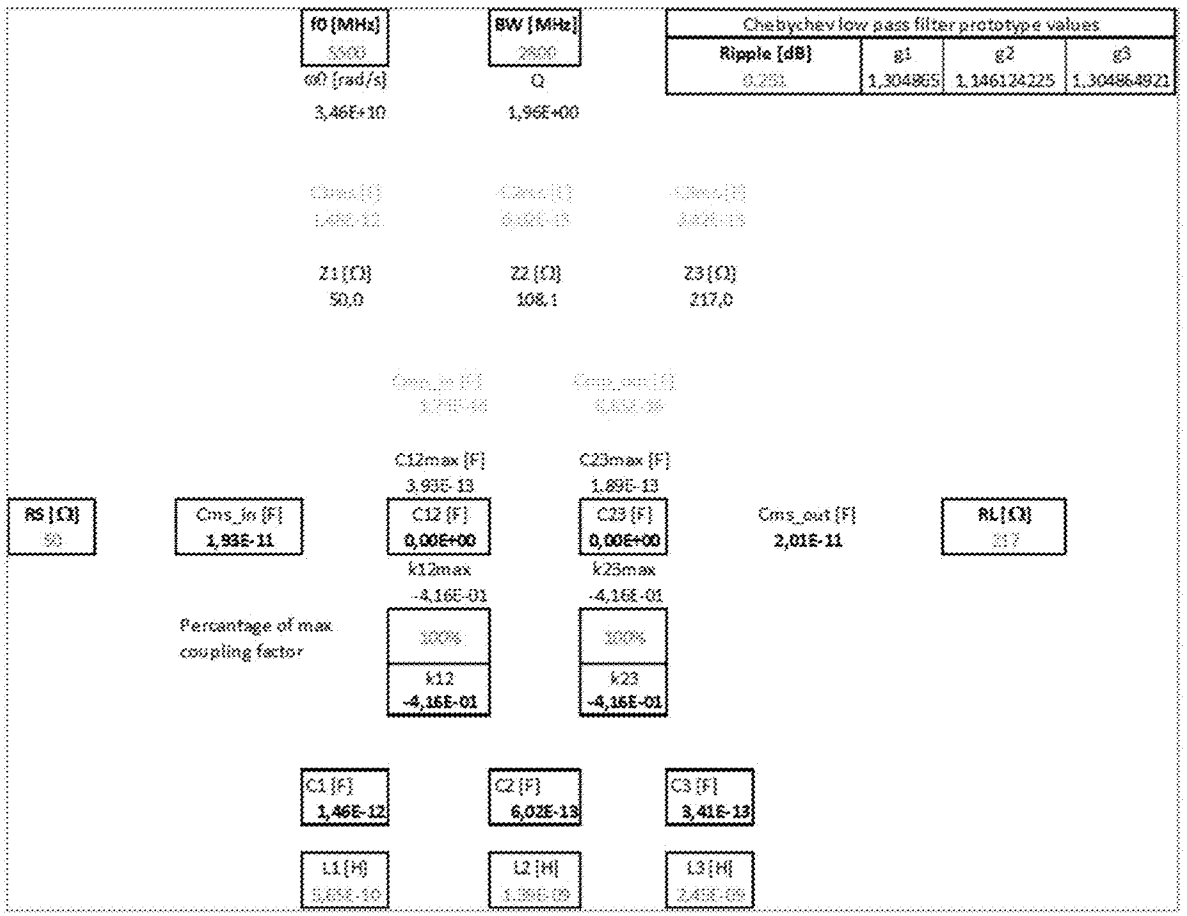

900
910
912
RS
908
Cms_in
920
L1
C1
k12
L2
C2
922
Cms_out
930
934
RL

FIG. 9



f0 [MHz]
5500

BW [MHz]
2800

Chebychev low pass filter prototype values			
Ripple [dB]	g1	g2	g3
0,281	1,304865	1,146124225	1,304864921

ω0 [rad/s]
3,46E+10

Q
1,96E+00

C1max [F]
[illegible]

C2max [F]
[illegible]

C3max [F]
[illegible]

Z1 [Ω]
50,0

Z2 [Ω]
108,1

Z3 [Ω]
217,0

Cms_in [F]
[illegible]

Cms_out [F]
[illegible]

C12max [F]
3,93E-13

C23max [F]
1,89E-13

RS [Ω]
50

Cms_in [F]
1,93E-11

C12 [F]
0,00E+00

C23 [F]
0,00E+00

Cms_out [F]
2,01E-11

RL [Ω]
217

k12max
-4,16E-01

k23max
-4,16E-01

Percentage of max coupling factor

100%
k12
-4,16E-01

100%
k23
-4,16E-01

C1 [F]
1,46E-12

C2 [F]
6,02E-13

C3 [F]
3,41E-13

L1 [H]
[illegible]

L2 [H]
[illegible]

L3 [H]
[illegible]

FIG. 10

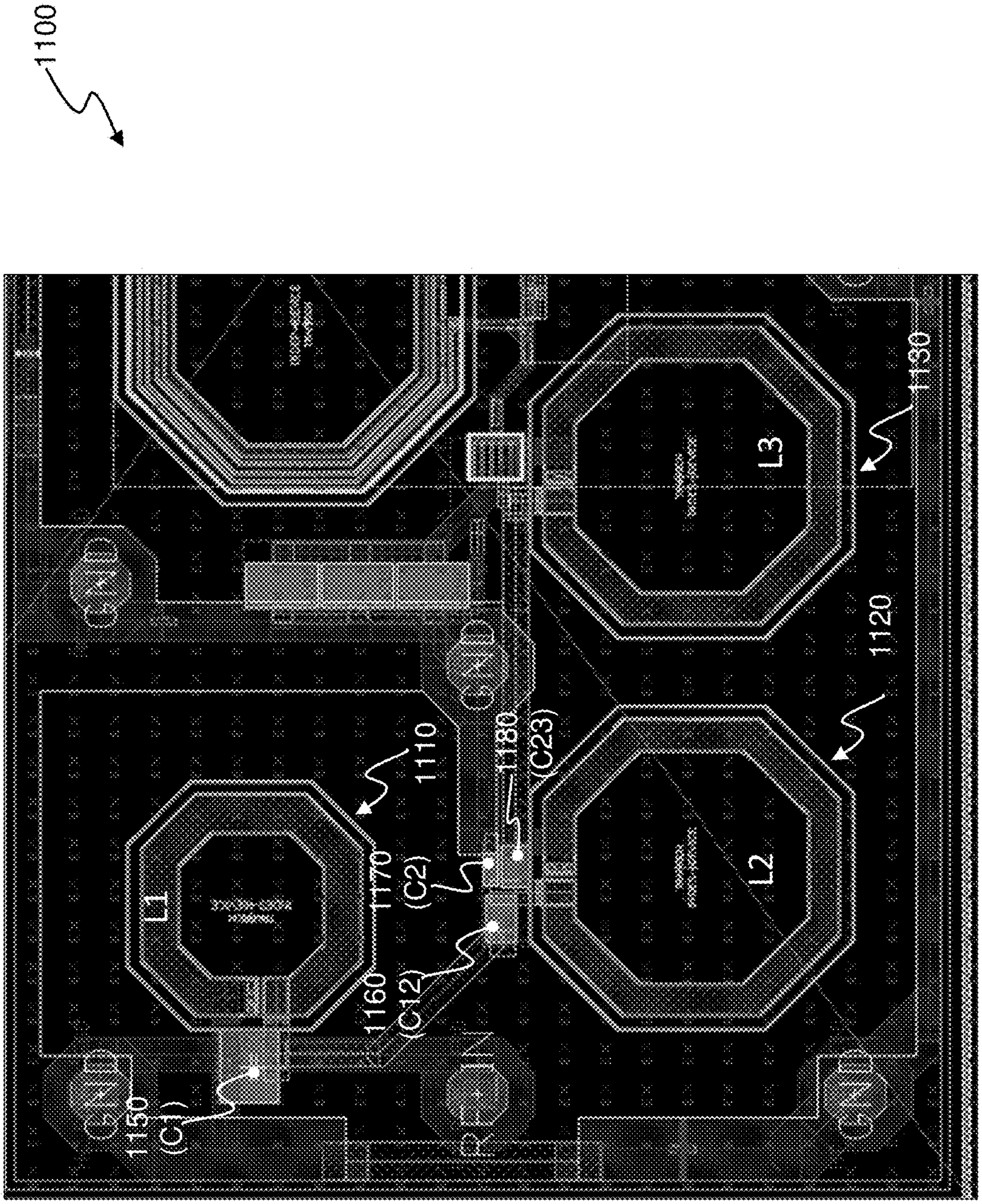

1100
1130
L3
1120
GND
GND
1110
1180
(C23)
L1
1170
(C2)
L2
1160
(C12)
1150
(C1)
GND
GND
GND

FIG. 11

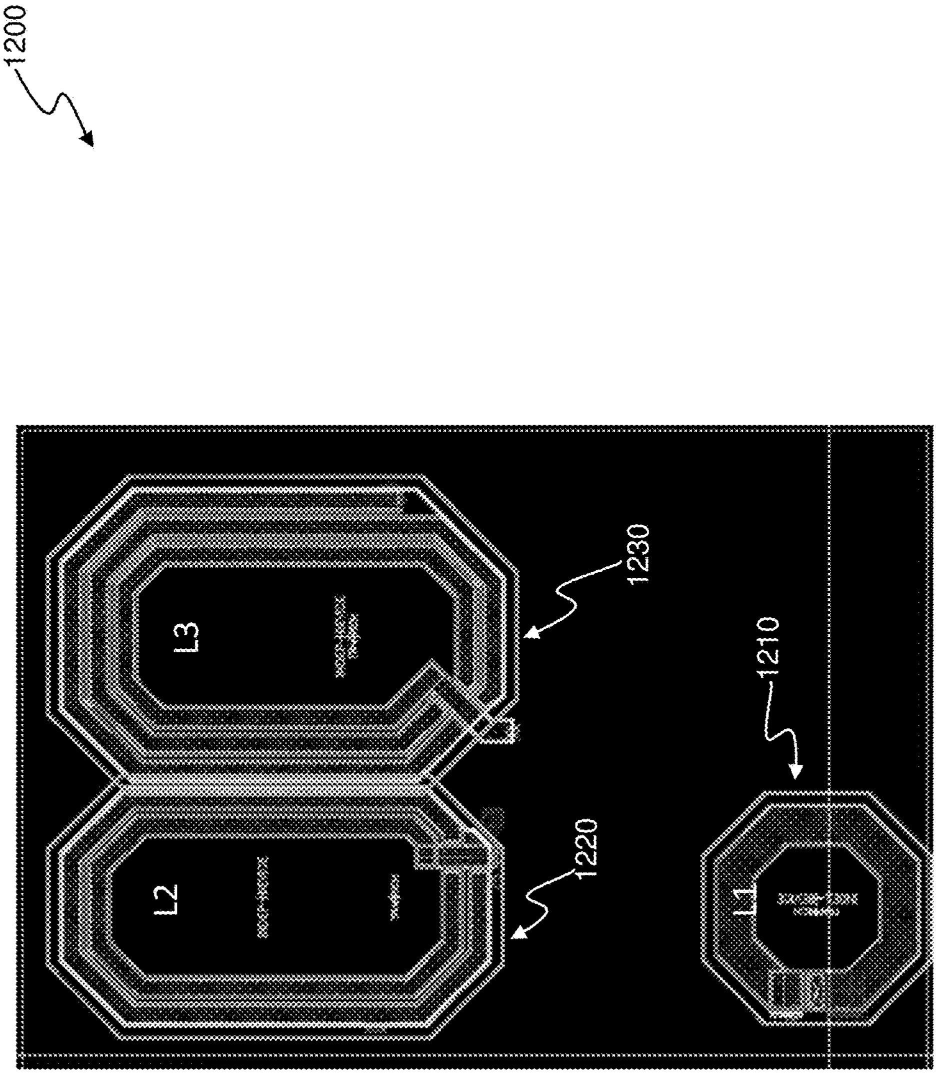


FIG. 12

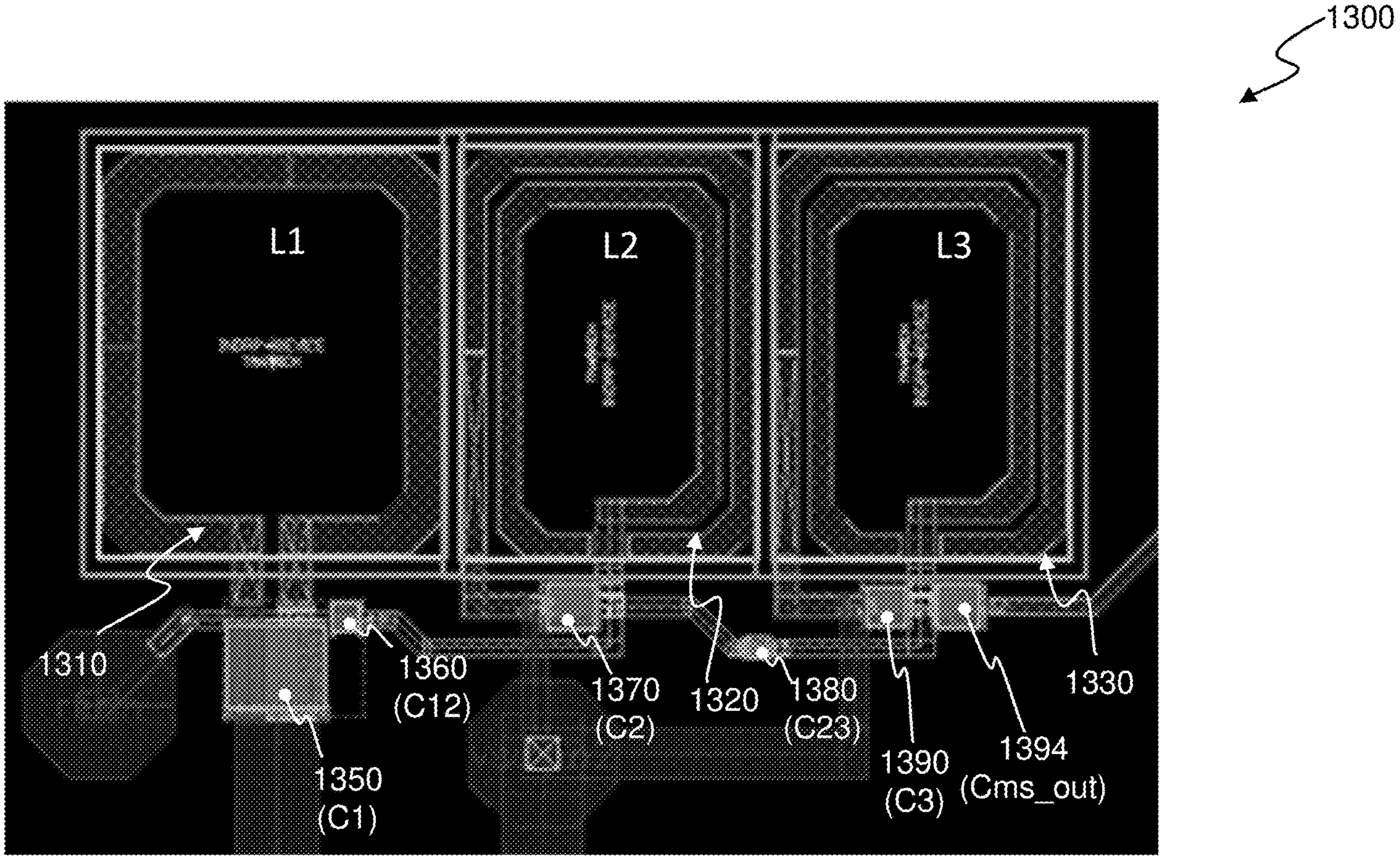

1300
L1
L2
L3
1310
1360
(C12)
1370
(C2)
1320
1380
(C23)
1330
1350
(C1)
1390
(C3)
1394
(Cms_out)

FIG. 13

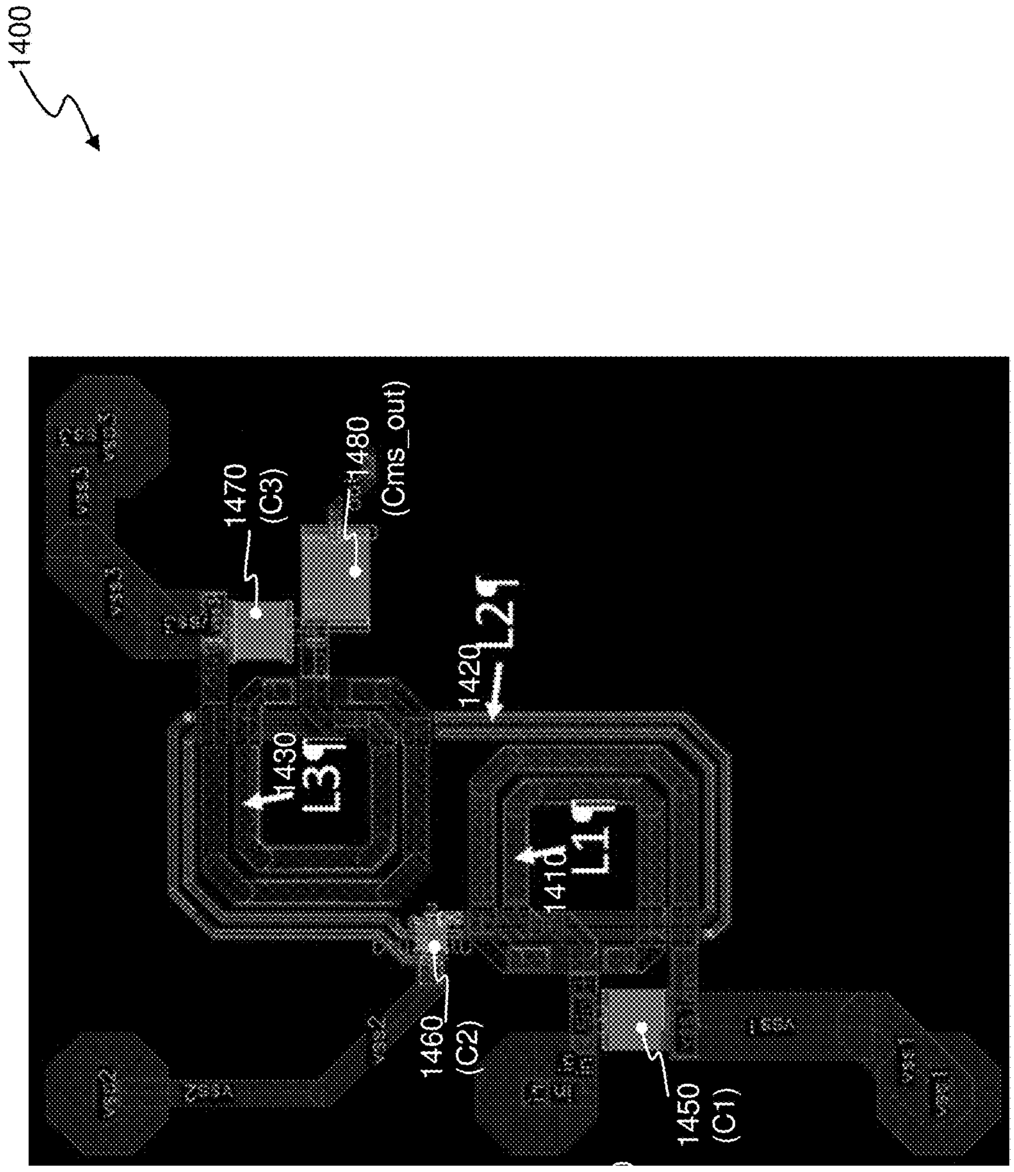

1400
1470
(C3)
1480
(Cms_out)
L2
1420
1430
L3
L1
1410
1460
(C2)
1450
(C1)
vss1
vss2
vss3

