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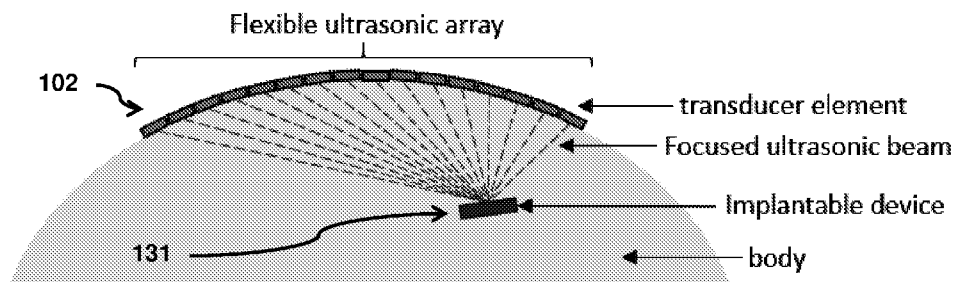


FIG. 3B

(57) Abstract: A targeted energy transmission method using an ultrasonic transducer array (101,102) on an implantable device (131) is disclosed. The method includes generating a first ultrasonic wave having at least one frequency and at least one amplitude by at least one ultrasonic transducer (111), transmitting the first ultrasonic wave to the implantable device (131), transmitting an echo signal from the implantable device (131) back to the ultrasonic transducer array (101,102), picking up the echo signal by the ultrasonic transducer array (101,102) such that the one or more ultrasonic transducers (111) acquire a plurality of received signals, coupling the received signals to a processor for generating time reversed signals; and modulating the one or more ultrasonic transducers (111) to generate time reversed waves according to the time reversed signals for transmitting the ultrasonic energy to the implantable device (131), wherein the time reversed waves undergo constructive interference at a location where the echo signal is transmitted from.



TARGETED ENERGY TRANSMISSION METHOD USING ONE OR MORE ULTRASONIC TRANSDUCERS ON AN IMPLANTABLE DEVICE

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CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 62/795,607, filed on January 23, 2019, which is incorporated by reference herein in its entirety.

TECHNICAL FIELD

[0002] The present disclosure generally relates to a targeted energy transmission method using one or more ultrasonic and/or acoustic transducers on an implantable device. In particular, the present disclosure is directed to a method for focusing ultrasonic energy and delivering energy to the implantable device.

BACKGROUND

[0003] With the advancement in implantable smart technologies, particularly the use of implantable autonomous sensors and actuators, the need for developing a better implantable medical device has increased. One area of research focuses on the improvement in the lifetime of an implantable medical device. A conventional implantable device is limited by the capacity of the power source, which is often bulky and requires replacement from time to time. Having battery implanted within the human body may also be hazardous. The battery requires more frequent replacement than other components in the electronic circuitry of the implantable device. Therefore, the replacement of batteries causes unnecessary risk of infection and discomfort from the intrusive operations.

[0004] Ultrasonic energy transmission has been utilized to transmit energy from an ultrasonic transducer and recharge the implantable device. Such an ultrasonically powered implantable device has the significant medical benefit of miniaturizing the implantable device and providing a safer power source. Typically, the implantable device comprises a rechargeable battery and an ultrasonic transceiver which can efficiently convert the ultrasonic power into electrical energy for supplying power. This method provides an efficient and relatively risk-free energy source, as well as a mean of bi-directional data transmission to and from the implantable device.

[0005] A research team in the UC Barkley proposed a system called “neural dust” in the US patent number US10118054B2. The system provides a method for acquiring an internal body biological condition from an implantable device. According to the method, one or more ultrasonic transducers are configured to transmit a carrier signal of ultrasonic waves to an implant device. The implant device receives the carrier signal, modulates the ultrasonic wave, and transmits the modulated signal to the ultrasonic transducer by backscattering. This method is a passive mode of monitoring triggered by an external interrogator, and there is no electric power stored in the implantable device for performing autonomous monitoring of the deep tissue biological condition. Furthermore, methods for focusing the ultrasonic wave and improving the efficiency of energy transmission from the transducer are not particularly addressed.

[0006] In order to achieve higher efficiency on ultrasonic energy delivery, the ultrasonic wave should ideally be focused on the implantable device. This may be done by using a single bowl-shaped ultrasonic transducer. However, such a bowl-shaped transducer has with a natural focus at a fixed depth. As the position of the focus is not flexible, the target of the ultrasonic wave is also not flexible. The same problem of focusing is also encountered when transducer array elements are used.

[0007] In light of the issues raised above, there is a need in the art to have an improved method for performing targeted energy transmission using rigid or flexible ultrasonic transducer array on an implantable device.

SUMMARY

[0008] Provided herein is a method for transmitting ultrasonic energy from an ultrasonic transducer array having one or more ultrasonic transducers to an implantable device by time

reversal focusing. The method comprises the steps of generating a first ultrasonic wave having at least one frequency and at least one amplitude by at least one ultrasonic transducer; transmitting the first ultrasonic wave to the implantable device, thereby an echo signal is reflected to the ultrasonic transducer array from the implantable device; receiving the echo signal by the ultrasonic transducer array such that the one or more ultrasonic transducers acquire a plurality of received signals based on the echo signal; coupling the received signals to a processor for generating time reversed signals; modulating the one or more ultrasonic transducers to generate time reversed waves according to the time reversed signals, wherein the time reversed waves undergo constructive interference at a location where the echo signal is transmitted from; and transmitting the time reversed waves to the implantable device for transmitting the ultrasonic energy from the time reversed waves to the implantable device.

[0009] According to certain aspects of the present disclosure, the method further comprises the step of reflecting the first ultrasonic wave as the echo signal, wherein the implantable device is a device having significantly higher acoustic impedance than adjacent tissues.

[0010] According to certain aspects of the present disclosure, the method further comprises iterating the steps of receiving the echo signal by the one or more ultrasonic transducers and coupling the received signals to the processor for generating time reversed signals for improving an ultrasonic energy targeting.

[0011] According to certain aspects of the present disclosure, the first ultrasonic wave is a plane wave or a random time-delayed wave as generated by two or more ultrasonic transducers such that a natural focus spot is not present.

[0012] According to certain aspects of the present disclosure, the processor is configured to perform time reversal focusing on each echo signal received by the one or more ultrasonic transducers. The processor is configured to perform post-processing filtering of noise and correcting a linearity and a frequency response of ultrasound generation by the ultrasonic transducers.

[0013] According to certain aspects, the ultrasonic energy from the time reversed waves is converted into electrical currents through piezoelectric elements, capacitive micromachined ultrasonic transducers (CMUTs), optical based transducers, or other materials.

[0014] According to certain aspects of the present disclosure, the implantable device comprises materials or substances with a non-linear ultrasonic property such that the echo signal has a frequency different from the first ultrasonic wave.

[0015] According to certain aspects of the present disclosure, the step of coupling the received signals to a processor for generating time reversed signals further comprises the steps of converting the received signals to digital signals using an analog-to-digital converter (ADC); writing the digital signals to a memory; performing a time-domain flip of the digital signals to obtain flipped digital signals; and converting the flipped digital signals to obtain the time reversed signals using a digital-to-analog converter (DAC).

[0016] According to certain aspects of the present disclosure, the step of coupling the received signals to a processor for generating time reversed signals further comprises the steps of coupling the received signals to a Fourier transform circuit and an envelope detector which is arranged in parallel to the Fourier transform circuit; generating a frequency component of the received signals using the Fourier transform circuit; generating a magnitude component of the received signals using the envelope detector; flipping the received signals by obtaining a conjugate in Fourier transform of the echo signal; and performing inverse Fourier transform to obtain the time reversed signals.

