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**Kuo et al.**

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(54) **ULTRA-LOW POWER RECEIVER**

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

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See application file for complete search history.

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(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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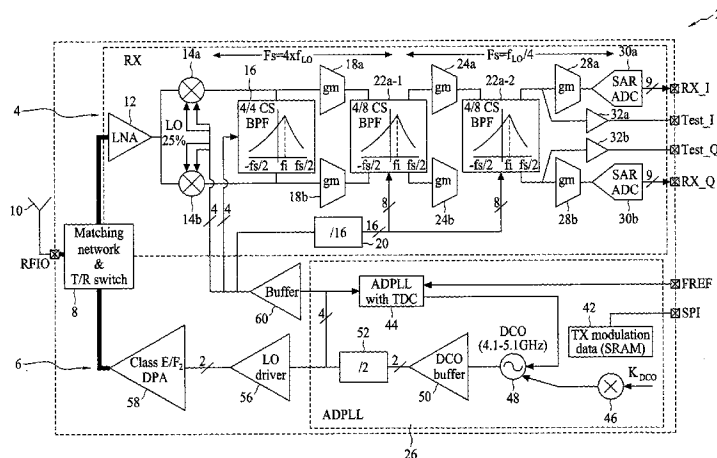
(57) **ABSTRACT**

An ultra-low-power receiver includes a low-noise amplifier configured to receive an input analog signal and generate an amplified signal and a mixer electrically coupled to the low-noise amplifier. The mixer is configured to convert said amplified signal into an intermediate frequency signal. A progressively reduced intermediate frequency filter is configured to process the intermediate frequency signal from the mixer in discrete time.

(51) **Int. Cl.**

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**H04L 29/08** (2006.01)

**20 Claims, 11 Drawing Sheets**



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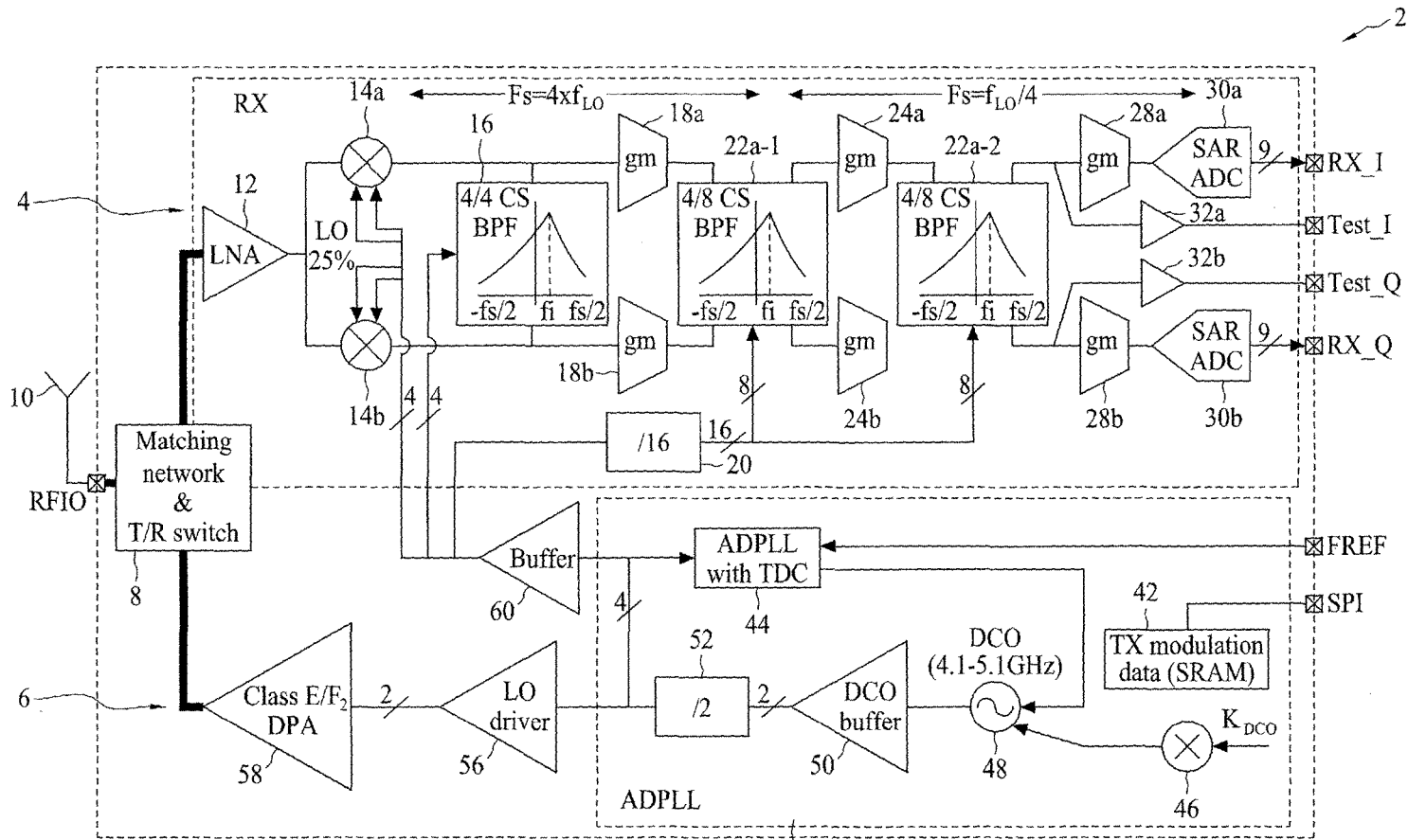