FIG. 14

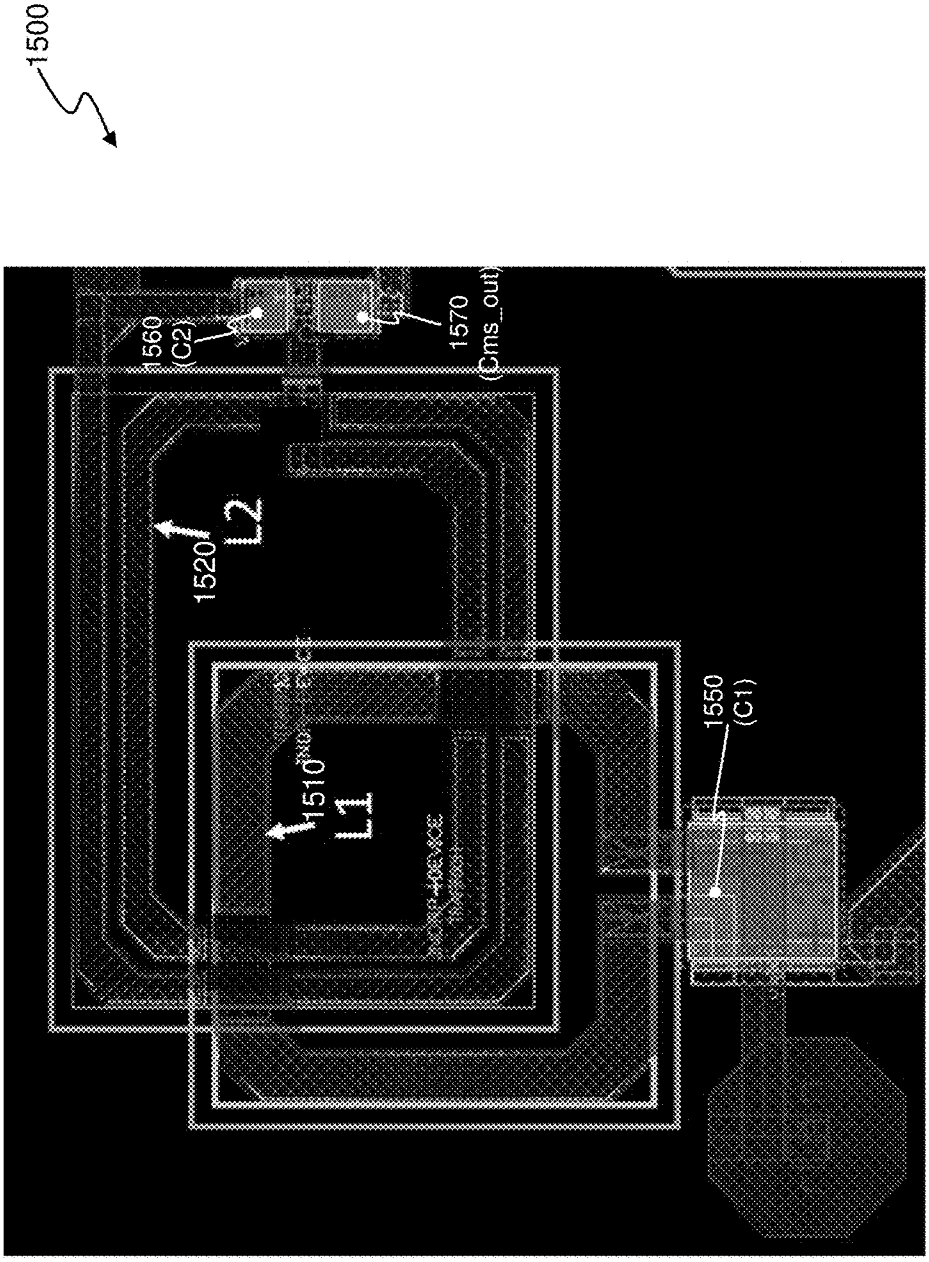


FIG. 15

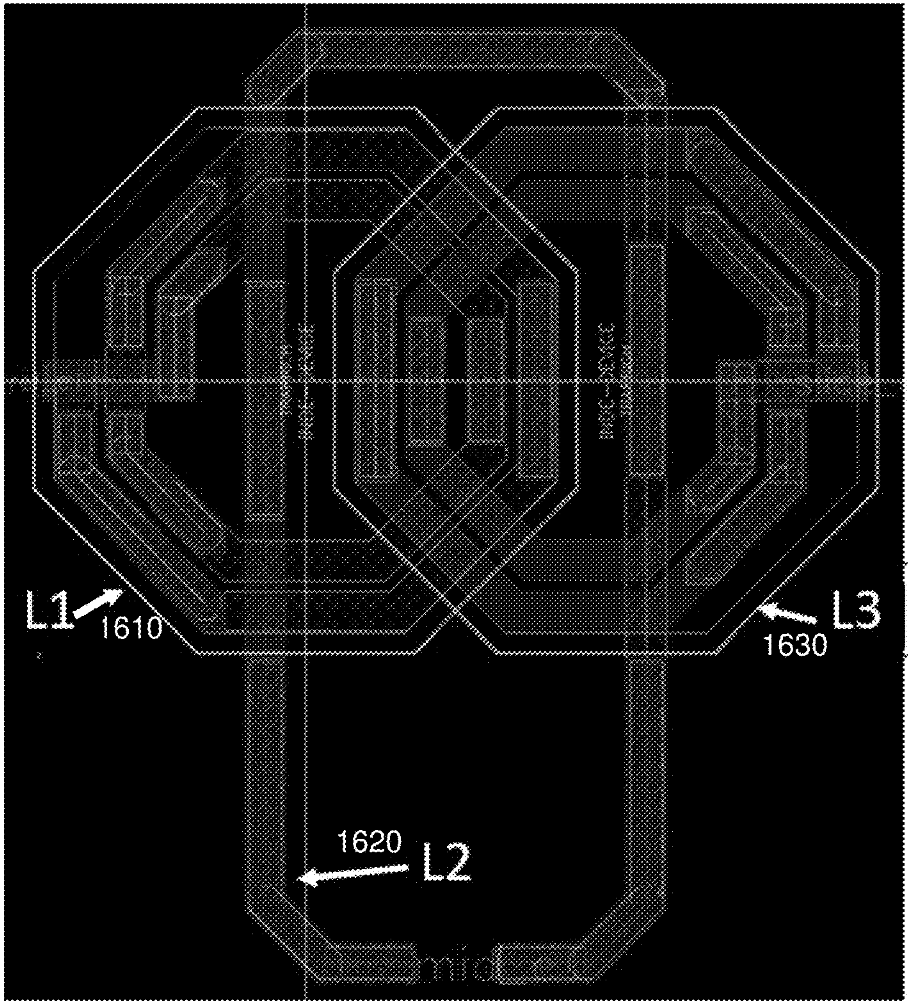


FIG. 16

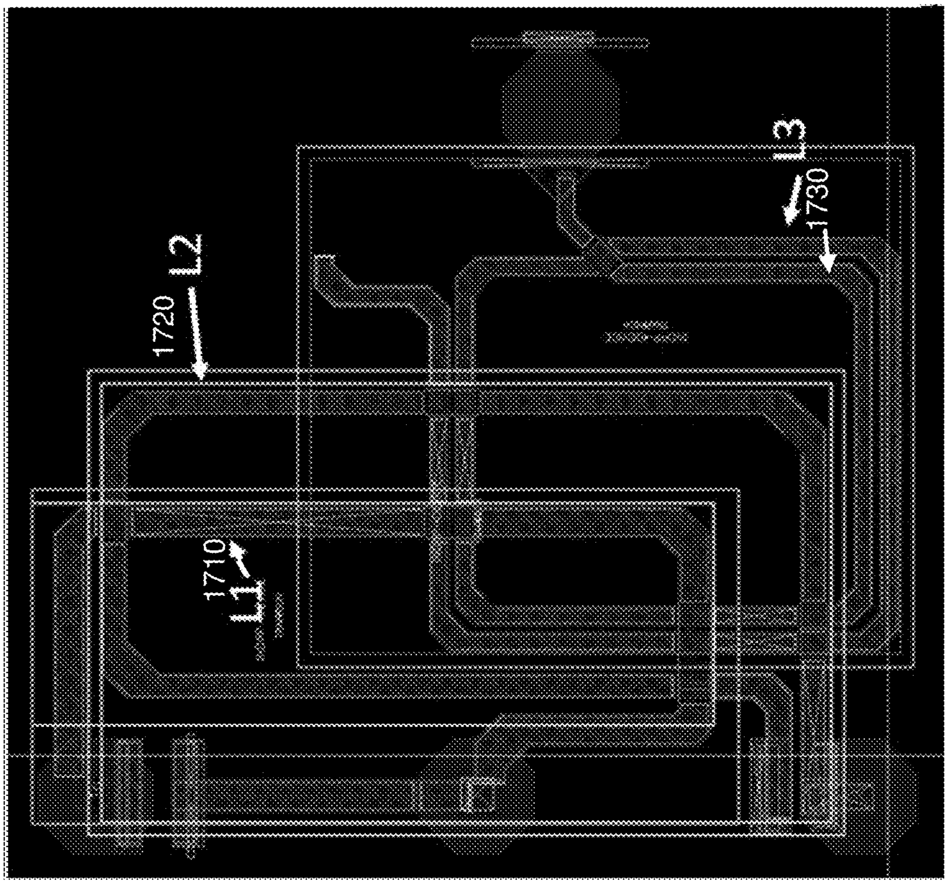


FIG. 17

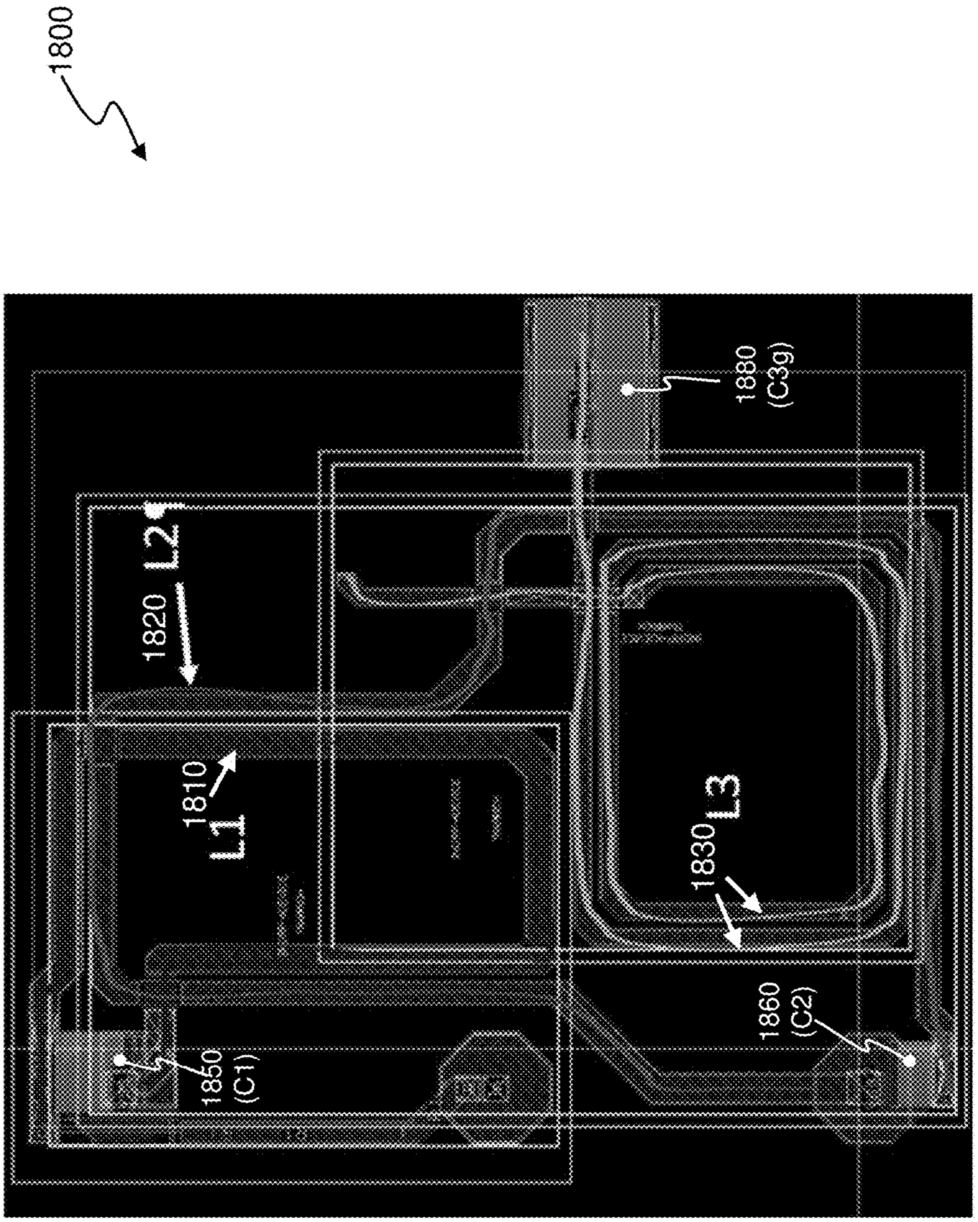


FIG. 18

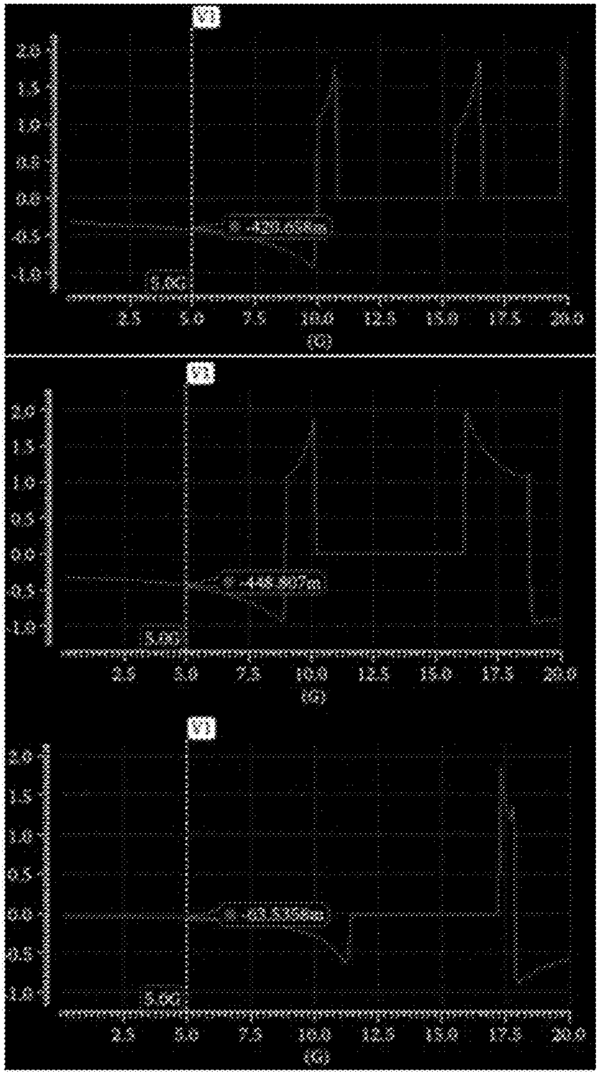
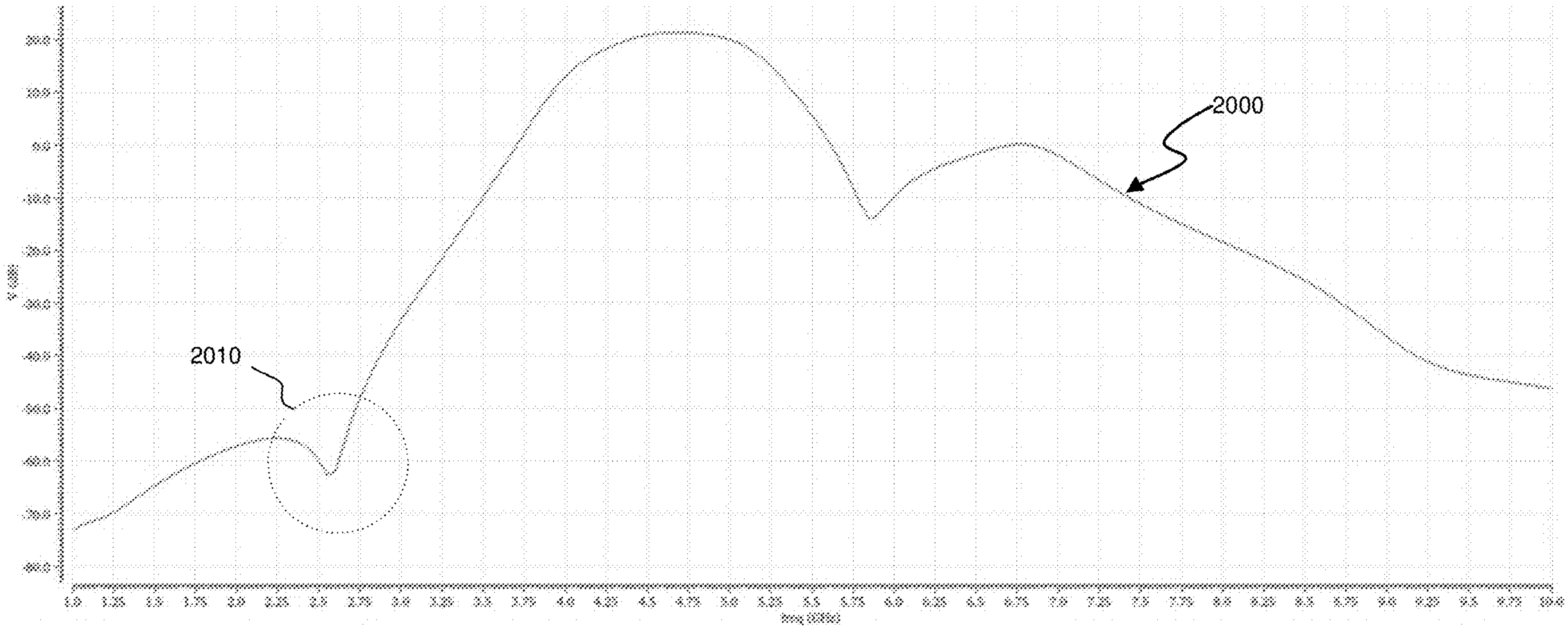
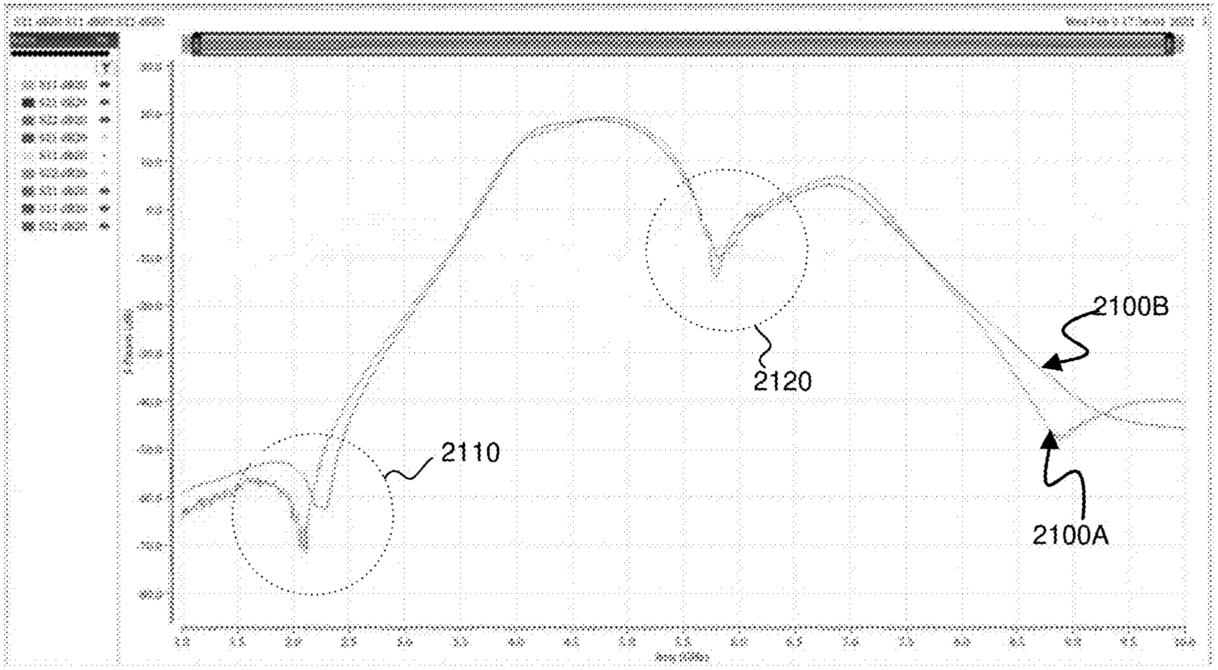

2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-429.656m
5.0G
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
(G)
-448.907m
-63.5358m

FIG. 19



Typical frequency response of a third order resonator filter

FIG. 20



Typical frequency response of a third order resonator filter with QA-notches, simulations and measurements (pink graph) compared