[0017] Also provided herein is a method for transmitting ultrasonic energy to a plurality of implantable devices in a living body simultaneously by time reversal focusing. Each of the plurality of implantable devices is configured to receive the ultrasonic energy from an ultrasonic transducer array. The time reversed waves from the ultrasonic transducer array undergo constructive interference at multiple locations where the plurality of implantable devices is positioned.

[0018] According to certain aspects of the present disclosure, each of the plurality of implantable devices is selectively responsive to a range of frequencies for selectively activating the one or more implantable devices.

[0019] This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used as an aid in determining the scope of the claimed subject matter. Other aspects and advantages of the present invention are disclosed as illustrated by the embodiments hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] The appended drawings, where like reference numerals refer to identical or functionally similar elements, contain figures of certain embodiments to further illustrate and clarify various aspects, advantages and features of the targeted energy transmission method as disclosed herein. It will be appreciated that these drawings and graphs depict only certain embodiments of the invention and are not intended to limit its scope. The targeted energy transmission method as disclosed herein, will be described and explained with additional specificity and detail through the use of the accompanying drawings in which:

[0021] FIG. 1A depicts the reflection of ultrasound by spinal vertebrae when a rigid ultrasonic transducer array is placed on a body. FIG. 1B depicts the reflection of ultrasound by spinal vertebrae when a flexible ultrasonic transducer array is placed on a body.

[0022] FIG. 2 is a photo of an exemplary flexible ultrasonic transducer array.

[0023] FIG. 3A depicts the focusing of ultrasonic waves onto one or more implantable devices using a rigid ultrasonic transducer array. FIG. 3B depicts the focusing of ultrasonic waves onto one or more implantable devices using a flexible ultrasonic transducer array.

[0024] FIG. 4A depicts transmitting a wavefront from an ultrasonic transducer through a scattering medium to an implantable device (reflector). FIG. 4B depicts reflecting an ultrasonic wave from the implantable device back to the ultrasonic transducers. FIG. 4C depicts transmitting a time reversed wave from the ultrasonic transducers through the scattering medium to the implantable device with a focus generated to the implantable device.

[0025] FIG. 5A depicts the acoustic intensity distribution of ultrasonic wave sent out by a concave-shaped transducer array with no field modulation by electronic time delay. FIG. 5B depicts the acoustic intensity distribution of ultrasonic wave sent out by a concave-shaped transducer array with plane wave transmission. FIG. 5C depicts the acoustic intensity distribution of ultrasonic wave sent out by a concave-shaped transducer array with random time-delay field. FIG. 5D depicts the acoustic intensity distribution of ultrasonic wave sent out by a single ultrasonic transducer in a concave-shaped transducer array.

[0026] FIG. 6 depicts a system diagram of the passive time reversal focusing method for achieving a maximum focusing on the implantable device in accordance with an exemplary embodiment of the present disclosure.

[0027] FIG. 7A depicts an exemplary structure of a system for performing time reversal focusing. FIG. 7B depicts another exemplary structure of the system for performing time reversal focusing.

[0028] FIG. 8 depicts a system diagram of the active time reversal focusing method using an active implantable device in accordance with an exemplary embodiment of the present disclosure.

[0029] FIG. 9 depicts a circuit diagram for the AC time delay circuit for the active implantable device in accordance with an exemplary embodiment of the present disclosure.

[0030] FIG. 10A depicts a brightness mode (B-mode) ultrasound image reconstructed from a plane wave activation using a rigid ultrasonic transducer array. FIG. 10B depicts a time reversal field generated from the B-mode ultrasound image shown in FIG. 10A.

[0031] FIG. 11A depicts the signal of an instantaneous impulse at the focused location at a depth of 10cm using time reversal focusing method. FIG. 11B depicts the signal of an instantaneous impulse at the focused location at a depth of 10cm using time-delayed focusing method.

[0032] FIG. 12A depicts the signal of a tone burst of 8 cycles at 1MHz at the focused location at a depth of 10cm using time reversal focusing method. FIG. 12B depicts the signal of a tone burst of 8 cycles at 1MHz at the focused location at a depth of 10cm time-delayed focusing method

[0033] FIG. 13A depicts the acoustic wavefront and the respective simulated acoustic intensity distribution for focusing the acoustic wave at a specific location from an arc-shaped transducer array. FIG. 13B depicts the acoustic wavefront and the respective simulated acoustic intensity distribution for activating a plane wave of ultrasound from an arc-shaped transducer array.

[0034] FIG. 14 depicts a typical voltage produced per unit of acoustic pressure of an ultrasonic transducer.

[0035] FIG. 15A depicts an exemplary focusing of ultrasound to an implantable device by activating the ultrasonic transducers with time-delay. FIG. 15B depicts an exemplary focusing of ultrasound to an implantable device by activating an optimal number of ultrasonic transducers.

[0036] FIG. 16 depicts a system diagram of the active time-delay focusing method using an active implantable device in accordance with an exemplary embodiment of the present disclosure.

[0037] FIG. 17 depicts the frequency spectrums of a fundamental signal and a first harmonic signal.

[0038] FIG. 18A depicts the image reconstructed from a known convex ultrasonic transducer array. FIG. 18B depicts the image reconstructed from a known S-shaped ultrasonic transducer array. FIG. 18C depicts the image reconstructed from a known concave ultrasonic transducer array.

[0039] FIG. 19A depicts an exemplary ultrasound image of a metal plate implanted in a chicken breast tissue. FIG. 19B depicts the intensity distribution of FIG. 19A when using time reversal method.

[0040] Skilled artisans will appreciate that elements in the figures are illustrated for simplicity and clarity and have not necessarily been depicted to scale.

DETAILED DESCRIPTION

[0041] The present disclosure generally relates to a targeted energy transmission method. More specifically, but without limitation, the present disclosure relates to a method for focusing ultrasonic energy and communicating with the implantable device using one or more ultrasonic transducers, such as a rigid or flexible ultrasonic transducer array. An objective of the present disclosure is to maximize the efficiency of the ultrasonic energy transmission by focusing the ultrasonic wave at the implantable device.

[0042] In the following embodiments, the targeted energy transmission method is merely exemplary in nature and is not intended to limit the disclosure or its application and/or uses. It should be appreciated that a vast number of variations exist. The detailed description will enable those of ordinary skill in the art to implement an exemplary embodiment of the present disclosure without undue experimentation, and it is understood that various changes or modifications may be made in the function and arrangement of the method described in the exemplary embodiment without departing from the scope of the present disclosure as set forth in the appended claims. In view of this disclosure, different embodiments described herein may be combined to form other embodiments of the invention. The headings used herein are for organizational purposes only and are not to be construed as limiting the subject matter described.

[0043] The benefits, advantages, solutions to problems, and any element(s) that may cause any benefit, advantage, or solution to occur or become more pronounced are not to be construed as a critical, required, or essential features or elements of any or all of the claims.

The invention is defined solely by the appended claims including any amendments made during the pendency of this application and all equivalents of those claims as issued.

[0044] For simplicity and clarity, relational terms such as “first,” “second,” “third,” and the like, if any, are used solely to distinguish one from another entry, item, or device, without necessarily requiring any actual such relationship or order between such entries, items, or devices.

[0045] As used herein, the terms “coupled” or “connected,” or any variant thereof, covers any coupling or connection, either direct or indirect, between two or more elements, unless otherwise indicated or clearly contradicted by context.

[0046] The present disclosure generally describes ultrasonic energy transmission and communication to and from one or more implantable devices. The term “implantable device” is used to describe a device in a subject for identify identification, sensing the physiological conditions, such as temperature, pressure, pH, pulse rate, oxygen, analyte, strain, glucose, or any combination thereof. The implantable device may comprise multiple channels, sensors, transmitters, or detectors. The implantable device may perform other functions such as releasing drugs or chemicals into the body, stimulating nerves and tissues, or treating heart issues. The implantable device is implanted in a living subject, wherein the subject may be a human or an animal. The term “ultrasonic energy,” as used herein, generally refers to the energy transmitted by acoustic waves having a frequency between 20kHz and 1GHz. The term “acoustic wave” is referring to a broadband acoustic wave having a frequency between 10kHz and 1GHz.