FIG. 1

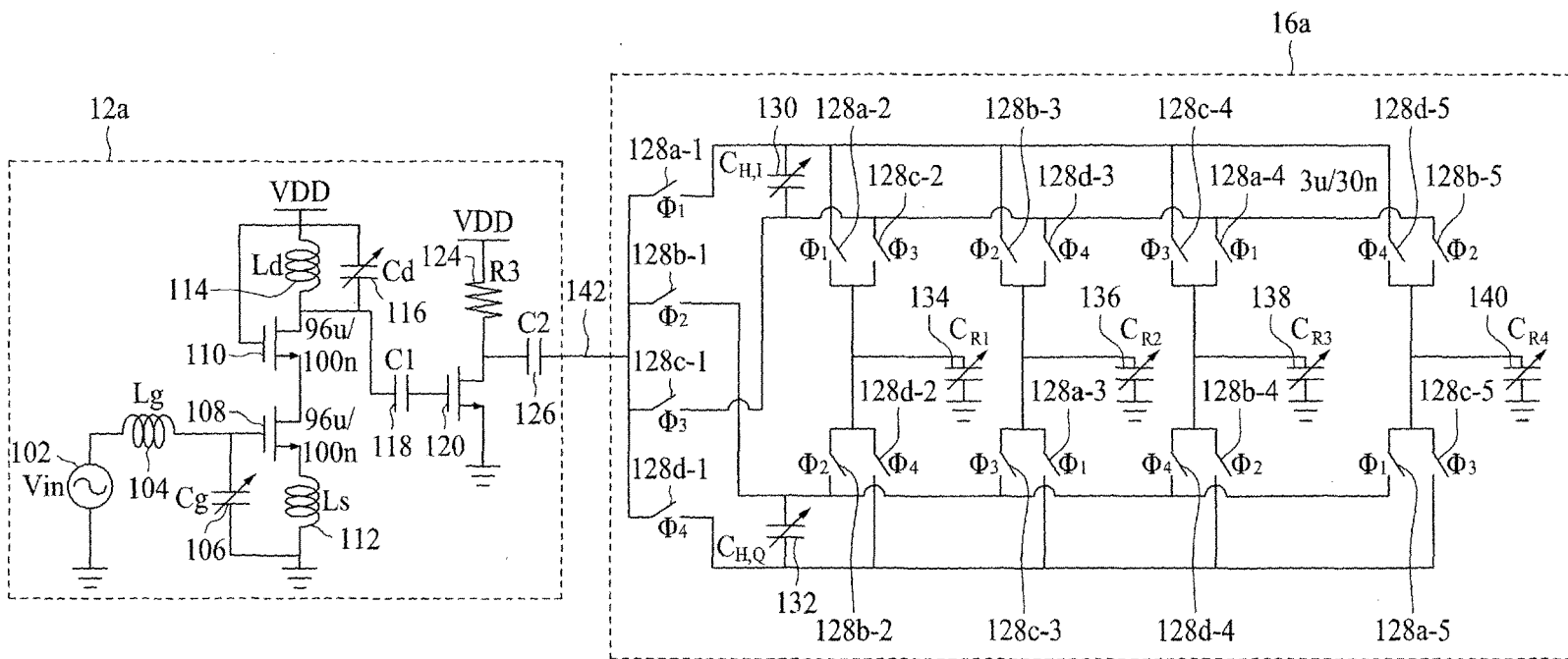


FIG. 2

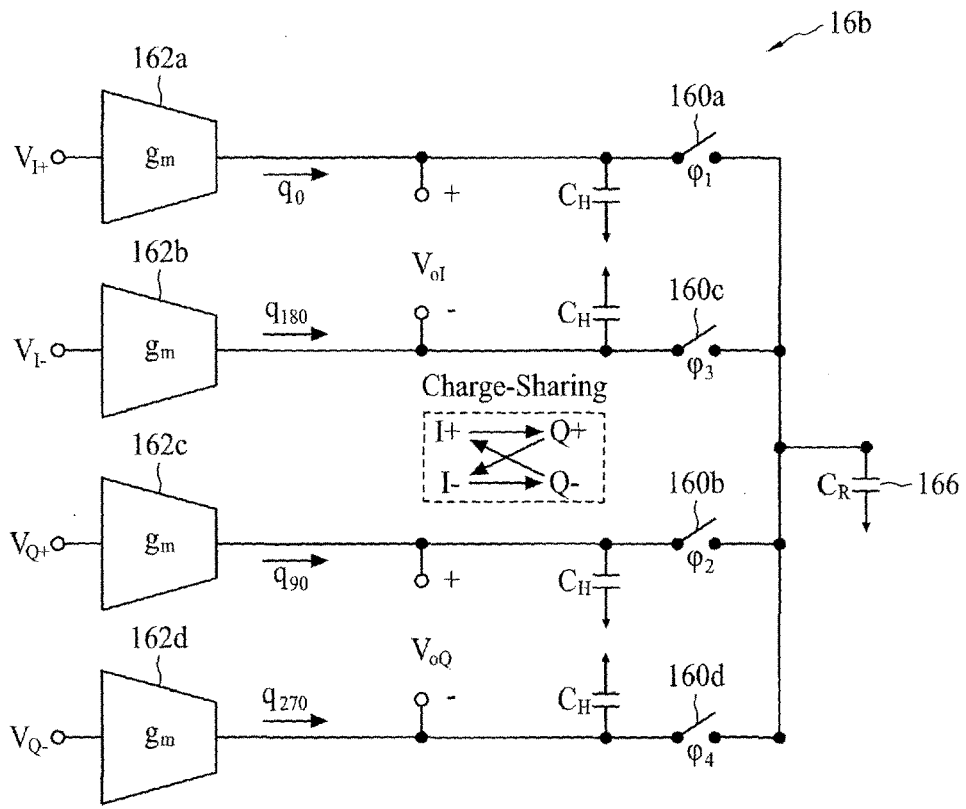


FIG. 3A

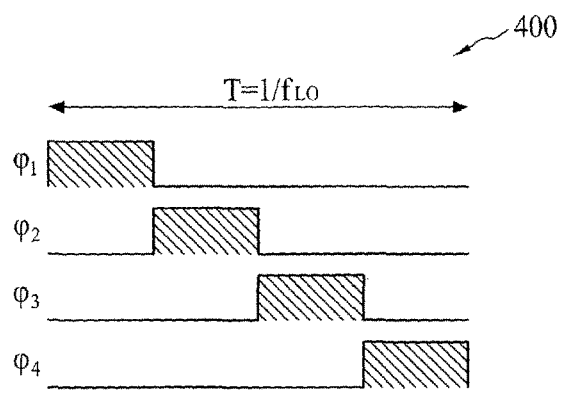


FIG. 3B

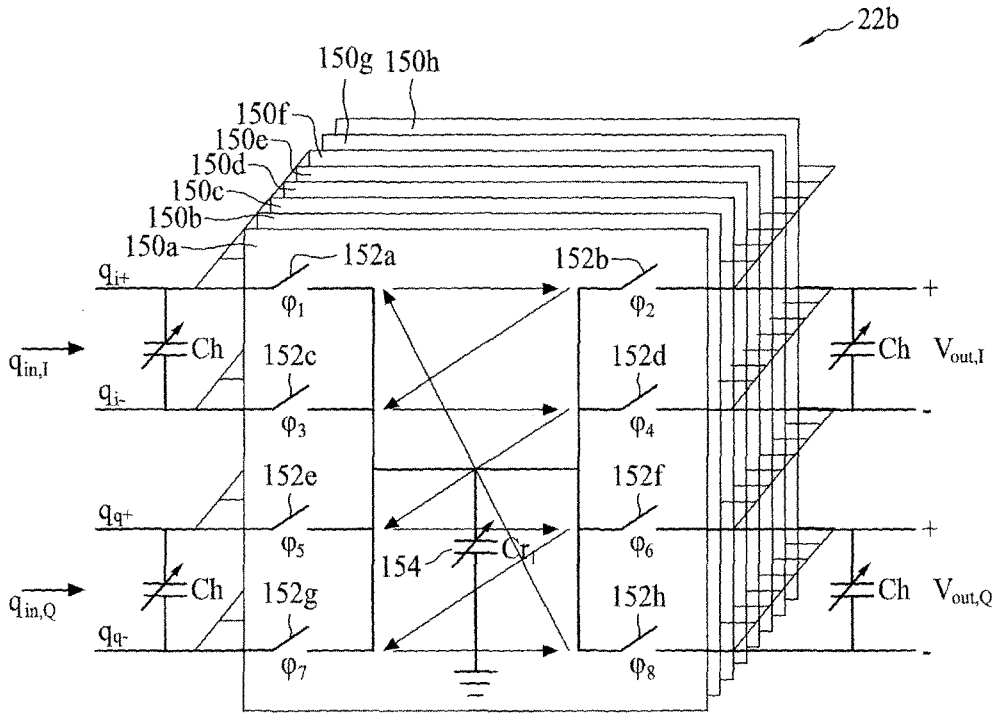


FIG. 4A

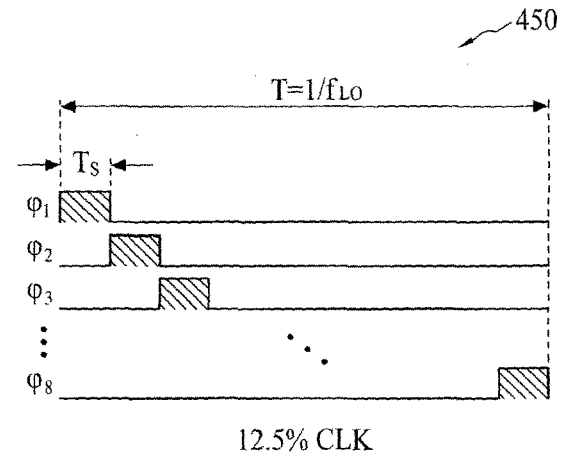


FIG. 4B

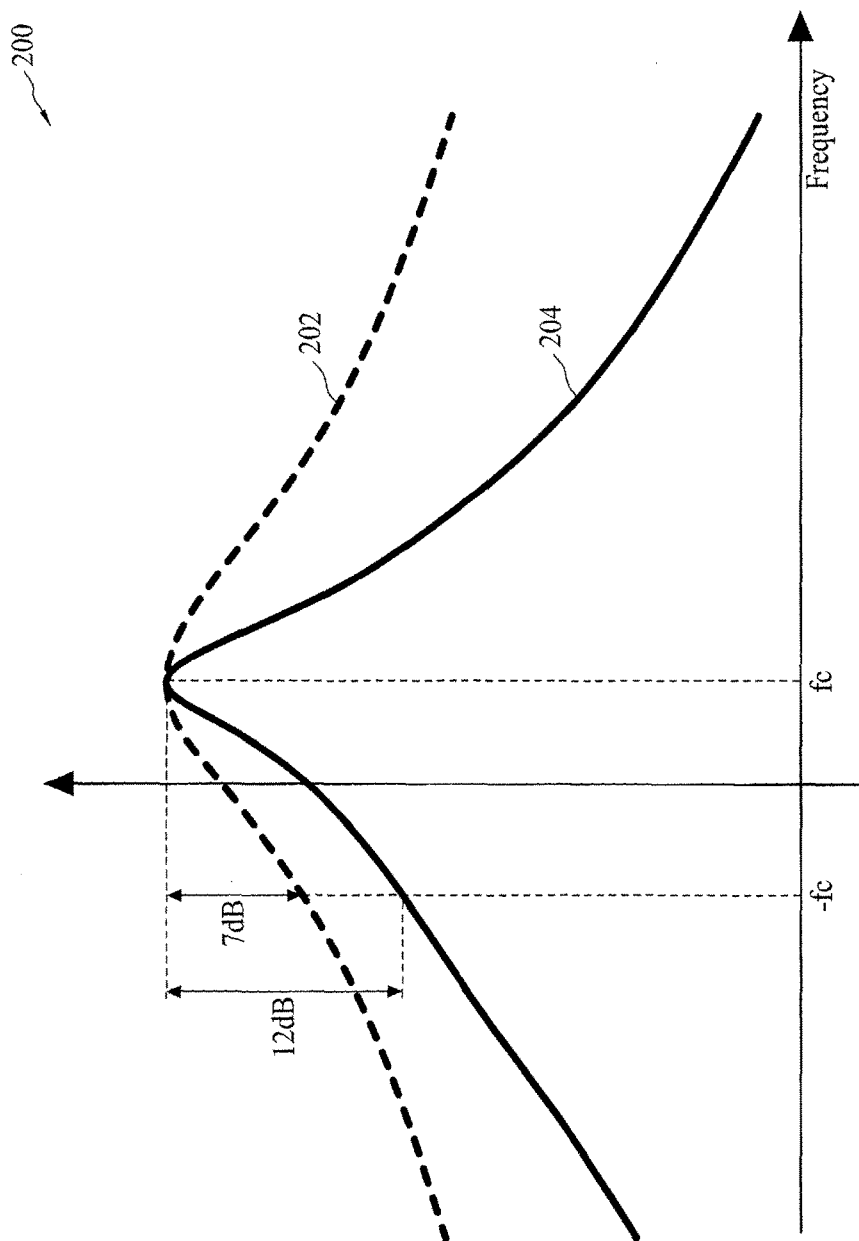


FIG. 5

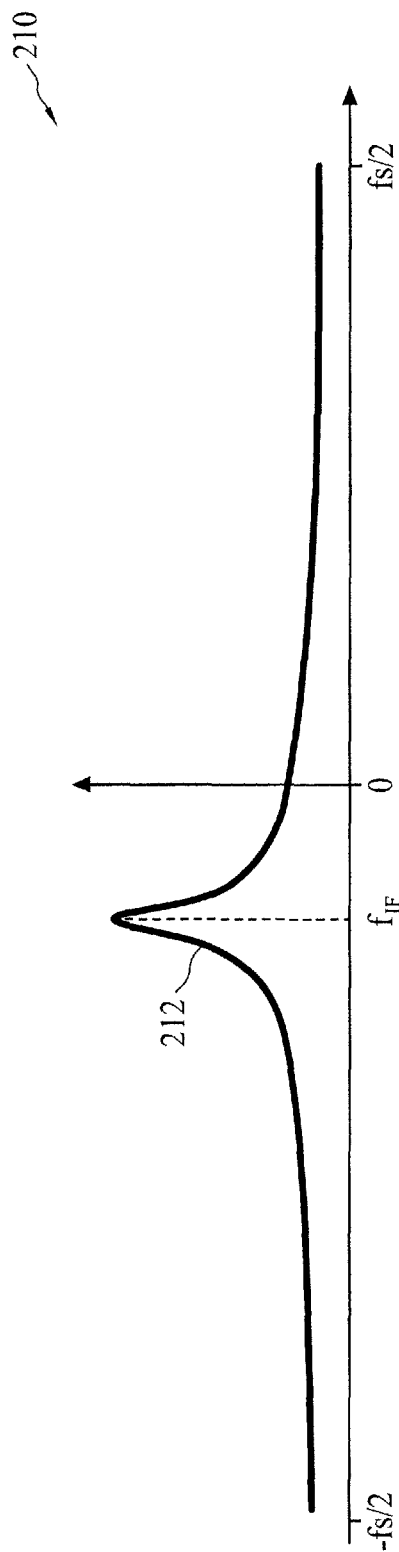


FIG. 6



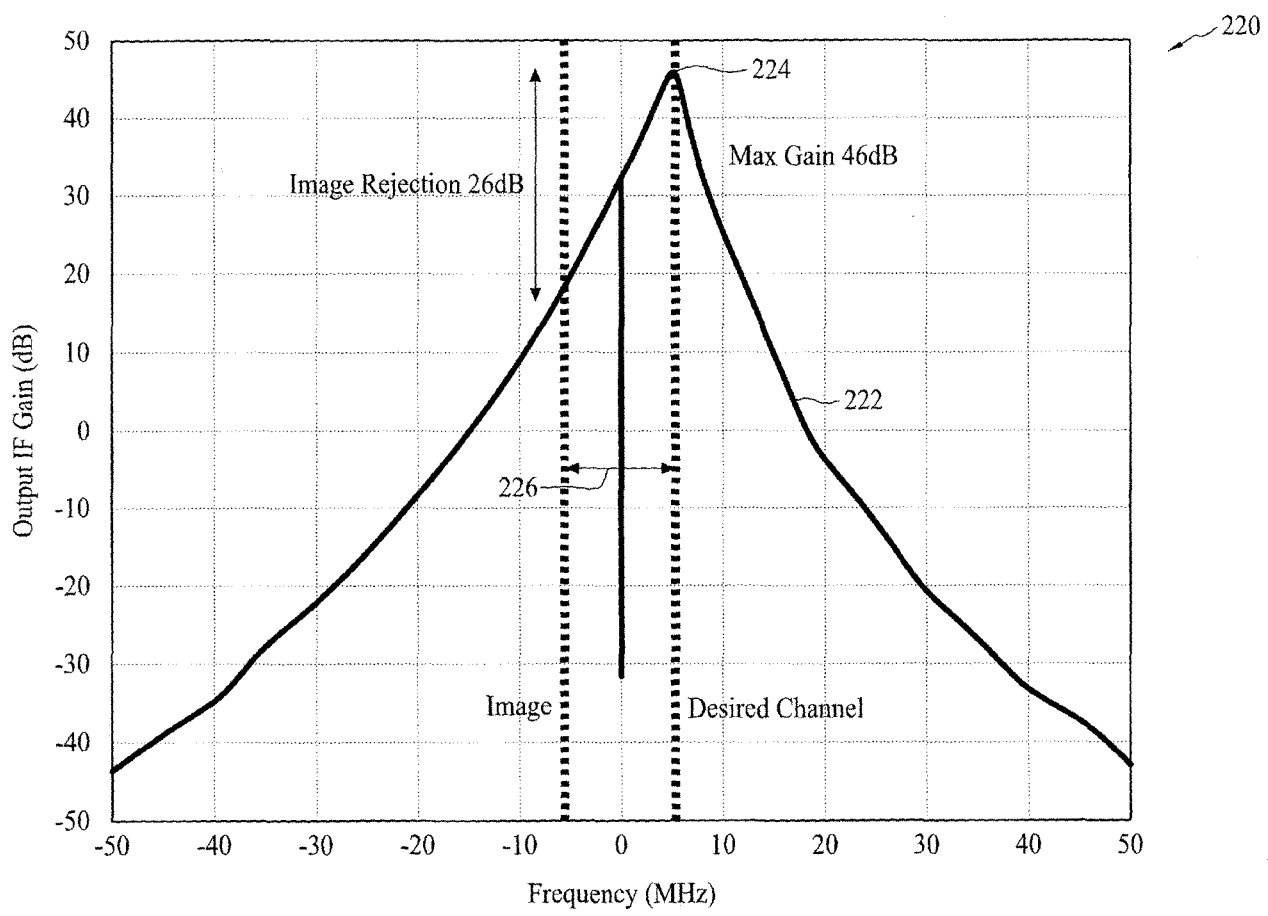


FIG. 7

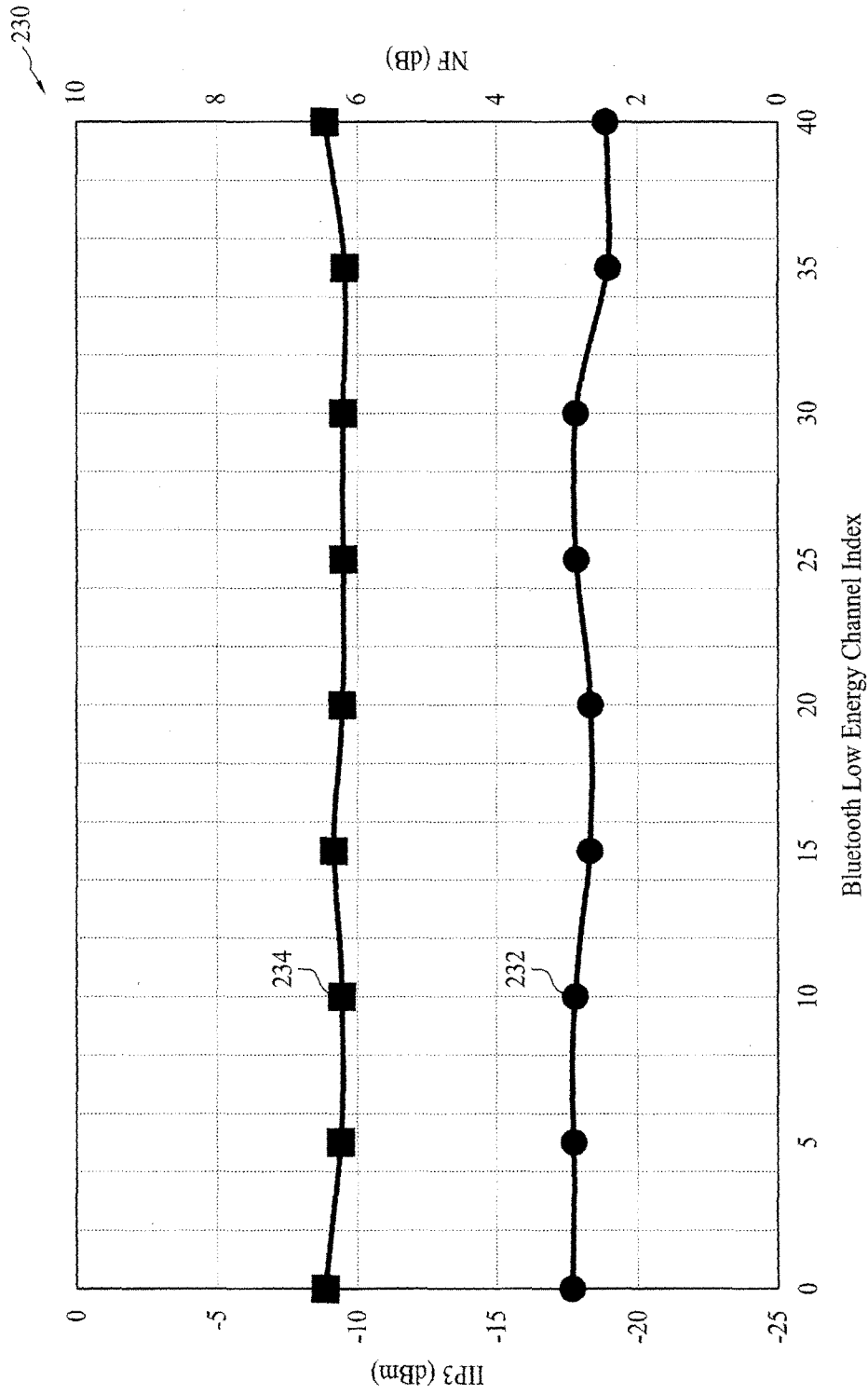


FIG. 8

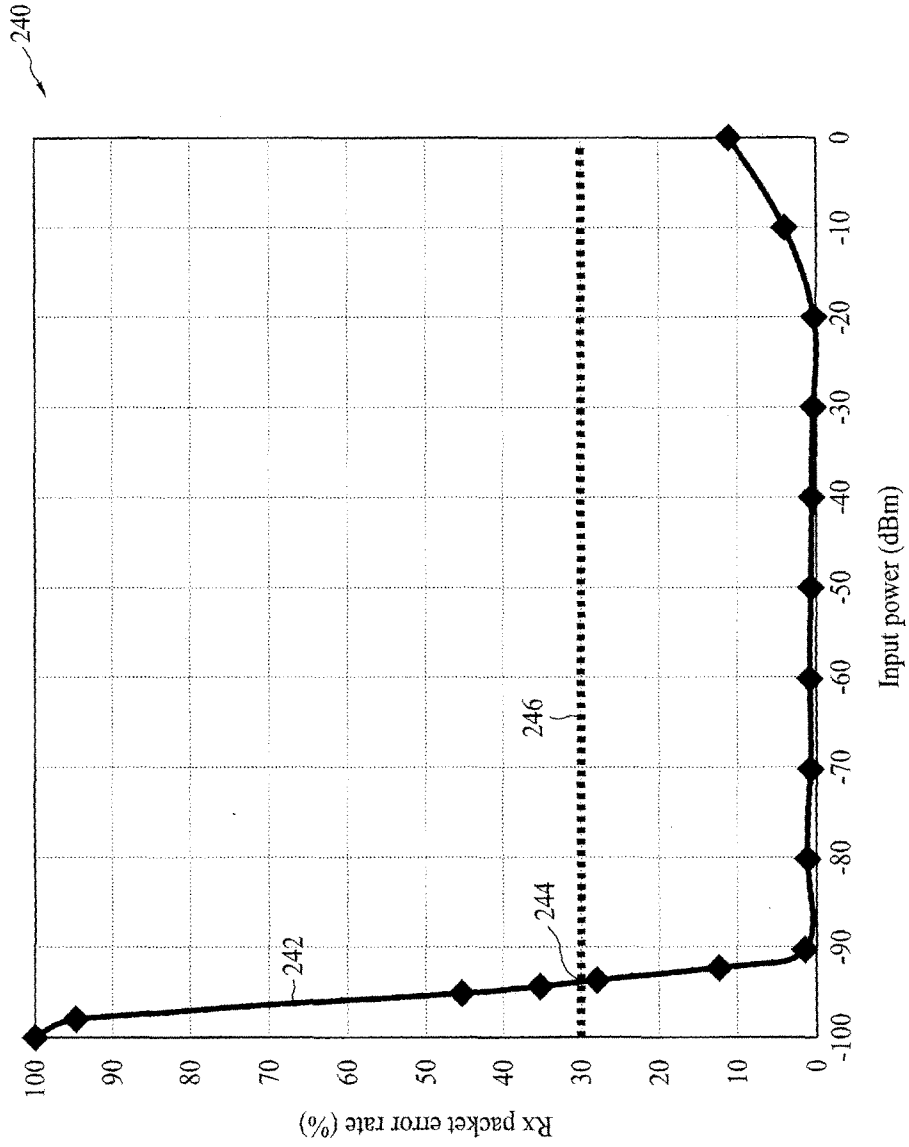


FIG. 9

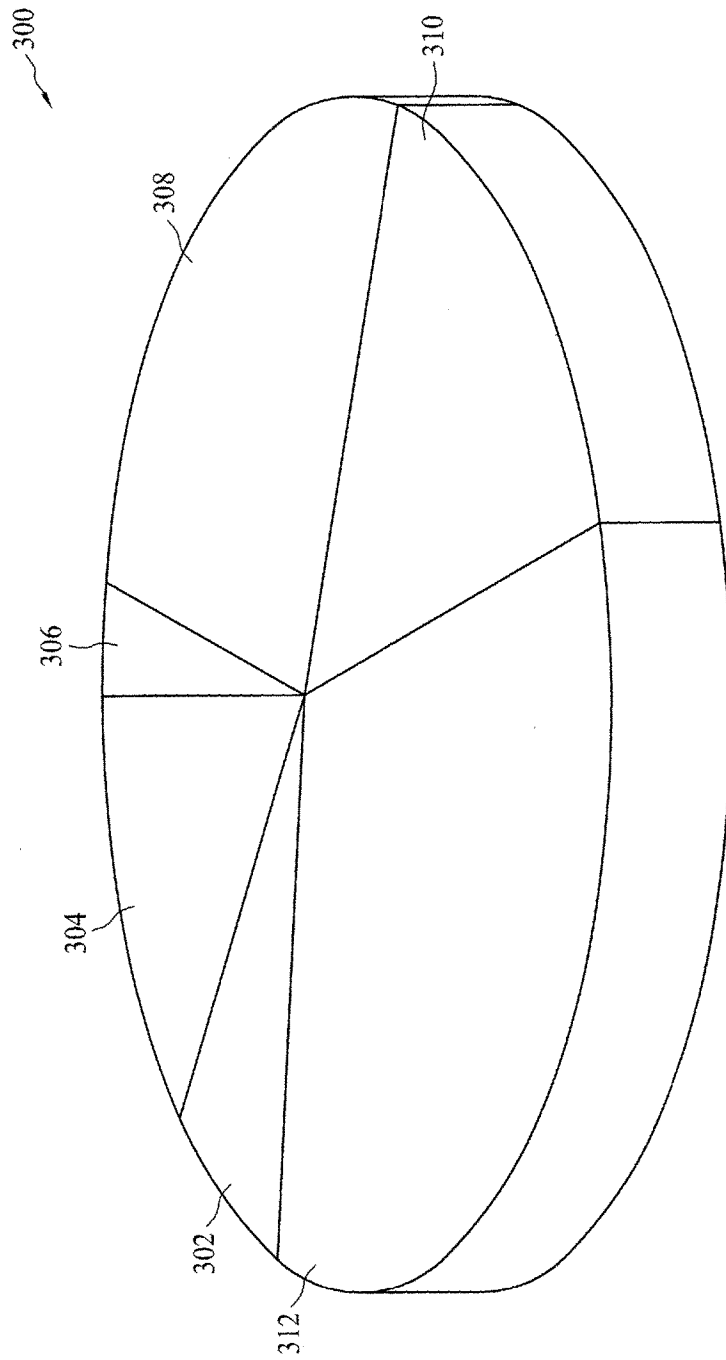


FIG. 10

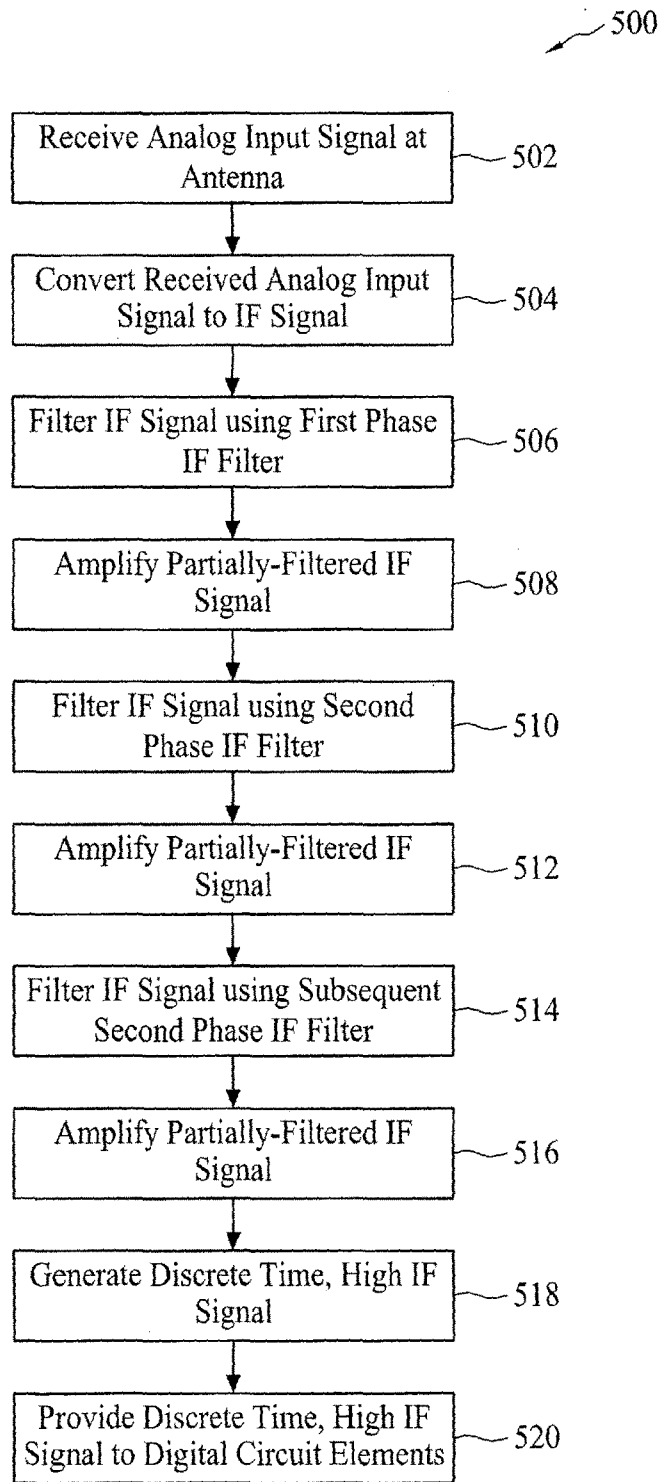


FIG. 11

## ULTRA-LOW POWER RECEIVER

## CROSS-REFERENCE TO RELATED APPLICATION

This application claims benefit of U.S. Provisional Patent Appl. Ser. No. 62/527,228, filed on Jun. 30, 2017, and entitled "ULTRA-LOW POWER RECEIVER," which is incorporated herein by reference in its entirety.

## BACKGROUND

Ultra-low-power wireless applications utilize radiofrequency (RF) transceivers powered by small power sources (such as coin cell batteries) to perform rapid burst transmission or reception of data. The ultra-low-power RF transceiver is maintained in a low-power, or sleep state, when not performing burst transmission/reception. Ultra-low-power transceivers are used in a variety of Internet of Things (IoT) implementations, including embedded devices, smart devices, smartphones, etc.

One use for ultra-low-power transceivers includes Bluetooth® Low Energy (BLE). BLE requires a minimum data packet error rate to ensure successful data transmission between ultra-low-power devices. Current ultra-low-power transceivers are unable to provide reduced power required by IoT devices with adequate noise filtering sufficient to maintain the minimum data packet error rate of BLE.

## BRIEF DESCRIPTION OF THE FIGURES

Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, various features are not necessarily drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

