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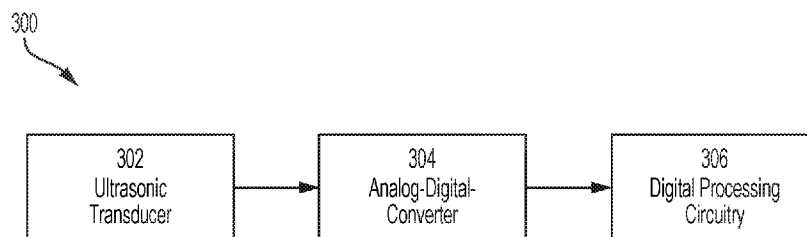


FIG. 3

(57) Abstract: An ultrasound device is describe in which analog ultrasonic transducer output signal are directly converted to digital signals. The ultrasound device includes microfabricated ultrasonic transducers directly coupled to a sigma delta analog-to-digital converter in some instances. The direct digital conversion may allow for omission of undesirable analog processing stages in the ultrasound circuitry chain. In some situations, the ADC may be integrated on the same substrate as the ultrasound transducer.



ANALOG TO DIGITAL SIGNAL CONVERSION IN ULTRASOUND DEVICE

RELATED APPLICATIONS

[0001] This Application claims the benefit under 35 USC §119(e) of U.S. Provisional Patent Application Serial No. 62/522,625, filed June 20, 2017 under Attorney Docket No. B1348.70049US00, and entitled "ANALOG TO DIGITAL SIGNAL CONVERSION IN ULTRASOUND DEVICE," which is hereby incorporated herein by reference in its entirety.

BACKGROUND

Field

[0002] The present application relates to ultrasound devices and the conversion of analog ultrasound transducer signals into digital signals.

Related Art

[0003] Ultrasound probes often include one or more ultrasound sensors which sense ultrasound signals and produce corresponding electrical signals. The electrical signals are processed in the analog or digital domain. Sometimes, ultrasound images are generated from the processed electrical signals.

BRIEF SUMMARY

[0004] According to an aspect of the present application, an ultrasound apparatus is provided, comprising an ultrasound sensor and an analog-to-digital converter (ADC) directly coupled to the ultrasound sensor to convert an analog output signal of the sensor into a digital signal. The ultrasound device may lack analog processing circuitry electrically between the ultrasound sensor and the ADC.

[0005] According to an aspect of the present application, a method of operating an ultrasound device is provided, comprising directly converting an analog electrical signal output by a microfabricated ultrasonic transducer into a digital signal.

[0006] According to an aspect of the present application, an ultrasound on a chip device is provided, comprising analog-to-digital converters (ADCs) directly coupled to

ultrasonic transducers and configured to convert analog output signals of the ultrasonic transducers into digital signals.

[0007] According to an aspect of the present application, an ultrasound on a chip device is provided, comprising a micromachined ultrasonic transducer (MUT), and an analog-to-digital converter (ADC) coupled to the MUT without intervening analog processing circuitry.

[0008] According to an aspect of the present application, an ultrasound device is provided, comprising a first substrate having a plurality of micromachined ultrasonic transducers integrated thereon, a second substrate having an analog-to-digital converter (ADC) integrated thereon, the ADC being coupled to an output of an ultrasonic transducer of the plurality of ultrasonic transducers without intervening analog processing circuitry, and transmit circuitry integrated on the second substrate, coupled to the plurality of ultrasonic transducers, and configured to control transmission of ultrasound signals by the plurality of ultrasonic transducers.

[0009] According to an aspect of the present application an ultrasound device is provided, comprising a first substrate having a plurality of micromachined ultrasonic transducers and transmit circuitry integrated thereon, the transmit circuitry coupled to the plurality of ultrasonic transducers and configured to control transmission of ultrasound signals by the plurality of ultrasonic transducers, and a second substrate having an analog-to-digital converter (ADC) integrated thereon, the ADC being coupled to an output of an ultrasonic transducer of the plurality of ultrasonic transducers without intervening analog processing circuitry.

[0010] According to an aspect of the present application, a method of operating an ultrasound device is provided, comprising converting an analog electrical signal output by a microfabricated ultrasonic transducer into a digital signal without first performing processing of the analog electrical signal in an analog domain.

BRIEF DESCRIPTION OF DRAWINGS

[0011] Various aspects and embodiments of the application will be described with reference to the following figures. It should be appreciated that the figures are not necessarily drawn to scale. Items appearing in multiple figures are indicated by the same reference number in all the figures in which they appear.

[0012] FIG. 1A is a block diagram of an ultrasound device including ultrasonic transducers, transmit circuitry, and receive circuitry on a single substrate.

[0013] FIG. 1B illustrates an alternative to the ultrasound device of FIG. 1A, in which the transmit circuitry and receive circuitry are divided among multiple substrates, according to a non-limiting embodiment of the present application.

[0014] FIG. 2 illustrates a non-limiting example of an ultrasound device including ultrasonic transducers, transmit circuitry, and receive circuitry having an analog-to-digital converter (ADC) coupled to an ultrasonic transducer without intervening analog processing circuitry, according to a non-limiting embodiment of the present application.

[0015] FIG. 3 illustrates an ultrasound signal chain in which an analog-to-digital converter is directly coupled to an ultrasonic transducer.

[0016] FIG. 4 illustrates an example of an ultrasonic transducer coupled with an ADC as may be implemented according to aspects of the present application.

[0017] FIG. 5 illustrates a non-limiting example of a digital-to-analog converter (DAC) having a controllable reference current.