[0047] In certain embodiments, the implantable device comprises one or more sensors for detecting the amount of the analyte, strain, or pH.

[0048] In certain embodiments, the implantable device comprises an optical detector for detecting blood pressure, blood oxygenation, melanin level, glucose, a pulse rate, any other spectral change signature relayed to health, or any optical absorption change related to health.

[0049] In certain embodiments, the implantable device comprises a temperature sensor, such as a thermistor or a thermocouple, for detecting temperature.

[0050] In certain embodiments, the implantable device comprises a pressure sensor, such as a micro-electro-mechanical system (MEMS) sensor, for measuring blood pressure, intracranial pressure, pulse rate, or other pressures in the body.

[0051] In certain embodiments, the implantable device comprises a potentiometric chemical sensor or an amperometric chemical sensor for detecting oxygen level, pH, or glucose.

[0052] In certain embodiments, the implantable device comprises drug release dispenser for releasing drugs or chemicals into the body.

[0053] In certain embodiments, the implantable device comprises micro-stimulators or electrodes for stimulating nerves or tissues or treating heart issues.

[0054] In certain embodiments, the implantable device can to send out electromagnetic waves or mechanical waves for stimulation of tissues, nerves, or organ.

[0055] In certain embodiments, the implantable device can induce local or large location temperature change.

[0056] In certain embodiments, the implantable device can introduce pressure change in the body system, using components that require real-time change in pressure, such as actuators or clamps.

[0057] In certain embodiments, the implantable device can introduce or detect a magnetic field, such as inductors or coils.

A. *ULTRASONIC TRANSDUCER ARRAY*

[0058] FIG. 1A and FIG. 1B illustrate a rigid ultrasonic transducer array **101** and a flexible ultrasonic transducer array **102** placed on a living body respectively. The ultrasonic transducer array comprises a plurality of ultrasonic transducers **111**, which can be piezoelectric elements, capacitive micromachined ultrasonic transducers (CMUTs), optical based transducers or other materials. In certain embodiments, the flexible ultrasonic transducer array **102** may comprise one single ultrasonic element, such as a CMUT named “Sonic Paper”. In some other cases, a single ultrasonic transducer **111** can be used instead of an array. Each of the ultrasonic transducers **111** in the array is controlled by a processor, which can configure each ultrasonic transducer to receive or transmit ultrasonic waves. This allows the one or more ultrasonic transducers **111** to transmit ultrasonic waves with different time delay, phase shift, pulse frequency, amplitude, and/or wavelength. In some embodiments, the one or more ultrasonic transducers **111** in the array can have regular spacing, irregular spacing, or be sparsely placed.

[0059] The one or more ultrasonic transducers **111** are connected to a processor or a computation system, which is configured to be selectively communicable with each or all

ultrasonic transducers **111** for transmitting or receiving ultrasonic wave. The processor may be formed as one or more central processing units (CPU), microcontroller units (MCU), general purpose microprocessors, application specific integrated circuits (ASIC), field programmable logic arrays (FPGA), programmable I/O devices, or other equivalent integrated or discrete electronic circuitry. In certain embodiments, the processor or the computation system may further include other components such as analog-to-digital converter (ADC), digital-to-analog converter (DAC), memory, display panel, power supply, and I/O ports.

[0060] The flexible ultrasonic transducer array **102** can be considered of having one or more ultrasonic transducers **111** attached on flexible and stretchable materials, flexible printed circuit board (PCB), or Kapton polyimide film, which allow a relative movement of location and orientation of adjacent ultrasonic transducers **111**. Therefore, the flexible ultrasonic transducer array **102** can allow better bending and fitting onto a complex geometry of the surface of a living body than the rigid ultrasonic transducer array **101**. An exemplary flexible ultrasonic transducer array **102** including an array of 128 ultrasonic transducers **111** is shown in FIG. 2.

[0061] The ultrasound transmitted from the ultrasonic transducers **111** interacts with the body tissues after entering the living body. The interaction may cause reflection, scattering, and refraction of the ultrasonic wave. This occurs at the tissue boundaries in which the tissues or medium has different acoustic impedance. Attenuation may also occur from absorption, which may happen within the same medium. The deviation in the acoustic impedance determines the amount of reflection, while the acoustic impedance (Z) is determined by the density of the tissues (ρ) and the speed of the acoustic wave (c), with the following equation:

$$Z = \rho c \quad (1)$$

A more significant change in density between two tissues will result in a larger change of acoustic impedance. The change in impedance between two mediums is called an acoustic impedance mismatch. Such a difference in acoustic impedance between two tissues accounts for the amount of reflection that occurs at the tissue boundary.

[0062] As the spinal vertebra **121** has a higher density than the neighboring tissues, the spinal vertebra **121** can, therefore, reflect the incident ultrasonic waves from the ultrasonic transducers **111**. The reflected ultrasonic waves can be picked up by the ultrasonic transducers **111** on the array. As the flexible ultrasonic transducer array **102** may provide better angular coverage on the living body, which can collect more acoustic information than

the rigid ultrasonic transducer array **101**. Therefore, in most applications, the flexible ultrasonic transducer array **102** is more preferred than the linearly arranged rigid ultrasonic transducer array **101**.

[0063] With the use of an ultrasonic transducer array (either rigid or flexible), the one or more ultrasonic transducers **111** can be configured to transmit ultrasonic waves each with different time delay, phase modulation, and waveform modulations. By applying time delay, the phases of the ultrasonic waves can add up in the target ultrasonic focusing region, such that the ultrasonic energy can have a maximum intensity at a defined focus.

[0064] Referring to FIG. **3A**, the rigid ultrasonic transducer array **101** focuses the ultrasonic beams onto an implantable device **131** inside a living body by applying different time delay to each ultrasonic transducers **111**. As the rigid ultrasonic transducer array **101** cannot make good contact to the surface of the living body, there is acoustic coupling between some of the ultrasonic transducers **111** and the living body. Similarly, as shown in FIG. **3B**, the flexible ultrasonic transducer array **102** also focuses the ultrasonic beams onto an implantable device **131** inside a living body by applying different time delay to each ultrasonic transducers **111**.

[0065] In order to target the ultrasonic wave to an implantable device **131**, dynamic monitoring the location of the implantable device **131** is needed. Dynamic monitoring means capturing real-time information in relation to the location of the implantable device **131**, which will then be used to calculate the targeted ultrasound delivery. The method of monitoring the location of the implantable device **131** and focusing the ultrasound are described in more details below. The method can also be applied to situations when two or more ultrasonically powered implantable devices **131** are implanted to a body.

[0066] One method for focusing the ultrasonic energy onto a targeted location is to perform time reversal focusing. The concept of time reversal focusing is a method based on reciprocity. In order to target the energy onto an implantable device **131** in a living body, an ultrasonic wave originated from an acoustic source is first propagated to the implantable device **131**, in which the implantable device **131** reflects or transmits the ultrasonic wave. In the case of reflecting the wave, a passive method is used to achieve time reversal. For the case of transmitting the wave, an active method is used instead.

