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(54) **METHODS AND SYSTEMS FOR CALIBRATING AN ANALOG FILTER**

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(51) **Int. Cl.**

H04B 1/10	(2006.01)
H04B 1/12	(2006.01)
H04B 17/00	(2015.01)
H04B 1/40	(2015.01)

(52) **U.S. Cl.**
CPC ***H04B 1/123*** (2013.01); ***H04B 17/0062*** (2013.01); ***H04B 17/0085*** (2013.01); *H04B 1/40* (2013.01)

(58) **Field of Classification Search**
CPC H03H 11/1217; H03H 11/1256; H03H 11/1291; H04B 1/30; H04B 1/123; H04B 17/0062; H04B 17/0085
USPC 375/350, 370, 373, 369
See application file for complete search history.

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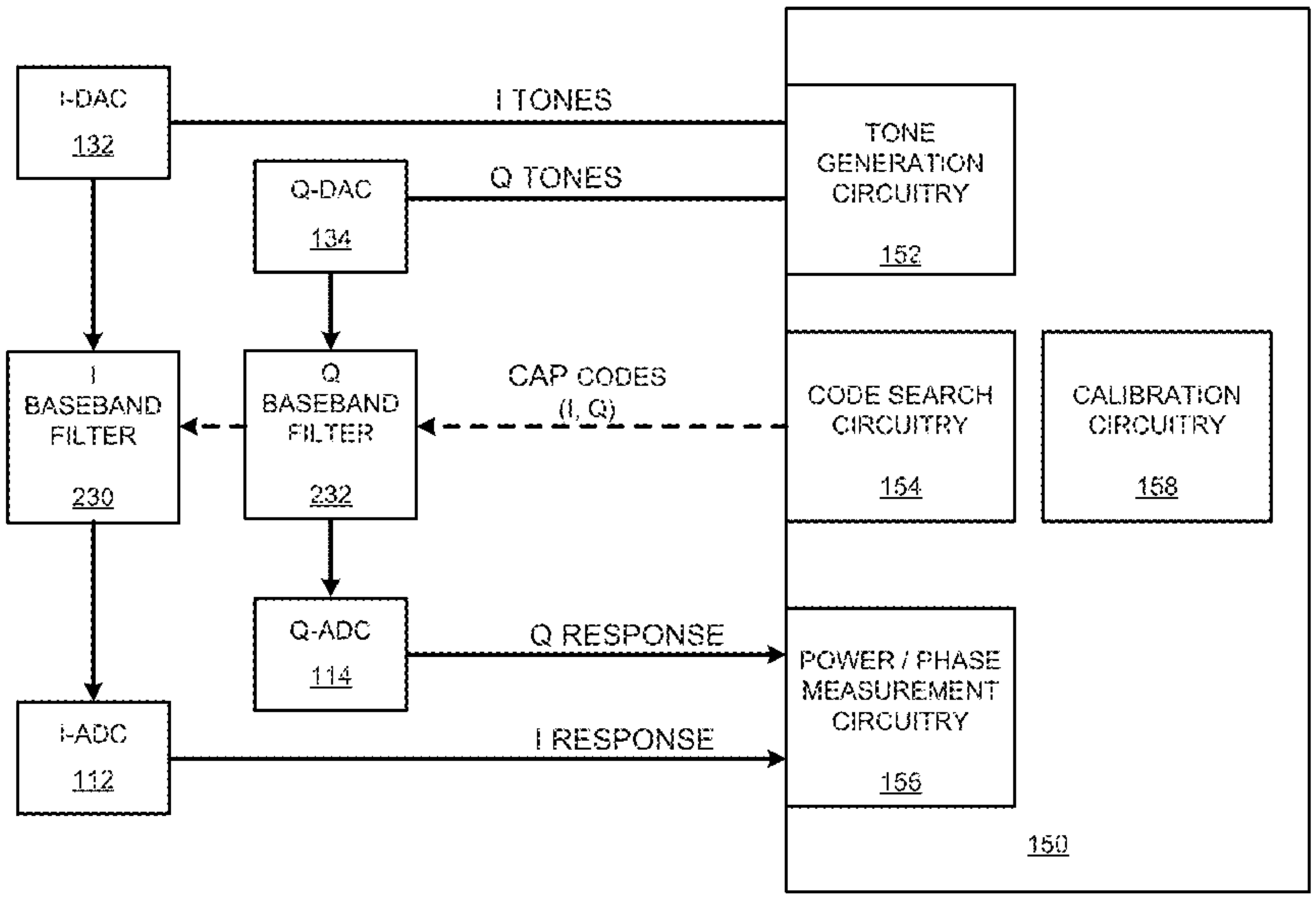
Primary Examiner — Qutbuddin Ghulamali

(57) **ABSTRACT**

Devices and methods capable of addressing filter responses are disclosed. For example, a method for compensating a first low-pass filter and a second low-pass filter is disclosed. The method includes injecting a reference tone f_R and a cutoff tone f_C into the first low-pass filter, and measuring respective filter responses of the reference tone f_R and the cutoff tone f_C while changing capacitor codes that control a cutoff frequency of the first low-pass filter until a first capacitor code I_{CODE} is determined that most accurately causes the first low-pass filter to utilize a desired cutoff frequency f_0, performing a similar operation for the second low-pass filter until a second capacitor code Q_{CODE} is determined, and calibrating for mismatch between the first low-pass filter and the second low-pass filter.

19 Claims, 7 Drawing Sheets



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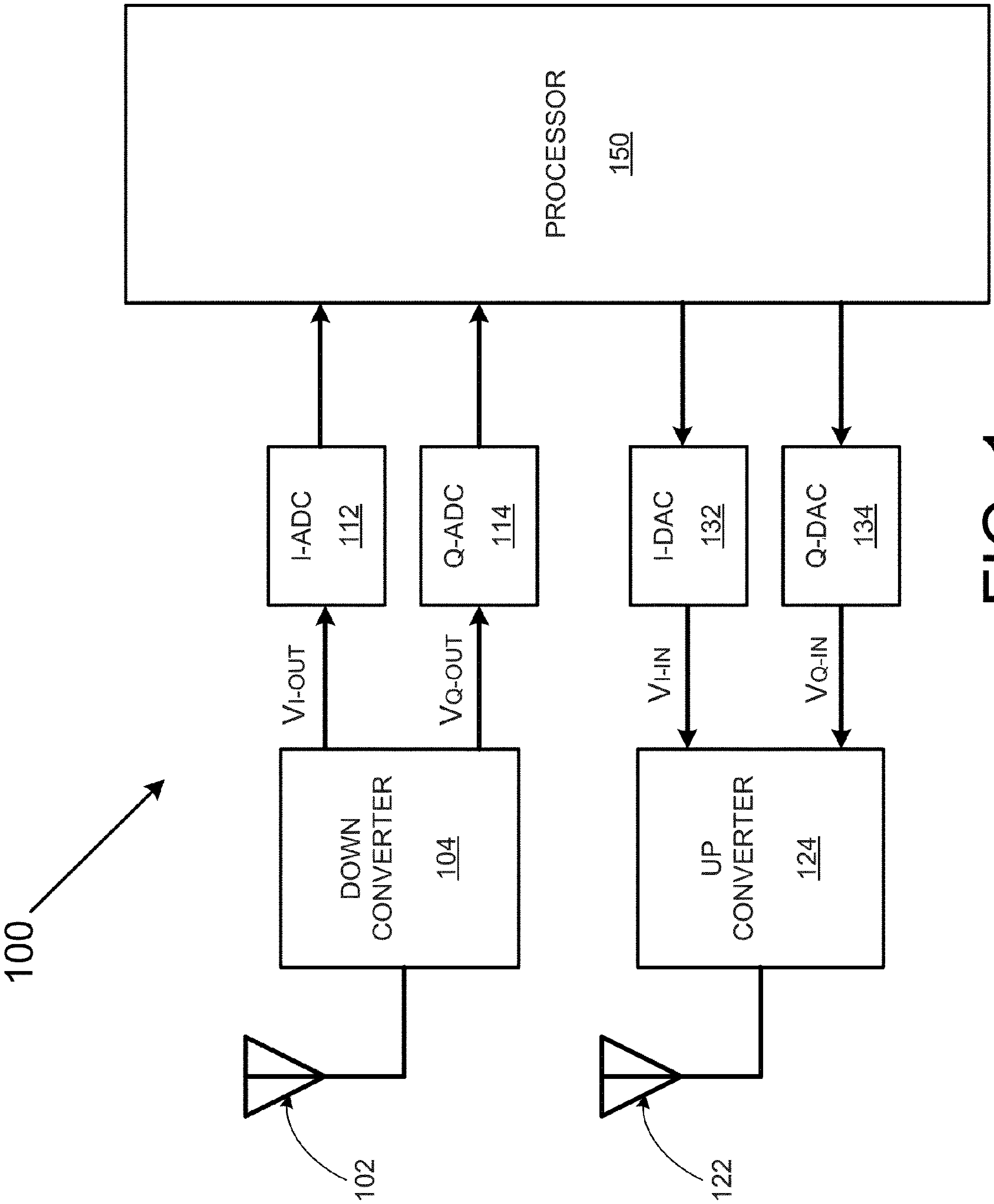
100
PROCESSOR
150
I-ADC
112
Q-ADC
114
I-DAC
132
Q-DAC
134
V_{I-OUT}
V_{Q-OUT}
V_{I-IN}
V_{Q-IN}
DOWN CONVERTER
104
UP CONVERTER
124
102
122