FIG. 1 illustrates an ultra-low-power transceiver including an ultra-low-power discrete-time receiver and an ultra-low-power transmitter, in accordance with some embodiments.

FIG. 2 illustrates a low-noise transconductance amplifier (LNTA) and four-phase charge-sharing band-pass filter of an ultra-low-power discrete time receiver, in accordance with some embodiments.

FIG. 3A illustrates a four-phase charge-sharing band-pass filter, in accordance with some embodiments.

FIG. 3B illustrates a control signal timing diagram of the four-phase charge-sharing band-pass filter of FIG. 3A, in accordance with some embodiments.

FIG. 4A illustrates an eight-phase charge-sharing band-pass filter, in accordance with some embodiments.

FIG. 4B illustrates a control signal timing diagram of the eight-phase charge-sharing band-pass filter of FIG. 4A, in accordance with some embodiments.

FIG. 5 illustrates a frequency response of the four-phase charge-sharing band-pass filter of FIG. 3A and the eight-phase charge-sharing band-pass filter of FIG. 4A, in accordance with some embodiments.

FIG. 6 illustrates a frequency response of an ultra-low-power receiver, in accordance with some embodiments.

FIG. 7 illustrates an intermediate frequency (IF) transfer function of an ultra-low-power receiver, in accordance with some embodiments.

FIG. 8 is a graph illustrating an input power level (IIP3) and a noise figure (NF) of an ultra-low-power discrete-time receiver, in accordance with some embodiments.

FIG. 9 is a graph illustrating receiver sensitivity of an ultra-low-power discrete-time receiver, in accordance with some embodiments.

FIG. 10 is a chart illustrating power usage of an ultra-low-power discrete-time receiver, in accordance with some embodiments.

FIG. 11 is flow chart illustrating a method of generating a discrete time, high IF signal, in accordance with some embodiments.

## DETAILED DESCRIPTION

The following disclosure provides many different embodiments, or examples, for implementing different features of the subject matter. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. For example, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed.