B. TIME REVERSAL FOCUSING

[0067] Now refer to FIGS. 4A-4C, the concept of the time reversal focusing is demonstrated. An array of ultrasonic transducers **100** may be arranged linearly or otherwise in other shapes. As exemplarily shown in FIG. 4A, one of the ultrasonic transducers **111** generates an ultrasonic wave having at least one frequency and at least one amplitude, and transmits the ultrasonic wave into a living body with an implantable device **131** therein. In certain embodiments, the ultrasonic wave can be transmitted into a living body with multiple implantable devices **131** therein, as long as all the implantable devices **131** are within the field-of-view. The frequency generated by the ultrasonic transducers **111** refers to the frequencies above the audible sound. In other alternative embodiments, two or more ultrasonic transducers **111** may be used to generate a plane wave or a random time-delayed wave instead of using one single ultrasonic transducer **111**. In certain embodiments, the center frequency of the ultrasonic transducer **111** is approximately 5MHz. The ultrasound transmitted can be an impulse or a tone burst. Between the ultrasonic transducer **111** and the implantable device **131**, there is a scattering medium **141** of body tissues. Refraction occurs when the ultrasonic wave is deflected from a straight path entering the scattering medium **141** to a direction with an angle of deflection. Generally, the ultrasonic wave is refracted at a medium with different acoustic impedance. The ultrasonic energy may also be absorbed, reflected, or scattered by the tissues. After passing through the scattering medium **141**, the ultrasonic wave hits the implantable device **131**. In one embodiment, the implantable device **131** is a device having significantly higher acoustic impedance than the adjacent tissues as the density is substantially higher. The implantable device **131** can act as a reflector, and the ultrasonic wave is reflected back as an echo signal using a passive method. In an alternative embodiment, the implantable device **131** can receive and convert the ultrasonic energy into electrical energy; thereby an ultrasonic transducer in the implantable device **131** generates an ultrasonic wave in an opposite direction. As the ultrasonic wave is generated by the implantable device **131**, this method is an active method using more complex electronic components.

[0068] As shown in FIG. 4B, the echo signal or the generated ultrasonic wave from the implantable device **131** travels in a scattering path through the scattering medium **141** back to the array of ultrasonic transducers **100**. As the scattering medium **141** has the same scattering and transmission properties when the ultrasonic wave travels through in a forward or backward manner. Therefore, by using a time reversal method, a focus at the point of reflection can be located.

[0069] The one or more ultrasonic transducers **111** acquire the echo signals or the generated ultrasonic waves, each with different properties of amplitude and time delay. The received signals **151** are coupled to the processor for generating the time-reversed signals **152**. As shown in FIG. **4C**, the time-reversed signals **152** are coupled from the processor to the one or more ultrasonic transducers **111** for generating time reversed waves, which are transmitted into the living body and dynamically focused at the implantable device **131**. After passing through the scattering medium **141**, the time reversed waves from the one or more ultrasonic transducers **111** can undergo constructive interference with the phase added up at the location where the reflection originally came from, and generate a focus of ultrasonic energy at the point of reflection. In the case of one single ultrasonic transducer **111**, the time reversed wave and any scattered or refracted waves thereof may undergo constructive interference at the location where the reflection originally came from. For example, if an ultrasonic transducer **111** in the array of ultrasonic transducers **100** receives pressure field of $p(x,t)$, where x is the location of the ultrasonic transducer **111** and t is the time, the corresponding time reversal signal will be $p'(x,T-t)$ where T is the overall delay constant necessary in the system. The intensity of focus at each location is directly proportional to the reflection intensity plus attenuation factors.

[0070] For the purpose of initial activation, the ultrasound field generated from the array of ultrasonic transducers **100** can be modulated by different time-delay to achieve a dynamic focusing onto the implantable device **131**. The modulation of ultrasound may improve the quality of transmission if a flexible ultrasonic transducer array **102** is used and the ultrasonic transducers **111** are not arranged linearly, such as in a concave shape. A concave-shaped array of ultrasonic transducers **100** would naturally have a focus where ultrasonic intensity is highest compared to the other neighboring regions, as demonstrated in the acoustic intensity distribution in FIG. **5A**. This would be particularly problematic for time-reversal focusing method as any reflected ultrasonic wave from the region with a natural focus has a higher intensity when comparing to the reflected ultrasonic wave from other regions.

[0071] In order to overcome this problem, the present disclosure provides a method of applying time delay focusing to different locations within the field-of-view by sweeping the ultrasound beams across all locations. However, this method may require a longer delay, which takes a lot of time for sweeping the ultrasound beams. Furthermore, accurate information of each ultrasonic transducer **111** in the array of ultrasonic transducers **100** is

required, which would be difficult or even impossible for a flexible ultrasonic transducer array **102**.

[0072] In one embodiment, as shown in FIG. **5B** and FIG. **5C**, the natural focus spot can be removed by configuring the ultrasonic transducers **111** to modulate the ultrasound field and generate a plane wave or a random time-delay field. The plane wave is a straight and flat wavefront generated by the array of ultrasonic transducers **100** with parallel and unfocused transmissions. The random time-delay field is generated by activating each of the ultrasonic transducers **111** with random delay. In another embodiment, as shown in FIG. **5D**, the natural focus spot can also be removed by configuring only one single ultrasonic transducer **111** to transmit a single ultrasonic wave. This method has weaker to no focusing effect.

[0073] Apart from the reflection of ultrasound by the implantable device **131**, undesired reflection may also occur when the ultrasonic wave is engaging body tissues inside the living body having acoustic impedance mismatched. In particular, the body structures, such as the bone and muscle tissues, can reflect the ultrasound. This reflection is not possible to be avoided. Therefore, it is important to ensure that the implantable device **131** can reflect more ultrasound than other structures in the body. One simple method is by selecting a material with higher impedance mismatch than the surrounding medium.

[0074] As a reflection of ultrasound is a result of the mismatch of acoustic impedance between two mediums. The fraction of energy being reflected R at a boundary between two mediums can be described as by the following equation:

$$R = \left(\frac{z_2 - z_1}{z_2 + z_1} \right)^2 \quad (2)$$

wherein z_1 and z_2 are the acoustic impedance of medium 1 and medium 2.

[0075] From Equation (2), it is apparent that the larger the acoustic impedance mismatch, the stronger the reflection echo can be generated. Therefore, the implantable device **131** can generate a stronger reflection of echo signal by having at least part the implantable device **131** made of a material of higher acoustic impedance mismatch with the human tissues. For example, an implantable device **131** for monitoring or stimulating muscle tissues is implanted at the region with the target human muscle tissues. The human muscle tissues have an acoustic impedance of $1.68 \times 10^6 \text{ kg}/(\text{sec} \cdot \text{m}^2)$. The material used in the implantable device **131** should have a higher acoustic impedance difference, such as stainless steel with an acoustic impedance of $46.02 \times 10^6 \text{ kg}/(\text{sec} \cdot \text{m}^2)$. With this arrangement, the implantable device **131** can reflect the ultrasonic wave with a strong echo signal.

[0076] Assuming that the implantable device **131** can generate a significantly stronger reflection of ultrasound than other physiological structures in the living body, then most of the acoustic energy reflecting to the array of ultrasonic transducers **100** comes from the reflection at the implantable device **131**. The received echo signals are then used to perform time reversal focusing. Most of the acoustic energy thereafter transmitted from the array of ultrasonic transducers **100** can be targeted back onto the point of reflection at the implantable device **131**. Advantageously, the variations incurred as a result of the position and orientation of each ultrasonic transducer **111** can be compensated. Therefore, the measurement and details of the precise physical position and orientation of the ultrasonic transducers **111** are not necessary; thereby this method enables the use of a flexible ultrasonic transducer array **102** without any details of each ultrasonic transducer **111**.

[0077] FIG. 6 shows a system diagram of the passive time reversal focusing method for achieving a maximum focusing on the implantable device **131**. This is an optional iterative method for optimizing the focus. Considering that the implantable device **131** reflects more ultrasound than other structures in the medium, this passive time reversal focusing method can iteratively increase the acoustic energy focused onto the implantable device **131** after each cycle of iteration.