FIG. 21

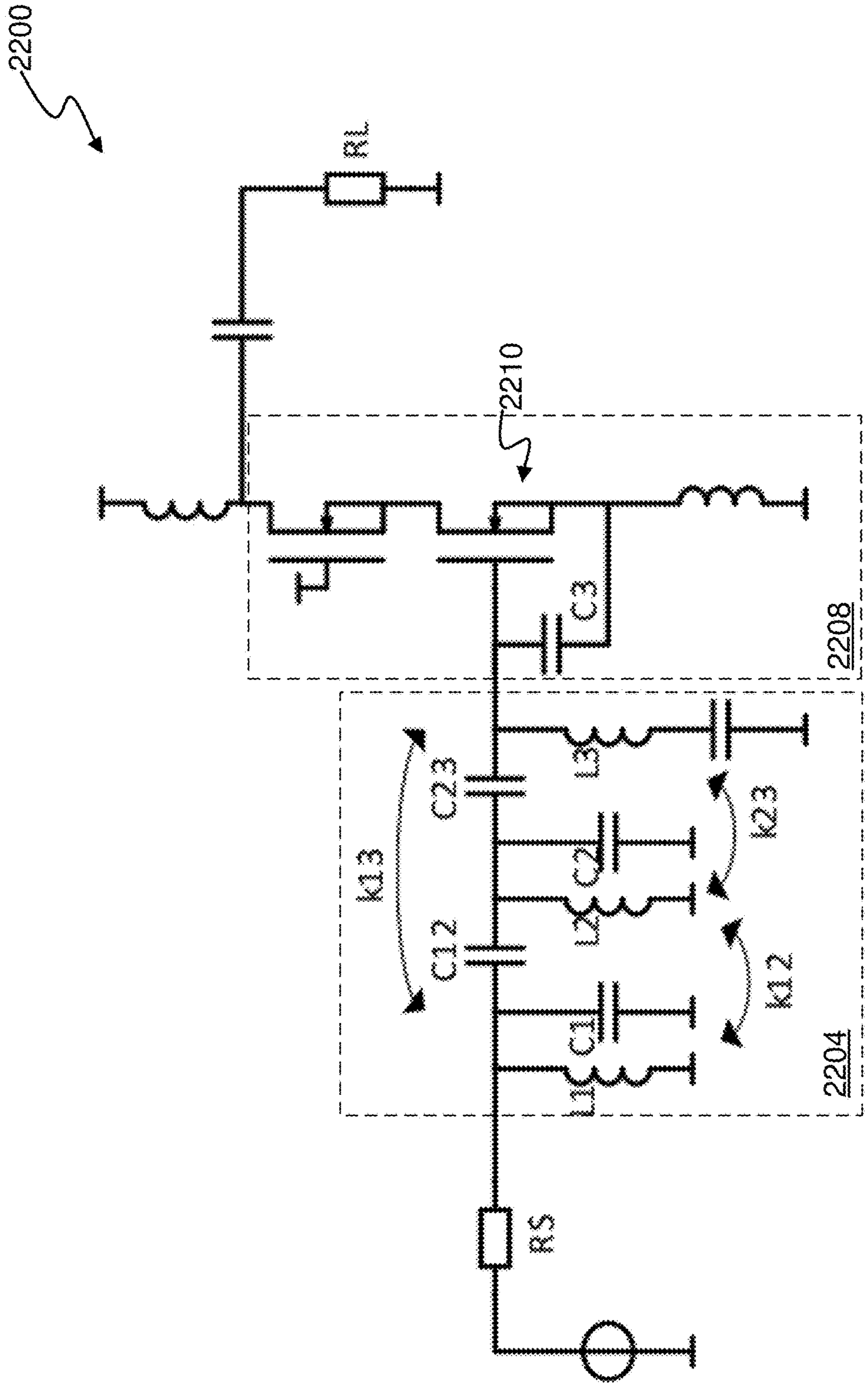


FIG. 22

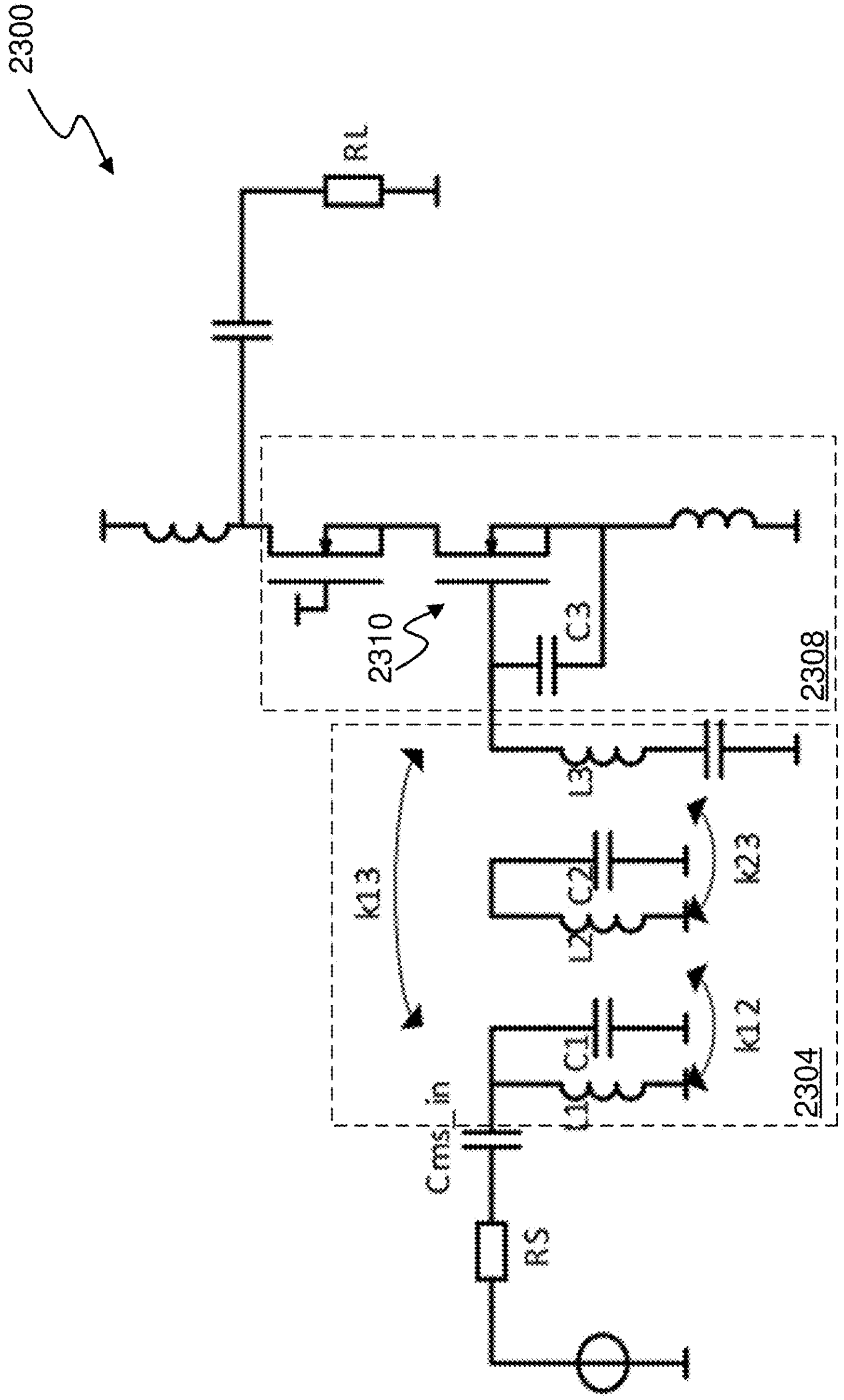


FIG. 23

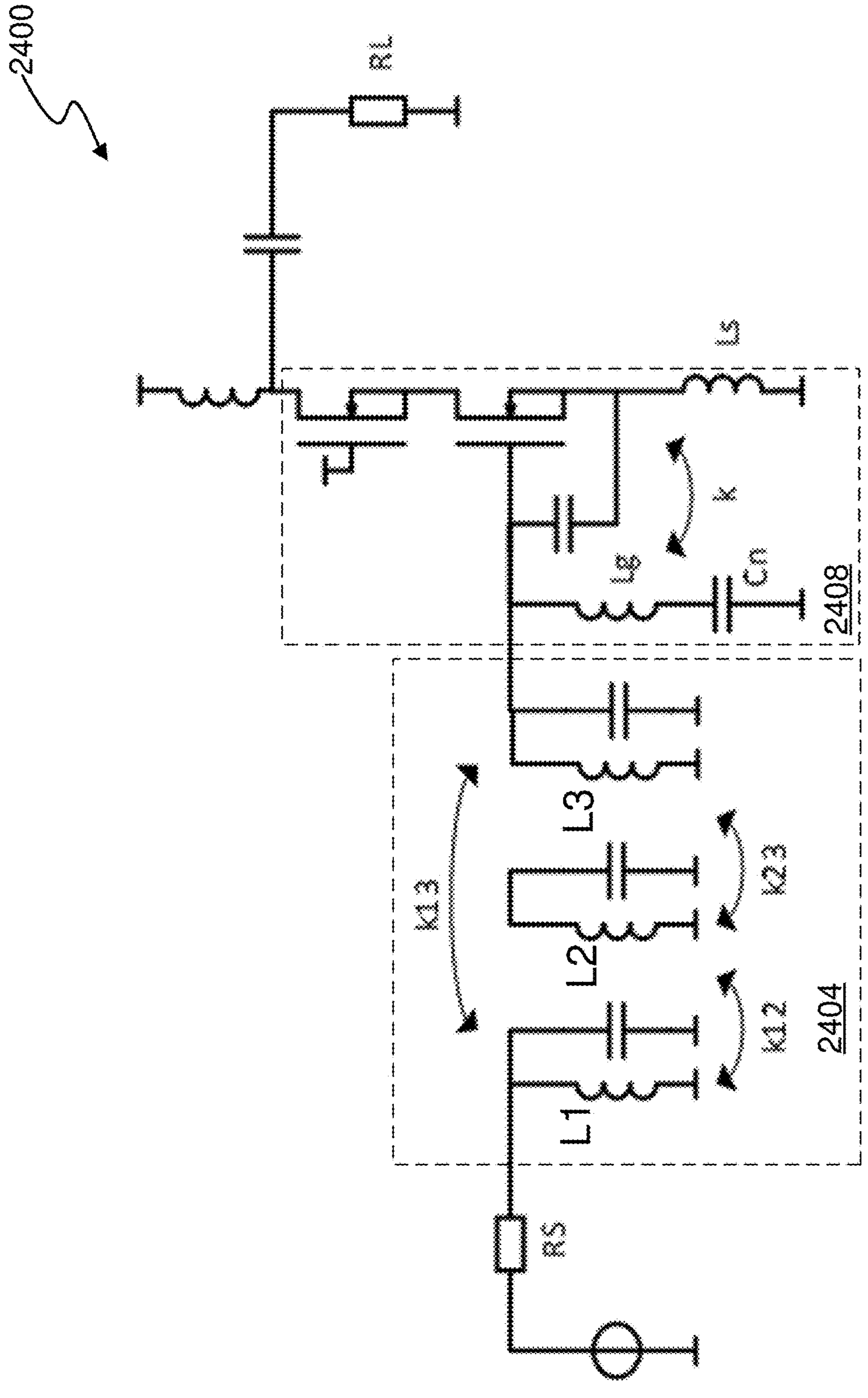


FIG. 24

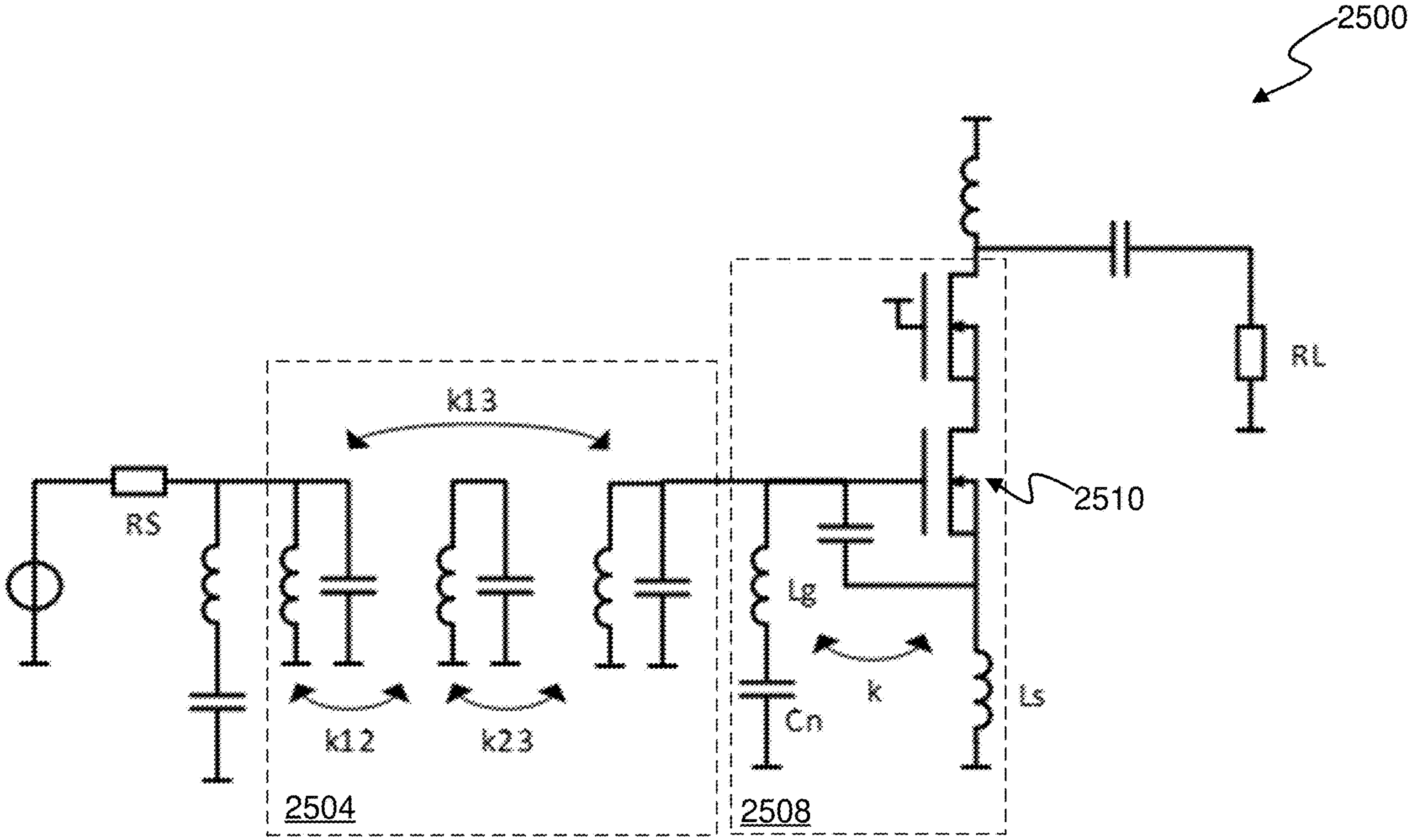


FIG. 25

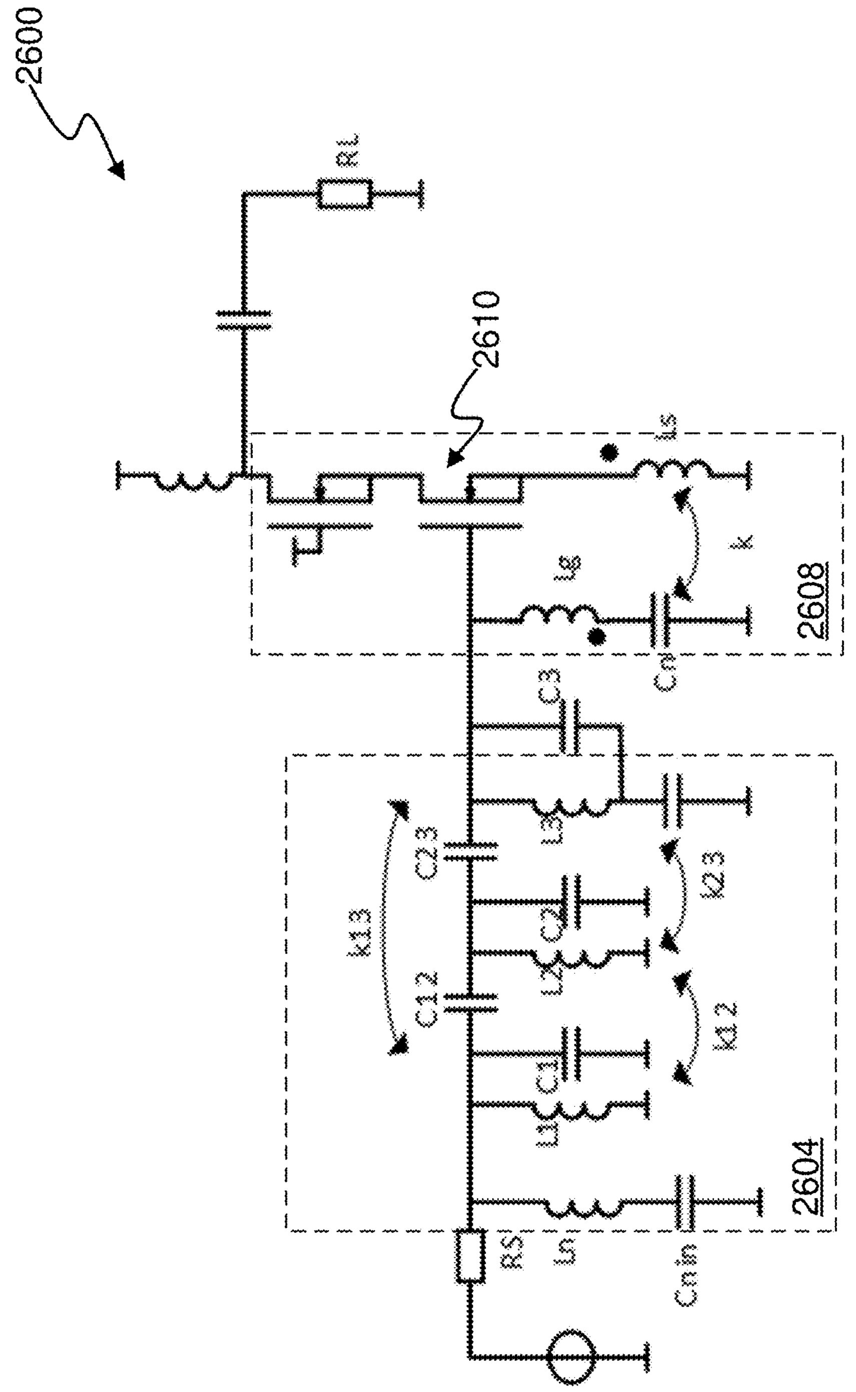

2600
RL
2610
Ls
Lg
k
Cn
2608
C3
L3
C23
k13
k23
C2
L2
C12
k12
C1
L1
2604
RS
Ln
Cn in

FIG. 26

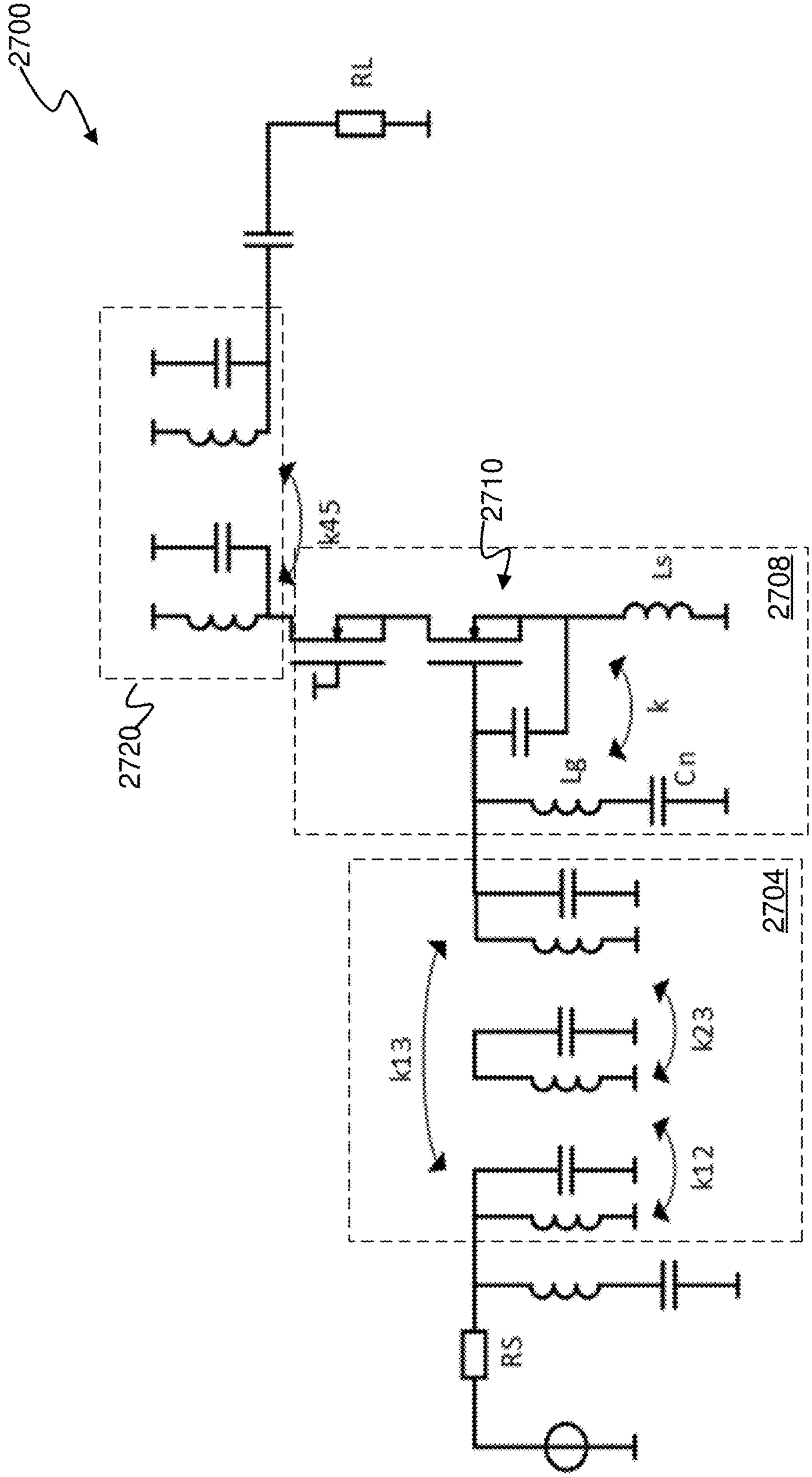
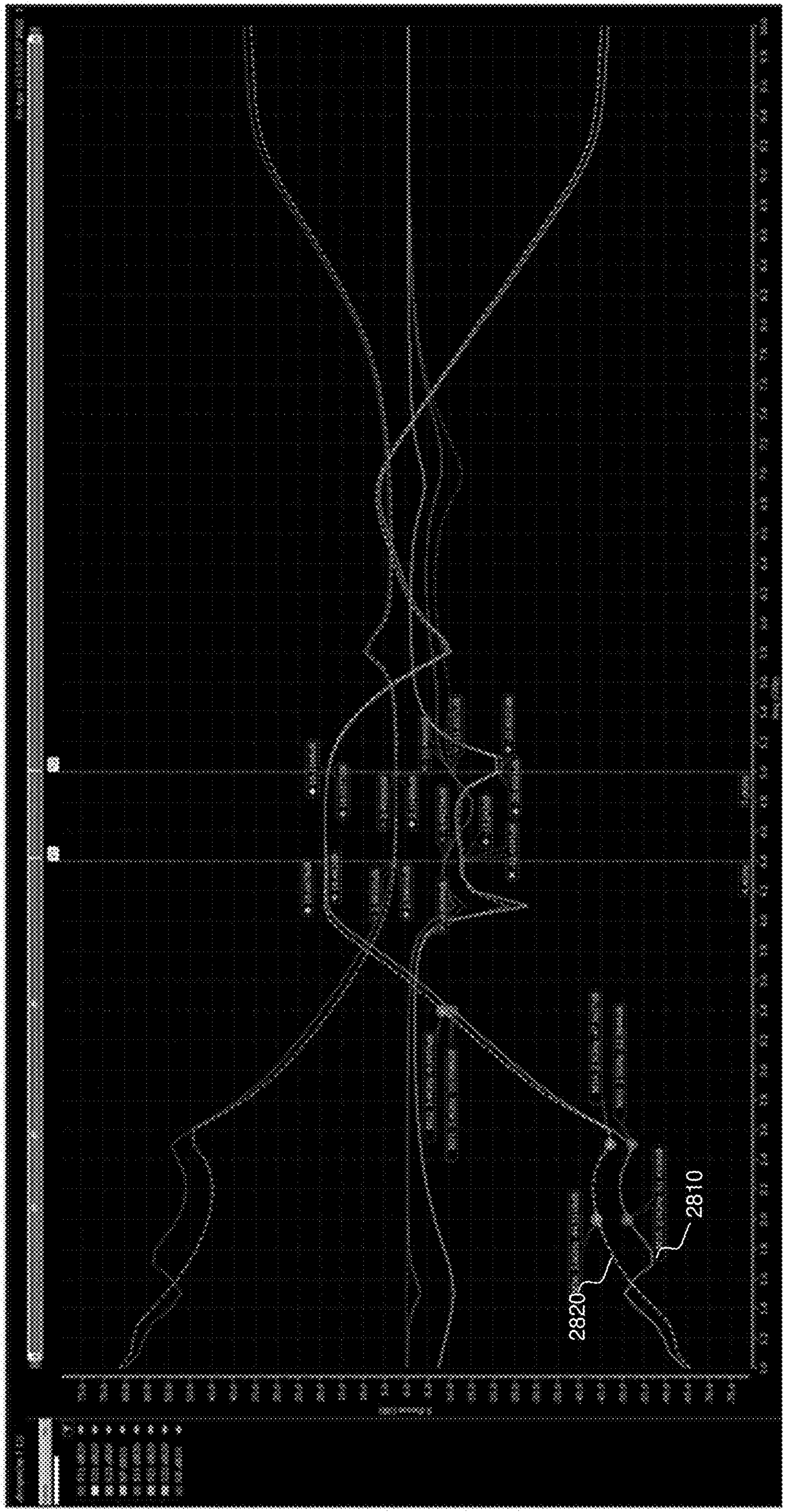


FIG. 27



Frequency response of a filter and LNA implementation with and without an additional input notch

FIG. 28