In various embodiments, a fully discrete-time (DT), high intermediate frequency (IF) transmission architecture is disclosed. The fully DT, high IF transmission architecture includes an ultra-low-power receiver. An ultra-low-power transmitter can be coupled to the transmission architecture. The ultra-low-power discrete-time receiver includes a low-noise amplifier, at least one mixer coupled to the low-noise filter, and an intermediate frequency filter configured to process an intermediate frequency signal in discrete time. The intermediate frequency filter can include a plurality of progressively reduced intermediate frequency filters to generate a discrete time, high intermediate frequency output signal. The discrete time, high intermediate frequency output signal can be digitized by one or more analog-to-digital converters and provided to signal processing circuitry, such as a signal processor.

FIG. 1 illustrates an ultra-low-power transceiver 2, in accordance with some embodiments. The ultra-low-power transceiver 2 includes an ultra-low-power discrete-time receiver 4 and an ultra-low-power transmitter 6. Each of the ultra-low-power discrete-time receiver 4 and the ultra-low-power transmitter 6 is coupled to a matching network 8 including a transmit/receive switch configured to selectively couple one of the ultra-low-power discrete-time receiver 4 or the ultra-low-power transmitter 6 to an antenna 10. The matching network 8 matches the impedance of the antenna 10 to the impedance of a selected one of the ultra-low-power discrete-time receiver 4 or the ultra-low-power transmitter 6.

In some embodiments, the ultra-low-power receiver 4 is configured to receive a signal from the antenna 10 and convert the signal to one or more discrete-time, high IF output signals, such as RX\_I and RX\_Q. The ultra-low-power receiver 4 can include a low-noise amplifier (LNA) 12 configured to receive an input signal from the matching network 8. Although embodiments are discussed herein