[0078] The passive time reversal focusing method can be used to deliver acoustic energy to an implantable device **131** using an ultrasonic transducer array **600** placed on a living body. The ultrasonic energy from the time reversed waves is converted into electrical currents through piezoelectric elements, CMUTs, optical based transducers, or other materials. The ultrasonic transducer array **600** can be a rigid ultrasonic transducer array **101** or a flexible ultrasonic transducer array **102**. The ultrasonic transducer array **600** can be configured to transmit a plane wave, a random time-delay field, or a single ultrasonic wave. In the case of transmitting ultrasonic energy a living body having a plurality of implantable devices **131** simultaneously, the time reversed waves undergo constructive interference at multiple locations where the plurality of implantable devices **131** is positioned. In certain embodiments, each of the plurality of implantable devices **131** is selectively responsive to a particular range of frequencies for selectively activating particular one or more implantable devices **131**.

[0079] In one embodiment, two or more ultrasonic transducers **111** are activated simultaneously to generate a plane wave in the form of a straight and flat wavefront. There is no focal point for transmission of the ultrasonic signal and natural focus is not resulted.

[0080] In one embodiment, two or more ultrasonic transducers **111** are activated, and each ultrasonic transducer **111** transmits the ultrasonic signal with a random and different time delay. The acoustic intensity distribution is not focused at any point and a random time-delay field can be transmitted.

[0081] In one embodiment, only one signal ultrasonic transducer **111** is activated to transmit the ultrasonic signal. Other ultrasonic transducers **111** in the ultrasonic transducer array **600** are still enabled as a receiver and acquire the echo signals for determining the position of the implantable device **131**.

[0082] The ultrasound transmitted from the ultrasonic transducer array **600** (Tx) enter the medium **610** of body tissues and may undergo refraction, scattering, attenuation, and reflection. As the implantable device **131** has a higher acoustic impedance difference, the reflected echo signal primarily comes from the implantable device **131**. The echo signal is picked up by the ultrasonic transducer array **600** and a plurality of received signals are acquired by the one or more ultrasonic transducers **111** of the ultrasonic transducer array **600** (Rx) for analysis.

[0083] The received signals are coupled to the processor **620**. Each ultrasonic transducer **111** can provide direct information of the phase and intensity of the received echo signal at its location and orientation, and compensate for any variation thereof. The processor **620** is configured to perform time reversal focusing on each echo signal. In certain embodiments, the processor **620** is also configured to perform post-processing filtering of noise and correcting the linearity and frequency response of ultrasound generation by the ultrasonic transducers **111**. The time reversed signal is coupled back to the ultrasonic transducer array **600** (Tx) for transmitting ultrasonic wave in accordance with the time reversed echo signals to the medium **610** of body tissues and dynamically focused at the implantable device **131**. During this transmission, the previous receiving ultrasonic transducers **111** are now configured to transmit the ultrasound. As the transmission is based on the time reversed echo signals, the acoustic energy transmitted from the ultrasonic transducer array **600** can advantageously target back onto the implantable device **131**.

[0084] An iterative method can be used in conjunction with the passive time reversal focusing method such that the precision of the targeting can be improved. As the implantable device **131** can reflect more ultrasound than other structures in the medium **610**, applying the time reversal method iteratively can increase the focused ultrasonic energy at the implantable device **131** in each iteration. During each iteration, the processor **620** determines whether the

ultrasonic energy targeting is improved. The iteration is repeated until there is no further improvement on the energy targeting. This iterative method can advantageously enhance the accuracy of focusing for achieving maximal focusing onto the implantable device **131**.

[0085] FIG. **7A** shows a system for performing time reversal focusing in accordance with one embodiment. The echo signal received by the ultrasonic transducer **111** is converted to a digital signal using an ADC **711**. The ADC **711** is generally implemented using a mix of integrated circuit devices and discrete components or integrated to the processor **620**. The digital signal is then written to the memory **712** of the processor **620** for processing time-domain flip **713**. The time-domain flip **713** is performed by time-flipping the digital signal from left to right to obtain a flipped digital signal. By coupling the flipped digital signal to a DAC **714**, a time reversed signal can be obtained. Preferably, the ADC **711** and the DAC **714** have the same number of bits in the digital domain. In certain embodiments, the time reversed signal may perform post-processing filtering of noise and correcting the linearity and frequency response of ultrasound generation by the ultrasonic transducer **111**.

[0086] FIG. **7B** shows another system for performing time reversal focusing in accordance with one embodiment. The echo signal received by the ultrasonic transducer **111** is coupled to a Fourier transform circuit **721** and an envelope detector **722** which is arranged in parallel to the Fourier transform circuit **721**. The Fourier transform circuit **721** is configured to generate a frequency component of the echo signal, and the circuit may comprise components such as multipliers and computational units. Alternatively, the Fourier transform circuit **721** can be implemented as an algorithm or a software executable by the processor **620** or a computer system. The envelope detector **722** is configured to receive the echo signal, track the voltage envelope of the echo signal, and generate a magnitude component of the echo signal.

[0087] The digital signal processing (DSP) circuit **723** receives the frequency component, and magnitude component of the echo signal from the Fourier Transform circuit **721** and the envelope detector **722** for flipping the echo signal. The DSP circuit **723** can be realized as an integrated circuit and operates to obtain the conjugate in Fourier transform of the echo signal. By using the inverse Fourier transform circuit **724**, the time domain of the time reversed signal can be obtained. Preferably, the Fourier transform circuit **721** and the inverse Fourier transform circuit **724** possess the same number of data samples. Alternatively, the inverse Fourier transform circuit **724** can be implemented as an algorithm or a software executable by the processor **620** or a computer system.

[0088] FIG. 8 shows a system diagram of the active time reversal focusing method using an active implantable device **810**, which transmit ultrasound. The active time reversal focusing method is similar to the passive time reversal focusing method but in a reversed manner. Initially, at least one ultrasonic transducer **111** is activated and transmits ultrasonic wave into the living body. The active implantable device **810** comprises a built-in ultrasonic transducer for receiving the ultrasonic wave. The ultrasonic wave delivers electrical energy to charge up the active implantable device **810**. In certain embodiments, the ultrasonic transducer **111** can perform synchronization with the active implantable device **810**. In certain embodiments, the electrical energy for charging the active implantable device **810** can be harvested from other sources such as heat, ions, kinetic motion, or magnetic field.

[0089] Once the active implantable device **810** is charged up with sufficient electrical energy, the built-in transducer of the active implantable device **810** can generate a second ultrasonic wave in the opposite direction to the incidental ultrasonic wave from the ultrasonic transducer **111**. In certain embodiments, the built-in transducer can send out the second ultrasonic wave in all directions with roughly the same intensity in order to reach all ultrasonic transducers **111** in the ultrasonic transducer array **800** for maximizing the efficiency. The second ultrasonic wave travels through the tissues of the living body, then picked up by the ultrasonic transducer array **800**. It is not necessary to have all ultrasonic transducers **111** in the ultrasonic transducer array **800** picking up the second ultrasonic wave. The ultrasonic transducer array **800**, which can be in rigid or flexible shape, can then perform time reversal focusing back to the active implantable device **810** with a more focused and higher energy. In certain embodiments, the one or more ultrasonic transducers **111** acquire a plurality of received signals, which is coupled to the processor **820**. The processor **820** is configured to perform time reversal focusing on each received signals. The time reversed signals are coupled back to the ultrasonic transducers **111** (Tx) for transmitting ultrasonic wave accordingly, such that the acoustic energy can advantageously dynamically focus at and target back onto the active implantable device **810**.

[0090] An iterative method can be used in conjunction with the active time reversal focusing method such that the precision of the targeting can be improved. During each iteration, the built-in transducer of the active implantable device **810** can transmit ultrasonic wave according to the incidental ultrasonic wave. By applying the time reversal method iteratively, the ultrasonic energy can be more focused on the active implantable device **810**. During each iteration, the processor **820** determines whether the energy targeting is improved.