DETAILED DESCRIPTION

[0018] Aspects of the present application relate to an ultrasound circuit including an ultrasonic transducer configured to produce an output (current or voltage) signal, and an analog-to-digital converter coupled directly to the ultrasonic transducer and configured to convert the analog signal from the ultrasonic transducer into a digital signal. In some embodiments, the transducer produces a current output signal, while in other embodiments the transducer produces a voltage output signal. The ADC may be coupled to the ultrasonic transducer without intervening analog processing circuitry, thus allowing for power savings by avoiding the power associated with analog processing such as amplification and filtering. For example, the circuit may lack a distinct amplifier (e.g., a trans-impedance amplifier or “TIA”), time gain compensation (TGC) circuit, and analog-to-digital converter driver. Still, the ADC may provide time gain compensation in at least some embodiments, thus providing an amplified digital signal representing the analog signal provided by the ultrasonic transducer.

[0019] According to an aspect of the present application, a method of processing electrical signals produced by an ultrasonic transducer is provided. The method comprises directly converting an analog electrical signal output by an ultrasonic transducer into a digital signal without first performing signal processing in the analog domain. Converting the analog signal to a digital signal may comprise performing time gain compensation. Subsequent to converting the electrical signal to a digital signal, further digital signal processing may optionally be performed.

[0020] According to an aspect of the present application, an ultrasound circuit includes an ADC with built-in time gain compensation (TGC) functionality. The ADC may include a digital-to-analog converter (DAC) with a controllable reference current. The reference current may be dynamically adjusted during a reception period in which the ultrasonic transducer receives an ultrasound signal, thus providing variable gain output from the ADC. As a result, a distinct analog TGC circuit may be omitted from the ultrasound circuit.

[0021] Aspects of the present application provide an ultrasound on a chip device comprising ultrasonic transducers and ADCs configured to digitize analog electrical signals produced by the ultrasonic transducers. The ultrasonic transducers may be microfabricated transducers, such as capacitive micromachined ultrasonic transducers (CMUTs), and the circuitry, such as the ADCs, may be integrated circuitry. The transducers and circuitry may be integrated on the same substrate, on different substrates, or a combination. For example, some of the circuitry may be integrated on a substrate with the transducers, while other circuitry may be on a separate substrate.

[0022] The aspects and embodiments described above, as well as additional aspects and embodiments, are described further below. These aspects and/or embodiments may be used individually, all together, or in any combination of two or more, as the application is not limited in this respect.

[0023] FIG. 1A is a block diagram of an ultrasound device including ultrasonic transducers, transmit circuitry, and receive circuitry on a single substrate, according to a non-limiting embodiment. As shown, the ultrasound device 100 comprises a substrate 102, an ultrasonic transducer arrangement 104, transmit circuitry 106, and receive circuitry 108.

[0024] The substrate 102 may be a semiconductor substrate, a complementary metal oxide semiconductor (CMOS) substrate (sometimes referred to herein simply as a

“MOS” substrate) or other substrate on which the illustrated components may be fabricated. As an example, the substrate 102 may be a silicon substrate or a composite substrate comprising a MEMS substrate bonded with a MOS substrate.

[0025] The ultrasonic transducers 102 may be microfabricated ultrasonic transducers in at least some embodiments. For example, CMUTs, piezoelectric micromachined ultrasonic transducers (PMUTs) or other microfabricated ultrasonic transducers may be used. Any suitable number and arrangement of the ultrasonic transducers may be used, as the various aspects of the present application are not limited in this respect. For example, the arrangement of ultrasonic transducers may include hundreds, thousands, tens of thousands, or hundreds of thousands of ultrasonic transducers. The transducers may be arranged in an array or any other suitable arrangement.

[0026] The transmit circuitry 106 may include analog and/or digital circuitry for controlling transmission of ultrasound signals from the ultrasonic transducers. Examples of suitable transmit circuitry are illustrated in FIG. 2 and described further below. For example, the transmit circuitry may include a decoder circuit, waveform generator, and a pulser. However, not all aspects of the present application include transmit circuitry, as some aspects of the present application are directed to an ultrasound receiver having receive circuitry for processing of received ultrasound signals.

[0027] The receive circuitry 108 may include analog and/or digital circuitry for processing ultrasound signals received by the ultrasonic transducers. According to an embodiment of the present application, the receive circuitry includes an ADC and digital processing circuitry configured to process the digital signals produced by the ADC. Further examples are described below in connection with FIGs. 2-4.

[0028] FIG. 1B illustrates an alternative ultrasound device 120 to the ultrasound device 100 of FIG. 1A, in which the transmit circuitry and receive circuitry are divided among multiple substrates, according to a non-limiting embodiment of the present application. The ultrasound device 120 includes two substrates, 122a and 122b, one or both of which may be any of the types of substrates described previously in connection with substrate 102, or any other suitable substrates. The substrates 122a and 122b need not be the same type of substrate as each other.

[0029] The division of transmit and receive circuitry across multiple substrates is non-limiting, as various implementations are possible. For example, analog transmit

circuitry may be on the substrate 122a with the ultrasonic transducers, while digital transmit circuitry may be on the substrate 122b. A receive switch may be on the substrate 122a, while digital receive circuitry may be on the substrate 122b. In some embodiments, all the receive circuitry 108 may be on either the substrate 122a or 122b, and the transmit circuitry may be divided across substrates 122a-122b. Alternatively the transmit circuitry may be entirely on either one of the substrates 122a-122b, and the receive circuitry may be divided between the substrates. Thus, various combinations are possible.

[0030] FIG. 2 illustrates a non-limiting example of an ultrasound device including ultrasonic transducers, transmit circuitry, and receive circuitry having an analog-to-digital converter (ADC) coupled to an ultrasonic transducer without intervening analog processing circuitry, according to a non-limiting embodiment of the present application. The ultrasound device 200 includes N ultrasonic transducers 202a...202n, wherein N is an integer. The ultrasonic transducers are sensors in some embodiments, producing electrical signals representing received ultrasound signals. The ultrasonic transducers may also transmit ultrasound signals in some embodiments. The ultrasonic transducers may be capacitive micromachined ultrasonic transducers (CMUTs) in some embodiments. The ultrasonic transducers may be piezoelectric micromachined ultrasonic transducers (PMUTs) in some embodiments. Alternative types of ultrasonic transducers may be used in other embodiments.