FIG. 1

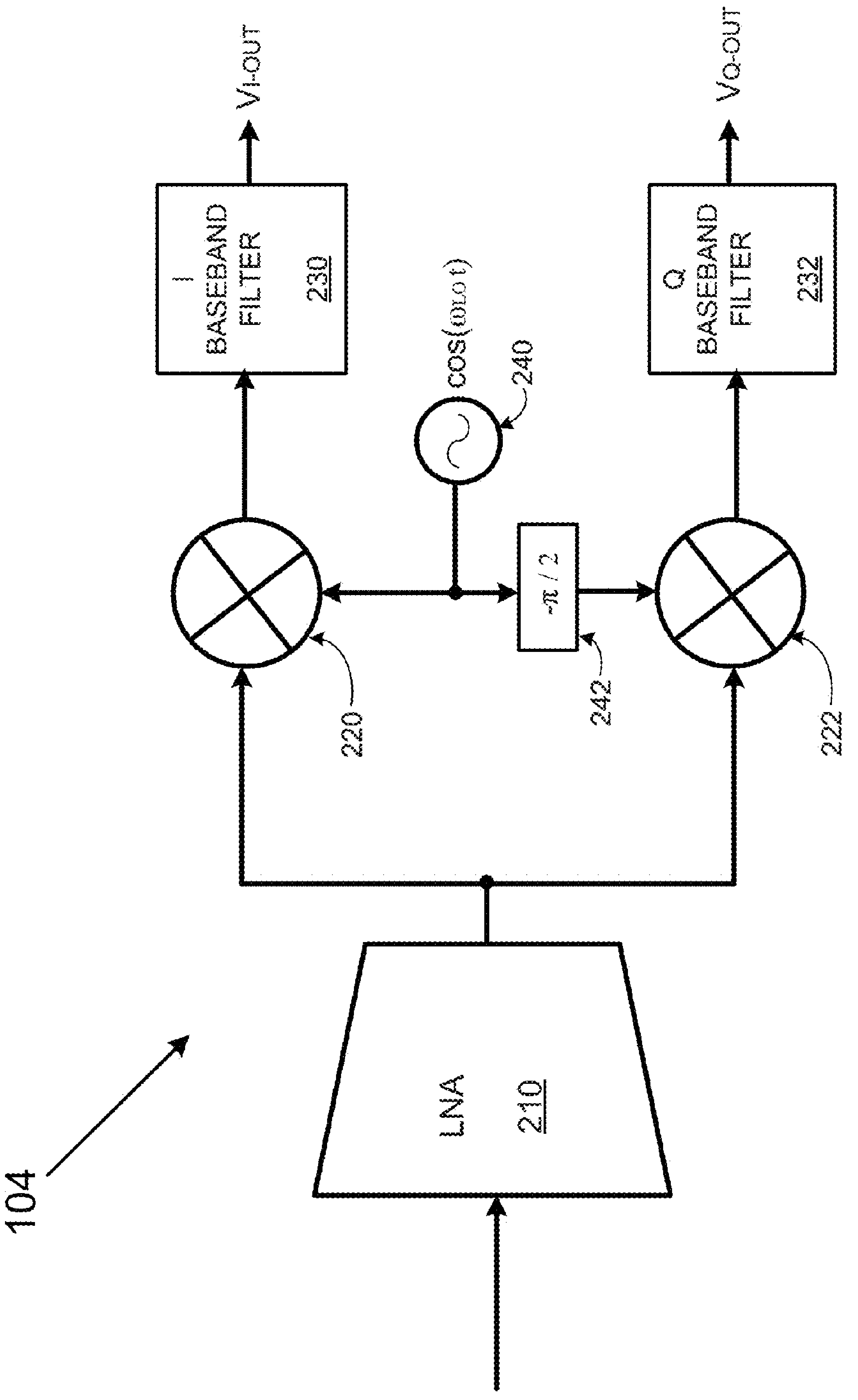
104
LNA
210
220
222
242
-π / 2
240
cos(ωLO t)
I
BASEBAND
FILTER
230
Q
BASEBAND
FILTER
232
VI-OUT
VQ-OUT

FIG. 2

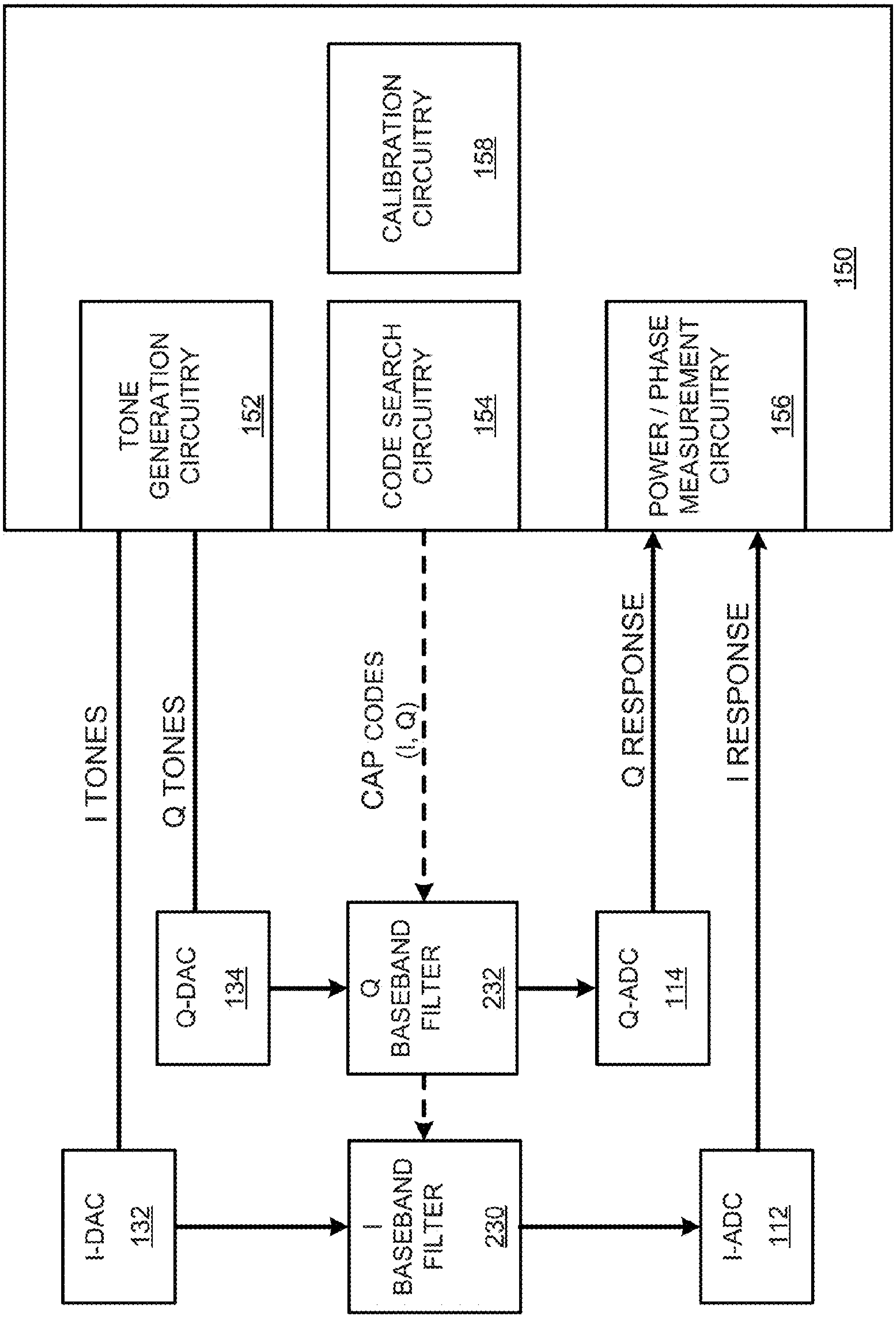
CALIBRATION CIRCUITRY
158
TONE GENERATION CIRCUITRY
152
CODE SEARCH CIRCUITRY
154
POWER / PHASE MEASUREMENT CIRCUITRY
156
150
I TONES
Q TONES
CAP CODES (I, Q)
Q RESPONSE
I RESPONSE
Q-DAC
134
Q BASEBAND FILTER
232
Q-ADC
114
I-DAC
132
I BASEBAND FILTER
230
I-ADC
112