The iteration is repeated until there is no further improvement on the energy targeting. This iterative method can advantageously enhance the accuracy of focusing for achieving maximal focusing onto the active implantable device **810**.

[0091] When the first ultrasonic wave is picked up by the built-in transducer, the ultrasonic wave is converted into electric current and coupled to an alternating current (AC) time delay circuit. An exemplary circuit diagram for the AC time delay circuit is shown in FIG. **9**. Other electronic circuits comprising resistor-capacitor (RC) pair, transistors, FPGA, ASIC, flip-flop, or other electronic components may be applied for introducing the time delay without departing from the spirit of the present disclosure. The purpose of using the AC time delay circuit is to introduce a time delay to the received ultrasonic wave, such that the ultrasonic wave originally transmitted by the ultrasonic transducers **111** during a transmission period is dissipated. Therefore, the active implantable device **810** can transmit a second ultrasonic wave back to the ultrasonic transducer array **800** during a detection period without interference by the ultrasound from the transmission period or any reflection thereof. In certain embodiments, the second ultrasonic wave comprises a synchronization signal having information on the time delay, which is received by the ultrasonic transducer array **800** for the processor **820** to determine the time required for the ultrasound to travel to the active implantable device **810**.

[0092] In the case of transmitting ultrasonic energy a living body having a plurality of active implantable device **810** simultaneously, the time reversed waves undergo constructive interference at multiple locations where the plurality of active implantable device **810** is positioned. In certain embodiments, each of the plurality of active implantable device **810** is selectively responsive to a particular range of frequencies for selectively activating particular one or more active implantable device **810**.

[0093] FIG. **10A** provides a brightness mode (B-mode) ultrasound image reconstructed from a plane wave activation using a rigid ultrasonic transducer array **101**. The experiment was performed on a piece of chicken breast sample, with a stainless steel surface embedded therein to emulate an implantable device. From the experimental results, a device with a higher acoustic impedance difference can be seen at the top right side of the ultrasound image with strong reflection. FIG. **10B** shows a time reversal field generated from the B-mode ultrasound image shown in FIG. **10A**. The experiment was conducted using Vantage 128TM (Verasonics Inc.), a 128 channels ultrasound system, and a 5MHz linear transducer with an array of 128 ultrasonic transducers. Although the figure is depicted in grayscale (not shown

in color), the color of the figure is in blue (darker area) and yellow (brighter area). The blue area represents low ultrasound intensity, and the yellow area represents high ultrasound intensity. The intensity on the time reversal field was generated from computer simulation at a homogeneous medium and the intensity shows the time average intensity within the entire burst and acoustic wave traveling period.

[0094] The time reversal focusing method of the present invention can also take into account the inhomogeneity of the medium of body tissues. As compared to the conventional time-delay focusing method, which focuses ultrasound by assuming a uniform and known speed across the medium, the time reversal focusing method can advantageously take into account any effect such as scattering and change in sound speed when propagating through the medium. Therefore, using the time reversal focusing method can mitigate noises and deformations of the ultrasound signals.

[0095] For demonstrating the difference, signals of (1) an instantaneous impulse and (2) an acoustic source of a tone burst of 1MHz with 7 cycles are used and focused at a location inside a medium of tissues at a depth of 10cm. The result for time reversal focusing method and time-delay focusing method are compared. The simulation was performed using the k-Wave simulation toolbox. It was assumed that the medium has an acoustic sound speed of 1540m/s and a density of 1000kg/m³, and the scattering medium has a sound speed of 1800m/s and a density of 1500kg/m³. The scattering medium is randomly distributed in the medium occupying approximately 1/4 of the medium space. Time reversal focusing method was conducted by simulating an acoustic wave focused at the position at 10cm depth inside the medium. The reflected acoustic wave was picked up and acquired by 216 ultrasonic transducers aligned linearly in the simulation space. By performing time reversal focusing of the received ultrasound signal, a time reversed ultrasonic wave was sent out from each of the ultrasonic transducers. For time-delay focusing, the 216 ultrasonic transducers sent out signals with time delay corresponding to the distance to the focal spot. By assuming that the speed of sound is 1540m/s, the time delay can be set so that the ultrasound signals would have reached the focal spot at the same time.

[0096] FIG. 11A and FIG. 11B show the comparison between time reversal focusing method and time-delay focusing method with an instantaneous impulse. FIG. 12A and FIG. 12B show the comparison between time reversal focusing method and time-delay focusing method with an acoustic source of a tone burst of 1MHz with 7 cycles. The signal to noise ratio (SNR) can be obtained by calculating the root mean square of the time after the signal,

and dividing by the maximum signal intensity. The SNR for the case of an instantaneous impulse was 3.01% for using the time reversal focusing method and 5.61% for using the time-delay method. The SNR of tone burst was 5.01% for using the time reversal focusing method and 12.92% for using the time-delay method.

C. IMAGE FORMATION AND TARGETED ENERGY DELIVERY

[0097] The location of the implantable device **131** can also be monitored by forming an ultrasonic image. This is done by the reflection of the ultrasonic wave from the surface of the implantable device **131**. Due to acoustic impedance mismatch of the implantable device **131** and the neighboring tissues, ultrasonic wave traveled to such surface is reflected at the boundary. Advantageously, the reflection of the acoustic wave can provide a location and structural information of the implantable device **131**, as well as other physical properties such as stiffness, temperature, and acoustic speed.

[0098] Referring to FIG. **13A**, the flexible ultrasonic transducer array **102**, operating as an acoustic wave source, is configured to generate acoustic waves. The acoustic wave generated at each ultrasonic transducer **111** is determined based on the relative location, orientation, and directionality of each ultrasonic transducer **111**, thereby time-delay focusing and/or electronic beamforming can be performed. Time-delay focusing and electronic beamforming are performed by controlling the timing and/or phase of the ultrasonic wave generation by the processor. In certain embodiments, time-delay focusing is performed by calculating the relative center location from the flexible ultrasonic transducer array **102** to a focus point **1301**, determining a delay for each ultrasonic transducers **111**, and generating a plurality of ultrasonic waves by the ultrasonic transducer **111** each with the delay, thereby an acoustic wavefront **1302** propagating to the focus point **1301** is obtainable with a constructive interference of the ultrasonic waves at the focus point **1301**. The constructive interference of the ultrasonic waves can generate stronger energy at the focus point **1301**. By performing the ultrasonic focusing method repeatedly and iteratively at different locations and depths, a complete scanning of the entire field-of-view can be performed. The echo received from each location can be combined with the time of reflection to generate a full ultrasonic image on the acoustic beam intensity distribution.

[0099] Referring to FIG. **13B**, an alternative method for forming an ultrasonic image is depicted. A rigid transducer array **101** or a flexible transducer array **102** may be used. For a flexible transducer array **102**, the method is performed by calculating a relative position and

orientation between the plurality of ultrasonic transducers **111** in real-time, determining a delay for each ultrasonic transducer **111**, and generating a plurality of ultrasonic waves by the ultrasonic transducer **111** each with the delay, thereby a plane acoustic wavefront **1312** is obtainable. The plane acoustic wavefront **1312** is a straight and flat wavefront. For a rigid transducer array **101**, the plane acoustic wavefront **1312** can be obtained by generating a plurality of ultrasonic waves by the ultrasonic transducer **111** simultaneously. By varying the steering angle of the ultrasonic transducers **111**, the reflecting surface inside the living body can form reflection matrices. The reflection matrices together with the location and orientation information of the transducer array can collectively be used to calculate the physical location of each reflecting surface and hence form an ultrasound image.