[0031] The ultrasound device 200 further comprises N circuitry channels 204a...204n. The circuitry channels may correspond to a respective ultrasonic transducer 202a...202n. For example, there may be eight ultrasonic transducers 202a...202n and eight corresponding circuitry channels 204a...204n. In some embodiments, the number of ultrasonic transducers 202a...202n may be greater than the number of circuitry channels.

[0032] The circuitry channels 204a...204n may include transmit circuitry, receive circuitry, or both. The transmit circuitry may include transmit decoders 206a...206n coupled to respective pulsers 208a...208n. The pulsers 208a...208n may control the respective ultrasonic transducers 202a...202n to emit ultrasound signals.

[0033] The receive circuitry of the circuitry channels 204a...204n may receive the (analog) electrical signals output from respective ultrasonic transducers 202a...202n. In the illustrated example, each circuitry channel 204a...204n includes a respective

receive circuit 210a...210n and an ADC 212a...212n. The receive circuit 210a...210n may be controlled to activate/deactivate readout of an electrical signal from a given ultrasonic transducer 202a...202n. An example of suitable receive circuits 210a...210n is a switch. That is, in one embodiment the receive circuits are controllable switches which are switched during transmit mode to disconnect the ultrasonic transducers from the receive circuitry and during receive mode to connect the ultrasonic transducers to the receive circuitry. Alternatives to a switch may be employed to perform the same function. It should thus be appreciated that the receive circuits 210a-210n may lack analog processing circuitry to process the analog signals produced by the respective ultrasonic transducers. Rather, the receive circuits 210a-210n may, in some embodiments, simply control provision of the analog electrical signals produced by the ultrasonic transducers to the remainder of the receive circuitry.

[0034] As shown, the receive circuitry further comprises ADCs 212a-212n. An example of a suitable ADC is illustrated in FIG. 4 and described further below. Generally, though, the ADCs may convert the analog electrical signals—which are current signals in at least some embodiments—produced by the ultrasonic transducers into digital signals. Optionally, the ADCs may have built-in TGC functionality, and thus may be considered a combined ADC and TGC circuit in some embodiments. Since, as described previously, the receive circuits 210a-210n may lack analog processing circuitry, the ultrasound device 200 represents an example of a device in which ADCs are coupled to the ultrasonic transducers without intervening analog processing circuitry. Thus, the analog output signals of the ultrasonic transducers may be digitized without performing analog processing (processing in the analog domain), in at least some embodiments.

[0035] Converting the analog signals produced by the ultrasonic transducers to digital signals without intervening analog processing may provide various benefits. For example, power may be reduced by omitting typical analog processing stages, such as analog amplification and filtering. Also, real estate on a chip or other substrate may be conserved by omitting analog processing components, allowing for a reduction in the size of the ultrasound device compared to alternatives implementing analog processing circuitry.

[0036] The ultrasound device 200 may further comprise digital processing circuitry 214, taking any suitable form and performing any desirable digital processing

functions. The digital processing circuitry may include a digital signal processor (DSP), a logic circuit, or any other suitable digital processing component. In the non-limiting example of FIG. 2, the digital processing circuitry 214 is illustrated as being shared by various circuitry channels. However, this illustration is non-limiting, as alternatives are possible. For example, further digital processing stages of the digital processing circuitry 214 may be specific to one or more of the circuitry channels.

[0037] In at least some embodiments, the digital processing circuitry 214 may perform decimation filtering owing to the lack of signal processing in the analog domain. Thus, a decimation filter 215 may be included and may be coupled at the output of the ADCs 212a-212n. While shown as part of the digital processing circuitry 214, the decimation filter 215 may alternatively be considered to be electrically between an ADC and the digital processing circuitry 214. That is, in some embodiments the decimation filter may be considered a separate component from the digital processing circuitry 214. In some embodiments, beamforming may be performed on the output signals of the ADCs 212a-212n prior to decimation with the decimation filter 215.

[0038] In some embodiments, additional processing in the digital domain may be performed to account for the analog characteristics of the circuit. For example, mapping of the digitized signal to the voltage as a function of time may be performed to account for the frequency response or other analog characteristics of the circuit.

[0039] While FIG. 2 illustrates a number of components as part of a circuit of an ultrasound device, it should be appreciated that the various aspects described herein are not limited to the exact components or configuration of components illustrated. For example, aspects of the present application may lack the transmit circuitry, the receive circuits 210a-210n, or other components.

[0040] The components of FIG. 2 may be located on a single substrate or on different substrates. For example, as illustrated, the ultrasonic transducers 202a...202n may be on a first substrate 216a and the remaining illustrated components may be on a second substrate 216b. The first and/or second substrates may be semiconductor substrates, such as silicon substrates, or any of the types of substrates described previously in connection with FIGs. 1A-1B. In an alternative embodiment, the components of FIG. 2 may be on a single substrate. For example, the ultrasonic transducers 202a...202n and the illustrated circuitry may be monolithically integrated on

the same die (e.g., a semiconductor die, such as silicon). Such integration may be facilitated by using CMUTs as the ultrasonic transducers.

[0041] According to an embodiment, the components of FIGs. 1A, 1B, or 2 form part of an ultrasound probe. The ultrasound probe may be handheld. In some embodiments, the components of FIGs. 1A, 1B, or 2 form part of an ultrasound patch configured to be worn by a patient, or part of an ultrasound pill to be swallowed by a patient.

[0042] As described, an aspect of the present application provides an ultrasound device having an ADC directly coupled to an ultrasonic transducer to convert analog electrical signals produced by the ultrasonic transducer into digital signals. FIG. 3 illustrates a non-limiting example. It should be appreciated that FIG. 3 may represent a subset of components of the ultrasound device of FIG. 2, namely the ultrasonic transducer, ADC, and further digital processing circuitry (e.g., digital processing circuitry 214 of FIG. 2).