including an LNA, it will be appreciated that the ultra-low-power receiver **4** can include any suitable amplifier, such as a low-noise amplifier, a low-noise transconductance amplifier (LNTA), an inductor-capacitor (LC) tank filter, and/or any other suitable LNA. An embodiment of the LNA **12** is discussed in more detail below with respect to FIG. **3**.

In some embodiments, the amplified analog signal is provided by the LNA **12** to a plurality of mixers **14a**, **14b**. The mixers **14a**, **14b** are each configured to receive a local oscillator (LO) signal (or quadrature signal) and the amplified analog signal. The LO signal can be provided by any suitable circuit element, such as, for example, a buffer **60** in the transmission side **6** of the ultra-low-power transceiver **2**, an independent local oscillator clock, and/or any other suitable circuit element. In some embodiments, each of the mixers **14a**, **14b** are configured to utilize a predetermined duty cycle of the LO signal. For example, in the illustrated embodiment, each of the mixers utilize a 25% duty cycle of the LO signal, although it will be appreciated that the mixers **14a**, **14b** can use any suitable duty cycle. Because the mixers **14a**, **14b** utilize a 25% duty cycle, the effective charge-sampling operation of the mixers **14a**, **14b** occurs at a frequency equal to  $4f_{LO}$ , where  $f_{LO}$  is the frequency of the local oscillator signal. The mixers **14a**, **14b** can include any suitable mixer, such as a single-to-differential passive mixer, a quadrature mixer, or any other suitable mixer. The mixers **14a**, **14b** convert the received amplified analog signal into an intermediate frequency (IF) signal based on the received LO signal. In some embodiments, the LO signal and the mixer **14a**, **14b** are selected such that the IF signal generated by the mixers **14a**, **14b** is set beyond a flicker corner (i.e.,  $1/f$  noise) of one or more noise transistors in the mixers **14a**, **14b**.