[0100] After forming the ultrasound image, image analysis is performed to recognize the implantable device **131** in the ultrasound image. Information such as brightness, shapes, thickness, stiffness, etc. can be used to identify the implantable device **131** within the ultrasound image. Pattern recognition could also be used to determine the location on the implant based on the specific shape and size of the implantable device **131**. Additionally, by manipulating the surface of the implantable device **131** or using different materials, the reflection pattern of the echo signal can be made unique, thereby the echo signal can be easily differentiated from other echoes coming from other surrounding tissues. Classification such as big data analysis can be used to classify objects under the ultrasound images and perform accurate recognition of the implantable device **131**. Besides from pattern recognition, other imaging techniques such as shear wave elastography, phase contrast method can be used to improve the determination of the location of the implantable device **131** from the image.

[0101] After determining the location and orientation of the implantable device **131**, focused energy is delivered to the implantable device **131** with maximum efficiency. The method comprises focusing the ultrasonic energy to the implantable device **131**, and converting the ultrasonic energy into electrical currents through piezoelectric elements, CMUTs, optical based transducers, or other materials. The ultrasonic transducer in the implantable device **131** generally has a specific frequency response. A typical voltage produced per unit of acoustic pressure of an ultrasonic transducer is shown in FIG. **14**. The energy transmission efficiency can be optimized by selecting a resonance frequency of the ultrasonic transducer for transmitting ultrasonic wave. In certain embodiments, the usable frequency range of the ultrasonic transducer can also be selected for transmission if a linear conversion of ultrasonic energy into electrical currents is required.

[0102] Now refer to FIG. 15A and FIG. 15B, after selecting the frequency range, a focused ultrasound field can be generated by calculating the traveling time of the acoustic wave from the ultrasonic transducer 111 to the focus. FIG. 15A shows an exemplary focusing of ultrasound to an implantable device 131 by activating all the ultrasonic transducers with time-delay. Similarly, FIG. 15B shows an exemplary focusing of ultrasound to an implantable device 131 by activating a number of the ultrasonic transducers 111. In both case, different time delays are applied to different ultrasonic transducers 111 when transmitting ultrasound so that the ultrasonic waves from the ultrasonic transducers 111 add up to obtain an acoustic wavefront 1501, 1502 propagating to a focus point with maximum energy transmission at the implantable device 131. The number of ultrasonic transducer 111 activated for transmission is determined according to the depth, location, and the orientation of the implantable device 131.

[0103] FIG. 16 shows a system diagram of the active time-delay focusing method using an active implantable device 1610 which transmit ultrasound. Initially, at least one ultrasonic transducer 111 is activated and transmits ultrasonic wave into the living body. The active implantable device 1610 comprises a built-in ultrasonic transducer for receiving the ultrasonic wave. The ultrasonic wave delivers electrical energy to charge up the active implantable device 1610. In certain embodiments, the ultrasonic transducer 111 can perform synchronization with the active implantable device 1610. In certain embodiments, the electrical energy for charging the active implantable device 1610 can be harvested from other sources such as heat, ions, kinetic motion, or magnetic field.

[0104] Once the active implantable device 1610 is charged up with sufficient electrical energy, the built-in transducer of the active implantable device 1610 can send out a second ultrasonic wave. The second ultrasonic wave travels through the tissues of the living body, then picked up by the ultrasonic transducer array 1600. It is not necessary for to have all ultrasonic transducers 111 in the ultrasonic transducer array 1600 picking up the second ultrasonic wave. The ultrasonic transducer array 1600, which can be in rigid or flexible shape, can then perform reconstruction to obtain information of the location and/or orientation of the active implantable device 1610. In certain embodiments, the plurality of ultrasonic transducers 111 acquires a plurality of received signals, which are coupled to the processor 1620. The processor 1620 is configured to perform image analysis and image focusing for reconstructing an image of the active implantable device 1610. The step of image focusing comprising a time-delay focusing and a simulated scatter-corrected focusing. A phase delay

focusing equation can be applied to all ultrasonic transducers **111** such that ultrasonic energy can be focused onto the active implantable device **1610** with a desired waveform. The phase delay focusing equation is formulated such that the phase delay at each ultrasonic transducer **111** can be set such that when an acoustic wave hits on the focus point, all waves add up with a constructive interference. More particularly, a time-delay or a phase-delay is introduced by taking into account the time of flight of the acoustic wave from each ultrasonic transducer **111** to the focus point. Generally, the phase delay focusing equation is based on a relative position and orientation between the one or more ultrasonic transducers **111**.

[0105] In the case of transmitting ultrasonic energy to a living body having a plurality of active implantable device **1610** simultaneously, the phase delay at each ultrasonic transducer **111** can be set such that constructive interference is resulted at multiple locations where the plurality of active implantable device **1610** is positioned. In certain embodiments, each of the plurality of active implantable device **1610** is selectively responsive to a particular range of frequencies for selectively activating particular one or more active implantable device **1610**.

[0106] The advantage of the active time-delay focusing method is that there can be a full control on the waveform that is delivered to the active implantable device **1610**. The waveform can be fully modulated in a manner to facilitate signal transduction as well as providing electrical energy for activating and communicating with the active implantable device **1610**.

[0107] An iterative method can be used in conjunction with the active time-delay focusing method such that the precision of the targeting can be improved. During each iteration, the built-in transducer of the active implantable device **1610** can transmit ultrasonic wave to the ultrasonic transducer array **1600**, and the processor **1620** can determine whether the energy targeting is improved. The iteration is repeated until there is no further improvement on the energy targeting. This iterative method can advantageously enhance the accuracy of focusing for achieving maximal focusing onto the active implantable device **1610**.

D. ADDITIONAL FEATURES AND EXPERIMENTAL RESULTS

[0108] In certain embodiments, the second ultrasonic wave sent out by the active implantable device **1610** can carry other data, such as temperature, pressure, pH value, glucose level, or other sensing data. The electrical energy received from the ultrasonic wave can power the sensors. While ultrasound has been used for signal transformation, a targeted signal transfer of the sensed data to the ultrasonic transducers **111**. The sensitivity can be

significantly enhanced even when receiving a weak second ultrasonic wave with the sensed data.

[0109] In certain embodiments, data or signal can be delivered to the active implantable device **1610** using different data modulations of the ultrasound wave, such as magnitude modulations, frequency modulations, and pulse modulations. The sensors in the active implantable device **1610** can receive commands from the processor **1620**, such as adjusting the gain of sensor amplifier or enabling a sensor regularly. Since the present invention provides a method of targeting the ultrasonic energy to the active implantable device **1610**, high efficiency of communication, and low noise due to multiple scattering can be achieved. Two-way communication between the active implantable device **1610** and the ultrasonic transducer array **1600** can be established.

[0110] In certain embodiments, the implantable device **131** (active or not) can have a non-linear effect on ultrasound sonication. This can be done by introducing materials or substances with non-linear ultrasonic property, for example, micro-bubbles are well known to have non-linear effect of ultrasound. These non-linear properties will generate harmonics of the reflected ultrasound wave. These harmonics usually have a frequency of half or an integer multiple of the sonication frequency.

[0111] As shown in FIG. 17, the frequency spectrums of a fundamental signal and a first harmonic signal are shown. As the harmonic signals are the frequency spectrums which do not overlap with the fundamental signal (signals originally sent out from the ultrasonic transducer array **100**), the implantable device **131** can be identified from other structures by selecting the frequency spectrum of the harmonic signals. Image reconstructions or time reversal could then be done on that harmonic spectrum to provide more specific monitoring and/or targeting.

[0112] For an active implantable device **810, 1610**, the ultrasound generated can have a different frequency of ultrasound than the charging ultrasound wave using a frequency changer. This can allow differentiation between the generated signal and the backscattered charging signal. In certain embodiments, shorter wait time or no wait time is needed for the generation of ultrasound after charging the active implantable device **810, 1610**.