FIG. 3

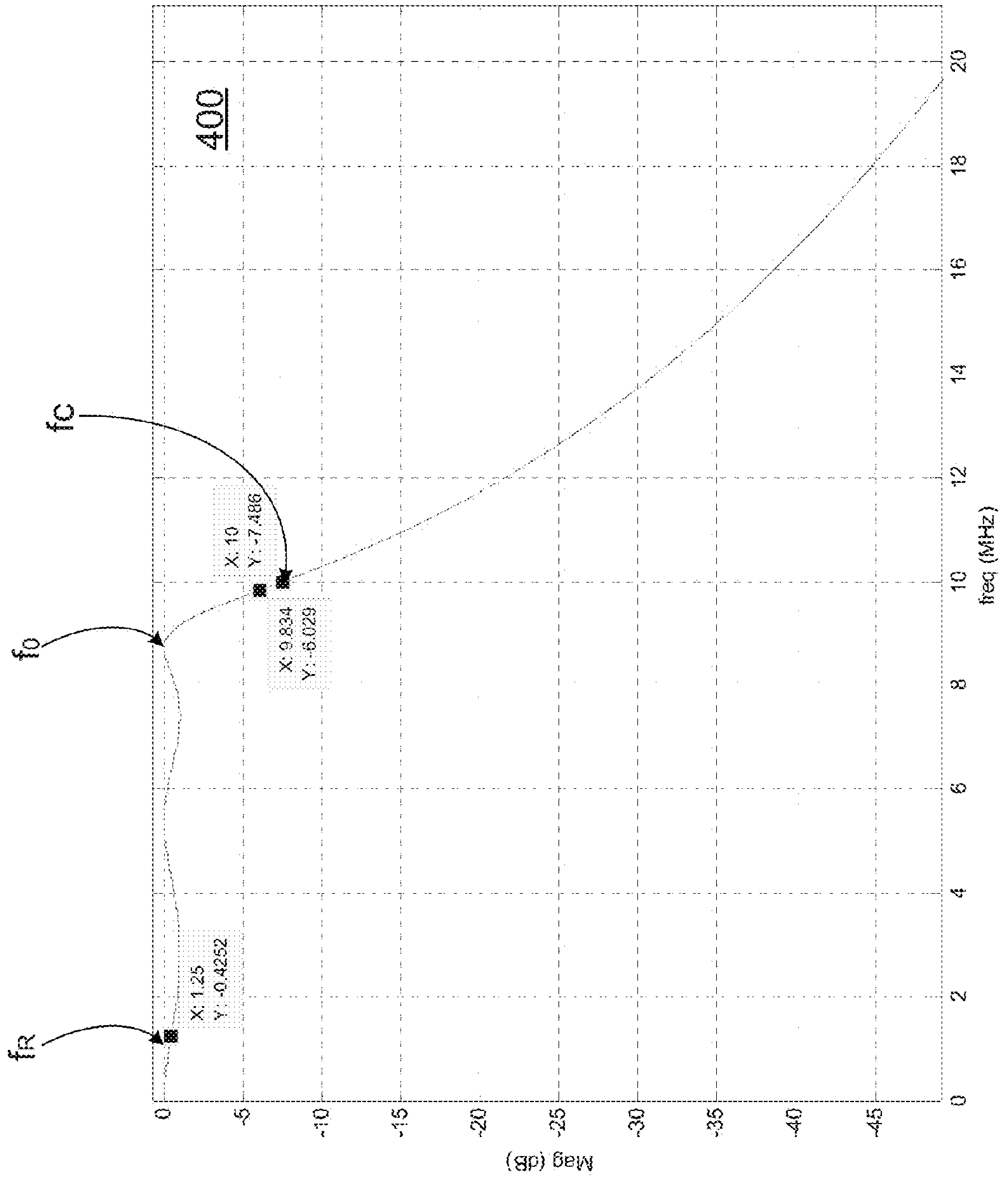
400
fC
f0
fR
X: 1.25
Y: -0.4252
X: 9.834
Y: -6.029
X: 10
Y: -7.486
0
2
4
6
8
10
12
14
16
18
20
freq (MHz)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
Mag (dB)

FIG. 4

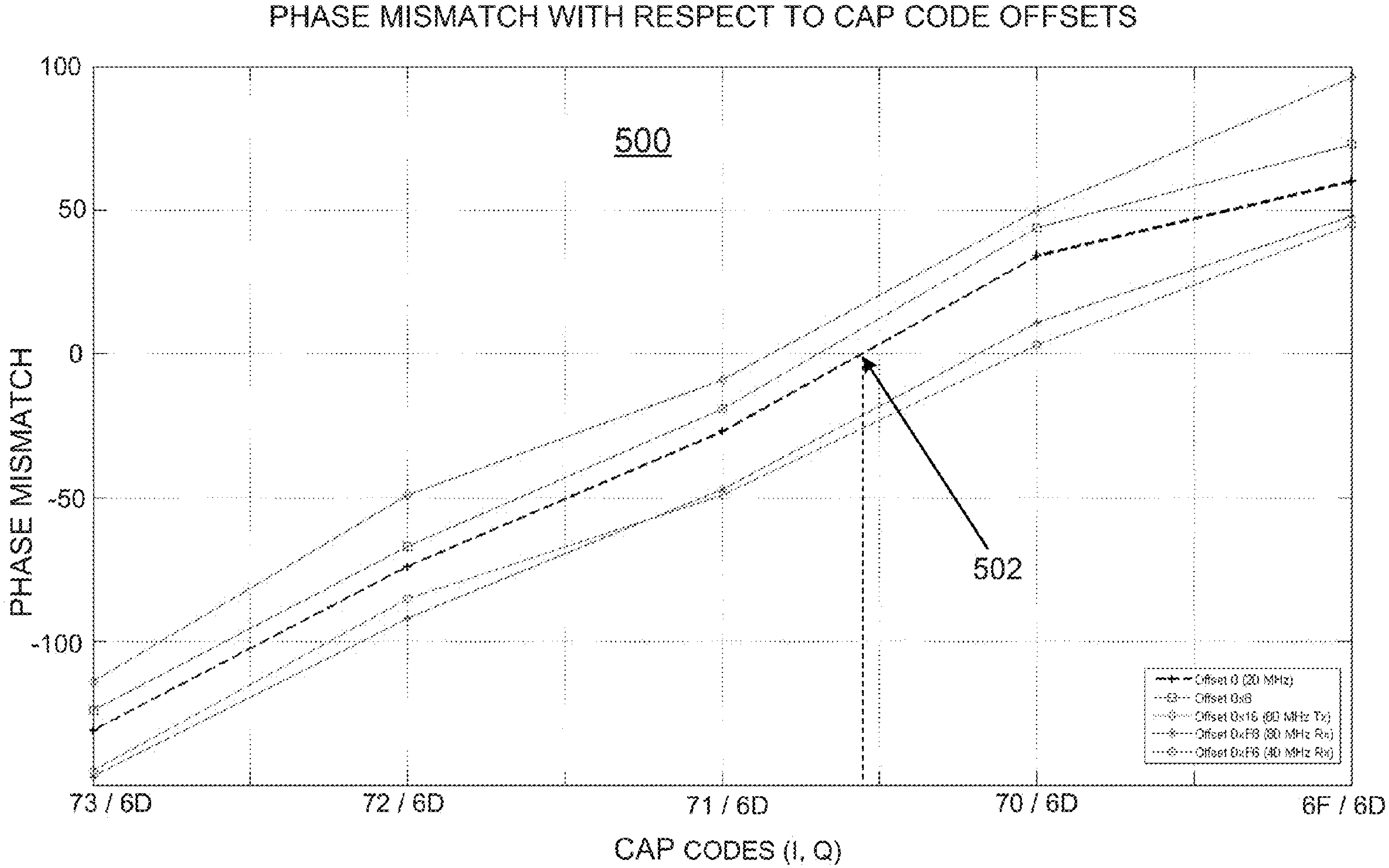
PHASE MISMATCH WITH RESPECT TO CAP CODE OFFSETS
500
PHASE MISMATCH
100
50
0
-50
-100
73 / 6D
72 / 6D
71 / 6D
70 / 6D
6F / 6D
CAP CODES (I, Q)
502
Offset 0 (20 MHz)
Offset 0x8
Offset 0x16 (60 MHz Tx)
Offset 0xF8 (80 MHz Rx)
Offset 0xF6 (40 MHz Rx)