The IF signal from the mixers **14a**, **14b** is provided to a plurality of progressively reduced sampling rate filters to generate discrete-time, high IF output signals. For example, in the illustrated embodiment, the IF signal is provided to a first phase IF filter **16** and a plurality of second phase IF filters **22a-1**, **22a-2**. The first phase IF filter **16** is configured to sample the IF signal received from the mixers **14a**, **14b** at a predetermined sampling rate. For example, in the illustrated embodiment, the first phase IF filter **16** is configured to sample the IF signal at a frequency of about  $4f_{LO}$ . The first phase IF filter **16** can include any suitable filter, such as a four-phase band-pass filter (BPF). The first phase IF filter **16** can include any suitable duty cycle, such as, for example, a 25% duty cycle. In some embodiments, the IF signal generated by the mixers **14a**, **14b** and provided to the progressively-reduced IF filters **16**, **22a** is set beyond a flicker corner (i.e.,  $1/f$  noise) of one or more noise transistors in the IF filters **16**, **22a**.

In some embodiments, the output of the first phase IF filter **16** is provided to one or more amplifiers **18a**, **18b**. The amplifiers **18a**, **18b** are configured to amplify the output of the first phase IF filter **16**. The amplified signal is provided to a second phase IF filter **22a-1** having a second sampling rate. The second phase IF filter **22a-1** is configured to sample and filter the amplified signal received from the first phase IF filter **16** and/or the amplifiers **18a**, **18b**. In some embodiments, the second phase IF filter **22a-1** includes a lower sampling rate as compared to the sampling rate of the first phase IF filter **16**. For example, in the illustrated embodiment, the second phase IF filter **22a-1** receives an input clock signal having a clock rate  $4\times$  slower than  $f_{LO}$  (e.g.,  $16\times$  slower than the sampling rate of the first phase IF filter **16**), although it will be appreciated that any other suitable lower sampling rate can be used.

The output of the second phase IF filter **22a-1** is provided to a plurality of analog amplifiers **24a**, **24b** which amplify the output signal and provide the amplified signal to an additional second phase IF filter **22a-2**. The additional second phase IF filter **22a-2** is similar to the initial second phase IF filter **22a-1**. The second phase IF filter **22a-2** is configured to sample and filter the amplified signal received from the initial second phase IF filter **22a-1**. Each of the second phase IF filters **22a** have the same sampling rate. For example, in the illustrated embodiment, each of the second phase IF filters **22a** receive an input clock signal having a clock rate  $4\times$  slower than  $f_{LO}$ . The second phase IF filters **22a** can include any suitable IF filters, such as, for example, 8-phase BPFs.

The sequential sampling by the first phase IF filter **16** and the second phase IF filters **22a** generates sufficient anti-aliasing filtering for conversion to discrete-time, high IF signals by the analog-to-digital converters (ADCs) **30a**, **30b**. In some embodiments, the output of second phase IF filter **22a-2** is amplified by analog amplifiers **28a**, **28b** prior to being provided to the ADCs **30a**, **30b**. The ADCs **30a**, **30b** can provide the discrete-time, high IF signals to one or more additional circuit elements, such as a digital signal processor.

In some embodiments, the ultra-low-power transmitter **6** is configured to receive a discrete-time signal from one or more additional circuit elements, such as a digital signal processor, and generate an analog signal for transmission by the antenna **10**. The ultra-low-power transmitter **6** includes an all-digital phase lock loop (ADPLL) **26**, a local oscillator driver **56**, and an amplifier **58**. The ADPLL **26** is configured to convert the discrete-time signal (SPI) received from the additional circuit elements into an analog signal. The analog signal is provided to the local oscillator driver **56**. The local oscillator driver **56** generates an output signal that is provided to an amplifier **58**. The amplifier **58** amplifies the output of the local oscillator driver **56** and provides the amplified output signal to the matching network **8** and the antenna **10**. In some embodiments, the amplifier **58** includes an all-digital power amplifier.

In some embodiments, the ADPLL **26** includes a two-staggered chain topology, as shown in the illustrated embodiment. The two-staggered chain topology includes a first chain having an ADPLL **44** including a time-to-digital convertor (TDC). The ADPLL **44** is configured to generate a first input signal of a digitally-controlled oscillator (DCO) **48**. The second input of the DCO **48** is generated by a second chain including a transmission modulation unit **42** and a mixer **46**. The DCO **48** receives the first input from the first chain and the second input from the second chain and generates an output analog signal. The analog signal is provided to a DCO buffer **50**. The analog output of the DCO buffer **50** can be provided to a divider **52**. The divider can be configured for any suitable division of the analog signal, such as, for example, a division by 2, 4, 8, 16, and/or any other suitable division. The divided output can be provided to the LO driver **56**.

In some embodiments, the divided output of the divider **52** can be further provided to a buffer **60**. The buffer **60** can be configured to generate one or more clock signals for the ultra-low-power receiver **4**, such as a clock signal provided to one or more of the IF filters **16**, **22a**. In other embodiments, the buffer **60** can be omitted and the clock signals of the ultra-low-power receiver **4** can be generated by a separate clock circuit (not shown).

The ultra-low power receiver **4** is robust to process, voltage, and temperature (PVT) variation. The IF filters **16**,

**22a** include a center frequency that is defined by one or more capacitor ratios and sampling rates of the IF filters **16**, **22a**. The capacitor ratios are insensitive to PVT variation. In addition, the sampling rates are generated by clock division from a stable reference, such as the DCO **48** and divider **52**. The capacitor ratios and sampling rates are controlled during manufacture. For example, capacitor banks of each of the IF filters **16**, **22a** can be digitally-programmed using binary-weighted capacitor arrays. Control of capacitor ratios and sampling rates of the filters **16**, **22a** during manufacturing provides precise control of the bandwidth of each of the filters **16**, **22a**. Control of the capacitor ratios further eliminates the need for transconductance, capacitance, and resistance calibration.

In some embodiments, the IF filters **16**, **22a** are passive, which provides excellent linearity and optimal power consumption. Power consumption in a passive filter structure (as described above) is due to turning on and/or off of switched-capacitor filters. By selecting an appropriate high-input impedance, the filters **16**, **22a** allow for the use of smaller transistors which are easier to turn on/off and therefore consume less power than traditional receivers. A high-input impedance also reduces transconductance at the amplifiers, as discussed in greater detail below.

FIG. 2 illustrates a low-noise transconductance amplifier (LNTA) **12a** coupled to a combination mixer and four-phase charge-sharing (CS) BPF **16a**, in accordance with some embodiments. The LNTA **12a** is similar to the LNA **12** discussed above, and similar description is not repeated herein. The LNTA **12a** is configured to receive an analog input signal **102**. The analog input signal **102** is provided to a gate of a first transistor **108**. A gate inductance  $L_g$  and a gate capacitance  $C_g$  are represented by respective inductor **104** and capacitor **106**. The first transistor **108** has a first source/drain terminal coupled to ground and including a source/drain inductance  $L_s$  represented by an inductor **112**. A second source/drain terminal of the first transistor **108** is coupled to a first source/drain terminal of a second transistor **110**.

The second transistor **110** includes a second source/drain terminal coupled to a first capacitor **118**. The second transistor **110** includes a source/drain capacitance  $C_d$  and a source/drain inductance  $L_d$  represented by capacitor **116** and inductor **114**, respectively. The gate of the second transistor **110** and the second source/drain terminal are coupled to an input voltage, VDD. The first capacitor **118** is coupled to a gate of a third transistor **120**. The third transistor **120** has a first source/drain terminal coupled to ground and a second source/drain terminal coupled to a resistor **124** and a second capacitor **126**. The resistor **124** is coupled to the supply voltage (VDD) and the second capacitor **126** is configured to provide an output signal to one or more circuit elements in an ultra-low-power receiver **4**, such as one or more amplifiers **14a**, **14b** and/or IF filters **16**.

The combined mixer and four phase BPF **16a** is similar to the mixers **14a**, **14b** and the first phase IF filter **16** discussed above, and similar description is not repeated herein. The combined mixer and four phase BPF **16a** includes a plurality of switches **128a-1** to **128a-5**, **128b-1** to **128b-5**, **128c-1** to **128c-5**, **128d-1** to **128d-5** (collectively switches **128**). Each of the switches **128** is controlled by a 25% duty cycle control signal. For example, in the illustrated embodiment, a first set of switches **128a-1-128a-4** (collectively “first switches **128a**”) are closed during a first 25% duty cycle of the LO signal, a second set of switches **128b-1-128b-4** (collectively “second switches **128b**”) are closed during a second 25% duty cycle of the LO signal, a third set of switches **128c-1-**

**128c-4** (collectively “third switches **128c**”) are closed during a third 25% duty cycle of the LO signal, and a fourth set of switches **128d-1-128d-4** (collectively “fourth switches **128d**”) are closed during a fourth 25% duty cycle of the LO signal. Although specific embodiments are discussed herein including a 25% duty cycle, it will be appreciated that the switches **128** can be controlled using any suitable duty cycle.