[0043] The ultrasound signal processing chain 300 of FIG. 3 includes an ultrasonic transducer 302, and ADC 304, and digital processing circuitry 306. The ADC may be directly coupled the ultrasonic transducer, without intervening analog processing circuitry.

[0044] The ultrasonic transducer 302 may be any of the types described previously herein in connection with FIGs. 1A, 1B, and 2. The ADC 304 may be a sigma delta ADC, such as a sigma delta continuous time ADC. A non-limiting example is illustrated in FIG. 4 and described further below. The ADC 304 may optionally include built-in TGC functionality, such that the ADC 304 may be considered a combined ADC and TGC circuit. In some embodiments, such as that shown in FIG. 3, an ADC may be provided for a respective ultrasonic transducer. In alternative embodiments, an ADC may be shared among multiple (two or more) ultrasonic transducers.

[0045] The digital processing circuitry 306 may be any suitable digital processing circuitry, including any of the types described previously in connection with digital processing circuitry 214 of FIG. 2.

[0046] FIG. 4 illustrates a non-limiting example of a suitable ADC 400 coupled directly to an ultrasonic transducer, according to a non-limiting embodiment of the present application. The ADC 400 represents an example of the implementation of any

one of ADCs 212a-212n. The ultrasonic transducer 402 is represented schematically as a capacitor *C* and current source *II*. The ultrasonic transducer may be, for example, a CMUT which produces a current output signal, represented by the current source.

[0047] The ADC of FIG. 4 may include a summer (or, more generally, a combiner) 404, a loop filter 406, a quantizer 408, and a digital-to-analog converter (DAC) 410. The ADC may receive an analog current signal from the ultrasonic transducer 402, filter the signal with filter 406, digitize the signal with the quantizer 408 and output the digital signal 412. The digital signal may also be fed back to the summer 404 via the DAC 410 to be combined with the analog signal from the ultrasonic transducer.

[0048] The summer 404 may be any suitable type of combiner component. In at least some embodiments, the summer 404 subtracts the current output by the DAC 410 from the current output by the ultrasonic transducer 402. Thus, any suitable circuitry for performing such a subtraction may be implemented. Because the output of the transducer may be a current and the output of the ADC 400 may also be a current, one implementation of the summer 404 is simply a node. That is, the summer 404 may not be a distinct component in some embodiments, but rather the output of the DAC 410 may simply be tied to the output of the ultrasonic transducer 402.

[0049] The loop filter 406 may be any suitable type of loop filter. For example, a first order filter, second order filter, or third order filter may be implemented. The loop filter may be a low pass filter (LPF) or a bandpass filter (BPF), and may be implemented using one or more operational amplifiers (op-amps), a voltage controlled oscillator (VCO), or a combination thereof. In some embodiments, the loop filter 406 may be a continuous time filter, which may provide the benefit of anti-aliasing protection. Still further alternatives are possible.

[0050] The quantizer 408 may be any suitable quantizer, such as a 1-bit or 2-bit quantizer. A switch 409 is illustrated for completeness, since such a switch is sometimes implemented as part of the quantization process of the quantizer 408. The switch may be controlled by a clock signal, *CLK*, which may be any suitable clocking signal of any suitable frequency.

[0051] The DAC 410 may be any suitable DAC for converting the digital signal output by the quantizer 408 to an analog signal for comparison with the analog signal from the ultrasonic transducer 402. As previously described, the inventors have

appreciated that in some embodiments it may be desirable to provide time gain compensation for the output signal of the ultrasonic transducer. Typically, an ultrasound signal attenuates with time, and thus time gain compensation may be performed to facilitate processing and analysis of a received ultrasound signal. Rather than using a distinct TGC circuit, typically in analog form, aspects of the present application utilize a controllable DAC to provide variable gain. The DAC 410 may have a controllable (or “adjustable” or “programmable”) reference current. A non-limiting example of a suitable DAC with a controllable current is illustrated in FIG. 5 and described further below. Increasing the reference current may result in greater output signal from the DAC. Thus, aspects of the present application adjust or vary the DAC reference current during the time period corresponding to reception of an ultrasound signal by the ultrasonic transducer 402. In this manner, the gain of the DAC, and thus the ADC, may be increased over time, providing TGC functionality without a distinct TGC circuit. Because changing the reference current of the DAC can change the meaning of the resulting bit output, in some embodiments further processing of the DAC output signal is provided to map the output digital code of the ADC to an appropriate value for the given reference current value.

[0052] FIG. 5 illustrates a non-limiting example of a DAC 500 having a controllable reference current. In this non-limiting example, the DAC is a one-bit DAC, but other embodiments may employ a multi-bit DAC. The DAC 500 includes switches *SW1*, *SW2*...*SWn*, current sources *I1*, *I2*...*In*, switches *S1* and *S2*, switches *Sd1*, *Sd2*...*Sdn*, and current sources *Id1*, *Id2*...*Idn*. A supply is provided at node 502. The output is taken from node 504. Suitable control signals may be provided to the switches *SW1-SWn* and *Sd1-Sdn* to provide a desired reference current (+Iref or −Iref) as described above in connection with DAC 410. For example, if *S1* is ON it produces +Iref and if *S2* is ON it produces −Iref. In this manner, TGC functionality may be realized. Again, though other DACs, including multi-bit DACs may be employed in alternative embodiments.

[0053] As should be appreciated from the non-limiting example of FIG. 4, an ADC may be provided which filters (via H(s) loop filter 406), amplifies, and digitizes an analog (current) signal from an ultrasonic transducer. Thus, analog amplification and filtering stages may be omitted, and the ADC may be coupled directly (or through a switch or other non-processing component) to the ultrasonic transducer. Thus, the power

and real estate associated with analog processing components may be avoided in at least some embodiments.