FIG. 5

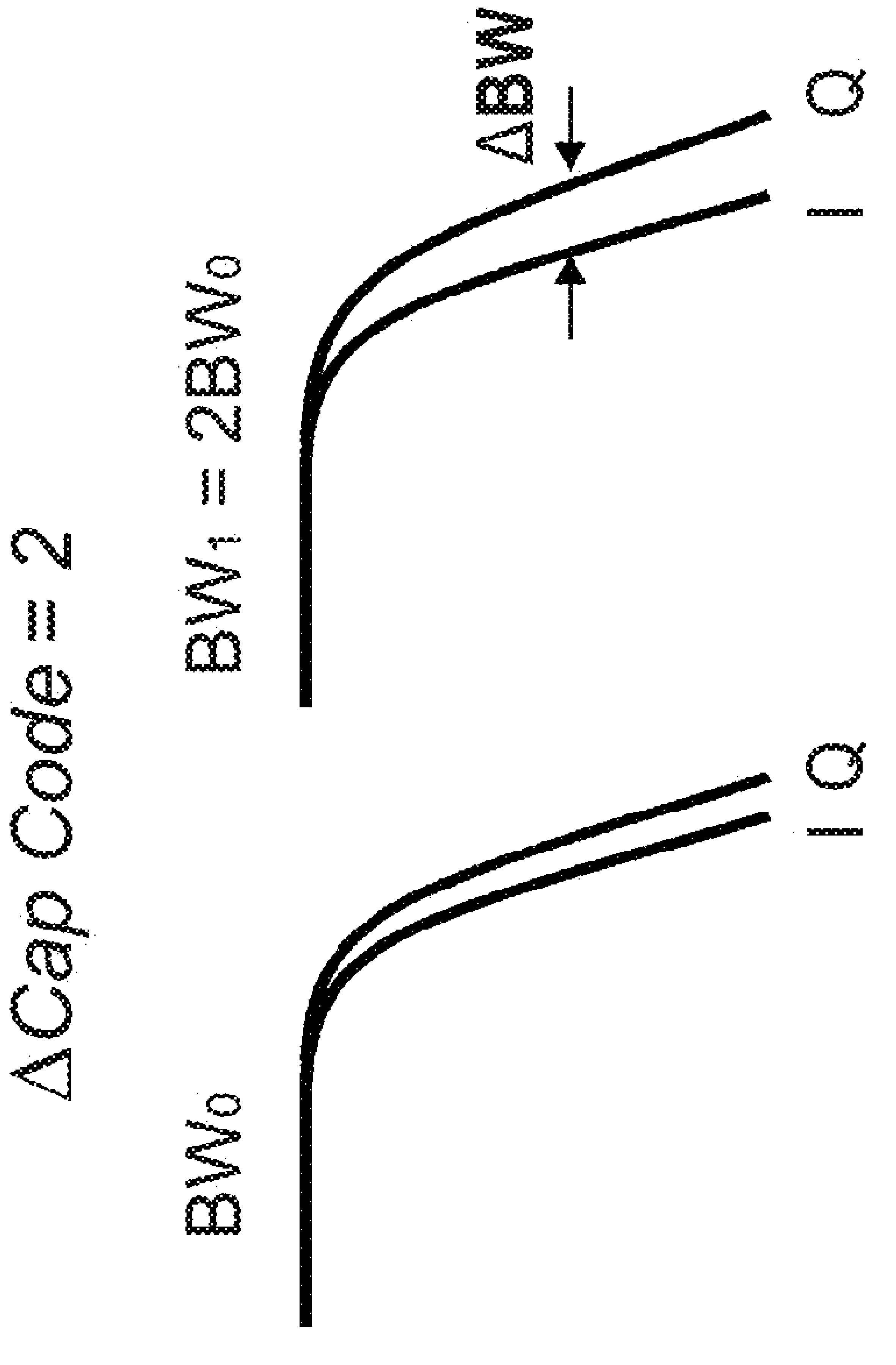
ΔCap Code = 2
BW₀
I
Q
BW₁ = 2BW₀
ΔBW
I
Q

FIG. 6A

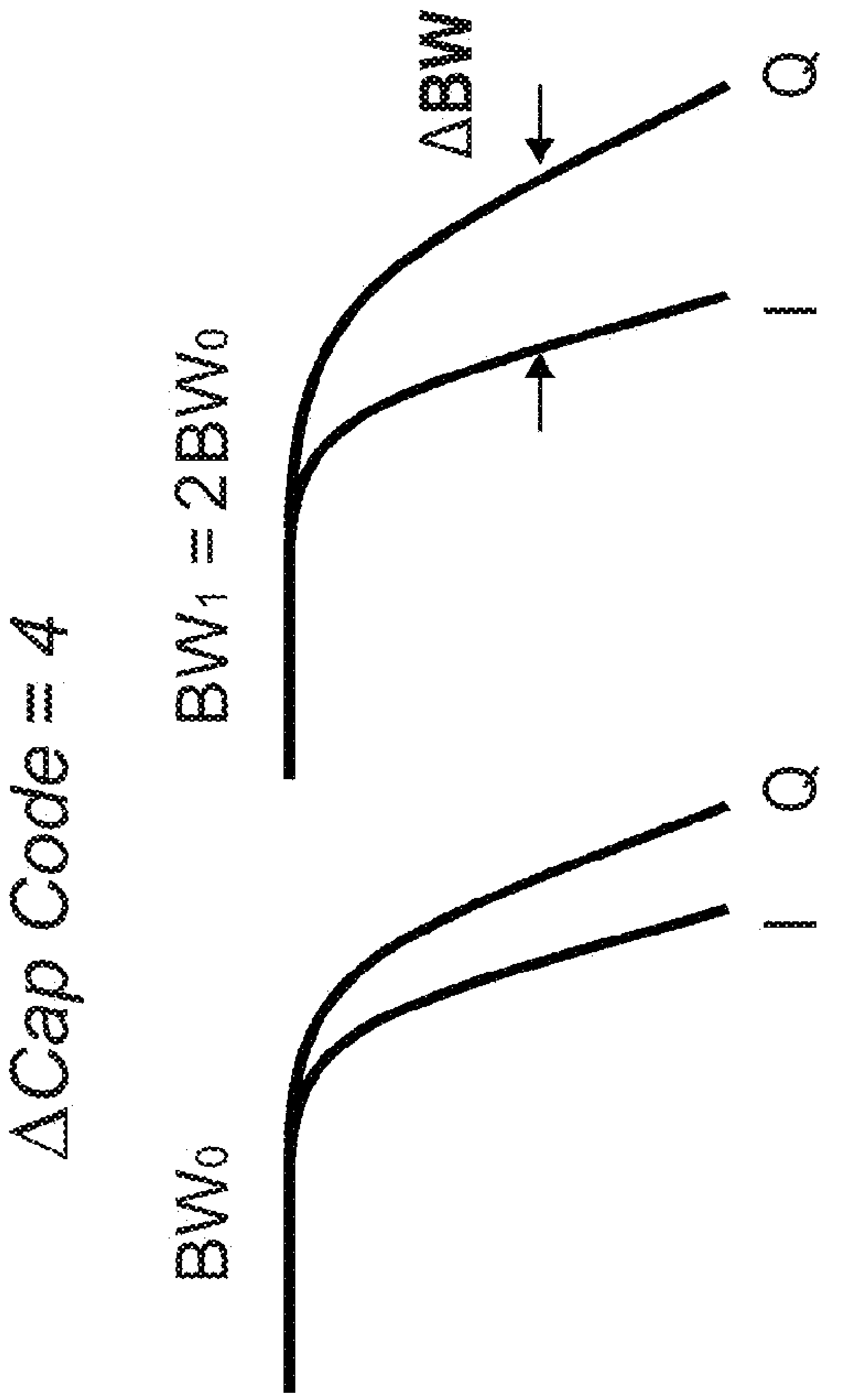
ΔCap Code = 4
BW₀
I
Q
BW₁ = 2BW₀
ΔBW
I
Q