In some embodiments, the four-phase BPF **16a** receives an input **142** from the LNTA **12a** and/or one or more amplifiers **14a**, **14b**. The four-phase BPF **16a** samples the input signal and generates a filtered output signal. The filtered output signal can be generated by a plurality of rotating capacitors **134-140** each coupled to a subset of the switches **128** including a predetermined arrangement of the switches **128**. The switches **128** in each subset of switches are controlled by corresponding control signals having duty cycles of a percentage of the LO signal and couple the capacitors **134-140** in a rotating fashion to the input **142**. The rotating capacitors provide an anti-aliasing filtering (e.g., band-pass filtering) to the input analog signal. The rotating capacitors **134-140** generate a charge-sharing (CS) effect. In some embodiments, the LNTA **12a** is biased by a current mirror (not shown) to compensate for PVT variation.

FIG. 3A illustrates an alternative four-phase CS BPF **16b**, in accordance with some embodiments. The four-phase CS BPF **16b** is similar to the first phase IF filter **16** discussed above, and similar description is not repeated herein. The four-phase CS BPF **16b** receives a plurality of inputs, such as positive and negative I components (e.g.,  $V_{1+}$ ,  $V_{1-}$ ) and positive and negative Q components (e.g.,  $V_{Q+}$ ,  $V_{Q-}$ ). Each of the inputs is provided to an analog amplifier **162a-162d**. The analog amplifiers **162a-162d** are configured to amplify the input signals. The amplified I component signals have a first voltage differential ( $V_{oI}$ ) and the amplified Q component signals have a second voltage differential ( $V_{oQ}$ ). The four-phase CS BPF **16b** includes a rotating capacitor  $C_R$  and a plurality of history capacitors  $C_H$ .

In some embodiments, the four-phase CS BPF **16b** includes a plurality of switches **160a-160d** each coupled to one of the plurality of analog amplifiers **162a-162d**. Each of the switches **160a-160d** is controlled by a corresponding control signal  $\Phi_1$ - $\Phi_4$ . Each of the control signals  $\Phi_1$ - $\Phi_4$  is equivalent to a 25% duty cycle of the LO signal such that each of the switches **160a-160d** is closed for 25% of the duty cycle of the LO signal. Each of the control signals  $\Phi_1$ - $\Phi_4$  correspond to non-overlapping duty cycles. FIG. 3B is a graph **400** illustrating a plurality of control signals  $\Phi_1$ - $\Phi_4$  each corresponding to a 25% duty cycle of an LO signal having a frequency equal to  $f_{LO}$ . Each of the plurality of switches **160a-160d** are further coupled to a capacitor **166**. The capacitor **166** is charged by the sequential opening and closing of the plurality of switches **160a-160d**. The sequential (or rolling) charging provides anti-aliasing filtering for a received analog signal.

FIG. 4A illustrates an eight-phase CS BPF **22b**, in accordance with some embodiments. The eight-phase CS BPF **22b** is similar to the second phase IF filters **22a** discussed above, and similar description is not repeated herein. The eight-phase CS BPF **22a** includes a plurality of layers **150a-150h**. Each of the plurality of layers **150a-150h** includes a plurality of switches **152a-152h** and a capacitor **154a-154h**. In each of the layers **150a-150h**, a first subset of the plurality of switches **152a-152h** is coupled to a first input  $q_{in,1}$ , a second subset of the plurality of switches **152a-152h** is coupled to a second input  $q_{in,2}$ , a third subset of the plurality of switches **152a-152h** is coupled to a first output  $V_{out,1}$ , and a fourth subset of the plurality of switches



**152a-152h** is coupled to a second output  $V_{out,O}$ . Each of the switches **152a-152h** is further coupled to a first side of the capacitor **154**. Each of the switches **152a-152h** is controlled by a control signal  $\Phi_1-\Phi_8$  corresponding to a selected duty cycle of an LO signal. For example, in the illustrated embodiment, each of the switches **152a-152h** is controlled by a control signal  $\Phi_1-\Phi_8$  that is active (e.g., high) during a period corresponding to a 12.5% duty cycle portion of an LO signal having a frequency  $f_{LO}$ , although it will be appreciated that other corresponding duty cycles can be selected. FIG. 4B is a graph **450** illustrating a plurality of control signals  $\Phi_1-\Phi_8$  each corresponding to a 12.5% duty cycle of an LO signal having a frequency equal to  $f_{LO}$ .

Each of the layers **150a-150h** includes a different arrangement of switches **152a-152h** in each of the first set, second set, third set, and fourth set of switches. For example, in the illustrated embodiment, the first layer **150a** has a first set of switches including a first switch **152a** and a third switch **152c**, a second set of switches including a fifth switch **152e** and a seventh switch **152g**, a third set of switches including a second switch **152b** and a fourth switch **152d**, and a fourth set of switches including a sixth switch **152f** and an eighth switch **152h**. Each of the subsequent layers **150b-150h** includes a different arrangement of switches in each of the first, second, third, and fourth set of switches.

FIG. 5 is a graph **200** illustrating the frequency response **202**, **204** of the four-phase BPF filter **16b** and the eight-phase CS BPF filter **22b** respectively, in accordance with some embodiments. As shown in FIG. 5, each of the four-phase CS BPF **16a** and the eight-phase CS BPF **22b** has an equal center frequency  $f_c$ . The four-phase CS BPF **16a** frequency response **202** has a 7 dB drop at a negative center frequency and the eight-phase CS BPF **22b** frequency response **204** has a 12 dB drop at the negative center frequency.

FIG. 6 is a graph **210** illustrating a filtering response **212** of one embodiment of the ultra-low-power receiver **4** of FIG. 1, in accordance with some embodiments. As shown in FIG. 6, the progressively reduced CS BPFs **16**, **22a** of the ultra-low-power receiver **4** provides band-pass filtering with a sharp drop-off centered around the intermediate frequency (IF) of the signal without generating replica peaks, as commonly occurs in continuous time or N-path filters. The filtering response **212** provides sufficient anti-aliasing filtering for generating the discrete-time signal at the ADCs **30a**, **30b**.

FIG. 7 is a graph **220** illustrating a gain response **222** of one embodiment of the ultra-low-power receiver **4** of FIG. 1, in accordance with some embodiments. The gain response **222** includes a max gain of 46 dB at the desired intermediate frequency **224** and an image rejection of 26 dB outside of the target channel **226**. Although the illustrated embodiment includes an intermediate frequency **224** of about 5 MHz, it will be appreciated that the ultra-low-power receiver **4** has a similar response at any suitable intermediate frequency. FIG. 8 is a graph **230** illustrating a third order input power level (IIP3) **232** and a noise figure (NF) **234** of an ultra-low-power receiver **4** configured to operate within the Bluetooth Low Energy channel index (shown on the x-axis). The IIP3 **232** includes a minimum of about 19 dBm and the noise figure **234** includes an average value of about 6 dB. The minimum of about 19 dBm illustrates a high linearity of the CS BPFs **16**, **22a** of the ultra-low-power receiver **4**. The noise figure **234** of about 6 dB illustrates the ratio of the output noise power of the ultra-low-power receiver **4** attributable to thermal noise. A value of about 6 dB indicates a low thermal noise of the ultra-low-power receiver **4** as compared to traditional receivers.

FIG. 9 is a graph **240** illustrating receiver sensitivity **242** of an ultra-low-power discrete-time receiver, in accordance with some embodiments. The receiver sensitivity **242** illustrates the error packet rate of an ultra-low-power receiver, such as the ultra-low-power receiver **4** discussed above. As shown in FIG. 9, the ultra-low-power receiver **4** has a transmission packet error rate **244** of less than 30% at -95 dBm. A less than 30% error rate is sufficient for communication between IoT and other devices using ultra-low-power transceivers. For example, the BLE standard **246** requires a packet error rate of 30.8% at -95 dBm, which is satisfied by the disclosed ultra-low-power transceiver **2**. It will be appreciated that other transmission packet error rates are possible and are within the scope of this disclosure.

FIG. 10 is a pie chart **300** illustrating a percentage distribution of power usage for an ultra-low-power transceiver **2**, in accordance with some embodiments. The first percentage **302** corresponds to power usage of divider **20** (equal to about 0.2 mW), the second percentage **304** corresponds to power usage of a DCO **48** (equal to about 0.4 mW), the third percentage **306** corresponds to power usage of an ADC **30a**, **30b** (equal to about 0.25 mW), the fourth percentage **308** corresponds to power usage of an LNA **12** (equal to about 0.7 mW), the fifth percentage **310** corresponds to power usage of a buffer **60** (equal to about 0.4 mW), and the sixth percentage **312** corresponds to generation of the discrete-time intermediate frequency signal, for example, by the plurality of progressively reduced CS BPFs **16**, **22a** (equal to about 0.8 mW). As illustrated in FIG. 10, the power consumption of the progressively reduced CS BPFs **16**, **22a** is lower than power consumption found in traditional receivers using traditional band-pass filters. Although specific embodiments having specific power percentages are discussed herein, it will be appreciated that any suitable power percentage can be allocated for the circuit components of an ultra-low-power transceiver **2** in accordance with various embodiments.