[0054] Having thus described several aspects and embodiments of the technology of this application, it is to be appreciated that various alterations, modifications, and improvements will readily occur to those of ordinary skill in the art. Such alterations, modifications, and improvements are intended to be within the spirit and scope of the technology described in the application. It is, therefore, to be understood that the foregoing embodiments are presented by way of example only and that, within the scope of the appended claims and equivalents thereto, inventive embodiments may be practiced otherwise than as specifically described.

[0055] As described, some aspects may be embodied as one or more methods. The acts performed as part of the method(s) 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.

[0056] 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.

[0057] 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.

[0058] 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.

[0059] As used herein, the term “between” used in a numerical context is to be inclusive unless indicated otherwise. For example, “between A and B” includes A and B unless indicated otherwise.

[0060] 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.

CLAIMS

1. An ultrasound on a chip device, comprising:
analog-to-digital converters (ADCs) coupled to ultrasonic transducers without intervening analog processing circuitry and configured to convert analog output signals of the ultrasonic transducers into digital signals.
2. The ultrasound on a chip device of claim 1, further comprising a semiconductor substrate, wherein the ADCs and ultrasonic transducers are integrated on the semiconductor substrate.
3. The ultrasound on a chip device of claim 1, wherein the ultrasonic transducers are capacitive micromachined ultrasonic transducers (CMUTs).
4. An ultrasound on a chip device of claim 1, wherein a first ultrasonic transducer of the ultrasonic transducers is a micromachined ultrasonic transducer (MUT).
5. The ultrasound on a chip device of claim 4, wherein the MUT is a capacitive micromachined ultrasonic transducer (CMUT).
6. The ultrasound on a chip device of claim 4, wherein the MUT is a piezoelectric micromachined ultrasonic transducer (PMUT).
7. The ultrasound on a chip device of claim 4, wherein a first ADC of the ADCs is coupled to the MUT through a switch.
8. The ultrasound on a chip device of claim 4, wherein a first ADC of the ADCs is coupled to the MUT and configured to perform time gain compensation of an electrical signal produced by the MUT.
9. The ultrasound on a chip device of claim 8, wherein the first ADC comprises a digital-to-analog (DAC) converter having a controllable reference current.

10. The ultrasound on a chip device of claim 4, wherein a first ADC of the ADCs is coupled to the MUT and comprises a controllable reference current.
11. The ultrasound on a chip device of claim 10, wherein the first ADC comprises a digital-to-analog converter (DAC).
12. The ultrasound on a chip device of claim 11, wherein the DAC uses the controllable reference current.
13. An ultrasound device, comprising:
 - a first substrate having a plurality of micromachined ultrasonic transducers integrated thereon;
 - a second substrate having an analog-to-digital converter (ADC) integrated thereon, the ADC being coupled to an output of an ultrasonic transducer of the plurality of ultrasonic transducers without intervening analog processing circuitry; and
 - transmit circuitry integrated on the second substrate, coupled to the plurality of ultrasonic transducers, and configured to control transmission of ultrasound signals by the plurality of ultrasonic transducers.
14. The ultrasound device of claim 13, further comprising transmit circuitry integrated on the first substrate and coupled electrically between the plurality of ultrasonic transducers and the transmit circuitry integrated on the second substrate.
15. The ultrasound device of claim 13, further comprising a switch coupled between the ultrasonic transducer and the ADC.
16. The ultrasound device of claim 13, further comprising a digital processing circuit integrated on the second substrate.
17. An ultrasound device, comprising:
 - a first substrate having a plurality of micromachined ultrasonic transducers and
 - transmit circuitry integrated thereon, the transmit circuitry coupled to the plurality of

ultrasonic transducers and configured to control transmission of ultrasound signals by the plurality of ultrasonic transducers; and

a second substrate having an analog-to-digital converter (ADC) integrated thereon, the ADC being coupled to an output of an ultrasonic transducer of the plurality of ultrasonic transducers without intervening analog processing circuitry.

18. The ultrasound device of claim 17, wherein the ADC is coupled to an output of the ultrasonic transducer without an intervening distinct time gain compensation circuit.

19. The ultrasound device of claim 17, wherein the ADC is coupled to an output of the ultrasonic transducer without an intervening distinct amplifier.

20. The ultrasound device of claim 17, wherein the ultrasound device lacks an averaging circuit coupled to receive output signals of the plurality of ultrasonic transducers.

21. A method of operating an ultrasound device, comprising:
directly converting an analog electrical signal output by a microfabricated ultrasonic transducer into a digital signal.

22. The method of operating an ultrasound device of claim 21, wherein converting the analog electrical signal into a digital signal comprises converting the analog electrical signal using a sigma delta continuous time analog-to-digital converter (ADC).

23. The method of claim 21, further comprising performing digital processing on the digital signal.

24. The method of claim 21, wherein converting the analog electrical signal into the digital signal comprises performing time gain compensation on the analog electrical signal.

25. The method of claim 24, wherein performing time gain compensation on the analog electrical signal comprises dynamically adjusting a reference current of a digital-to-analog converter (DAC).
26. A method of operating an ultrasound device, comprising:
converting an analog electrical signal output by a microfabricated ultrasonic transducer into a digital signal without first performing processing of the analog electrical signal in an analog domain.
27. The method of claim 26, further comprising performing time gain compensation on the analog electrical signal as part of converting the analog electrical signal into a digital signal.
28. The method of claim 26, wherein the analog electrical signal is a current signal.