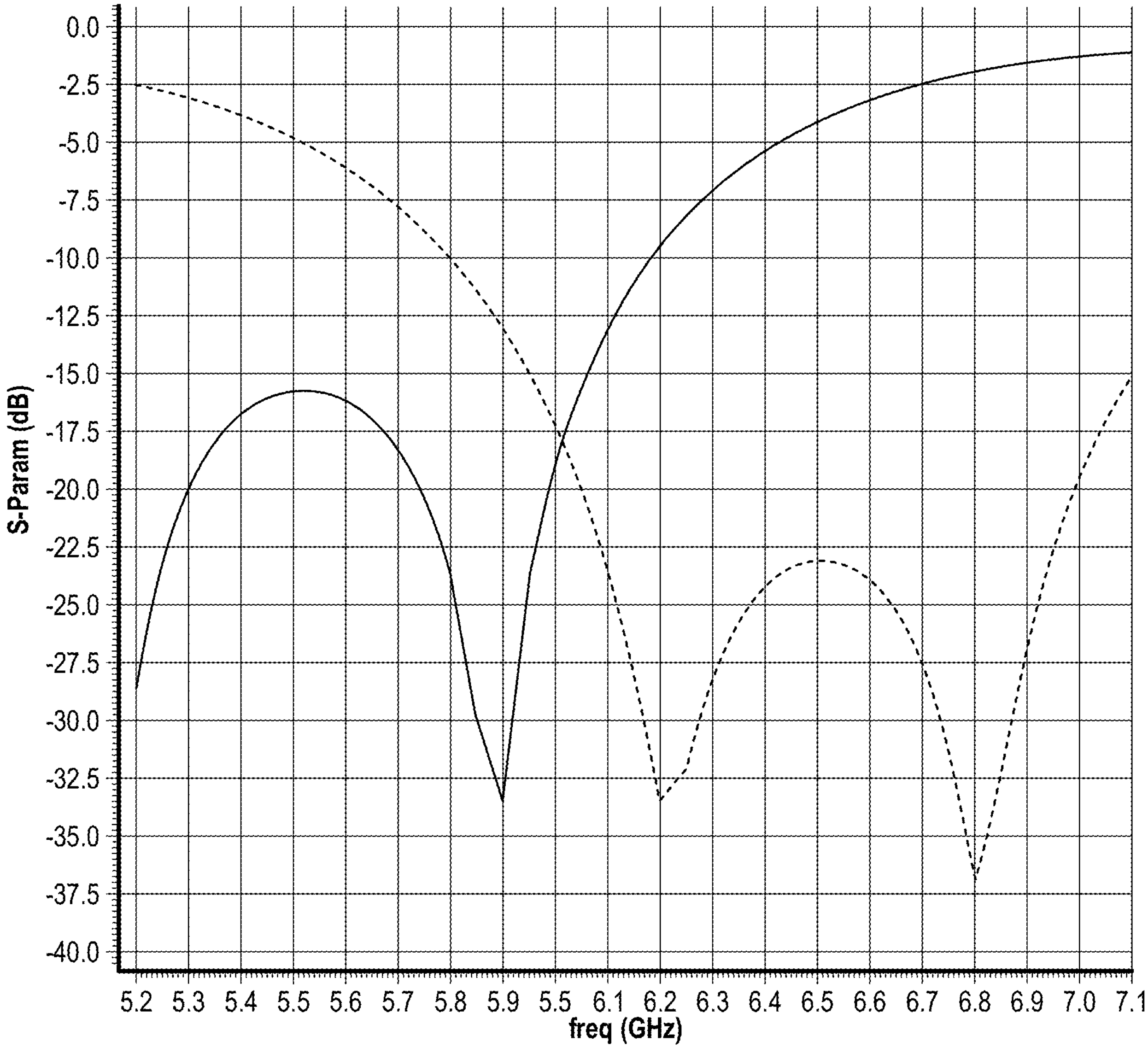

S-Param (dB)
0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
-17.5
-20.0
-22.5
-25.0
-27.5
-30.0
-32.5
-35.0
-37.5
-40.0
5.2
5.3
5.4
5.5
5.6
5.7
5.8
5.9
5.5
6.1
6.2
6.3
6.4
6.5
6.6
6.7
6.8
6.9
7.0
7.1
freq (GHz)

FIG. 29

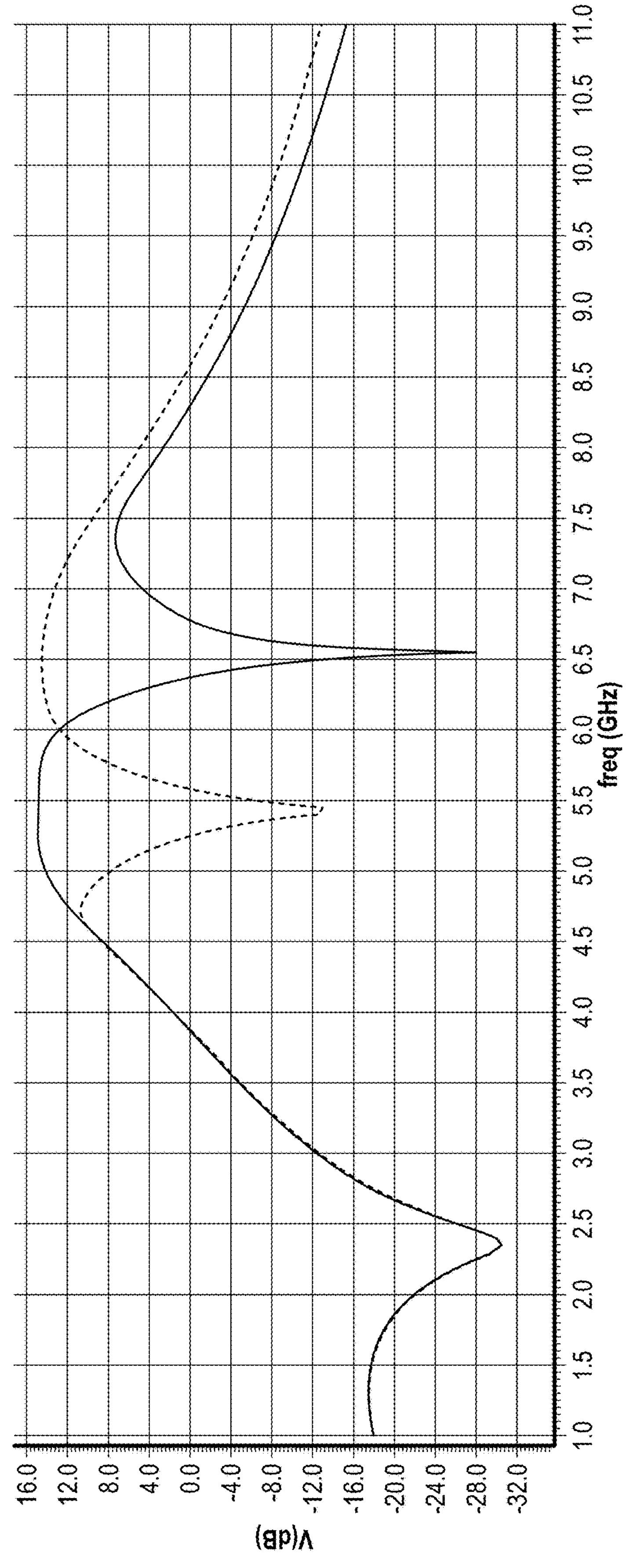

V(dB)
16.0
12.0
8.0
4.0
0.0
-4.0
-8.0
-12.0
-16.0
-20.0
-24.0
-28.0
-32.0
freq (GHz)
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
10.5
11.0

FIG. 30

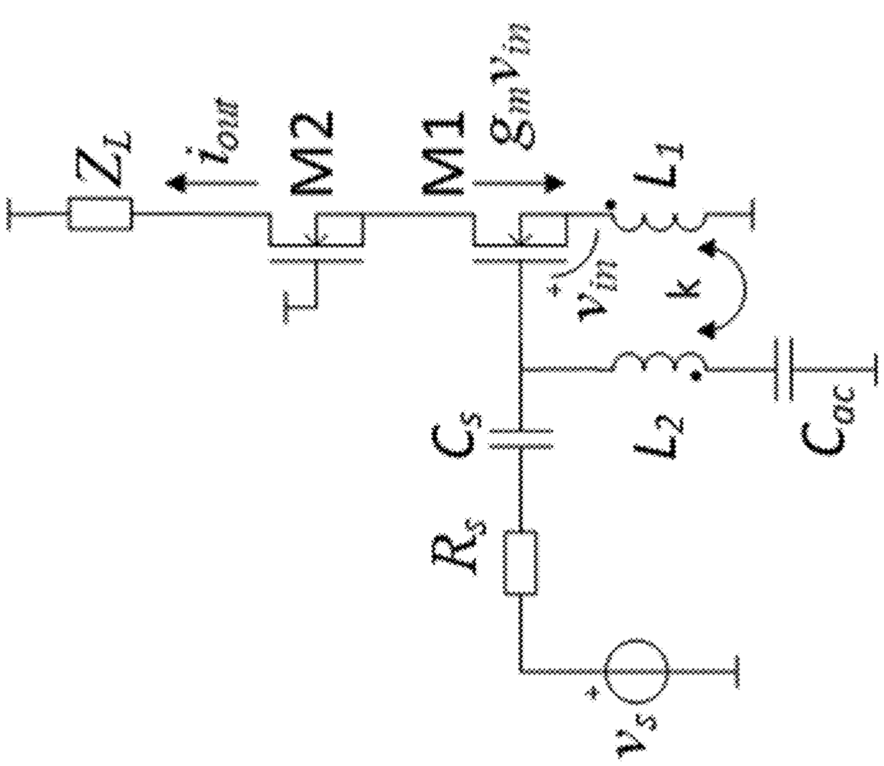
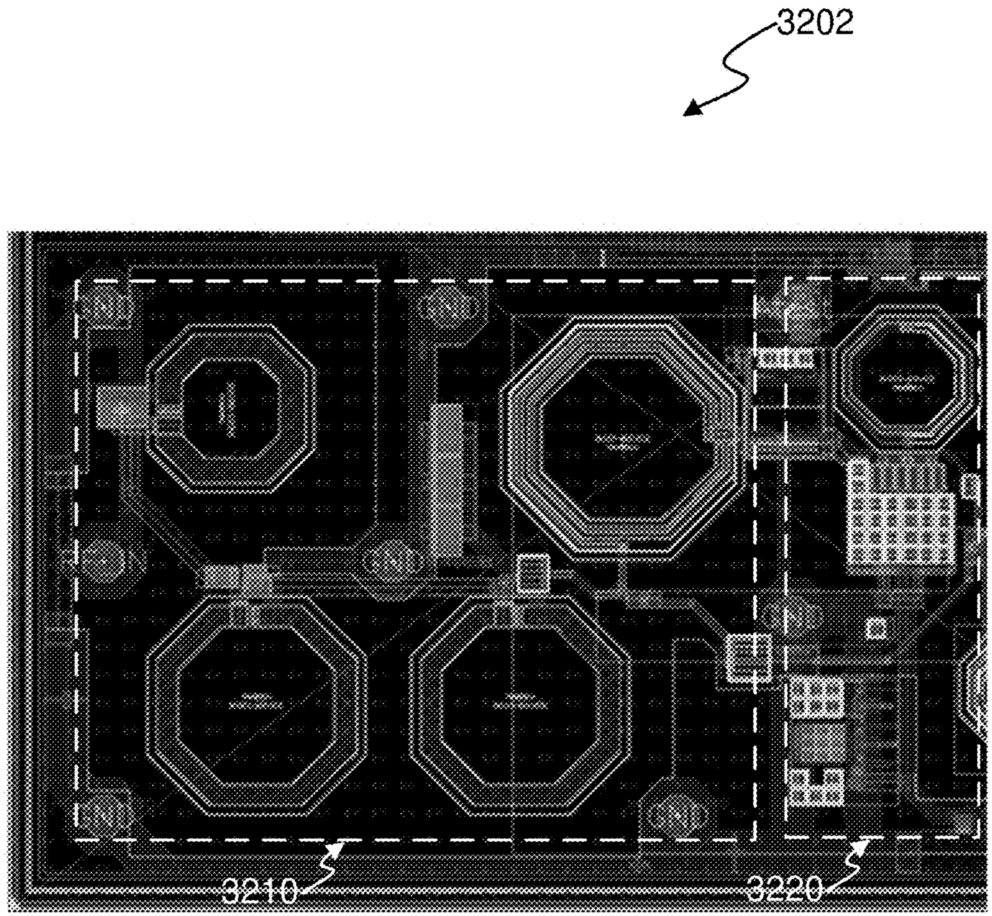
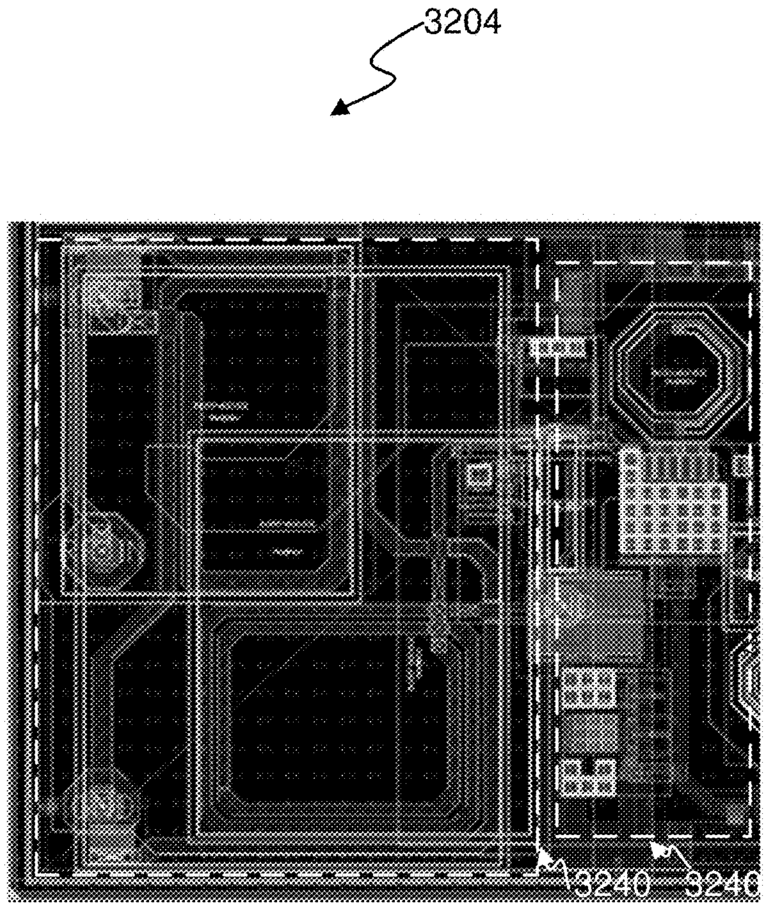