FIG. 6B

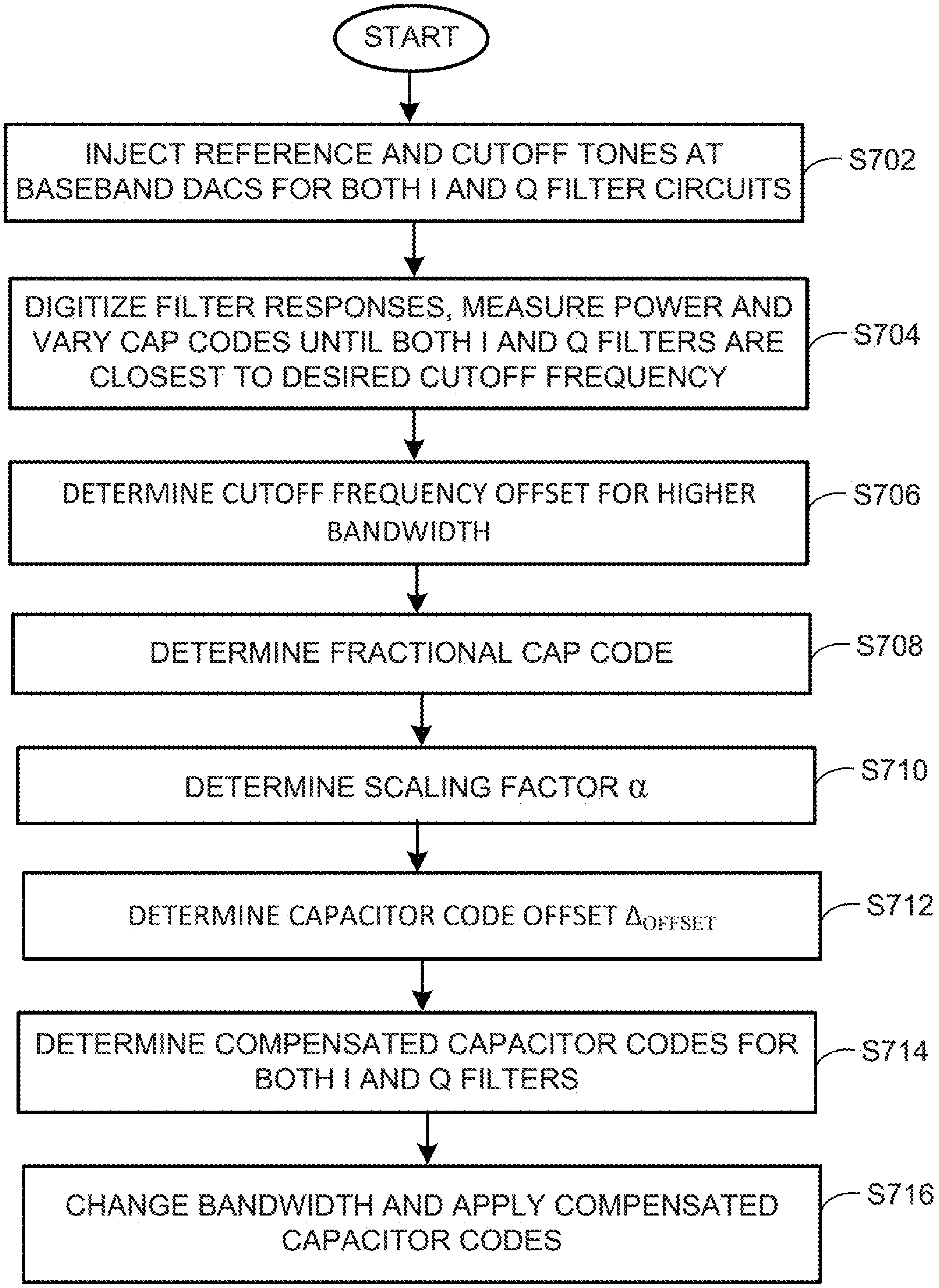
START
INJECT REFERENCE AND CUTOFF TONES AT BASEBAND DACS FOR BOTH I AND Q FILTER CIRCUITS
S702
DIGITIZE FILTER RESPONSES, MEASURE POWER AND VARY CAP CODES UNTIL BOTH I AND Q FILTERS ARE CLOSEST TO DESIRED CUTOFF FREQUENCY
S704
DETERMINE CUTOFF FREQUENCY OFFSET FOR HIGHER BANDWIDTH
S706
DETERMINE FRACTIONAL CAP CODE
S708
DETERMINE SCALING FACTOR α
S710
DETERMINE CAPACITOR CODE OFFSET Δ_{OFFSET}
S712
DETERMINE COMPENSATED CAPACITOR CODES FOR BOTH I AND Q FILTERS
S714
CHANGE BANDWIDTH AND APPLY COMPENSATED CAPACITOR CODES
S716

FIG. 7

METHODS AND SYSTEMS FOR CALIBRATING AN ANALOG FILTER

INCORPORATION BY REFERENCE

This application claims the benefit of U.S. Provisional Application No. 61/911,740 entitled "Analog Filter Calibration" filed on Dec. 4, 2013, the content of which is incorporated herein by reference in its entirety.

BACKGROUND

Wireless communication devices, such as cellular telephones, contain sophisticated integrated electronics used to receive and transmit wireless data. Unfortunately, the analog electronics of such integrated electronics is subject to process variation from one wafer to the next. This can result in characteristics of various components—e.g., resistor values and capacitor values—varying to the point that it may be impossible to use a particular device without some form of individualized device compensation. The issue of component variation can even extend to devices within a single chip. Thus, even two identically-designed devices in a single chip can and do exhibit substantial mismatch. This problem tends to increase in severity as integrated circuit geometries continue to shrink.

SUMMARY

Various aspects and embodiments of the invention are described in further detail below.

In an embodiment, a method for compensating for non-idealities in a filter circuit that includes programmable filter circuitry including a first low-pass filter and a second low-pass filter both having a common desired cutoff frequency f_0 is disclosed. The method includes, for a first desired bandwidth BW_0 corresponding to the common desired cutoff frequency f_0, injecting a reference tone f_R and a cutoff tone f_C into the first low-pass filter, and measuring respective filter responses of the reference tone f_R and the cutoff tone f_C while changing capacitor codes that control a cutoff frequency $f_{0\text{-}I}$ of the first low-pass filter until a first capacitor code I_{CODE} is determined that most accurately causes the first low-pass filter to utilize the desired cutoff frequency f_0; for the first desired bandwidth BW_0, injecting the reference tone f_R and the cutoff tone f_C into the second low-pass filter, and measuring respective filter responses of the reference tone f_R and the cutoff tone f_C while changing capacitor codes that control a cutoff frequency $f_{0\text{-}Q}$ of the second low-pass filter until a second capacitor code Q_{CODE} is determined that most accurately causes the second low-pass filter to utilize the desired cutoff frequency f_0; and further calibrating for mismatch between the first low-pass filter and the second low-pass filter for one or more additional bandwidths greater than the first desired bandwidth BW_0.

In another embodiment, a device for compensating for non-idealities in a filter circuit that includes programmable filter circuitry including a first low-pass filter and a second low-pass filter both having a common desired cutoff frequency f_0 corresponding to a first desired bandwidth BW_0 is disclosed. The device includes code search circuitry that controls the first low-pass filter and the second low-pass filter; tone generation circuitry that injects a reference tone f_R and a cutoff tone f_C into both the first low-pass filter and the second low-pass filter; measurement circuitry that: (1) measures respective filter responses of the reference tone f_R and the cutoff tone f_C while the code search circuitry changes capacitor codes that control a cutoff frequency $f_{0\text{-}I}$ of the first low-pass filter until a first capacitor code I_{CODE} is determined that most accurately causes the first low-pass filter to utilize the desired cutoff frequency f_0; and (2) measures respective filter responses of the reference tone f_R and the cutoff tone f_C while the code search circuitry changes capacitor codes that control a cutoff frequency $f_{0\text{-}Q}$ of the second low-pass filter until a second capacitor code Q_{CODE} is determined that most accurately causes the second low-pass filter to utilize the desired cutoff frequency f_0; and calibration circuitry configured to calibrate for mismatch between the first low-pass filter and the second low-pass filter for one or more additional bandwidths greater than a first desired bandwidth BW_0 of the desired cutoff frequency f_0.

BRIEF DESCRIPTION OF THE DRAWINGS

Various embodiments of this disclosure that are proposed as examples will be described in detail with reference to the following figures, wherein like numerals reference like elements.

FIG. **1** is a block diagram of an example wireless communications device capable of transmitting and receiving wireless signals.

FIG. **2** depicts a block diagram of the down-converter of FIG. **1**.

FIG. **3** depicts the wireless communications device of FIG. **1** reconfigured so as to be capable of self-calibration.

FIG. **4** is a power response of an example low-pass filter used in the wireless communications device of FIG. **1**.

FIG. **5** depicts examples of phase mismatch that can occur between to identically-designed low-pass filters as a function of capacitor codes.

FIGS. **6**A and **6**B depict examples of how mismatch for low-pass filters for a particular bandwidth becomes worse at higher bandwidths.

FIG. **7** is a flowchart outlining a set of example operations for providing compensating for mismatched low-pass filters.

DETAILED DESCRIPTION OF EMBODIMENTS

The disclosed methods and systems below may be described generally, as well as in terms of specific examples and/or specific embodiments. For instances where references are made to detailed examples and/or embodiments, it is noted that any of the underlying principles described are not to be limited to a single embodiment, but may be expanded for use with any of the other methods and systems described herein as will be understood by one of ordinary skill in the art unless otherwise stated specifically.

One of the most significant disadvantages of modern telecommunications equipment is that process variations for integrated circuits will cause analog components to vary not just between different wafers, but even for different devices on a single chip. Thus, two identically-designed low-pass filters on a single chip can be expected to have different cutoff frequencies. These differences can be problematic. For example, modern Orthogonal Frequency Division Modulation (OFDM) systems require a pair of matched low-pass filters in their RF-to-baseband and baseband-to-RF conversion circuitry, and even small amounts of mismatch can cause an OFDM device to operate poorly and outside of an industry specification.

To address these component variations, designers often incorporate some form of calibration circuitry so that individual filters can be adjusted to better conform with device specifications. Analog low-pass filters, for example, may contain banks of capacitors that can be programmably placed in and out of circuit such that a cutoff frequency may be fine-tuned.