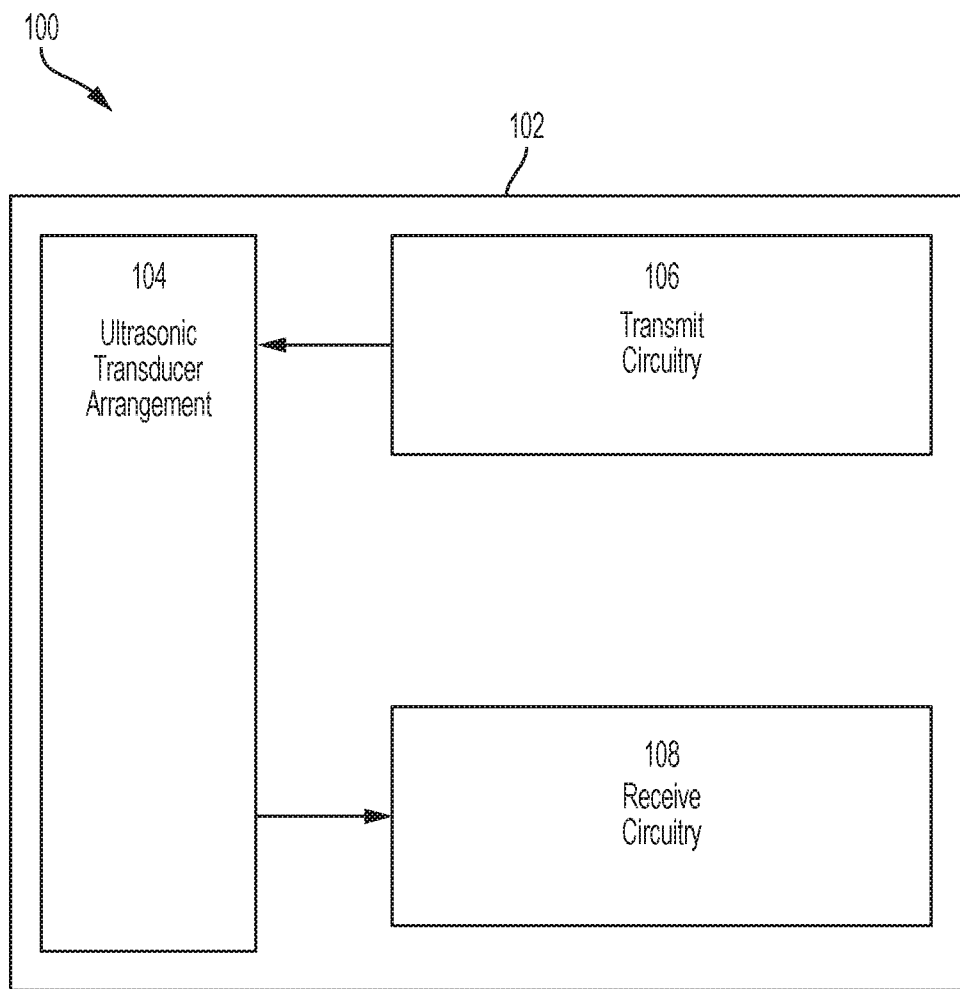


FIG. 1A

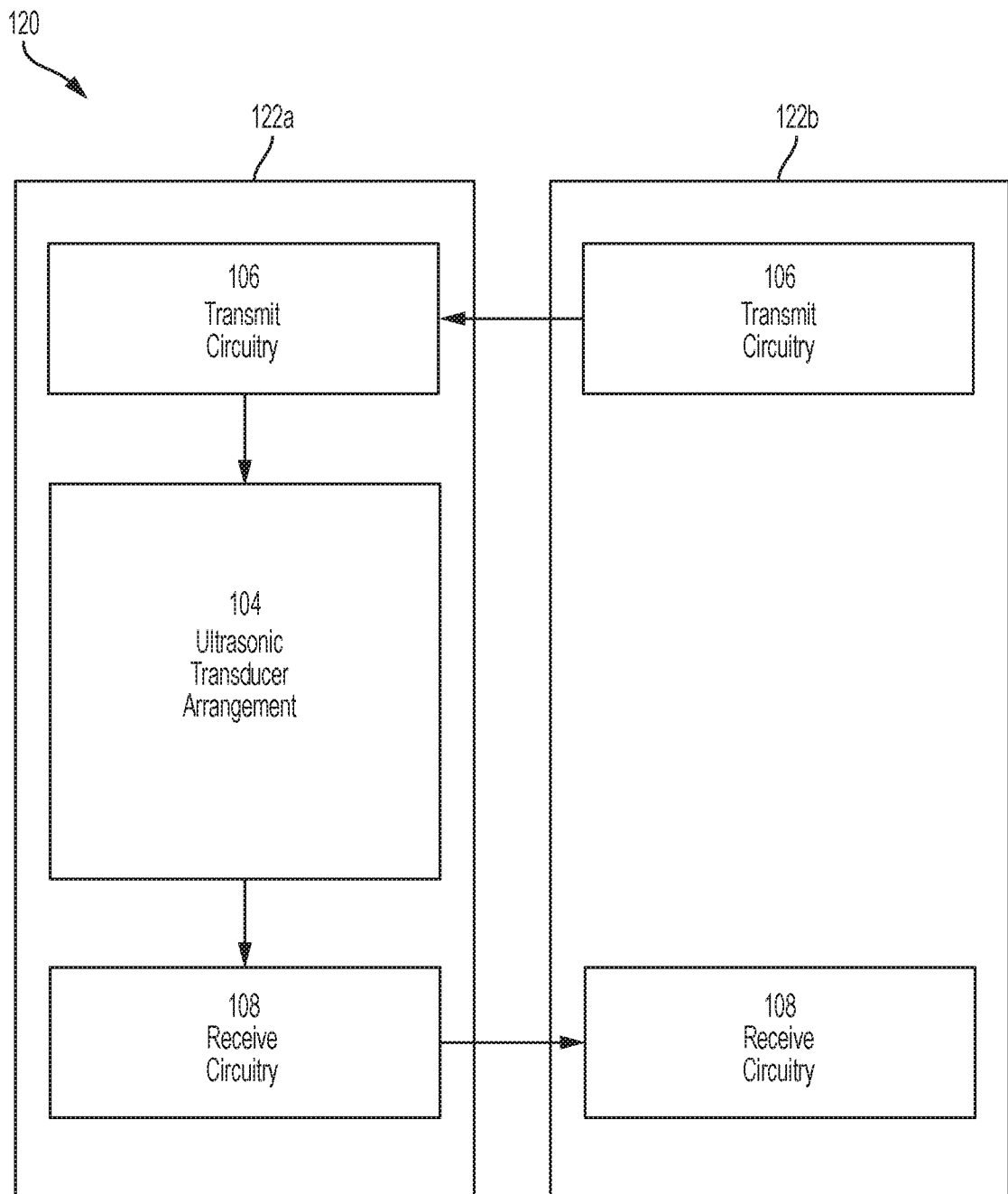


FIG. 1B

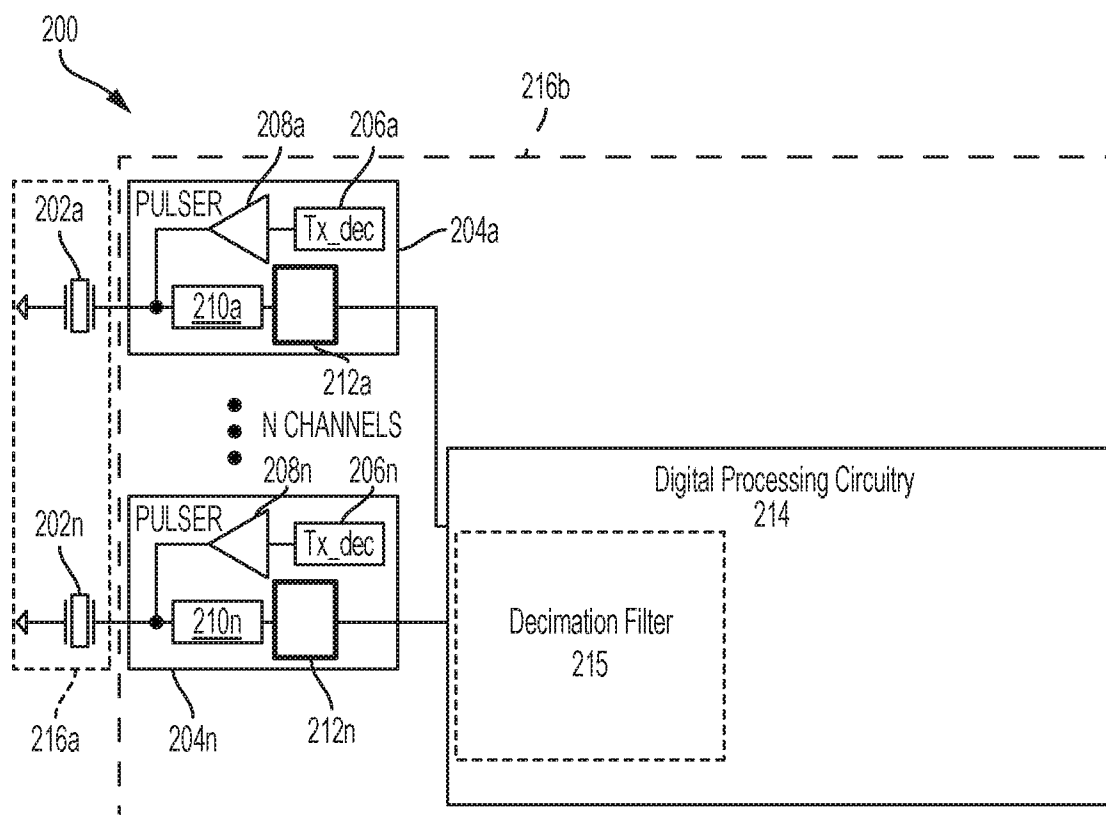


FIG. 2

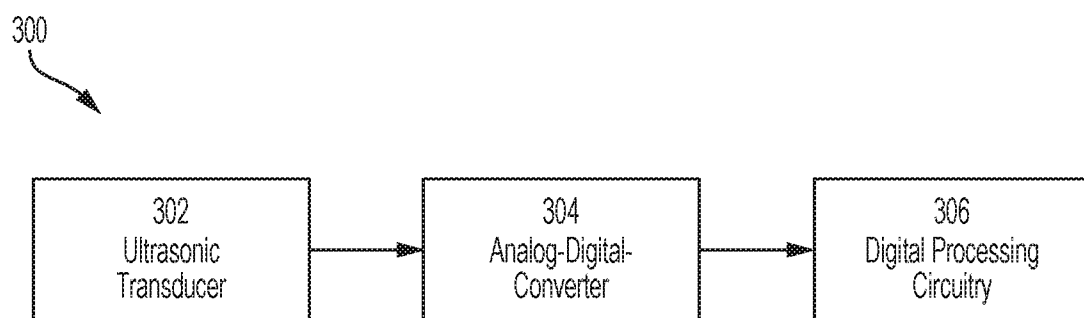


FIG. 3

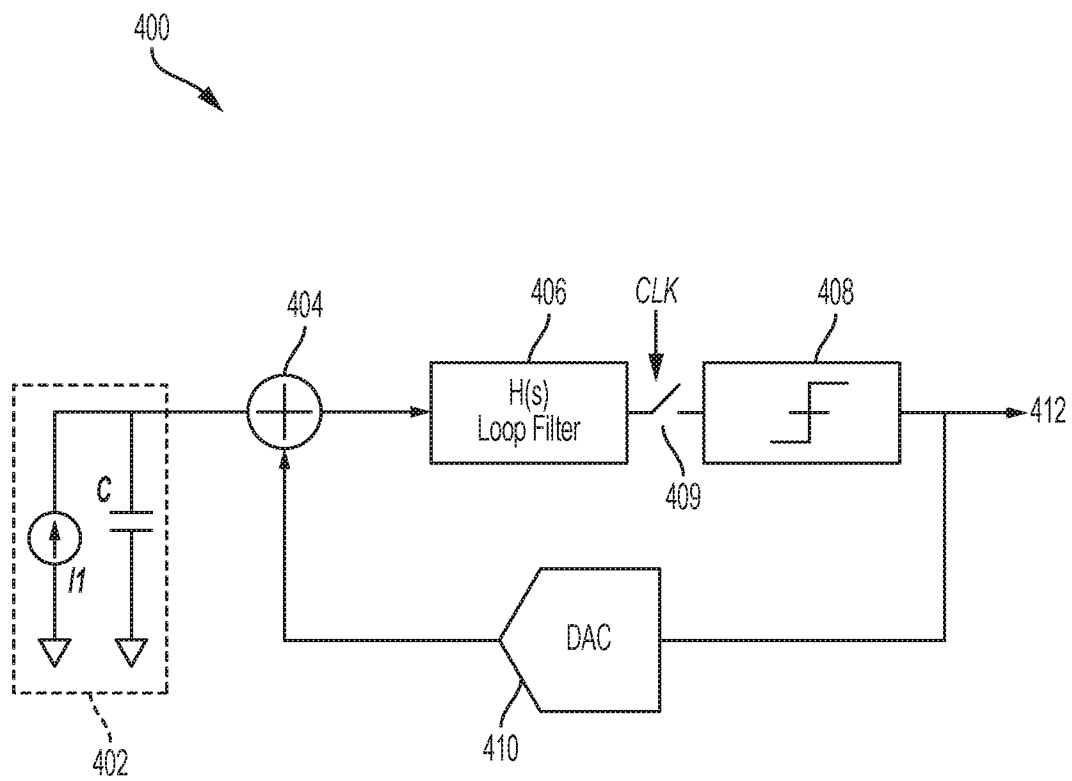


FIG. 4

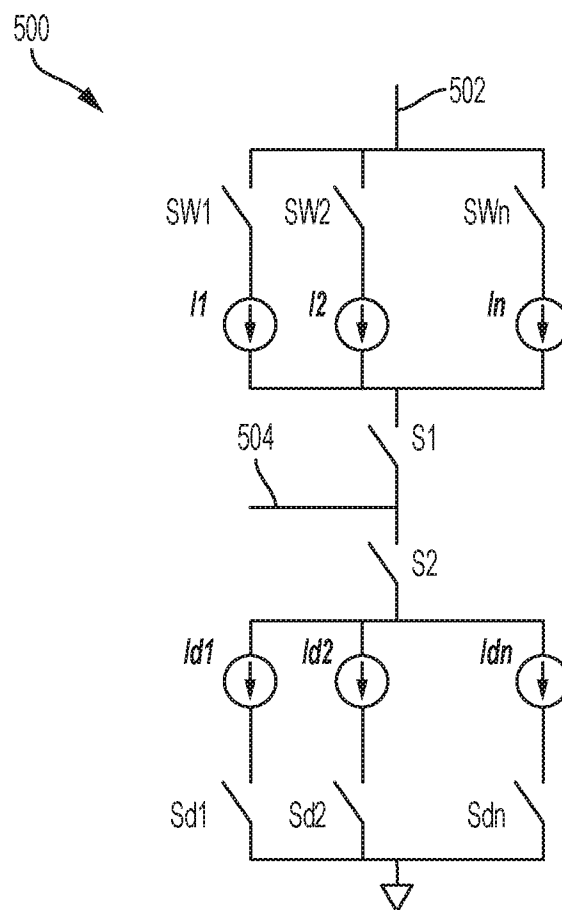


FIG. 5

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US18/38166

A. CLASSIFICATION OF SUBJECT MATTER

IPC - H03M 1/12, 1/66; G11C 7/16; A61N 7/00; A61B 8/00; G01S 7/282 (2018.01)

CPC - A61B 8/4477, 8/4483, 8/4488, 8/4494, 8/46; H03M 1/001, 1/005, 1/12, 1/66; G11C 7/16; G01S 7/282

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

See Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2017/097968 A1 (KONINKLIJKE PHILIPS N.V.) June 15, 2017; abstract, page 5, line 33-page 6, line 4, page 12, lines 25-30, page 15, lines 26-34, claims 1, 9, figures 9, 11	21-23, 26