FIG. 31



Electrically coupled resonator filter and source-degenerated LNA

FIG. 32A



Magnetic coupled resonator filter and source-degenerated LNA

FIG. 32B

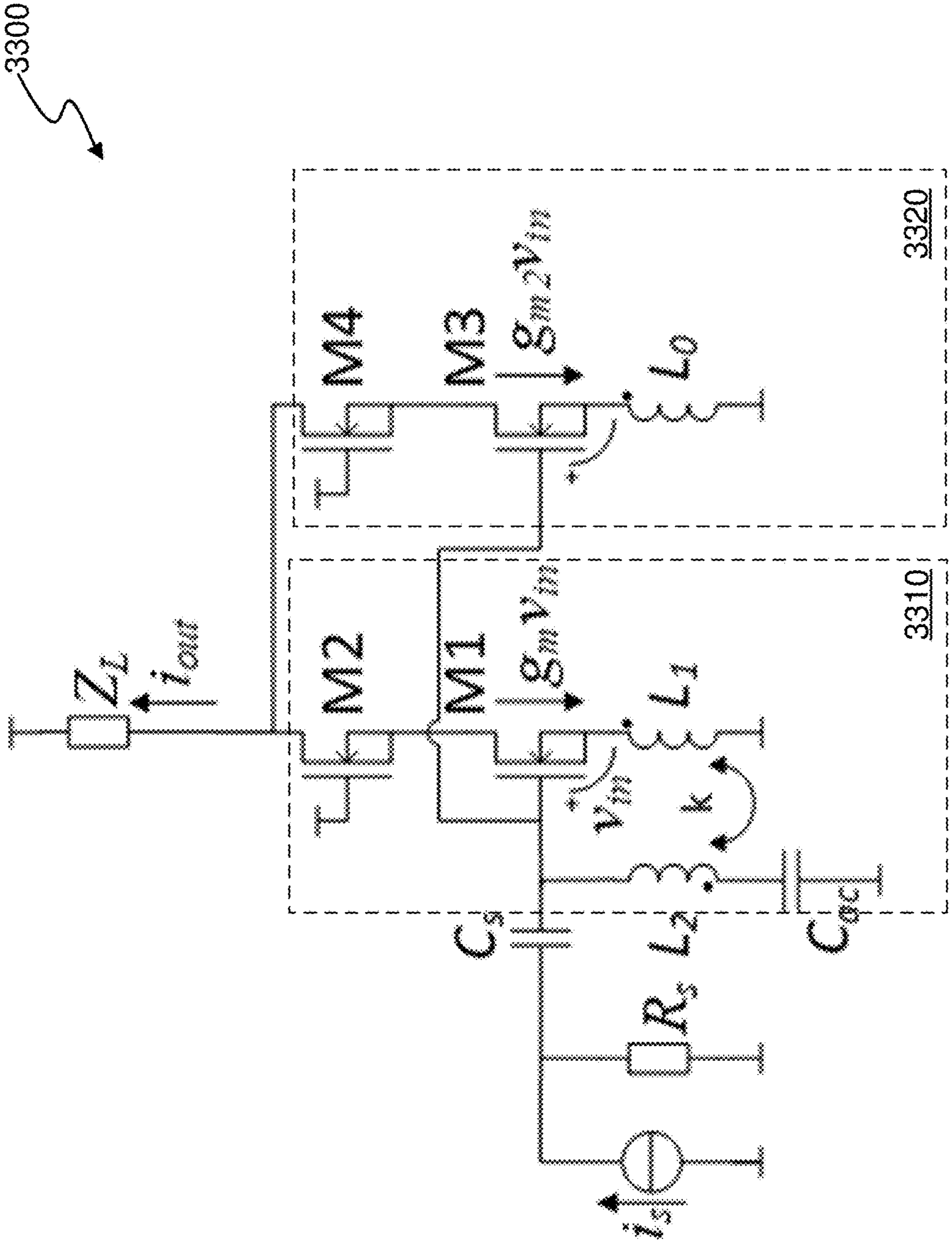

3300
3320
3310
M4
M3
M2
M1
$g_{m2}v_{in}$
$g_m v_{in}$
L_0
L_1
L_2
k
v_{in}
Z_L
i_{out}
C_s
R_s
C_{ac}
i_s

FIG. 33

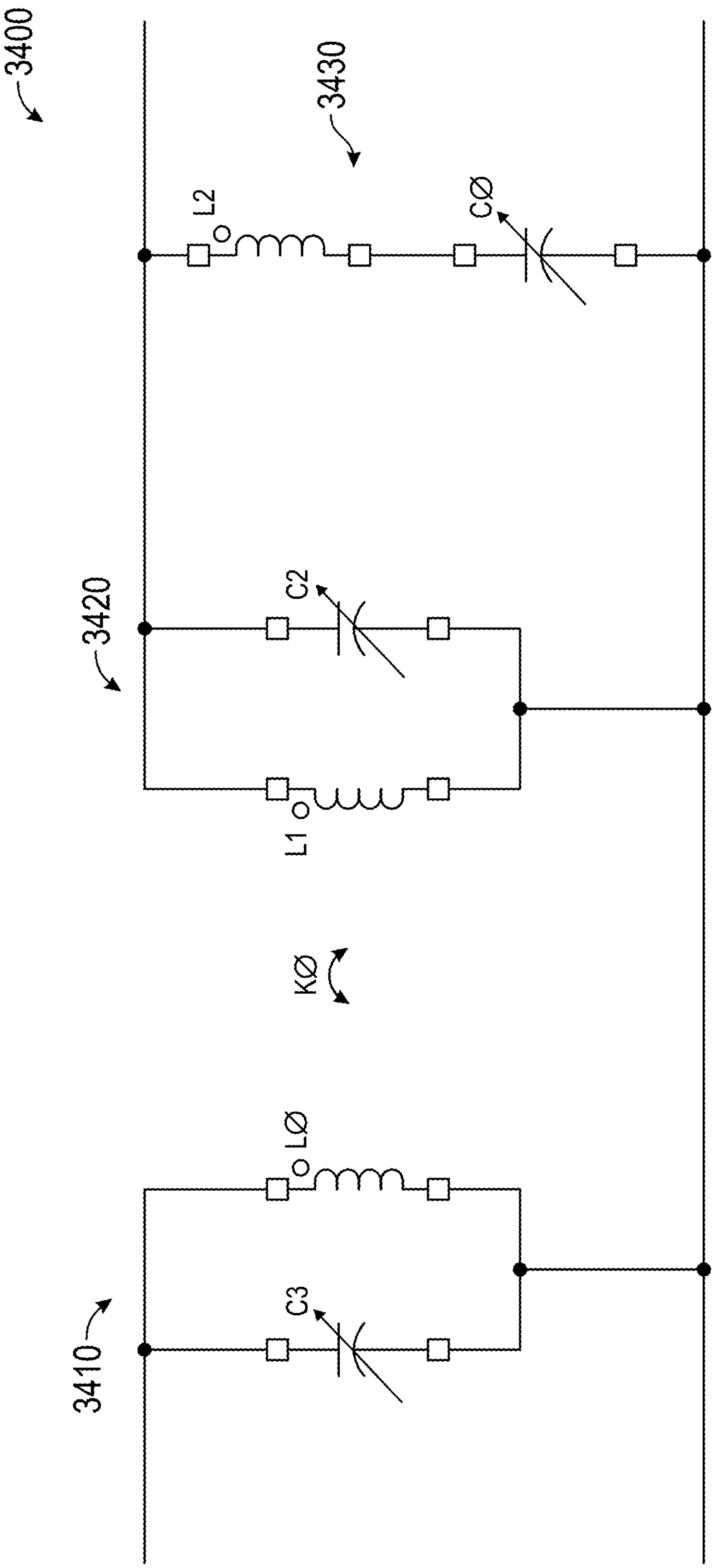


FIG. 34

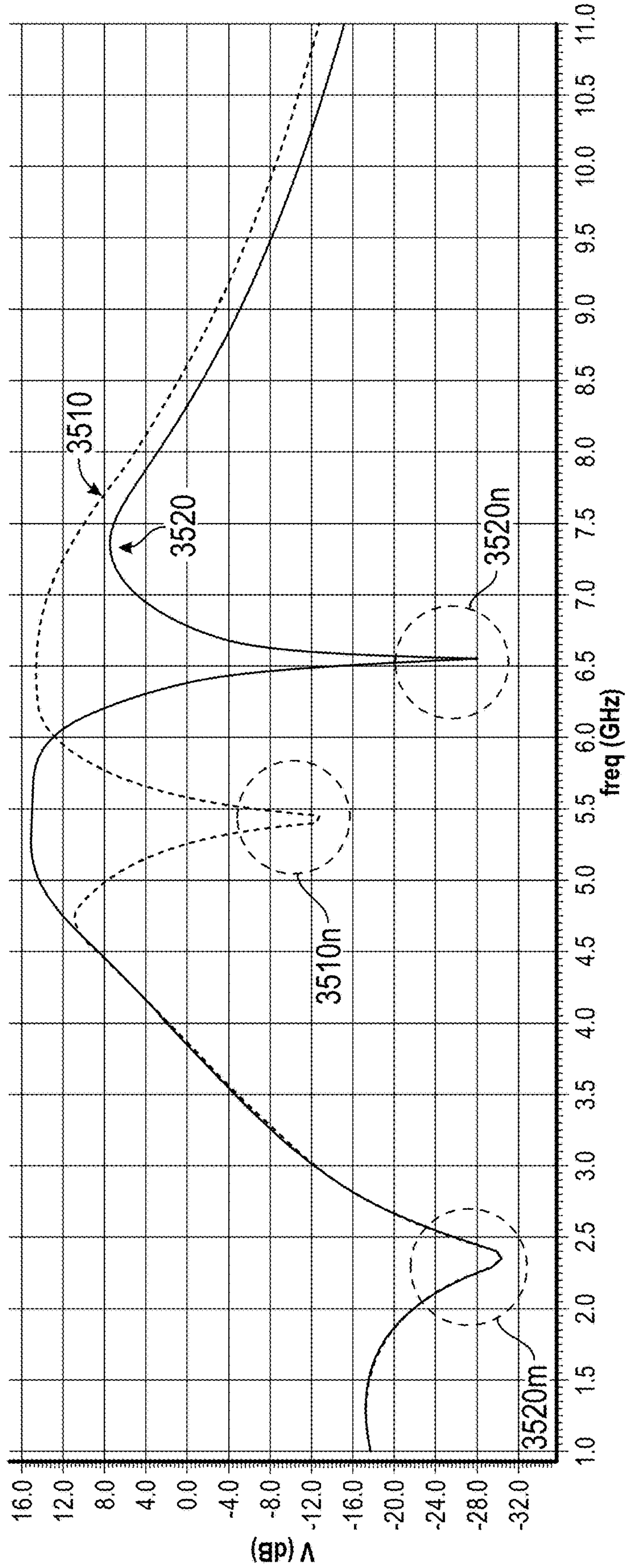

V (dB)
16.0
12.0
8.0
4.0
0.0
-4.0
-8.0
-12.0
-16.0
-20.0
-24.0
-28.0
-32.0
freq (GHz)
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
10.5
11.0
3510
3520
3510n
3520n
3520m

FIG. 35

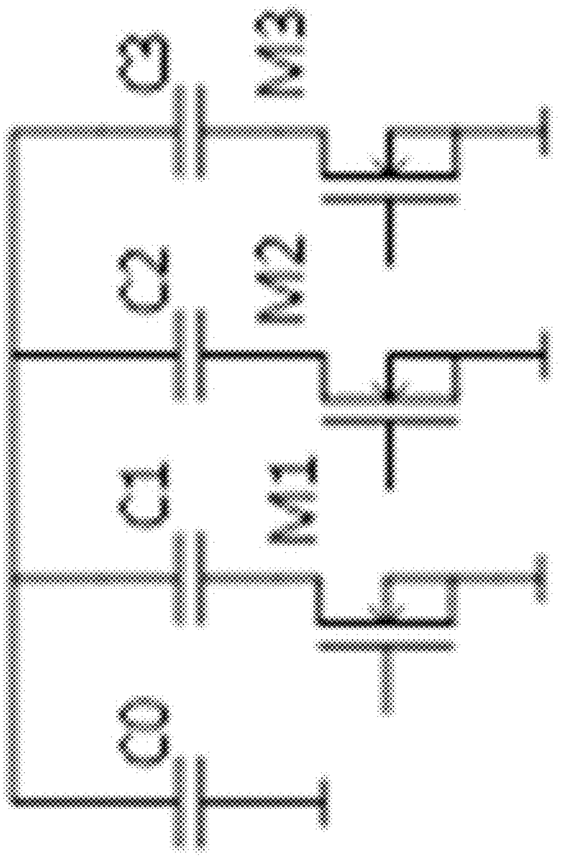


FIG. 36

SYSTEM AND METHOD FOR COUPLED RESONATOR FILTERING

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority under 35 U.S.C. § 119(e) of Provisional Application No. 63/402,882 entitled SYSTEM AND METHOD FOR INTEGRATED FILTERING AND AMPLIFICATION, filed Aug. 31, 2022. This application is related to Application No. ______ (Attorney Docket No. DOCK-031/02US), entitled INTEGRATED COUPLED RESONATOR FILTERING, filed on even date herewith, and to Application No. ______ (Attorney Docket No. DOCK-031/03US), entitled SYSTEM AND METHOD FOR INTEGRATED FILTERING AND AMPLIFICATION, filed on even date herewith.

FIELD

[0002] The present disclosure generally relates to filter circuits and, more particularly, to coupled resonator filters.

BACKGROUND

[0003] Coupled resonator filters are extensively described in literature and in scientific papers. See, e.g., "*The Design of Direct Coupled Band Pass Filters*", published by Iowa Hills Software (Jul. 10, 2016), which has been used for the calculations of an electrically coupled resonator filter. Most of the published documents and literature relating to coupled resonator filters are concerned with cavity-based resonator filters. See, e.g., the reference text *Microwave Filters for Communication Systems* by Richard J. Cameron et al. There are also Internet-based calculators that can be used to calculate component parameters of capacitively coupled resonator filters. See, e.g., the site https://rf-tools.com/lc-filter/. This particular online calculator is limited to calculating component parameters based upon capacitive coupling and equal load and source impedances. FIG. **1** is a screen shot of an exemplary user interface **100** generated by the coupled resonator filter calculator found at https://rf-tools.com/lc-filter/.

[0004] FIG. **2** provides an example of a source-gate feedback LNA topology **200** of a type described in the existing literature. See for instance the paper "*Analysis and Design of a Transformer-Feedback-Based Wideband Receiver", IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES*, VOL. 61, NO. 3, MARCH 2013, Bhagavatula and Rudell. The output matching of the low-noise amplifier (LNA) **210** in FIG. **2** to the load is realized with an LC matching network **220** including an inductance **224** (L_O), a capacitance **226** (C_{match}) and a resistance **228** (R_O) (which may include an inherent resistance associated with La and an added physical resistance), wherein the inductance **224** (L_O) and the capacitance **226** (C_{match}) are used for impedance transformation. The input impedance of the LNA in FIG. **2** is defined by the properties of the active device **230** (M1) in combination with the feedback network consisting of a first inductance **240** (L_1) which is coupled to a second inductance **242** (L_2).

SUMMARY

[0005] Disclosed herein are innovative techniques for on-chip integrated RF filtering and amplification. These innovative techniques may be utilized in high performance RF integrated circuits and front-end modules (FEM) incorporated in, for example, cell phones, routers and personal computers.

[0006] In one aspect the disclosure pertains to a coupled resonator filter including first, second and third parallel resonators. The first parallel resonator includes a first capacitance connected in parallel with a first inductance. The second parallel resonator includes a second capacitance connected in parallel with a second inductance. The third parallel resonator includes a third capacitance connected in parallel with a third inductance. Magnetic coupling between the first inductance and the second inductance magnetically couples the first parallel resonator and the second parallel resonator in accordance with a first coupling factor; magnetic coupling between the second inductance and the third inductance magnetically couples the second parallel resonator and the third parallel resonator in accordance with a second coupling factor; and magnetic coupling between the first inductance and the third inductance magnetically couples the first parallel resonator and the third parallel resonator in accordance with a third coupling factor. A frequency response of the coupled resonator filter includes a notch when values of the first coupling factor, the second coupling factor and the third coupling factor satisfy predetermined conditions.

[0007] The disclosure also relates to an integrated circuit coupled resonator filter including first, second and third parallel resonators. The first parallel resonator includes a first capacitance connected in parallel with a first inductance. The second parallel resonator includes a second capacitance connected in parallel with a second inductance. The third parallel resonator includes a third capacitance connected in parallel with a third inductance. Magnetic coupling between the first inductance and the second inductance magnetically couples the first parallel resonator and the second parallel resonator in accordance with a first coupling factor; magnetic coupling between the second inductance and the third inductance magnetically couples the second parallel resonator and the third parallel resonator in accordance with a second coupling factor; and magnetic coupling between the first inductance and the third inductance magnetically couples the first parallel resonator and the third parallel resonator in accordance with a third coupling factor. A frequency response of the coupled resonator filter includes a notch when values of the first coupling factor, the second coupling factor and the third coupling factor satisfy predetermined conditions.

[0008] The inductances of the coupled resonator filters may be implemented in various configurations and in various layers of the integrated circuit. For example, the first inductance, the second inductance and the third inductance may be implemented on multiple layers of the integrated circuit and at least partially overlap. Alternatively, at least the first inductance and the second inductance may be implemented on a same layer of the integrated circuit and not overlap. The third inductance may also be implemented on the same layer of the integrated circuit and not overlap with the first inductance and the second inductance.

[0009] In another configuration two of the first inductance, the second inductance, and third inductance are implemented on a first layer of the integrated circuit and a remaining one of the first inductance, the second inductance, and third inductance is implemented on a second layer of the integrated circuit. In one implementation of this configuration at least one of the two of the first inductance, the second inductance, and third inductance implemented on the first layer of the integrated circuit overlaps the remaining one of the first inductance, the second inductance, and third inductance implemented on the second layer of the integrated circuit.

[0010] Each of the first inductance, the second inductance, and third inductance may be implemented on different layers of the integrated circuit. In this case the first inductance, the second inductance, and third inductance may be arranged to at least partially overlap. Alternatively, two of the first inductance, the second inductance, and third inductance are arranged to at least partially overlap.

[0011] In another aspect the disclosure relates to an integrated circuit coupled resonator filter including a low-noise amplifier and first, second and third parallel resonators. The first parallel resonator includes a first capacitance connected in parallel with a first inductance. The second parallel resonator includes a second capacitance connected in parallel with a second inductance. The third parallel resonator includes a third capacitance connected in parallel with a third inductance, the third parallel resonator being coupled to an input of the low-noise amplifier. A first coupling capacitance is connected between the first parallel resonator and the second parallel resonator. The coupling capacitance capacitively couples the first parallel resonator and the second parallel resonator. A second coupling capacitance is connected between the second parallel resonator and the third parallel resonator. The second coupling capacitance capacitively couples the second parallel resonator and the third parallel resonator. Magnetic coupling between the first inductance and the second inductance magnetically couples the first parallel resonator and the second parallel resonator in accordance with a first coupling factor; magnetic coupling between the second inductance and the third inductance magnetically couples the second parallel resonator and the third parallel resonator in accordance with a second coupling factor; and magnetic coupling between the first inductance and the third inductance magnetically couples the first parallel resonator and the third parallel resonator in accordance with a third coupling factor. A frequency response of the coupled resonator filter includes a notch when values of the first coupling factor, the second coupling factor and the third coupling factor satisfy predetermined conditions.

[0012] The disclosure also pertains to an integrated circuit coupled resonator filter including a low-noise amplifier and first, second and third parallels resonators. The first parallel resonator includes a first capacitance connected in parallel with a first inductance. The second parallel resonator includes a second capacitance connected in parallel with a second inductance. The third parallel resonator includes a third capacitance in parallel with a third inductance and is coupled to an input of the low-noise amplifier. Magnetic coupling between the first inductance and the second inductance magnetically couples the first parallel resonator and the second parallel resonator in accordance with a first coupling factor; magnetic coupling between the second inductance and the third inductance magnetically couples the second parallel resonator and the third parallel resonator in accordance with a second coupling factor; and magnetic coupling between the first inductance and the third inductance magnetically couples the first parallel resonator and the third parallel resonator in accordance with a third coupling factor. A frequency response of the coupled resonator filter includes a notch when values of the first coupling factor, the second coupling factor and the third coupling factor satisfy predetermined conditions.

[0013] In yet another aspect the disclosure relates to an integrated circuit coupled resonator filter which includes a low-noise amplifier, an Nth order coupled resonator filter, and an Mth order coupled resonator filter. The Nth order coupled resonator filter is coupled to an input of the low-noise amplifier and includes N magnetically coupled parallel resonators arranged in succession, where N is at least 3 and where the N magnetically-coupled parallel resonators are configured to induce substantially only magnetic coupling therebetween. The Mth order coupled resonator filter is coupled to an output of the low-noise amplifier and includes M magnetically coupled parallel resonators arranged in succession, where M is at least 3 and where the M magnetically-coupled parallel resonators are configured to induce substantially only magnetic coupling therebetween.

[0014] A first parallel resonator of the N parallel resonators may be connected to a signal source and configured with an input impedance equal to an impedance of the signal source. An M^{th} parallel resonator of the M parallel resonators may be connected to a signal load and configured with an output impedance equal to an impedance of the signal load.

[0015] A frequency response of the N^{th} order coupled resonator filter may include a first notch at a first frequency which is dependent upon coupling characteristics between parallel resonators of the N parallel resonators. A frequency response of the M^{th} order coupled resonator filter may include a second notch at a second frequency dependent upon coupling characteristics between parallel resonators of the M parallel resonators.

[0016] The disclosure is further directed to a programmable coupled resonator filter arrangement including an Nth order coupled resonator filter. The Nth order coupled resonator filter includes N magnetically coupled parallel resonators arranged in succession, where N is at least 3. Each of the N magnetically coupled parallel resonators includes an inductance in parallel with a programmable capacitance arrangement. A frequency response of the coupled resonator filter arrangement includes a first notch at a first frequency dependent upon coupling characteristics between parallel resonators of the N parallel resonators.

[0017] Each programmable capacitance arrangement may include a capacitance connected to a switch where each switch includes a terminal connected to signal ground.