Unfortunately, because calibration processes cannot exactly match every pair of low-pass filters due to practical circuit limitations, filter mismatch will occur not just under the conditions for which the calibration took place, but will likely be worse for other conditions that the filters must address. For example, assuming that two digital filters are calibrated using a bandwidth of 20 MHz, amplitude and phase variations between the two filters will increase for bandwidths of 40 MHz, and increase more for bandwidths of 80 MHz. Part of these increasing variations is caused by non-ideal components within analog filters, and part is due to the fact that the analog filters will need to be reprogrammed to address different cutoff frequencies as a function of bandwidth. By way of example, a analog low-pass filter for an OFDM communication system operating for a bandwidth of 20 MHz will require an 8.75 MHz cutoff frequency while an 18.75 MHz cutoff frequency will be needed for a 40 MHz bandwidth, and a 38.75 MHz cutoff frequency will be needed for an 80 MHz bandwidth.

FIG. **1** is a block diagram of an example wireless communications device **100** capable of transmitting and receiving wireless signals. As shown in FIG. **1**, the wireless communications device **100** includes a receive antenna **102**, a down-converter **104**, a first (I Channel) Analog-To-Digital Converter (I-ADC) **112**, a second (Q Channel) Analog-To-Digital Converter (Q-ADC) **114**, a transmit antenna **122**, an up-converter **124**, a first (I Channel) Digital-To-Analog Converter (I-DAC) **132**, a second (Q Channel) Digital-To-Analog Converter (Q-DAC) **134**, and a processor **150**. As the operations of the various components **102**-**150** of FIG. **1** are well understood, a detailed description of their operation under normal communications will be omitted.

FIG. **2** depicts a block diagram of the down-converter **104** of FIG. **1**. As shown in FIG. **2**, the down-converter **104** includes a low-noise amplifier (LNA) **210**, a first mixer **220**, an I-baseband filter **230**, a second mixer **222**, a Q-baseband filter **232**, a local oscillator (LO) **240** capable of producing a local oscillation signal $\cos(\omega_{LO}\ t)$, where ω_{LO} is the local oscillation frequency, and a phase shift device **242** capable of shifting the local oscillation signal $\cos(\omega_{LO}\ t)$ by $-\pi/2$ radians. As with FIG. **1**, because the operations of the various components **210**-**232** are well understood, a detailed description of their operation under normal communications will be omitted. However, it is to be appreciated that, because wireless communication devices are often limited to only transmitting or receiving at any given point in time, most if not all of the various components **210**-**232** can be used for the up-converter **124** of FIG. **1** without detriment. Such an arrangement has a further advantage in that only a single pair of low-pass filters will need to be calibrated.

FIG. **3** depicts the wireless communications device **100** of FIG. **1** reconfigured so as to be capable of self-calibration. Also shown in FIG. **3**, functional components of the processor **150** dedicated to filter calibration are displayed. Such functional components include tone generation circuitry **152**, code search circuitry **154**, power/phase measurement circuitry **156** and calibration circuitry **158**. In various embodiments, the embedded circuitries **152**-**158** may individually be made from dedicated logic, may exists as software/firmware routines located in a tangible, non-transitory memory and operated upon by one or more processors, or exist as combinations of software/firmware processors and dedicated logic.

In operation, each of the I-baseband (low-pass) filter **230** and the Q-baseband (low-pass) filter **232** are calibrated such that each will, to a practical extent possible, have a common desired cutoff frequency f_0 corresponding to a first desired bandwidth BW_0. While there is no limitation as to the particular bandwidths or cutoff frequencies that may be used, for the purposes of explanation the first desired bandwidth BW_0 is 20 MHz, and the corresponding desired cutoff frequency f_0 is 8.75 MHz. Similarly, while there is no limitation as to the types of low-pass filters that may be used, for the purposes of explanation and practical example, the I-baseband filter **230** and Q-baseband filter **230** are both fifth-order Chebyshev Type-1 filters using switch-capacitor technology.

Initial calibration starts with the tone generation circuitry **152** (via the I-DAC **132** and the Q-DAC **134**) injecting both a reference tone f_R and a cutoff tone f_C into each of the I-baseband filter **230** and the Q-baseband filter **232**. The I-baseband filter **230** and the Q-baseband filter **232**, in turn, provide a respective output response consistent with their respective non-ideal cutoff frequencies, $f_{0\text{-}I}$ and $f_{0\text{-}Q}$, while the power/phase measurement circuitry **156** (via the I-ADC **112** and the Q-ADC **114**) measures the respective filter responses.

During this time, the code search circuitry **154** will vary separate digital control codes ("capacitor codes" or "cap codes") to the I-baseband filter **230** and the Q-baseband filter **232** until the respective non-ideal cutoff frequencies, $f_{0\text{-}I}$ and $f_{0\text{-}Q}$, match the ideal cutoff frequency f_0 as close as possible given the available resolution of the capacitor codes. For example, assuming that the I-baseband filter **230** and the Q-baseband filter **232** each have a capacitor code resolution of 8 bits, the code search circuitry **154** can provide any number of search algorithms to provide capacitor codes within a range of [−128 to 127] until respective particular capacitor codes are selected that most accurately causes the baseband filters {**230**, **232**} to utilize the desired cutoff frequency f_0. These selected capacitor codes will be referred to below as the first capacitor code I_{CODE} and the second capacitor code Q_{CODE}.

FIG. **4** is a power response **400** of an example low-pass filter useable in the wireless communications device of FIG. **1** and useful to explain how the reference tone f_R and the cutoff tone f_C may be used to select an appropriate capacitor code and utilize an appropriate cutoff frequency. As shown in FIG. **4**, the power response **400** is atypical of a fifth-order Type-1 Chebyshev filter. The reference tone f_R, which is well within the pass-band region, is assigned a value of 1.25 MHz, and the cutoff tone f_C is assigned a value of 10 MHz. The power ratio of the responses for the reference tone f_R and the cutoff tone f_C will vary as a function of the cutoff frequency f_0 so as become larger as the cutoff frequency f_0 decreases, and become smaller as the cutoff frequency f_C increases. The power ratio for an ideal cutoff frequency f_0 of 8.75 MHz can be precisely determined, and a capacitor code can be adjusted until the power response **400** best reflects a known, predictable power ratio for the filter responses of the reference tone f_R and the cutoff tone f_C.

Returning to FIG. **3**, once the appropriate capacitor codes $\{I_{CODE}, Q_{CODE}\}$ are selected, the calibration circuitry **158** performs further calculations so as to better calibrate the I-baseband filter **230** and the Q-baseband filter **232** to compensate for filter mismatch for one or more additional bandwidths greater than bandwidth BW_0.

Typically, the one or more additional bandwidths will be a multiple of BW_0. For example, in various embodiments, a second desired bandwidth BW_1 will equal $N \times BW_0$, where N is a positive integer greater than 1.

While bandwidths may be multiples of one another, respective cutoff frequencies for such larger bandwidths will not be multiples of one another. For instance, assuming

BW_0=20 MHz and f_0=8.75 MHz, a second bandwidth BW_1 of 40 MHz will use a respective cutoff frequency f_1 of 18.75 MHz, which represents a "cutoff frequency offset" Δf of 1.25 MHz (18.75 MHz–(2*8.75 MHz)=1.25 MHz). Similarly, again assuming BW_0=20 MHz and f_0=8.75 MHz, a second bandwidth BW_1 of 80 MHz will use a respective cutoff frequency f_1 of 38.75 MHz, which represents a cutoff frequency offset Δf of 3.75 MHz (38.75 MHz MHz–(4*8.75 MHz)=3.75 MHz).

Although employing a cutoff frequency offset can be highly advantageous, such offsets are problematic in that the offsets may cause mismatch between a pair of low-pass filters at BW_1 to increase to a point where the increased mismatch causes a wireless device to fall outside of performance specifications. Accordingly, the calibration circuitry **158** is configured to, for a respective second cutoff frequency f_1 for a second/higher bandwidth BW_1, determine a capacitor code offsets ΔI_{OFFSET} and ΔQ_{OFFSET} commensurate with the frequency offset Δf, add the capacitor code offset ΔI_{OFFSET} to the first capacitor code I_{CODE} to produce a first compensated capacitor code $I_{C\text{-}CODE}$, and add the capacitor code offset ΔQ_{OFFSET} to the second capacitor code Q_{CODE} to produce a second compensated capacitor code $Q_{C\text{-}CODE}$.

However, the capacitor code offsets must not just reflect the frequency offset Δf, but must also take into consideration a "fractional capacitor code" CI_{FRAC} corresponding to the first desired bandwidth BW_0, the fractional capacitor code CI_{FRAC} being a value that lies between two consecutive capacitor codes [I_{CODE}, I_{CODE+1}] on I rail, keeping Qcode unchanged, and that ideally corresponds to both a zero phase difference and a zero power difference between a first low-pass filter and a second low-pass filter.