FIG. 11 is a flow chart **500** illustrating operation of an ultra-low-power receiver, in accordance with some embodiments. At step **502**, a signal is received by an antenna **10**. The signal is a predetermined signal having a predetermined intermediate frequency and a predetermined modulation. At step **504**, the signal is provided from the antenna **10** to one or more mixers **14a**, **14b**. The mixers **14a**, **14b** are configured to convert the received signal to an intermediate frequency (IF) signal.

At step **506**, the IF signal is filtered by a first phase IF filter **16**. The first phase IF filter **16** is configured to filter the mixed signal at a first predetermined sampling rate. For example, in some embodiments, the first phase IF filter **16** is configured to sample the mixed signal at a sampling rate of  $4f_{LO}$ , where  $f_{LO}$  is the local oscillator frequency of the ultra-low-power transceiver **2**. It will be appreciated that other sampling rates can be used and are within the scope of this disclosure. The first phase IF filter **16a** generates a partially-filtered IF signal. At step **508**, the partially-filtered IF signal is amplified by one or more analog amplifiers **18a**, **18b**.

At step **510**, the partially-filtered IF signal is further filtered by a second phase IF filter **22a-1**. The second phase IF filter **22a-1** is configured to filter the partially-filtered IF signal at a second predetermined sampling rate. For example, in some embodiments, the second phase IF filter **22a-1** is configured to sample the partially-filtered IF signal at a sampling rate of  $f_{LO}/4$ . It will be appreciated that other sampling rates can be used and are within the scope of this

disclosure. In some embodiments, the second sampling rate is less than the first sampling rate.

At optional step 512, the partially-sampled IF signal generated by the second phase IF filter 22a-1 is amplified by one or more analog amplifiers 24a, 24b. At step 514, the amplified signal (or non-amplified partially-filtered IF signal of the second phase IF filter 22a-1) is provided to a subsequent second phase IF filter 22a-2 for further filtering and sampling. The subsequent second phase IF filter 22a-2 is configured to sample the partially-processed IF signal at the same sampling rate as the initial second phase IF filter 22a-1. The progressively reduced IF filters 16, 22a generate an analog signal having a strong IF with sufficient anti-aliasing filtering for generation of a discrete time, high IF signal.

At optional step 516, the output of the subsequent second phase IF filter 22a-2 is amplified by one or more analog amplifiers 28a, 28b. The output of the subsequent second phase IF filter 22a-2 is provided to one or more analog-to-digital converters 30a, 30b. At step 518, the analog-to-digital converters 30a, 30b generate the discrete time, high IF signal by digitizing the input analog signal having a strong IF. At step 520, the discrete time, high IF signal is provided to one or more digital circuit elements for signal processing.

In various embodiments, an ultra-low-power receiver is disclosed. The receiver includes a low-noise amplifier configured to receive an input analog signal and generate an amplified signal and a mixer electrically coupled to the low-noise amplifier. The mixer is configured to convert said amplified signal into an intermediate frequency signal. A progressively reduced intermediate frequency filter is configured to process the intermediate frequency signal from the mixer in discrete time.

In various embodiments, an ultra-low-power transceiver is disclosed. The ultra-low-power transceiver includes an antenna configured to receive an input analog signal, a receiver, and a transmitter. The receiver includes a low-noise amplifier configured to receive the input analog signal from the antenna and generate an amplified signal. A mixer is electrically coupled to the low-noise amplifier and is configured to convert said amplified signal into an intermediate frequency signal. A first-phase intermediate frequency filter having a first sampling rate and a second-phase intermediate frequency filter having a second sampling rate are progressively coupled to the mixer. The second sampling rate is lower than the first sampling rate.

In various embodiments, a method of generating a discrete time, high IF signal is disclosed. The method includes receiving an analog signal, converting the analog signal to an intermediate frequency signal, and filtering the intermediate frequency signal in discrete time. The intermediate frequency signal is filtered by a progressively-reduced intermediate frequency filter. A discrete time, high intermediate frequency signal is generated based on the filtered signal.

The foregoing outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may

make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

What is claimed is:

1. A receiver, comprising:

a low-noise amplifier configured to receive an input analog signal and generate an amplified signal, wherein the low-noise amplifier is single ended;

a mixer electrically coupled to the low-noise amplifier, the mixer configured to convert said amplified signal into an intermediate frequency signal;

a progressively reduced intermediate frequency filter configured to process the intermediate frequency signal from the mixer in discrete time, wherein the progressively reduced intermediate frequency filter comprises a first phase band-pass filter and a second phase band-pass filter, wherein the first-phase band pass filter is a four-phase band pass filter.

2. The receiver of claim 1, wherein the second phase band-pass filter is an eight-phase band pass filter.

3. The receiver of claim 1, wherein the first phase band-pass filter has a first sampling rate and the second phase band-pass filter has a second sampling rate, and wherein the first sampling rate is higher than the second sampling rate.

4. The receiver of claim 3, wherein the first sampling rate is equal to  $4f_{LO}$ , where  $f_{LO}$  is a local oscillator frequency used by the mixer and the second sampling rate is equal to  $f_{LO}/4$ .

5. The receiver of claim 1, wherein the first phase band-pass filter comprises a first set of switches coupled to a first capacitor, a second set of switches coupled to a second capacitor, a third set of the switches coupled to a third capacitor, and a fourth set of switches coupled to a fourth capacitor.

6. The receiver of claim 5, wherein each of the first set, the second set, the third set, and the fourth set of switches includes one of a first switch, a second switch, a third switch, and a fourth switch each operated at a duty cycle equal to 25% of a local oscillator frequency.

7. The receiver of claim 1, wherein the second phase band-pass filter comprises a first set of switches coupled to a first capacitor, a second set of switches coupled to a second capacitor, a third set of the switches coupled to a third capacitor, a fourth set of switches coupled to a fourth capacitor, a fifth set of switches coupled to a fifth capacitor, a sixth set of switches coupled to a sixth capacitor, a seventh set of the switches coupled to a seventh capacitor, and an eighth set of switches coupled to an eighth capacitor.

8. The receiver of claim 7, wherein each of the sets of switches includes one of a first switch, a second switch, a third switch, a fourth switch, a fifth switch, a sixth switch, a seventh switch, and an eighth switch each operated at a duty cycle equal to 12.5% of a local oscillator frequency.

9. The receiver of claim 1, wherein the progressively reduced intermediate frequency filter comprises at least one charge-sharing intermediate frequency filter.

10. The receiver of claim 1, comprising an analog-to-digital converter electrically coupled to the progressively reduced intermediate frequency filter and configured to provide a discrete-time output signal.

11. The receiver of claim 1, wherein said amplified signal is a current signal.

12. A receiver, comprising:

a low-noise amplifier configured to receive an input analog signal and generate an amplified signal, wherein the low-noise amplifier is single ended;

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a mixer electrically coupled to the low-noise amplifier, the mixer configured to convert said amplified signal into an intermediate frequency signal;

a progressively reduced intermediate frequency filter configured to process the intermediate frequency signal from the mixer in discrete time, wherein the progressively reduced intermediate frequency filter comprises a first phase band-pass filter and a second phase band-pass filter, wherein the low-noise amplifier comprises an inductor-capacitor (LC) tank filter.

13. The receiver of claim 12, wherein the first phase band-pass filter has a first sampling rate and the second phase band-pass filter has a second sampling rate, and wherein the first sampling rate is higher than the second sampling rate.

14. The receiver of claim 13, wherein the first sampling rate is equal to  $4f_{LO}$ , where  $f_{LO}$  is a local oscillator frequency used by the mixer and the second sampling rate is equal to  $f_{LO}/4$ .

15. The receiver of claim 12, wherein the first-phase band pass filter is a four-phase band pass filter.

16. The receiver of claim 15, wherein the second phase band-pass filter is an eight-phase band pass filter.

17. An ultra-low-power transceiver, comprising:  
 an antenna configured to receive an input analog signal;  
 a receiver, comprising:

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a low-noise amplifier configured to receive the input analog signal from the antenna and generate an amplified signal;

a mixer electrically coupled to the low-noise amplifier, the mixer configured to convert said amplified signal into an intermediate frequency signal;

a first-phase intermediate frequency filter having a first sampling rate; and

a second-phase intermediate frequency filter having a second sampling rate, wherein the second sampling rate is lower than the first sampling rate; and

a transmitter coupled to the antenna.

18. The ultra-low-power transceiver of claim 17, wherein the first sampling rate is equal to  $4f_{LO}$  and the second sampling rate is equal to  $f_{LO}/4$ , where  $f_{LO}$  is a local oscillator frequency.

19. The ultra-low-power transceiver of claim 17, wherein at least one of the first-phase intermediate frequency filter or the second-phase intermediate frequency filter is a charge-sharing filter.

20. The ultra-low-power transceiver of claim 17, wherein at least one of the first-phase intermediate frequency filter or the at least one second-phase intermediate frequency filter is a band-pass filter.

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