[0018] The programmable coupled resonator filter arrangement may further include a series resonant circuit connected in parallel with any of the N magnetically coupled parallel resonators. The frequency response of the coupled resonator filter arrangement may include a second notch at a second frequency dependent upon a resonance frequency of the series resonant circuit.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] The features, nature and advantages of the present disclosure will become more apparent from the detailed description set forth below when taken in conjunction with the drawings in which like reference characters identify correspondingly throughout and wherein:

[0020] FIG. **1** is a screen shot of an exemplary user interface generated by an online coupled resonator filter calculator.

[0021] FIG. **2** illustrates an exemplary topology of a source-gate feedback low-noise amplifier (LNA).

[0022] FIG. **3** illustrates an exemplary topology of a source-degenerated LNA.

[0023] FIG. **4**A is a system block diagram of a receiver with filtering and amplification in accordance with the disclosure.

[0024] FIG. **4**B is a system block diagram of a receiver operative to perform Q-boosted filtering and amplification in accordance with the disclosure.

[0025] FIG. **4**C is a block diagram of an exemplary implementation of a Q-boosted band stop filter.

[0026] FIG. **5**A is an extended system block diagram of a receiver with filtering and amplification in accordance with the disclosure.

[0027] FIG. **5**B is an extended system block diagram of a receiver operative to perform Q-boosted filtering and amplification in accordance with the disclosure.

[0028] FIG. **6** schematically illustrates a third order coupled resonator filter with both magnetic and electrical coupling in accordance with the disclosure.

[0029] FIG. **7** schematically illustrates a third order coupled resonator filter with only magnetic coupling in accordance with the disclosure.

[0030] FIG. **8** schematically illustrates a second order coupled resonator filter with both magnetic and electrical coupling in accordance with the disclosure.

[0031] FIG. **9** schematically illustrates a second order coupled resonator filter with only magnetic coupling in accordance with the disclosure.

[0032] FIG. **10** is a screen shot of an interface for an electronic spreadsheet used for determination of filter component parameters.

[0033] FIG. **11** illustrates an exemplary layout of inductors included in a third order resonator filter with primarily electric coupling.

[0034] FIG. **12** illustrates an exemplary layout of inductors in a third order resonator filter with combined electric and magnetic coupling.

[0035] FIG. **13** illustrates an exemplary layout of a third order resonator filter with combined electric and magnetic coupling.

[0036] FIG. **14** illustrates an exemplary layout of a third order resonator filter with only magnetic coupling.

[0037] FIG. **15** illustrates an exemplary layout of a second order resonator filter with only magnetic coupling.

[0038] FIG. **16** illustrates an exemplary layout of inductors in a third order resonator filter with only magnetic coupling.

[0039] FIG. **17** illustrates an exemplary layout of inductors in a third order resonator filter with only magnetic coupling.

[0040] FIG. **18** illustrates an exemplary layout of a third order resonator filter with only magnetic coupling.

[0041] FIG. **19** illustrates results of an electromagnetic simulation characterizing the coupling factor between inductors of the layout in FIG. **18**.

[0042] FIG. **20** illustrates a typical frequency response of a third order resonator filter.

[0043] FIG. **21** illustrates both simulated and measured frequency responses of the receiver of FIG. **5**B as implemented with a third order resonator filter configured to introduce frequency response notches in accordance with the disclosure.

[0044] FIG. **22** schematically illustrates a coupled resonator filter combined with source degenerated LNA in accordance with the disclosure.

[0045] FIG. **23** schematically illustrates a magnetically-only coupled resonator filter combined with a source degenerated LNA.

[0046] FIG. **24** schematically illustrates a magnetically-only coupled resonator filter combined with a source-gate feedback LNA.

[0047] FIG. **25** schematically illustrates a magnetically-only coupled resonator filter combined with a source-gate feedback LNA and configured to produce a frequency response having an input notch.

[0048] FIG. **26** schematically illustrates a coupled resonator filter combined with source-gate feedback LNA and an input notch circuit.

[0049] FIG. **27** schematically illustrates a magnetically-only coupled resonator filter combined with source-gate feedback LNA, input notch circuit, and magnetically only coupled resonator filter at the output.

[0050] FIG. **28** illustrates a frequency response of a filter and LNA implementation with and without an additional input notch.

[0051] FIG. **29** illustrates output return loss (S22) for a tunable filter where a broadband response is achieved by the coupled resonator filter at the output.

[0052] FIG. **30** illustrates a notched frequency response of the receiver of FIG. **5**B as implemented with a magnetically-only coupled resonator filter where the filter center frequency is programmable for two different frequency bands.

[0053] FIG. **31** schematically illustrates a CMOS implementation of source-gate feedback LNA topology.

[0054] FIG. **32**A illustrates an exemplary layout of an electrically coupled resonator filter and source-degenerated LNA.

[0055] FIG. **32**B illustrates an exemplary layout of a magnetically coupled resonator filter and source-degenerated LNA.

[0056] FIG. **33** schematically illustrates a CMOS implementation of source-gate feedback LNA topology configured for distortion cancelling.

[0057] FIG. **34** is a schematic view of tunable coupled resonator filter.

[0058] FIG. **35** illustrates frequency responses of the tunable coupled resonator filter of FIG. **34** when configured in two different filter modes.

[0059] FIG. **36** illustrates an exemplary capacitor filter bank of a type that may be used to implement the programmable capacitances within the filter of FIG. **34**.

DETAILED DESCRIPTION

[0060] Disclosed herein are innovative techniques for on-chip integrated RF filtering, noise and distortion suppression, and amplification. These innovative techniques may be utilized in high performance RF integrated circuits and front-end modules incorporated within, for example, mobile phones, routers and personal computers.

[0061] The innovative techniques described in the present disclosure may be broadly divided into the following two groups: (i) integrated magnetically and electrically coupled on-chip resonator filters, and (ii) on-chip coupled resonator filters combined with a low-noise amplifier ("LNA"). The innovations within groups (i) and (ii) can work stand-alone but are also advantageously combined. A detailed description of the innovations within each group is provided in the following sections.

Exemplary Receiver Architecture with Filtering and Amplification

[0062] FIG. **4**A is a system block diagram of a receiver **400** with filtering and amplification in accordance with the disclosure. As illustrated in FIG. **4**A, the receiver **400** includes first and second Nth order coupled resonator filters **410**, **420**, a low-noise amplifier **430** connected to an output of the coupled resonator filter **410**, and a variable attenuator **440** interposed between the LNA **430** and the coupled resonator filter **420**. The first Nth order coupled resonator filter **410** receives an input signal from a signal source **434** having a source resistance **436** (R_S). A coupled notch circuit **450** may be added to the coupled resonator filter in order to improve out-of-band attenuation as described hereinafter. Placing the second Nth order coupled resonator filter **420** at the output of the receiver **400**, where it is coupled to the load **460** (R_L), can render the output matching more wideband relative a conventional single resonator resonant load and matching network of the type shown in FIG. **3**. Although the exemplary receiver **400** of FIG. **4**A includes first and second Nth order coupled resonator filters implemented as described hereinafter, other embodiments of receivers in accordance with the disclosure may include additional coupled resonator filters, attenuators and the like. In other receiver embodiments within the scope of the present disclosure the number of coupled resonator filters and their degree (e.g., N=3, 4, etc.), and whether such filters are augmented with coupled notch circuits, will depend upon the filtering requirements or specifications associated with a particular application.

[0063] As shown in FIG. **4**A, in one embodiment the receiver **400** includes a bypass mode switch module **464**. When the switch module **464** is in a closed configuration, the low-noise amplifier **430** and variable attenuator **440** are bypassed; otherwise, signal energy from the resonator filter **410** is amplified by the LNA **430** and variably attenuated by the variable attenuator **440** before being provided to the second Nth order coupled resonator filter **420**.

[0064] Turning now to FIG. **4**B, a system block diagram is provided of a receiver **400'** operative to perform Q-boosted filtering and amplification in accordance with the disclosure. As may be appreciated, the architecture of the receiver **400'** is substantially similar to that of the receiver **400**. However, in lieu of the first and second Nth order coupled resonator filters **410**, **420**, the receiver **400'** includes first and second Q-boosted coupled resonator filter modules **412**, **422**. As shown, the first Q-boosted coupled resonator filter module **412** includes an Nth order coupled resonator filter **410'** and a coupled notch circuit **450'**, which may be substantially similar or identical to the Nth order coupled resonator filter **410** and coupled notch circuit **450** of FIG. **4**A. In the first Q-boosted coupled resonator filter module **412**, the Nth order coupled resonator filter **410'** and coupled notch circuit **450'** are connected to a regenerative feedback & Q-boosting circuit **470**. In one embodiment the regenerative feedback & Q-boosting circuit **470** includes an active device (e.g., a MOSFET) configured with a positive feedback loop. This arrangement results in the active device producing a negative transconductance, which offsets parasitic losses inherent in inductive elements coupled resonator filter **410'** and coupled notch circuit **450'** and thereby improves the quality factor (Q) of each. By boosting the Q of the coupled resonator filter **410'** and coupled notch circuit **450'** it is possible to obtain very sharp attenuation at edges of the filter band conjunctively produced by the filters **410'**, **450'**.

[0065] The second Q-boosted coupled resonator filter module **422** includes an Nth order coupled resonator filter **420'**, which may be substantially similar or identical to the Nth order coupled resonator filter **420** of FIG. **4**A. In addition, the second Q-boosted coupled resonator filter module **422** includes a regenerative feedback & Q-boosting circuit **480** connected to the Nth order coupled resonator filter **420'**. The regenerative feedback & Q-boosting circuit **480** may be configured similarly to the Q-boosting circuit **470** in order to boost the Q of the coupled resonator filter **420'**.

[0066] Attention is now directed to FIG. **4**C, which is a block diagram of an exemplary implementation of the regenerative feedback & Q-boosting circuit **480** as a Q-boosted band stop filter **480'**. As shown, the Q-boosted band stop filter **480'** is connected in parallel with the Nth order coupled resonator filter **420'** and is coupled to load **479** (R_L). The Nth order coupled resonator filter **420'** receives an input signal from a signal source **474** having a source resistance **476** (R_S). In the implementation of FIG. **4**C, the Q-boosted band stop filter **480'** includes a series resonant circuit **482** having a capacitance **486** and an inductance **488**. A specially configured regenerative electronic circuit **490** in parallel with the capacitance **486** adds a negative resistance across the capacitance **486**. By careful selection of the parameters of the circuit **490**, the losses in at least the inductance **488** are cancelled by the added negative resistance and the Q-factor of the series resonant circuit **482** is thereby increased.

[0067] The Q-boosting circuit **480** implemented as the Q-boosted band stop filter **480'** offers a number of advantages relative to conventional methods for improving receiver performance. For example, improving the sharpness of filter frequency response characteristics in receivers has typically involved utilizing higher order filters or adding bulky and expensive acoustic wave filtering elements. Moreover, simply utilizing conventional band stop filters to improve the sharpness of filter characteristics at filter band edges is generally not a viable approach since even to the extent such filters may improve filter roll off characteristics their relatively low quality factors can result in degradation of the shape of the filter passband and induce interference in neighboring bands.

[0068] The high quality factor of the Q-boosted band stop filter **480'** relative to conventional band stop filters enables it improve filter roll off/sharpness characteristics without otherwise degrading filter passband characteristics or causing interference in adjacent frequency bands. In order to facilitate the implementation of the Q-boosted band stop filter **480'** in integrated circuits, embodiments of the filter **480'** have been designed to overcome various challenges that have prevented the introduction of positive feedback amplifiers in integrated filter technologies for Q boosting purposes. For example, the circuit **490** is dimensioned to ensure that the overall resistive part of the resonator **420'** remains positive so as to preclude oscillatory behaviour. The negative resistance effected by the circuit **490** reduces the losses of the inductance in each resonator **410'**, **420'**, which can at resonance be approximated with its parallel equivalent. At frequencies far away from the resonance frequency, the reactive elements of the resonator **410'**, **420'** become dominant and the negative resistance can be neglected. As a consequence, signals in in out-of-band frequencies are generally unaffected.

[0069] Referring now to FIG. 5A, there is shown an extended system block diagram of a receiver **500** with filtering and amplification in accordance with the disclosure. As is illustrated in FIG. 5A, the receiver **500** includes an Nth order magnetically coupled resonator filter **510** serially coupled to a band stop filter **520**, a low-noise amplifier **530** connected to an output of the band stop filter **520**, and a variable attenuator **540** interposed between the LNA **530** and an output matching network **550**. The Nth order coupled resonator filter **510** and a coupled notch circuit **512** receive an input signal from a signal source **502** having a source resistance **504** (R_S). The receiver **500** may further include an additional band stop filter **560** and an output low pass filter **570** coupled to load **574** (R_L). The coupled notch circuit **512** may be added to the coupled resonator filter **510** in order to improve out-of-band attenuation in similar manner as the coupled notch filter **450** (FIG. **4**). Although the exemplary receiver **500** of FIG. 5A includes only a single Nth order coupled resonator filter, other embodiments of receivers in accordance with the disclosure may include additional coupled resonator filters, attenuators and the like.

[0070] As shown in FIG. 5A, in one embodiment the receiver **500** includes a bypass mode switch module **578**. When the switch module **589** is in a closed configuration, the low-noise amplifier **530** and variable attenuator **540** are bypassed; otherwise, signal energy from the band stop filter **520** is amplified by the LNA **530** and variably attenuated by the variable attenuator **540** before being provided to the output matching network **550**. The receiver **500** may include a temperature-controlled bias module **582** for biasing active components of the low-noise amplifier **530** as a function of temperature so as to, for example, make the gain of the low-noise amplifier substantially independent of temperature.

[0071] Turning now to FIG. 5B, an extended system block diagram is provided of a receiver **500'** operative to perform Q-boosted filtering and amplification in accordance with the disclosure. As may be appreciated, the architecture of the receiver **500'** is substantially similar to that of the receiver **500**. However, in lieu of the Nth order coupled resonator filter **510**, the receiver **500'** includes a Q-boosted coupled resonator filter module **508**. As shown, the Q-boosted coupled resonator filter module **508** includes an Nth order coupled resonator filter **510'** and a coupled notch circuit **512'**, which may be substantially similar or identical to the Nth order coupled resonator filter **510** and coupled notch circuit **512** of FIG. **5**A. As shown, in the Q-boosted coupled resonator filter module **508** the Nth order coupled resonator filter **510'** and coupled notch circuit **512'** are connected to a regenerative feedback & Q-boosting circuit **514**. In one embodiment the regenerative feedback & Q-boosting circuit **514** is implemented in essentially the same manner as the Q-boosted band stop filter **480'** of FIG. 4C. That is, the circuit **514** is implemented to include an active device (e.g., a MOSFET) configured with a positive feedback loop. This arrangement results in the active device producing a negative transconductance, which offsets parasitic losses inherent in inductive elements in the coupled resonator filter **510'** and the coupled notch circuit **512'** and thereby improves the quality factor (Q) of each. By boosting the Q of the coupled resonator filter **510'** and coupled notch circuit **512'** it is possible to obtain very sharp attenuation at edges of the filter band conjunctively produced by the filters **510'**, **512'**.

Integrated Magnetically and Electrically Coupled Resonator Filters

[0072] Attention is now directed to FIG. **6**, which schematically illustrates a third order coupled resonator filter **600** with both magnetic and electrical coupling in accordance with the disclosure. As shown, an input matching capacitance **608** (Cms_in) is connected in series with a signal source **610** having a source resistance **612** (R_S). The three resonators of the third order coupled resonator filter **600** consist of the parallel combination of a first resonator **620** (L1 and C1), a second resonator **622** (L2 and C2), and a third resonator **624** (L3 and C3) respectively. The filter **600** includes an output matching capacitance **630** (Cms_out) connected in series with a load represented by load resistance **634** (R_L).

[0073] The electrical coupling between the first and second resonators of the resonator filter **600** is achieved by a first capacitance **640** (C12), and a second capacitance **644** (C23) provides the electrical coupling between the second and third resonator. The amount of magnetic coupling between the first and second resonator is characterized by the coupling factor k12, and k23 gives the amount of magnetic coupling between the second and third resonator. The direct magnetic coupling between the first and third resonator is characterized by k13. The coupling factor between two on-chip inductors is characterized by Electro-Magnetic simulations and is defined by the equation:

$$k12 = \frac{M}{\sqrt{L1L2}}$$

[0074] where M is the mutual inductance between L1 and L2. The coupling factor k23 may be similarly represented as a function of L2 and L3.

[0075] Although the filter **600** could theoretically be implemented using an arbitrarily large number of resonators, it is anticipated that using either two or three resonators will be the most practical approach for purposes of on-chip integration. The mathematical expressions enabling calculation of the parameters of filter **600** have been derived and entered into an electronic spreadsheet (e.g., an Excel sheet) to facilitate computation. These expressions are described in a separate section below.

[0076] FIG. **10** illustrates a screen shot of an interface **1000** for an electronic spreadsheet used for determination of filter component parameters in accordance with the disclosure. In one implementation the following procedure is employed to derive the component values of the filter **600**, and of other coupled resonator filters described herein, using the spreadsheet.

[0077] (1) Choose source and load impedances

[0078] (2) Choose filter bandwidth and center frequency

[0079] (3) Choose desired inductance values

[0080] (4) Choose the passband ripple of the filter

[0081] (5) Choose the amount of magnetic coupling that is desired (from −100 to +100%).

[0082] When the values associated with steps (1) through (5) of the procedure have been entered into the electronic spreadsheet (e.g., into the cells of the interface **1000** with blue text as shown in FIG. **10**), all the component values are calculated based on mathematical expressions which have been derived and are described herein.

[0083] It may be appreciated that implementing a filter with only electric coupling puts constraints on the implementation of a filter realized as an integrated circuit, as the inductors must be separated far away from each other to avoid magnetic coupling between the inductors in the resonators and thereby deviation from the intended filter performance. This separation disadvantageously requires a layout consuming a large chip-area. In contrast, the present inventors have found that combining electrical and magnetic coupling yields multiple benefits such as, for example, reduced chip area. When only magnetic coupling is used, the required chip area becomes even smaller and the routing to capacitances connecting the different resonators can be removed. This results in the layout becoming significantly easier to implement.

[0084] Turning now to FIG. **7**, a schematic illustration is provided of a third order coupled resonator filter **700** having only magnetic coupling. As in the case of the third order coupled resonator filter **600** of FIG. **6**, the third order coupled resonator filter **700** includes three resonators consisting of the parallel combination of a first resonator **720** (L1 and C1), a second resonator **722** (L2 and C2), and a third resonator **724** (L3 and C3) respectively. The filter **700** includes an output matching capacitance **730** (Cms_out) connected in series with a load represented by load resistance **734** (RL).

[0085] As shown, the filter **700** lacks an input matching capacitance (the input matching capacitance **608** present in the filter **600** is not included in the filter **700**) in series with a source impedance **712** (RS) of a signal source **710**. This forces the impedance level of the first resonator **720** (L1, C1) to be equal to the source impedance **712** (RS) if a suitable input match is to be realized. The removal of the first matching capacitance Cms_in in the filter **700** is advantageous from an electrostatic discharge (ESD) point of view since the shunt inductor L1 will protect the input from ESD pulses and thereby remove the need for dedicated ESD protection diodes. Such diodes may cause distortion when large signals are applied at the input of the filter **700**.

[0086] FIG. **14** illustrates an exemplary layout of a third order resonator filter **1400** with only magnetic coupling. When only magnetic coupling is used as in the filter **1400**, the inductors L1, L2 and L3 can be laid out to overlap each other, which is beneficial from the point of view of conserving chip area. As also can be appreciated when only magnetic coupling is used, the routing to the coupling capacitors (C12 and C23 in FIG. **6**) is not required as the coupling capacitors are equal to zero, which simplifies the layout.

[0087] FIG. **8** schematically illustrates a second order coupled resonator filter **800** with both magnetic and electrical coupling in accordance with the disclosure. As shown, the filter **800** includes an input matching capacitance **808** (Cms_in) is connected in series with a signal source **810** having a source resistance **812** (RS). The two resonators included within the filter **800** consist of a first resonator **820** and a second resonator **822** formed from the parallel combinations of L1 and C1, and L2 and C2, respectively. The electrical coupling between the two resonators is achieved by the capacitance **840** (C12), and the amount of magnetic coupling is characterized by the coupling factor k12. The filter **800** includes an output matching capacitance **830** (Cms_out) connected in series with a load represented by load resistance **834** (RL).

[0088] FIG. **9** schematically illustrates a second order coupled resonator filter **900** with only magnetic coupling. The filter **900** includes an input matching capacitance **908** (Cms_in) connected in series with a signal source **910** having a source resistance **912** (RS). The two resonators included within the filter **900** consist of a first resonator **920** and a second resonator **922** formed from the parallel combinations of L1 and C1, and L2 and C2, respectively. As may be appreciated from FIG. **9**, the filter lacks a coupling capacitor (i.e., coupling capacitor C12 present in the filter **800** of FIG. **8** is removed) and the frequency response of the filter **900** is achieved with magnetic coupling only. The filter **900** includes an output matching capacitance **930** (Cms_out) connected in series with a load represented by load resistance **934** (RL).