FIG. **5** depicts a chart **500** showing examples of phase mismatch that can occur between two identically-designed low-pass filters as a function of capacitor codes and capacitor code offsets $\Delta I_{OFFSET}/\Delta Q_{OFFSET}$ to be used for other bandwidths. As shown in FIG. **5**, five example responses are provided representing different capacitor code offsets $\Delta I_{OFFSET}/\Delta Q_{OFFSET}$, with the center (dotted) line representing a capacitor code offset $\Delta I_{OFFSET}/\Delta Q_{OFFSET}=0$. The X-axis is a dimension being a combined I-Q capacitor code [I_{CODE}, Q_{CODE}], and the Y-axis is a second dimension representing respective measured phase offsets between a first low-pass filter and a second low-pass filter as a function of the respective combined I-Q capacitor codes. The point **502** at which the dotted line displays zero phase mismatch occurs about halfway between I-Q capacitor code [71,6D] (signed hexadecimal notation representing a difference of 4) and I-Q capacitor code [70,6D] (signed hexadecimal notation representing a difference of 3).

The fractional capacitor code CI_{FRAC} will be a real, non-integer, number, and as such is incompatible with programmable filter circuitry that relies on discrete switches to program/calibrate. As such, the capacitor code offset $\Delta I_{OFFSET}/\Delta Q_{OFFSET}$ may be determined by rounding the fractional capacitor code CI_{FRAC} to a nearest integer, adding the capacitor code offset ΔI_{OFFSET} to the first capacitor code I_{CODE} to produce the first compensated capacitor code $I_{C\text{-}CODE}$, and adding the capacitor code offset ΔQ_{OFFSET} to the second capacitor code Q_{CODE} to produce the second compensated capacitor code $Q_{C\text{-}CODE}$.

In various embodiments, the capacitor code offsets ΔI_{OFFSET} and ΔQ_{OFFSET} are calculated by rounding to the nearest integer the formula [(1+α Δfc)*ΔC_{FRAC}], where ΔC_{FRAC} is a difference between the fractional first capacitor code CI_{FRAC} and the second capacitor code Q_{CODE}, α is a scaling factor derived from empirical data, and Δfc is a capacitor code difference corresponding to the cutoff frequency offsets ΔI_{OFFSET} and ΔQ_{OFFSET}. If Δfc=0, then the capacitor code offset calculation is reduced to rounding to the nearest integer the formula [ΔC_{FRAC}]. However, assuming Δfc≠0, scaling factor α must be factored.

While a scaling factor α may be determined in a number of ways, in a number of embodiments a scaling factor α is determined based on empirical data. FIGS. **6**A and **6**B depict examples of how mismatch for low-pass filters for a particular bandwidth becomes worse at higher bandwidths. While FIGS. **6**A and **6**B are exemplary, conceptually they are based on real-world experience so as to demonstrate that filter mismatch will increase as a function of Δfc and the magnitude of BW_1. An appropriate scaling factor α will reflect desired compensation for different Δfc and different magnitudes of BW_1.

Again returning to FIG. **3**, once the calibration circuitry **158** has determined the first compensated capacitor code $I_{C\text{-}CODE}$ and the second compensated capacitor code $Q_{C\text{-}CODE}$, the processor **150** applies the first compensated capacitor code $I_{C\text{-}CODE}$ to the first/I-baseband (low-pass) filter **230**, and applies the second compensated capacitor code $Q_{C\text{-}CODE}$ to the second/Q-baseband (low-pass) filter **232**, where after the baseband filters **230** and **232** may be used for higher bandwidths.

FIG. **7** is a flowchart outlining a set of example operations for providing compensating for mismatched low-pass filters, such as the I-baseband filter **230** and Q-baseband filter **232** discussed above and with respect to FIGS. **1**-**6**. Such operations compensate for non-idealities in a filter circuit that includes programmable filter circuitry including a first low-pass filter and a second low-pass filter both having a common desired cutoff frequency f_0. It is to be appreciated to those skilled in the art in light of this disclosure that, while the various functions of FIG. **7** are shown according to a particular order for ease of explanation, that certain functions may be performed in different orders or in parallel.

At S**702**, for a first desired bandwidth BW_0 corresponding to the common desired cutoff frequency f_0, a reference tone f_R and a cutoff tone f_C are injected into both the first low-pass filter and the second low-pass filter using, for example, separate DACs under the control of some form of tone generation circuitry.

At S**704**, the responses of the first low-pass filter and the second low-pass filter are digitized using respective ADCs so as to measure power responses of the reference tone f_R and cutoff tone f_C. During this time, a capacitor code that controls a cutoff frequency $f_{0\text{-}I}$ of the first low-pass filter is varied until a first capacitor code I_{CODE} is determined that most accurately causes the first low-pass filter to utilize the desired cutoff frequency f_0. Similarly, a capacitor code that controls the second low-pass filter is varied until a second capacitor code Q_{CODE} is determined that most accurately causes the second low-pass filter to utilize the desired cutoff frequency f_0.

At S**708**, a fractional capacitor code CI_{FRAC} is determined again noting that a fractional capacitor code CI_{FRAC} is a non-integer value that lies between two consecutive capacitor codes [I_{CODE}, I_{CODE+1}], and that ideally corresponds to both a zero phase difference and a zero power difference between the first low-pass filter and the second low-pass filter. While the particular methodology may vary from embodiment to embodiment, one approach to determining the fractional capacitor code C_{FRA} may be had by interpolating a line using a plurality of points with each point having (See, FIG. **5**) a first dimension being a combined I-Q capacitor code [I_{CODE}, Q_{CODE}], and a second dimension being a respective measured phase offset between the first low-pass filter and the second low-pass filter using a respective combined I-Q capacitor code, then selecting a combined I-Q capacitor code value that corresponds to a substantially zero phase difference between the first low-pass filter and the second low-pass filter.

At **S710**, a scaling factor α is derived, for example, from empirical data. At **S712**, capacitor code offsets ΔI_{OFFSET} and ΔQ_{OFFSET} are determined by rounding to the nearest integer a scaled value=$[(1+\alpha\ \Delta fc)*\Delta C_{FRAC}]$, where ΔC_{FRAC} is a difference between the fractional first capacitor code ΔC_{FRAC} and the second capacitor code Q_{CODE}, α is the scaling factor derived at **S710**, CI_{FRAC} is the fractional capacitor code derived at **S708**, and Δfc is a capacitor code difference corresponding to the cutoff frequency offset Δf determined at **S706**.

At **S714**, a first compensated capacitor code $I_{C\text{-}CODE}$ is calculated by adding the capacitor code offset ΔI_{OFFSET} to the first capacitor code I_{CODE}. Similarly, a second compensated capacitor code $Q_{C\text{-}CODE}$ is calculated by adding the capacitor code offset ΔQ_{OFFSET} to the second capacitor code Q_{CODE}. At **S716**, an operating bandwidth is changed from BW0 to BW1, the first compensated capacitor code $I_{C\text{-}CODE}$ is applied to the first/I low-pass filter, and the second compensated capacitor code $Q_{C\text{-}CODE}$ is applied to the second/Q low-pass filter.

While the invention has been described in conjunction with the specific embodiments thereof that are proposed as examples, it is evident that many alternatives, modifications, and variations will be apparent to those skilled in the art. Accordingly, embodiments of the invention as set forth herein are intended to be illustrative, not limiting. There are changes that may be made without departing from the scope of the invention.

What is claimed is:

1. A method for compensating for non-idealities in a filter circuit that includes programmable filter circuitry including a first low-pass filter and a second low-pass filter both having a common desired cutoff frequency f**0**, the method comprising:

- for a first desired bandwidth BW**0** corresponding to the common desired cutoff frequency f**0**, injecting a reference tone IR and a cutoff tone fC into the first low-pass filter, and measuring respective filter responses of the reference tone fR and the cutoff tone fC while changing capacitor codes that control a cutoff frequency f**0**-I of the first low-pass filter until a first capacitor code ICODE is determined that causes the first low-pass filter to match the desired cutoff frequency f**0** as close as possible given an available resolution of the capacitor codes;
- for the first desired bandwidth BW**0**, injecting the reference tone fR and the cutoff tone fC into the second low-pass filter, and measuring respective filter responses of the reference tone fR and the cutoff tone fC while changing capacitor codes that control a cutoff frequency f**0**-Q of the second low-pass filter until a second capacitor code QCODE is determined that causes the second low-pass filter to match the desired cutoff frequency f**0** as close as possible given the available resolution of the capacitor codes; and
- further calibrating for mismatch between the first low-pass filter and the second low-pass filter for one or more additional bandwidths greater than the first desired bandwidth BW**0**.

2. The method of claim **1**, wherein the one or more additional bandwidths include a second desired bandwidth BW_1, where $BW_1=N\times BW_0$, where N is a positive integer greater than 1.

3. The method of claim **2**, wherein calibrating for mismatch between the first low-pass filter and the second low-pass filter includes:

- for a respective second cutoff frequency f_1, where $f_1=(N\times f_0)+\Delta f$, where Δf is a cutoff frequency offset for the second desired bandwidth BW_1:
    - determining a capacitor code offsets ΔI_{OFFSET} and ΔQ_{OFFSET};
    - adding the capacitor code offset ΔI_{OFFSET} to the first capacitor code I_{CODE} to produce a first compensated capacitor code $I_{C\text{-}CODE}$; and
- adding the capacitor code offset ΔQ_{OFFSET} to the second capacitor code Q_{CODE} to produce a second compensated capacitor code $Q_{C\text{-}CODE}$, wherein the second cutoff frequency $f_1=(N\times f_0)+\Delta f$, where Δf is a cutoff frequency offset for the second desired bandwidth BW_1.