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Y		16, 28
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A		8, 9, 14, 24, 25, 27
Y	WO 2015/189149 A1 (KONINKLIJKE PHILIPS N.V.) December 17, 2015; abstract, page 10, lines 6-13, claim 1, figure 3	1-7, 10-13, 15-20
--		--
A		8, 9, 14, 24, 25, 27
Y	US 2014/0088425 A1 (INDUSTRIAL TECHNOLOGY RESEARCH INSTITUTE) March 27, 2014; figure 2, paragraph [0019]	1-7, 10-12
Y	US 2017/0169899 A1 (CORNELL UNIVERSITY) June 15, 2017; figure 1B, paragraphs [0066], [0067], [0074]	2
Y	US 2017/0163276 A1 (BUTTERFLY NETWORK INC.) June 8, 2017; figure 1, paragraphs [0019], [0021]-[0027]	3-7, 10-13, 15-20
--		--
A		8, 9, 14, 24, 25, 27
Y	US 2011/0205096 A1 (KATSIS, D et al.) August 25, 2011; figure 3, paragraph [0029], claims 1, 6	10-12
Y	US 2010/0327695 A1 (GOEL, A et al.) December 30, 2010; figure 1, paragraphs [0030], [0031], [0034], claims 11, 13	13, 15-20



Further documents are listed in the continuation of Box C.



See patent family annex.

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"P" document published prior to the international filing date but later than the priority date claimed

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later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&"

document member of the same patent family

Date of the actual completion of the international search

11 August 2018 (11.08.2018)

Date of mailing of the international search report

10 SEP 2018

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/US18/38166

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2015/0041317 A1 (XAGENIC INC.) February 12, 2015; claim 1	28
A	US 2009/0184853 A1 (UDUPA, A et al.) July 23, 2009; the entire document	1-28
A	US 2011/0148682 A1 (RIGBY, K et al.) June 23, 2011; the entire document	1-28