[0089] Attention is now directed to FIGS. **11-18**, which provide examples of different inductor layouts capable of being utilized to implement coupled resonator filters of the present disclosure. As may be appreciated, there are innumerable ways to implement the layout of inductors resulting in the desired coupling factors between resonators of the coupled resonator filters of the disclosure. As but one example, FIG. **11** illustrates an exemplary layout of inductors included in a third order resonator filter **1100** with primarily electric coupling. As shown, a first inductor **1110** (L1) is included within a first resonator, a second inductor **1120** (L2) is included within a second resonator, and a third inductor **1130** L3 is included within a third resonator, where the reference numerals **1110**, **1120**, **1130** respectively identify outer boundaries of the layouts of the inductors L1, L2 and L3. As can be seen in this first example, the inductors **1110**, **1120**, **1130** (L1, L2, L3) of the filter **1100** are separated apart from each other, resulting in a magnetic coupling factor that is small. As a consequence, the resonator coupling is thereby primarily electric and defined by the capacitances between the resonators. In the embodiment of FIG. **11** the coupling factor between the inductors **1110**, **1120**, **1130** (L1, L2, L3) small (i.e., on the order of 10 m or smaller).

[0090] Consistent with the circuit element nomenclature of FIG. **6**, the third order resonator filter **1100** of FIG. **11** is seen to include a first capacitance **1150** (C1) proximate the first inductor **1110** (L1). The filter **1100** also includes several capacitance proximate the second inductor **1120** (L2); namely, a second capacitance **1160** (C12), a third capacitance **1170** (C2) and a fourth capacitance **1180** (C23). In the embodiment of FIG. **11**, the filter **1100** has been designed such that the capacitance C3 in the third order coupled resonator filter **600** of FIG. **6** has a value of zero and is therefore not shown in the layout of FIG. **11**.

[0091] FIG. **12** illustrates an exemplary layout of inductors in a third order resonator filter **1200** with combined electric and magnetic coupling. As shown, a first inductor **1210** (L1) is included within a first resonator, a second inductor **1220** (L2) is included within a second resonator, and a third inductor **1230** (L3) is included within a third resonator, where the reference numerals **1210**, **1220**, **1230**

respectively identify outer boundaries of the layouts of the inductors L1, L2 and L3. In the example of FIG. **12**, the second and third inductors **1220**, **1230** (L2 and L3) are laid out next to each other, resulting in both electric and magnetic coupling. On the other hand, the first and second resonators are separated by a relatively large distance (i.e., the separation between the first and second inductors **1210**, **1220** (L1,L2) is substantially larger than the de minimis separation between the second and third inductors **1220**, **1230** (L2, L3). As a consequence, the coupling between the first and second resonators is almost entirely realized by electric coupling. This was corroborated by characterizing the coupling factors between the inductors **1210**, **1220**, **1230** through electromagnetic simulation which, as expected, yielded nearly entirely electric coupling between the first and second resonators and between the second and third resonators: k12=−7 m, k23=−100 m, and k13=−5 m. The layout of FIG. **12** shows only the three inductances L1, L2, L3 present within the coupled resonator **600** of FIG. **6**.

[0092] Reference is now made to FIG. **13**, which illustrates an exemplary layout of a third order resonator filter **1300** with combined electric and magnetic coupling. As shown, a first inductor **1310** (L1) is included within a first resonator, a second inductor **1320** (L2) is included within a second resonator, and a third inductor **1330** (L3) is included within a third resonator, where the reference numerals **1310**, **1320**, **1330** respectively identify conductive trace elements of the inductors L1, L2 and L3. In the resonator filter **1300** all three inductors **1310**, **1320**, **1330** (L1, L2, L3) are laid out immediately adjacent to each other. This proximity between the inductors **1310**, **1320**, **1330** (L1, L2, L3) results in magnetic coupling between the first, second and third resonators of the filter **1300**, which is supplemented with electric coupling to achieve the desired filter transfer function. The coupling factors between the inductors **1310**, **1320**, **1330** (L1, L2, L3) has been characterized through electromagnetic simulation: k12=−93 m, k23=−111 m, and k13=−10 m. As may be appreciated, the layout of the third order resonator filter **1300** is much more area efficient than the layout of the filter **1100** (FIG. **11**).

[0093] Consistent with the circuit element nomenclature of FIG. **6**, the third order resonator filter **1300** of FIG. **13** is seen to include a first capacitance **1350** (C1) proximate the first inductor **1310** (L1). The filter **1300** also includes a second capacitance **1360** (C12) proximate the first capacitance **1350** (C1) and a third capacitance **1370** (C2) proximate the second inductor **1320** (L2). A fourth capacitance **1380** (C23) is interposed between the inductors **1320**, **1330** (L2, L3). A fifth capacitance **1390** (C3) and a sixth capacitance **1394** (Cms_out) are proximate the third inductor **1330** (L3).

[0094] Turning now to FIGS. **14-18**, there are illustrated coupled resonator filters having layouts which are even more area efficient than the layout of filter **1300**. This area efficiency is achieved by laying out the inductors in these filters so as to at least partially overlap each other.

[0095] FIG. **14** illustrates an exemplary layout of a third order resonator filter **1400** with only magnetic coupling. A first resonator of the resonator filter **1400** includes a first inductor **1410** (L1), a second resonator includes a second inductor **1420** (L2), and a third resonator includes a third inductor **1430** (L3), where the reference numerals **1410**, **1420**, **1430** respectively identify conductive trace elements of the inductors L1, L2, L3. The coupling factors between the inductors **1410**, **1420**, **1430** of the third order resonator filter **1400** have been characterized by electromagnetic simulation as follows: k12=−480 m, k23=−480 m, and k13=−24 m.

[0096] Consistent with the circuit element nomenclature of FIG. **6**, the third order resonator filter **1400** of FIG. **14** is seen to include a first capacitance **1450** (C1) proximate the first inductor **1410** (L1). The filter **1400** also includes a second capacitance **1460** (C2) interposed between the inductors **1410**, **1430** (L1, L3). A third capacitance **1470** (C3) and a fourth capacitance **1480** (Cms_out) are proximate the third inductor **1430** (L3). In the embodiment of FIG. **14**, the filter **1400** has been designed such that capacitances C12 and C23 in the third order coupled resonator filter **600** of FIG. **6** have values of zero and are therefore not shown in the layout of FIG. **14**.

[0097] FIG. **15** illustrates an exemplary layout of a second order resonator filter **1500** with only magnetic coupling. A first resonator of the resonator filter **1500** includes a first inductor **1510** (L1) and a second resonator includes a second inductor **1520** (L2), where the reference numerals **1510**, **1520** respectively identify conductive trace elements of the inductors L1, L2. The coupling factor, k12, between the inductors **1510** and **1520** of the second order resonator filter **1500** has been characterized by electromagnetic simulation as follows: k12=−240 m. As may be appreciated from FIG. **15**, in the filter **1500** the inductors **1510**, **1520** (L1, L2) are only partially overlapping to achieve the desired coupling factor between its two resonators.

[0098] Consistent with the circuit element nomenclature of FIG. **6**, the third order resonator filter **1500** of FIG. **15** is seen to include a first capacitance **1550** (C1) proximate the first inductor **1510** (L1). The filter **1500** also includes a second capacitance **1560** (C2) and a third capacitance **1570** (Cms_out) proximate the second inductor **1520** (L2). In the embodiment of FIG. **15**, the filter **1500** has been designed such that capacitance C12 in the third order coupled resonator filter **600** of FIG. **6** has a value of zero and is therefore not shown in the layout of FIG. **15**.

[0099] FIG. **16** illustrates an exemplary layout of the inductances of a third order resonator filter **1600** with only magnetic coupling. A first resonator of the resonator filter **1600** includes a first inductor **1610** (L1), a second resonator includes a second inductor **1620** (L2), and a third resonator includes a third inductor **1630** (L3). In FIG. **16** the reference numerals **1610**, **1630** respectively identify outer boundaries of the layouts of the inductors L1, L3 and the reference numeral **1620** identifies a conductive trace element of the inductor L2.

[0100] FIG. **17** illustrates an exemplary layout of the inductances of a third order resonator filter **1700** with only magnetic coupling. A first resonator of the resonator filter **1700** includes a first inductor **1710** (L1), a second resonator includes a second inductor **1720** (L2), and a third resonator includes a third inductor **1730** (L3). In FIG. **17** the reference numerals **1710**, **1730** respectively identify conductive traces of the layouts of the inductors L1, L3 and the reference and the reference numeral **1720** identifies an outer boundary of the inductor L2. The coupling factors between the inductors **1710**, **1720**, **1730** of the third order resonator filter **1700** have been characterized by electromagnetic simulation as follows: k12=−297 m, k23=−297 m, and k13=−23 m. The layouts of FIGS. **16** and **17** show only the three inductances L **1**, L2, L3 present within a third order coupled resonator filter with magnetic coupling; that is, the capacitances within the coupled resonator filters **1600**, **1700** are not shown

[0101] FIG. **18** illustrates an exemplary layout of a third order resonator filter **1800** with only magnetic coupling. A first resonator of the resonator filter **1800** includes a first inductor **1810** (L1), a second resonator includes a second inductor **1820** (L2), and a third resonator includes a third inductor **1830** (L3). In FIG. **18** the reference numerals **1810**, **1820**, **1830** respectively identify path markings superimposed on conductive traces forming the inductors L1, L3

[0102] Consistent with the circuit element nomenclature of FIG. **6**, the third order resonator filter **1800** of FIG. **18** is seen to include a first capacitance **1850** (C1) proximate the first inductor **1410** (L1). The filter **1400** also includes a second capacitance **1860** (C2) placed within a bottom left corner of the layout of FIG. **18**. A third capacitance (C3) is not shown in FIG. **18** as it corresponds to the input capacitance of an LNA connected to the filter **1800**. In the embodiment of FIG. **18**, the filter **1800** has been designed such that capacitances C12 and C23 present in the third order coupled resonator filter **600** of FIG. **6** have values of zero and are therefore not shown in the layout of FIG. **18**. A fourth capacitance **1880** (C3g) is placed in series with the ground connection of the third inductor **1830** (L3), which generates an additional notch.

[0103] FIG. **19** illustrates results of electromagnetic simulation of the third order resonator filter **1800** of FIG. **18**. Specifically, FIG. **19** shows a first coupling factor k12 between the inductors L1 and L2 in the filter **1800**, a second coupling factor k23 between the inductors L2 and L3, and a third coupling factor k13 between the inductors L1 and L3. As may be appreciated from FIG. **19**, it can be seen that the magnetic coupling is strong between adjacent overlapping resonators and weak between non-adjacent resonators; that is, k12 and k23 are relatively large in view of the substantial overlap between L1/L2 and L2/L3, and k13 is relatively small in view of the lack of overlap between L1 and L3. This is consistent with the results of electromagnetic simulation of the coupling factors of FIG. **19**: k12=−420 m, k23=−448 m, and k13=−63 m.

[0104] Besides being area efficient, another advantage of the magnetic-only coupled resonator filters described herein is that it is easy to program the center frequency and bandwidth of such filers. As the capacitors are connected to the filter in a shunt fashion, it is thereby straightforward to add additional capacitance by ground connected MOS switches in order achieve desired center frequency and bandwidth parameters.

[0105] When magnetic coupling is introduced between the first and third inductor of a coupled resonator filter of the present disclosure, the signal that is fed to the output with magnetic coupling between the first and last inductor will be added with the signal that is fed via the second, middle inductor. At a specific frequency these two signals will be added with opposite phase, which results in a notch at that specific frequency.

[0106] Reference is now made to FIG. **20**, which illustrates a typical notched frequency response **2000** of a circuit including a third order resonator filter and an LNA. In FIG. **20** it is noted that the response **2000** includes the gain from the LNA, which is approximately 20 dB. As shown in the frequency response **2000** of FIG. **20**, a frequency response notch **2010** is tuned to be located at 2.5 GHz. The location of this frequency response notch can be selected by choosing an appropriate magnetic coupling between the first and last resonator, i.e., between the resonators including L1 and L3 within the coupled resonator filters described herein. Turning to FIG. **21**, a comparison is shown between the measured and simulated frequency responses **2100**A and **2100**B of the receiver of FIG. **5** as implemented with a coupled resonator filter configured to generate a notched frequency response. As shown, the measured and simulated frequency responses **2100**A and **2100**B each includes first and second frequency response notches **2110** and **2120**. In accordance with the disclosure, the relative signs (polarities) of the coupling factors of the coupled resonator filter are set to certain relative values in order to effect the signal path cancellation necessary to produce this notched frequency response. That is, unless coupling between the various inductors within the coupled resonator is of the correct sign such signal cancellation will not occur and notches will not be created in the frequency response. For example, in the embodiment of FIG. **18** the filter **1800** is configured such that all coupling factors (k12, k23, k13) are negative. However, if the filter **1800** had been configured such that the coupling from the first to the last resonator (k13) would have been chosen to have opposite sign while keeping k12 and k23 negative, a frequency response notch such as the notch **2010** of FIG. **20** would not have been present in the frequency response of the filter **1800**. Rather, configuring a resonator filter to have k12 with opposite sign would require k13 to be positive in order to achieve the signal path cancellation necessary to produce a notched frequency response. Finally, it should be mentioned that the input impedance of the LNA loading the filter can be chosen arbitrarily as matching between the source impedance and the LNA input impedance can be included in the filter. It is thereby possible to design an LNA with an input impedance which is optimal from noise point of view.

[0107] More generally, it has been found that a frequency response of the coupled resonator filters described herein include a notch when values of the first coupling factor, the second coupling factor and the third coupling factor satisfy predetermined conditions. The predetermined conditions include a condition that the first coupling factor, the second coupling factor and the third coupling factor are negative. The predetermined conditions also include a condition that the first coupling factor and the second coupling factor are positive, and the third coupling factor is negative. The predetermined conditions further include a condition that the first coupling factor and the second coupling factor are of opposite polarity and the third coupling factor is positive. A condition that an absolute value of the first coupling factor and the second coupling factor is greater than 0.25 and an absolute value of the third coupling factor is less than 0.25 is also included among the predetermined condition. It has further been found that such a notch is included in the frequency response of the coupled resonator filter at a frequency dependent upon the value of the third coupling factor and a product of the first coupling factor and the second coupling factor.

[0108] Finally, it should be mentioned that the input impedance of an LNA loading the coupled resonator filter can be chosen arbitrarily. This is because the filter can be designed to include matching to match the source impedance and the LNA input impedance. It is thereby possible to design an LNA with an input impedance which is optimal from a noise point of view.

On-Chip Coupled Resonator Filters Combined with LNA

[0109] Attention is now directed to FIGS. **22** and **23**, which illustrate active filter circuits **2200** and **2300**. As shown in FIG. **22**, the active filter circuit **2200** is comprised of a coupled resonator filter **2204** combined with source degenerated LNA **2208**. Similarly, in FIG. **23** the active filter circuit **2300** is seen to include a coupled resonator filter **2304** and a source degenerated LNA **2308**. It has been found that when the on-chip coupled resonators described herein are connected to a conventional source-degenerated LNA **300** of the type shown in FIG. **3**, the gate capacitance of the input stage **310** of the LNA **300** may be used as the capacitance in the third resonator of coupled resonator filters. See, e.g., capacitance C3 in the circuits **2200** (FIG. **22**) and **2300** (FIG. **23**). Making the input device **2210**, **2310** of the LNA an integral part of the filters **2200**, **2300** advantageously improves noise performance and reduces die area. A bias voltage is applied to the gate of input devices **2210**, **2310** through the inductance L3.

[0110] FIG. **2** illustrates a source-gate feedback LNA topology **200** capable of being used as an alternative to the source degenerated LNA topology of, for example, FIGS. **22** and **23**. An exemplary circuit implementing this technology is depicted in FIG. **24**, which schematically illustrates active filter circuit **2400**.

[0111] Turning to FIG. **24**, the active filter circuit **2400** is comprised of a coupled resonator filter **2404** combined with a source-gate feedback LNA **2408**. As may be appreciated from FIG. **24**, the coupled resonator filter **2404** relies upon only magnetic coupling; that is, the values of the coupling coefficients k12, k13, k23 are determined exclusively by the configuration of the inductive elements L1, L2, L3 within the filter **2404**.

[0112] FIGS. **31** and **33** illustrate exemplary CMOS implementations of source-gate feedback LNA topologies **3100**, **3300** capable of being utilized as alternatives to the source degenerated topologies described herein. In the exemplary implementation of FIG. **33**, the exemplary topology **3300** is configured for distortion cancelling and includes a source-gate feedback LNA **3310** and a distortion canceling network **3320**.

[0113] FIG. **26** schematically illustrates an active filter **2600** having a coupled resonator filter **2604** combined with a source-gate feedback LNA **2608** that is configured to produce a frequency response having an input notch circuit (Ln, Cn in). As shown, the input notch circuit (Ln, Cn in) is connected to the input source and may be utilized in cases in which additional low frequency attenuation is required.

[0114] FIG. **28** illustrates a frequency response of a filter and LNA implementation with and without an additional input notch circuit; that is, the frequency response **2810** of a filter having the topology of the active filter **2600** and the frequency response **2820** of a substantially identical filter lacking an input notch circuit (Ln, Cn in). In the case of FIG. **28** the active filter **2600** was implemented by selecting the values of the notch circuit (Ln, Cn in) such that the input notch in the frequency response occurred at around 1.7 GHz. As may be appreciated from FIG. **28**, this results in an improvement of the low frequency attenuation as illustrated in FIG. **28** (compare the frequency response **2820** (dotted yellow graph) with the frequency response **2810** (orange graph)). When a source-gate feedback topology is used in the LNA, a second frequency response notch can be created by adding a notch circuit comprised of a capacitor in series with the gate inductance of the LNA. See, e.g., active filter circuits **2500**, **2600**, **2700** of FIGS. **25**-**27** in which notch capacitance Cn is connected in series with the inductance Lg of the gate of each LNA input device **2510**, **2610**, **2710**.

[0115] Referring to FIG. **25**, the active filter **2500** includes a magnetically only coupled resonator filter **2504** combined with a source-gate feedback LNA **2508** and an input notch circuit (Lg, Cn).

[0116] Turning now to FIG. **27**, the active filter **2700** includes a magnetically only coupled resonator filter **2704** combined with a source-gate feedback LNA **2708**, input notch circuit (Lg, Cn), and magnetically only coupled resonator filter **2720** (having coupling factor k45) at the output of the filter **2700**. The broadband matching that is achieved when a coupled resonator filter is added to the output of the LNA (as depicted in FIG. **27**) is shown in FIG. **29**.

[0117] FIGS. **32**A and **32**B illustrate the improvements in area efficiency possible using magnetically coupled resonator filters in accordance with the disclosure. Specifically, FIG. **32**A depicts an example layout **3200**A of an electrically coupled resonator filter and source-degenerated LNA and FIG. **32**B shows an example layout **3200**B of a magnetic coupled resonator filter and source-degenerated LNA. The example of FIGS. **32**A and **32**B show that an area reduction of approximately ~30-40% may be obtained using resonators relying essentially exclusively upon magnetic coupling. It may be appreciated that additional area saving is possible with further optimization.

Programmable Coupled Resonator Filter

[0118] By having a magnetically only coupled resonator filter it is straight forward to implement band programming of the filter, which is useful in a receiver where the filter response can be tuned to the band of interest. The frequency response of the receiver of FIG. **5** as implemented with a magnetically-only coupled resonator filter which is programmable to receive two different frequency bands (Wi-Fi 6 between 5-6 GHz and Wi-Fi 6E between 6-7 GHz) is shown in FIG. **30**.

[0119] To make a filter programmable, the capacitors in the filter should be tuned as different capacitance values can be achieved by switching in/out additional capacitances in the filter. This is preferable to switching in/out inductances, which are bulky and occupy large die area. Switches in silicon technologies are generally selected to be either PMOS or NMOS based on which is easiest to program if the source of the switch is connected to signal ground. Accordingly, it is preferable that capacitances to be programmed are grounded in one of the switch's terminals.

[0120] Turning now to FIG. **34**, an exclusively magnetically coupled resonator filter **3400** is shown which includes two coupled resonators **3410**, **3420** and a notch circuit **3430** at its output. In the embodiment of FIG. **34** where all capacitances (C) are programmable and connected to ground. FIG. **36** illustrates an exemplary capacitor filter bank **3600** of a type that may be used to implement the programmable capacitances within the filter **3400**. The frequency responses **3510**, **3520** of the filter **3400**, when programmed for either WiFi-6 (5-6 GHz) or in the WiFi-6E (6-7 GHz) frequency band, respectively, are shown in FIG. **35**. As may be appreciated from FIG. **35**, the frequency response notch **3510***n*, **3520***n* produced by the notch circuit

3430 is centred in the low band below the passband when the filter is tuned to the high band and vice versa.

[0121] During operation of the filter **3400**, the notch circuit **3430** helps with the tuning of the output resonator **3420**. When the notch circuit **3530** is tuned below the passband the notch circuit **3430** is inductive in the passband and extra parallel capacitance is needed as compensation. This is at the same time as the minimum capacitance is needed in the resonator **3420** to tune it to a high frequency, which therefore reduces the needed tuning range of the capacitor bank **3600** of the output resonator **3420**. In other embodiments a second notch circuit can also be attached at the other side of the filter (e.g., in parallel with resonator **3410**) so as to improve attenuation.