4. The method of claim **3**, wherein

- BW_0=20 MHz, BW_1=40 MHz, f_0=8.75 MHz, f_1=18.75 MHz, and Δf=1.25 MHz; or wherein
- BW_0=20 MHz, BW_1=80 MHz, f_0=8.75 MHz, f_1=38.75 MHz, and Δf=3.75 MHz.

5. The method of claim **3**, wherein calibrating for mismatch between the first low-pass filter and the second low-pass filter further includes:

- determining a fractional capacitor code CI_{FRAC} corresponding to the first desired bandwidth BW_0, the fractional capacitor code CI_{FRAC} being a value that lies between two consecutive capacitor codes $[I_{CODE}, I_{CODE+1}]$, and that ideally corresponds to both a zero phase difference and a zero power difference between the first low-pass filter and the second low-pass filter; and
- using the fractional capacitor code CI_{FRAC} to determine the capacitor code offsets ΔI_{OFFSET} and ΔQ_{OFFSET}.

6. The method of claim **5**, wherein determining the fractional capacitor code CI_{FRAC} includes:

- interpolating a line using a plurality of points with each point having a first dimension being a combined I-Q capacitor code $[I_{CODE}, Q_{CODE}]$, and a second dimension being a respective measured phase offset between the first low-pass filter and the second low-pass filter using a respective combined I-Q capacitor code; and
- selecting a combined I-Q capacitor code value that corresponds to a substantially zero phase difference between the first low-pass filter and the second low-pass filter.

7. The method of claim **5**, wherein using the fractional capacitor code C_{FRAC} to determine the capacitor code offset ΔI_{OFFSET} and ΔQ_{OFFSET} includes:

- rounding the fractional capacitor code CI_{FRAC} to a nearest integer to produce the capacitor code offset ΔI_{OFFSET} and ΔQ_{OFFSET};
- adding the capacitor code offset ΔI_{OFFSET} to the first capacitor code I_{CODE} to produce the first compensated capacitor code $I_{C\text{-}CODE}$; and
- adding the capacitor code offset ΔQ_{OFFSET} to the second capacitor code Q_{CODE} to produce the second compensated capacitor code $Q_{C\text{-}CODE}$.

8. The method of claim **7**, wherein using the fractional capacitor code CI_{FRAC} to determine the capacitor code offsets ΔI_{OFFSET} and ΔQ_{OFFSET} includes:

- rounding to the nearest integer a scaled value=$[(1+\alpha\Delta fc)*\Delta C_{FRAC}]$ to produce the capacitor code offsets ΔI_{OFFSET} and ΔQ_{OFFSET}, where ΔC_{FRAC} is a difference between the first capacitor code CI_{FRAC} and the second capacitor code Q_{CODE}, a is a scaling factor derived from empirical data, and Δfc is a capacitor code difference corresponding to the cutoff frequency offset Δf;

adding the capacitor code offset ΔI_{OFFSET} to the first capacitor code I_{CODE} to produce the first compensated capacitor code $I_{C\text{-}CODE}$; and

adding the capacitor code offset ΔQ_{OFFSET} to the second capacitor code Q_{CODE} to produce the second compensated capacitor code $Q_{C\text{-}CODE}$.

9. The method of claim **8**, further comprising:

applying the first compensated capacitor code $I_{C\text{-}CODE}$ to the first low-pass filter; and

applying the second compensated capacitor code $Q_{C\text{-}CODE}$ to the second low-pass filter.

10. A wirelessly operating device that operates according to the method of claim **1**.

11. A device for compensating for non-idealities in a filter circuit that includes programmable filter circuitry including a first low-pass filter and a second low-pass filter both having a common desired cutoff frequency f_0 corresponding to a first desired bandwidth BW_0, the device comprising:

code search circuitry that controls the first low-pass filter and the second low-pass filter;

tone generation circuitry that injects a reference tone f_R and a cutoff tone f_C into both the first low-pass filter and the second low-pass filter,

measurement circuitry that: (1) measures respective filter responses of the reference tone f_R and the cutoff tone f_C while the code search circuitry changes capacitor codes that control a cutoff frequency $f_{0\text{-}1}$ of the first low-pass filter until a first capacitor code I_{CODE} is determined that causes the first low-pass filter to match the desired cutoff frequency f_0 as close as possible given an available resolution of the capacitor codes; and (2) measures respective filter responses of the reference tone f_R and the cutoff tone f_C while the code search circuitry changes capacitor codes that control a cutoff frequency $f_{0\text{-}Q}$ of the second low-pass filter until a second capacitor code Q_{CODE} is determined that causes the second low-pass filter to match the desired cutoff frequency f_0 as close as possible given the available resolution of the capacitor codes; and

calibration circuitry configured to calibrate for mismatch between the first low-pass filter and the second low-pass filter for one or more additional bandwidths greater than a first desired bandwidth BW_0 of the desired cutoff frequency f_0.

12. The device of claim **11**, wherein each of the one or more additional bandwidths include a second desired bandwidth BW_1, where $BW_1 = N \times BW_0$, where N is a positive integer greater than 1.

13. The device of claim **12**, wherein the calibration circuitry is further configured to:

for a respective second cutoff frequency f_1 for the second bandwidth BW_1, determine a capacitor code offsets ΔI_{OFFSET} and ΔQ_{OFFSET};

add the capacitor code offset ΔI_{OFFSET} to the first capacitor code I_{CODE} to produce a first compensated capacitor code $I_{C\text{-}CODE}$; and

add the capacitor code offset ΔQ_{OFFSET} to the second capacitor code Q_{CODE} to produce a second compensated capacitor code $Q_{C\text{-}CODE}$;

wherein the second cutoff frequency $f_1 = (N \times f_0) + \Delta f$, where Of is a cutoff frequency offset for the second desired bandwidth BW_1.

14. The device of claim **13**, wherein the calibration circuitry is further configured to calibrate for mismatch between the first low-pass filter and the second low-pass filter by:

determining a fractional capacitor code CI_{FRAC} corresponding to the first desired bandwidth BW_0, the fractional capacitor code CI_{FRAC} being a value that lies between two consecutive capacitor codes $[I_{CODE}, I_{CODE+1}]$, and that ideally corresponds to both a zero phase difference and a zero power difference between the first low-pass filter and the second low-pass filter; and

using the fractional capacitor code CI_{FRAC} to determine the capacitor code offset ΔI_{OFFSET} and ΔQ_{OFFSET}.

15. The device of claim **14**, wherein the calibration circuitry is further configured to determining the fractional capacitor code CI_{FRAC} by:

interpolating a line using a plurality of points with each point having a first dimension being a combined I-Q capacitor code $[I_{CODE}, Q_{CODE}]$, and a second dimension being a respective measured phase offset between the first low-pass filter and the second low-pass filter using a respective combined I-Q capacitor code; and

selecting a combined I-Q capacitor code value that corresponds to a substantially zero phase difference between the first low-pass filter and the second low-pass filter.

16. The device of claim **15**, wherein the calibration circuitry is further configured to use the fractional capacitor code C_{FRAC} to determine the capacitor code offset Δ_{OFFSET} by:

rounding the fractional capacitor code C_{FRAC} to a nearest integer to produce the capacitor code offset Δ_{OFFSET};

adding the capacitor code offset Δ_{OFFSET} to the first capacitor code I_{CODE} to produce the first compensated capacitor code $I_{C\text{-}CODE}$; and

adding the capacitor code offset Δ_{OFFSET} to the second capacitor code Q_{CODE} to produce the second compensated capacitor code $Q_{C\text{-}CODE}$.

17. The device of claim **15**, wherein using the fractional capacitor code CI_{FRAC} to determine the capacitor code offsets ΔI_{OFFSET} and ΔQ_{OFFSET} includes:

rounding to the nearest integer $[(1+\alpha\Delta fc)*\Delta C_{FRAC}]$ to produce the capacitor code offsets ΔI_{OFFSET} and ΔQ_{OFFSET}, where ΔC_{FRAC} is a difference between the first capacitor code CI_{FRAC} and the second capacitor code Q_{CODE}, a is a scaling factor derived from empirical data, and Δfc is a capacitor code difference corresponding to the cutoff frequency offset Δf;

adding the capacitor code offset ΔQ_{OFFSET} to the first capacitor code I_{CODE} to produce the first compensated capacitor code $I_{C\text{-}CODE}$; and

adding the capacitor code offset ΔQ_{OFFSET} to the second capacitor code Q_{CODE} to produce the second compensated capacitor code $Q_{C\text{-}CODE}$.

18. The device of claim **11**, wherein the device is configured to:

applies the first compensated capacitor code $I_{C\text{-}CODE}$ to the first low-pass filter; and

applies the second compensated capacitor code $Q_{C\text{-}CODE}$ to the second low-pass filter.

19. A wirelessly operating device that incorporates the device of claim **11**.

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