Mathematical Framework for Filter Parameter Calculation

[0122] Although not necessary for one skilled in the art to make and use the disclosed coupled resonator filters, and disclosed combinations of such filters with low noise amplifiers, set forth below is a mathematical framework underpinning an exemplary approach to calculating the parameters. In particular, the following mathematical framework describes the parameter calculations used in the spreadsheet **1000** of FIG. **10**, where each calculated cell in the spreadsheet **1000** is described below.

[0123] Input parameters:

[0124] f0 [MHz] is the center frequency of the filter.

[0125] BW [MHz] is the bandwidth of the filter.

[0126] Ripple [dB] is the target in-band filter ripple.

[0127] RS and RL [Ω] are the target source and load impedances respectively.

[0128] Percentage of max coupling factor is the amount of magnetic coupling, 100% means magnetic coupling only and 0% means electric coupling only.

[0129] L1, L2 and L3 [H] are the target inductance values of the three resonators.

[0130] Calculated Parameters:

$$\omega 0\left[\frac{\text{rad}}{\text{s}}\right] = 2\pi f0$$

$$Q = \frac{f0}{BW}$$

[0131] C1res, C2res and C3res [F] (greyed out cells in the spreadsheet **1000**) are calculated from the center frequency and the inductance value of each resonator:

$$Cx = \frac{1}{\omega 0^2 Lx}$$

[0132] These capacitance values are greyed out because these are only used for calculation purposes.

[0133] Z1, Z2 and Z3 [Ω] are calculated from the center frequency, the Q-value and the filter prototype values: Zx=ω0 Q gx Lx

[0134] Cmp_in is calculated from a relation between the source impedance and the impedance level of the first resonator:

$$\text{Cmp\_in}[F] = \frac{\sqrt{\left(\frac{Z1}{RS} - 1\right)}}{Z1\omega 0}$$

[0135] This capacitance value is greyed out in the spreadsheet **1000** because it is only used for calculation purposes.

[0136] Cmp_out is calculated from a relation between the load impedance and the impedance level of the last resonator:

$$\text{Cmp\_out}[F] = \frac{\sqrt{\left(\frac{Z3}{RL} - 1\right)}}{Z3\omega 0}$$

[0137] This capacitance value is greyed out in the spreadsheet **1000** because it is only used for calculation purposes.

[0138] Cms_in and Cms_out are the matching capacitances required to impedance match between the source impedance and the impedance level of the first resonator, and between the load impedance and the impedance level of the last resonator respectively.

[0139] C1, C2 and C3 [F] are calculated from the other capacitance values: C1 [F]=C1res–C12–Cmsp_in, C1 [F]=C2res–C12–C23, and C3 [F]=C3res–C23–Cmsp_out

[0140] C12max and C23max [F] are the coupling capacitors between the resonators for the case when only electric coupling is used, and are calculated from the equations:

$$C12\ \max\ [F] = \frac{1}{\omega 0\sqrt{Z1Z2}}$$

$$C23\ \max\ [F] = \frac{1}{\omega 0\sqrt{Z2Z3}}$$

[0141] For the case when only magnetic coupling is used, k12max and k23max are the coupling coefficients between the inductances of the first and second, and the second and third resonators respectively, and are calculated from the equations:

$$k12\ \max = \frac{1}{Q\sqrt{g1g2}}$$

$$k23\ \max = \frac{1}{Q\sqrt{g2g3}}$$

where the spreadsheet **1000** may be configured to calculate the Chebychev low pass filter prototype values (g1, g2 and g3) with well known equations as used in various filter tables.

[0142] The effective coupling coefficients and capacitances between the resonators are calculated from a linear ratio of the percentage of the max coupling factor:

$$C12[F] = \left(1 - \frac{k12}{k12\ \text{max}}\right) C12\ \text{max}$$

$$C23[F] = \left(1 - \frac{k23}{k23\ \text{max}}\right) C23\ \text{max}$$

$$k12 = \text{Percantage}\ \ k12\ \ \text{max}$$

$$k23 = \text{Percantage}\ \ k23\ \ \text{max}$$

[0143] The equations k12max, k23max, C12 [F], C23 [F], k12, and k23 have been derived by the present inventors. The equations used in the spreadsheet **1000** of FIG. **10** are taken from the book "*Microwave Filters for Communication Systems*" by Richard J. Cameron et al. Unless otherwise mentioned, the other equations set forth above may be found in the publication entitled "The Design of Direct Coupled Band Pass Filters", published by Iowa Hills Software (Iowa-Hills.com) on Jul. 10, 2016.

[0144] Described herein are integrated magnetically and electrically coupled resonator filters which improve upon existing filters in a number of respects. A principal novel feature of the integrated magnetically and electrically coupled resonator filters described herein is that the layout becomes area efficient when the coupling between inductors can be used as being part of the intended design instead of being something unwanted. In addition, inductors can be laid out in an overlapping fashion to generate exclusively magnetic coupling. The inductors can also be laid adjacent to each other, and insufficient magnetic coupling can be complemented with electrical coupling to establish the intended filter transfer function.

[0145] Another important novel feature is that coupling between the first and last resonator generates a notch which can be used to suppress unwanted signals in a specific frequency. In addition, the first inductor can be used as ESD protection when the impedance level of the first resonator is chosen to be the same as the source impedance.

[0146] It may be further appreciated that the disclosed filters can be used for impedance transformation to the LNA for optimal noise performance. Moreover, filter tuning becomes straight forward when exclusively magnetic coupling is used.

[0147] Also described herein are novel configurations of on-chip coupled resonator filters combined with LNAs. It may be appreciated that the teachings of the present disclosure extend to embodiments in which the LNA is replaced with other types of amplifiers such as, for example, a power amplifier. In the context of these configurations the present inventors have unexpectedly found that the gate capacitance of the LNA can be an integral part of the filter. Moreover, the inventors have found that using a shunt gate inductance at the input of the LNA improves low frequency attenuation. In addition, it has been found that a notch can be generated for increased attenuation at a specific frequency by adding a series capacitance to the gate inductance of the LNA. Moreover, a notch can be generated for increased attenuation at a specific frequency by adding an additional series resonant circuit in parallel with any of the resonators in the filter.

[0148] In certain embodiments an on-chip resonator filter can be added to the LNA at both its input and output for broadband matching. The coupled resonator filter can be used to convert a single-ended signal into a differential signal without adding additional passive components. The coupled resonator filter can also be used to convert a differential signal into a single-ended signal without adding additional passive components.

[0149] The disclosure also pertains to a novel programmable magnetically-only coupled resonator filter in combination with a notch circuit. The disclosed magnetically-only coupled filter utilizes programmable capacitances which are grounded on one terminal, which simplifies programmability. In addition, the notch circuit reduces the tuning range of the programmable capacitances.

[0150] Where methods described above indicate certain events occurring in certain order, the ordering of certain events may be modified. Additionally, certain of the events may be performed concurrently in a parallel process when possible, as well as performed sequentially as described above. Accordingly, the specification is intended to embrace all such modifications and variations of the disclosed embodiments that fall within the spirit and scope of the appended claims.

[0151] The foregoing description, for purposes of explanation, used specific nomenclature to provide a thorough understanding of the claimed systems and methods. However, it will be apparent to one skilled in the art that specific details are not required in order to practice the systems and methods described herein. Thus, the foregoing descriptions of specific embodiments of the described systems and methods are presented for purposes of illustration and description. They are not intended to be exhaustive or to limit the claims to the precise forms disclosed; obviously, many modifications and variations are possible in view of the above teachings. The embodiments were chosen and described in order to best explain the principles of the described systems and methods and their practical applications, they thereby enable others skilled in the art to best utilize the described systems and methods and various embodiments with various modifications as are suited to the particular use contemplated. It is intended that the following claims and their equivalents define the scope of the systems and methods described herein.

[0152] Also, various inventive concepts may be embodied as one or more methods, of which an example has been provided. The acts performed as part of the method may be ordered in any suitable way. Accordingly, embodiments may be constructed in which acts are performed in an order different than illustrated, which may include performing some acts simultaneously, even though shown as sequential acts in illustrative embodiments.

[0153] All definitions, as defined and used herein, should be understood to control over dictionary definitions, definitions in documents incorporated by reference, and/or ordinary meanings of the defined terms.

[0154] The indefinite articles "a" and "an," as used herein in the specification and in the claims, unless clearly indicated to the contrary, should be understood to mean "at least one."

[0155] The phrase "and/or," as used herein in the specification and in the claims, should be understood to mean "either or both" of the elements so conjoined, i.e., elements that are conjunctively present in some cases and disjunctively present in other cases. Multiple elements listed with "and/or" should be construed in the same fashion, i.e., "one or more" of the elements so conjoined. Other elements may optionally be present other than the elements specifically identified by the "and/or" clause, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, a reference to “A and/or B”, when used in conjunction with open-ended language such as “comprising” can refer, in one embodiment, to A only (optionally including elements other than B); in another embodiment, to B only (optionally including elements other than A); in yet another embodiment, to both A and B (optionally including other elements); etc.

[0156] As used herein in the specification and in the claims, “or” should be understood to have the same meaning as “and/or” as defined above. For example, when separating items in a list, “or” or “and/or” shall be interpreted as being inclusive, i.e., the inclusion of at least one, but also including more than one, of a number or list of elements, and, optionally, additional unlisted items. Only terms clearly indicated to the contrary, such as “only one of” or “exactly one of,” or, when used in the claims, “consisting of,” will refer to the inclusion of exactly one element of a number or list of elements. In general, the term “or” as used herein shall only be interpreted as indicating exclusive alternatives (i.e. “one or the other but not both”) when preceded by terms of exclusivity, such as “either,” “one of,” “only one of,” or “exactly one of.” “Consisting essentially of,” when used in the claims, shall have its ordinary meaning as used in the field of patent law.

[0157] As used herein in the specification and in the claims, the phrase “at least one,” in reference to a list of one or more elements, should be understood to mean at least one element selected from any one or more of the elements in the list of elements, but not necessarily including at least one of each and every element specifically listed within the list of elements and not excluding any combinations of elements in the list of elements. This definition also allows that elements may optionally be present other than the elements specifically identified within the list of elements to which the phrase “at least one” refers, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, “at least one of A and B” (or, equivalently, “at least one of A or B,” or, equivalently “at least one of A and/or B”) can refer, in one embodiment, to at least one, optionally including more than one, A, with no B present (and optionally including elements other than B); in another embodiment, to at least one, optionally including more than one, B, with no A present (and optionally including elements other than A); in yet another embodiment, to at least one, optionally including more than one, A, and at least one, optionally including more than one, B (and optionally including other elements); etc.

[0158] In the claims, as well as in the specification above, all transitional phrases such as “comprising,” “including,” “carrying,” “having,” “containing,” “involving,” “holding,” “composed of,” and the like are to be understood to be open-ended, i.e., to mean including but not limited to. Only the transitional phrases “consisting of” and “consisting essentially of” shall be closed or semi-closed transitional phrases, respectively, as set forth in the United States Patent Office Manual of Patent Examining Procedures, Section 2111.03.

What is claimed is:

1. A coupled resonator filter comprising:

a first parallel resonator including a first capacitance connected in parallel with a first inductance;

a second parallel resonator including a second capacitance connected in parallel with a second inductance; and

a third parallel resonator including a third capacitance connected in parallel with a third inductance;

wherein magnetic coupling between the first inductance and the second inductance magnetically couples the first parallel resonator and the second parallel resonator in accordance with a first coupling factor;

wherein magnetic coupling between the second inductance and the third inductance magnetically couples the second parallel resonator and the third parallel resonator in accordance with a second coupling factor;

wherein magnetic coupling between the first inductance and the third inductance magnetically couples the first parallel resonator and the third parallel resonator in accordance with a third coupling factor:

wherein a frequency response of the coupled resonator filter includes a notch when values of the first coupling factor, the second coupling factor and the third coupling factor satisfy predetermined conditions.

2. The coupled resonator filter of claim **1** wherein the predetermined conditions include a condition specifying that the notch is included in the frequency response of the coupled resonator filter at a frequency dependent upon the value of the third coupling factor and a product of the first coupling factor and the second coupling factor.

3. The coupled resonator filter of claim **1** further including a first coupling capacitance connected between the first parallel resonator and the third parallel resonator, the first coupling capacitance capacitively coupling the first parallel resonator and the third parallel resonator.

4. The coupled resonator filter of claim **3** further including a second coupling capacitance connected between the first parallel resonator and the second parallel resonator, the second coupling capacitance capacitively coupling the first parallel resonator and the second parallel resonator.

5. The coupled resonator filter of claim **4** further including a third coupling capacitance connected between the second parallel resonator and the third parallel resonator, the third coupling capacitance capacitively coupling the second parallel resonator and the third parallel resonator.

6. The coupled resonator filter of claim **1** wherein the predetermined conditions include a condition that the first coupling factor, the second coupling factor and the third coupling factor are negative.

7. The coupled resonator filter of claim **1** wherein the predetermined conditions include a condition that the first coupling factor and the second coupling factor are positive and the third coupling factor is negative.

8. The coupled resonator filter of claim **1** wherein the predetermined conditions include a condition that the first coupling factor and the second coupling factor are of opposite polarity and the third coupling factor is positive.

9. The coupled resonator filter of claim **1** wherein predetermined conditions include a condition that an absolute value of the first coupling factor and the second coupling factor is greater than 0.25 and an absolute value of the third coupling factor is less than 0.25.

10. The coupled resonator of claim **1** further including a series resonant circuit connected in parallel with any of the first parallel resonator, the second parallel resonator and third parallel resonator wherein a frequency response of the coupled resonator filter includes an additional notch at a frequency dependent upon a resonance frequency of the series resonant circuit.

11. The coupled resonator filter of claim **1** wherein the first coupling factor is characterized by a first coupling coefficient k12 and where the second coupling factor is characterized by a second coupling coefficient k23, where:

$$k12 = \frac{1}{Q\sqrt{g1g2}}$$

$$k23 = \frac{1}{Q\sqrt{g2g3}}$$

and where:

$$Q = \frac{f0}{BW}$$

where f0 is a center frequency of the filter, BW is a bandwidth of the filter, and g1, g2, g3 are filter prototype values.

12. The coupled resonator filter of claim **4** where a maximum absolute value of the magnetic coupling between the first inductance and the second inductance is characterized by a first maximum coupling coefficient k12max, a maximum magnetic coupling between the second inductance and the third inductance is characterized by a second maximum coupling coefficient k23max, where:

$$k12\,\mathrm{max} = \frac{1}{Q\sqrt{g1g2}}$$

$$k23\,\mathrm{max} = \frac{1}{Q\sqrt{g2g3}}$$

$$C12[F] = \left(1 - \frac{k12}{k12\,\mathrm{max}}\right)C12\,\mathrm{max}$$

$$C23[F] = \left(1 - \frac{k23}{k23\,\mathrm{max}}\right)C23\,\mathrm{max}$$

$$k12 = \text{Percantage } k12 \text{ max existing between first and second inductances}$$

$$k23 = \text{Percantage } k23 \text{ max existing between second and thrid inductances}$$

$$C12 \text{ denotes the first coupling capacitance}$$

$$C12 \text{ denotes the second coupling capacitance}$$

and where:

$$Q = \frac{f0}{BW}$$

where f0 is a center frequency of the filter, BW is a bandwidth of the filter, g1, g2, g3 are filter prototype values, and C12max and C23max are coupling capacitances respectively connected between the first and second parallel resonators, and between the second and third parallel resonators, in the absence of magnetic coupling.

13. An integrated circuit coupled resonator filter comprising:

a first parallel resonator including a first capacitance connected in parallel with a first inductance; and

a second parallel resonator including a second capacitance connected in parallel with a second inductance;

wherein the first inductance and the second inductance are implemented on multiple layers of the integrated circuit and at least partially overlap;

wherein magnetic coupling between the first inductance and the second inductance magnetically couples the first parallel resonator and the second parallel resonator in accordance with a first coupling factor of greater than 0.5.

14. The integrated circuit coupled resonator filter of claim **13** wherein the first coupling factor is greater than 0.6.

15. The integrated circuit coupled resonator filter of claim **13** wherein the first coupling factor is greater than 0.7

16. The integrated circuit coupled resonator filter of claim **13** further including a third parallel resonator including a third capacitance connected in parallel with a third inductance;

wherein magnetic coupling between the second inductance and the third inductance magnetically couples the second parallel resonator and the third parallel resonator;

wherein magnetic coupling between the first inductance and the third inductance magnetically couples the first parallel resonator and the third parallel resonator.

17. A coupled resonator filter arrangement comprising:

an Nth order coupled resonator filter including N parallel resonators arranged in succession, where N is at least 3;

wherein a frequency response of the coupled resonator filter arrangement includes a first notch at a first frequency dependent upon coupling characteristics between non-successive parallel resonators of the N parallel resonators;

a series resonant circuit connected in parallel with any of the N parallel resonators wherein the frequency response of the coupled resonator filter arrangement includes a second notch at a second frequency dependent upon a resonance frequency of the series resonant circuit.

18. The coupled resonator of claim **17** wherein the non-successive parallel resonators include a first parallel resonator of the N parallel resonators and a third parallel resonator of the N parallel resonators wherein a second parallel resonator of the N parallel resonators is interposed between the first parallel resonator and the third parallel resonator.

19. The coupled resonator filter arrangement of claim **18** wherein:

the first parallel resonator includes a first capacitance connected in parallel with a first inductance;

the second parallel resonator including a second capacitance connected in parallel with a second inductance; and

a third parallel resonator including a third capacitance connected in parallel with a third inductance;

wherein magnetic coupling between the first inductance and the second inductance magnetically couples the first parallel resonator and the second parallel resonator in accordance with a first coupling factor;

wherein magnetic coupling between the second inductance and the third inductance magnetically couples the second parallel resonator and the third parallel resonator in accordance with a second coupling factor;

wherein magnetic coupling between the first inductance and the third inductance magnetically couples the first parallel resonator and the third parallel resonator in accordance with a third coupling factor.

20. The coupled resonator filter arrangement of claim **19** wherein the first coupling factor, the second coupling factor and the third coupling factor are negative.

21. The coupled resonator filter of claim **19** wherein the first coupling factor and the second coupling factor are positive and the third coupling factor is negative.

22. The coupled resonator filter of claim **19** wherein the first coupling factor and the second coupling factor are of opposite polarity and the third coupling factor is positive.

23. The coupled resonator filter of claim **19** wherein an absolute value of the first coupling factor and the second coupling factor is greater than 0.25 and an absolute value of the third coupling factor is less than 0.25.

24. A coupled resonator filter comprising:

a first parallel resonator including a first capacitance connected in parallel with a first inductance;

a second parallel resonator including a second capacitance connected in parallel with a second inductance; and

a third parallel resonator including a third capacitance connected in parallel with a third inductance;

wherein magnetic coupling between the first inductance and the second inductance magnetically couples the first parallel resonator and the second parallel resonator in accordance with a first coupling factor;

wherein magnetic coupling between the second inductance and the third inductance magnetically couples the second parallel resonator and the third parallel resonator in accordance with a second coupling factor;

wherein magnetic coupling between the first inductance and the third inductance magnetically couples the first parallel resonator and the third parallel resonator in accordance with a third coupling factor and wherein a frequency response of the coupled resonator filter includes a notch under at least one of the following conditions: (i) the first coupling factor, the second coupling factor and the third coupling factor are negative, (ii) the first coupling factor and the second coupling factor are positive and the third coupling factor is negative, and (iii) the first coupling factor and the second coupling factor are of opposite polarity and the third coupling factor is positive.

25. The coupled resonator filter of claim **24** wherein an absolute value of the first coupling factor and the second coupling factor is greater than a strong coupling threshold and an absolute value of the third coupling factor is less than a weak coupling threshold.

26. The coupled resonator filter of claim **25** wherein the strong coupling threshold is 0.25 and the weak coupling threshold is 0.1.

27. A programmable coupled resonator filter arrangement comprising:

an Nth order coupled resonator filter including N magnetically-coupled parallel resonators arranged in succession, where N is at least 3;

wherein each of the N magnetically-coupled parallel resonators includes an inductance in parallel with a programmable capacitance arrangement; and

wherein a frequency response of the coupled resonator filter arrangement includes a first notch at a first frequency dependent upon coupling characteristics between parallel resonators of the N parallel resonators.

28. The programmable coupled resonator filter arrangement of claim **27** wherein each programmable capacitance arrangement includes a capacitance connected to a switch and wherein each switch includes a terminal connected to signal ground.

29. The programmable coupled resonator filter arrangement of claim **27** further including a series resonant circuit connected in parallel with any of the N magnetically-coupled parallel resonators wherein the frequency response of the coupled resonator filter arrangement includes a second notch at a second frequency dependent upon a resonance frequency of the series resonant circuit.

30. The programmable coupled resonator filter of claim **28** wherein each switch is implemented using one of a PMOS transistor and an NMOS transistor and wherein the source of the one of the PMOS transistor and the NMOS transistor is connected to signal ground.

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