[0113] Multiple implantable devices **131** can be present in the field of view of the ultrasound transducer array **100**. In order to identify the implantable devices **131**, other than analyzing the possible shape and structural features, an active implantable device **810, 1610** can be coded with different frequencies to make it identifiable. The active implantable device

810, 1610 with different frequencies transmission can be identified by the ultrasound transducer array **100** by simple frequency filtering of signals.

[0114] Frequency encoding could also be used to selectively activate a particular implantable device **131**. For example, the ultrasound sensor of each implantable device **131** can have different resonance frequencies which would only be activated with ultrasound wave of specific frequencies. In one embodiment, filtering circuit or computerized designs within the receiving part of the implantable device **131** can be used to allow activation of implantable device **131** only when a certain frequency of ultrasound is received. This can allow different activation time of implantable device **131** within the field of view of the ultrasound transducer array **100** by frequency selection.

[0115] FIG. **18A** shows an image reconstructed from a known convex ultrasonic transducer array **100**. FIG. **18B** shows another image reconstructed from a known S-shaped ultrasonic transducer array **100**. FIG. **18C** shows yet another image reconstructed from a known concave ultrasonic transducer array **100**. In all three cases, a plane wave is used for activation.

[0116] FIG. **10A** and FIG. **10B** show an ultrasound image reconstructed of a piece of chicken breast sample with a stainless steel surface embedded. FIG. **19A** and FIG. **19B** show the B-mode ultrasound image and the time reversal field generated for another similar experience. Time reversal method was used to target the ultrasound back to the stainless steel surface. The intensity distribution at the location of the stainless steel is approximately 2 times larger than the neighboring tissues.

[0117] The present disclosure may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The present embodiment is, therefore, to be considered in all respects as illustrative and not restrictive. The scope of the disclosure is indicated by the appended claims rather than by the preceding description, and all changes that come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein.

What is claimed is:

1. A method for transmitting ultrasonic energy from an ultrasonic transducer array having one or more ultrasonic transducers to an implantable device by time reversal focusing, the method comprising the steps of:
 - generating a first ultrasonic wave having at least one frequency and at least one amplitude by at least one ultrasonic transducer;
 - transmitting the first ultrasonic wave to the implantable device, thereby an echo signal is reflected to the ultrasonic transducer array from the implantable device;
 - receiving the echo signal by the ultrasonic transducer array such that the one or more ultrasonic transducers acquire a plurality of received signals based on the echo signal;
 - coupling the received signals to a processor for generating time reversed signals;
 - modulating the one or more ultrasonic transducers to generate time reversed waves according to the time reversed signals, wherein the time reversed waves undergo constructive interference at a location where the echo signal is transmitted from; and
 - transmitting the time reversed waves to the implantable device for transmitting the ultrasonic energy from the time reversed waves to the implantable device.
2. The method of claim 1, further comprising the step of reflecting the first ultrasonic wave as the echo signal, wherein the implantable device is a device having significantly higher acoustic impedance than adjacent tissues.
3. The method of claim 1, further comprising iterating the steps of receiving the echo signal by the one or more ultrasonic transducers and coupling the received signals to the processor for generating time reversed signals for improving an ultrasonic energy targeting.
4. The method of claim 1, wherein the first ultrasonic wave is a plane wave or a random time-delayed wave as generated by two or more ultrasonic transducers such that a natural focus spot is not present.

5. The method of claim 1, wherein the processor is configured to perform time reversal focusing on each echo signal received by the one or more ultrasonic transducers.
6. The method of claim 5, wherein the processor is configured to perform post-processing filtering of noise and correcting a linearity and a frequency response of ultrasound generation by the ultrasonic transducers.
7. The method of claim 1, wherein the ultrasonic energy from the time reversed waves is converted into electrical currents through piezoelectric elements, capacitive micromachined ultrasonic transducers (CMUTs), optical based transducers, or other materials.
8. The method of claim 1, wherein the implantable device comprises materials or substances with a non-linear ultrasonic property such that the echo signal has a frequency different from the first ultrasonic wave.
9. The method of claim 1, wherein the step of coupling the received signals to a processor for generating time reversed signals further comprises the steps of:
 - converting the received signals to digital signals using an analog-to-digital converter (ADC);
 - writing the digital signals to a memory;
 - performing a time-domain flip of the digital signals to obtain flipped digital signals; and
 - converting the flipped digital signals to obtain the time reversed signals using a digital-to-analog converter (DAC).
10. The method of claim 1, wherein the step of coupling the received signals to a processor for generating time reversed signals further comprises the steps of:
 - coupling the received signals to a Fourier transform circuit and an envelope detector which is arranged in parallel to the Fourier transform circuit;
 - generating a frequency component of the received signals using the Fourier transform circuit;

generating a magnitude component of the received signals using the envelope detector;
flipping the received signals by obtaining a conjugate in Fourier transform of the echo signal; and
performing inverse Fourier transform to obtain the time reversed signals.

11. A method for transmitting ultrasonic energy to a plurality of implantable devices in a living body simultaneously by time reversal focusing, wherein each of the plurality of implantable devices is configured to receive the ultrasonic energy from an ultrasonic transducer array in accordance with the method of claim 1, and wherein the time reversed waves from the ultrasonic transducer array undergo constructive interference at multiple locations where the plurality of implantable devices is positioned.
12. The method of claim 11, wherein each of the plurality of implantable devices is selectively responsive to a range of frequencies for selectively activating the one or more implantable devices.
13. A method for transmitting ultrasonic energy from an ultrasonic transducer array having one or more ultrasonic transducers to an active implantable device by time reversal focusing, the method comprising the steps of:
 - generating a first ultrasonic wave having at least one frequency and at least one amplitude by at least one ultrasonic transducer;
 - transmitting the first ultrasonic wave to the implantable device, wherein the first ultrasonic wave is received by a built-in transducer in the implantable device;
 - converting the first ultrasonic wave into electrical energy;
 - generating a second ultrasonic wave based on the first ultrasonic wave, wherein the second ultrasonic wave is transmitted in an opposite direction to the first ultrasonic wave;
 - receiving the second ultrasonic wave by the ultrasonic transducer array such that the one or more ultrasonic transducers acquire a plurality of received signals based on the second ultrasonic wave;
 - coupling the received signals to a processor for generating time reversed signals;

modulating the one or more ultrasonic transducers to generate time reversed waves according to the time reversed signals, wherein the time reversed waves undergo constructive interference at a location where the echo signal is transmitted from; and

transmitting the time reversed waves to the implantable device for transmitting the ultrasonic energy from the time reversed waves to the implantable device.

14. The method of claim 13, wherein the active implantable device comprises a delay circuit for introducing a time delay to the first ultrasonic wave such that the echo signal is transmitted after dissipating the first ultrasonic wave.
15. The method of claim 14, wherein the delay circuit is an alternating current (AC) time delay circuit.
16. The method of claim 14, wherein the second ultrasonic wave comprises a synchronization signal having information on the time delay.
17. The method of claim 13, wherein the active implantable device comprises a frequency changer such that the second ultrasonic wave has a frequency different from the first ultrasonic wave.
18. The method of claim 13, wherein the active implantable device is configured to be activated by the first ultrasonic wave having a predetermined frequency for enabling a selection of the active implantable device.
19. The method of claim 13, wherein the processor is configured to encode commands to the first ultrasonic wave by data modulations such as magnitude modulations, frequency modulations, and pulse modulations.
20. A method for transmitting ultrasonic energy to a plurality of active implantable devices in a living body simultaneously by time reversal focusing, wherein each of the plurality of active implantable devices is configured to receive the ultrasonic energy from an ultrasonic transducer array in accordance with the method of claim 13, and wherein the time reversed waves from the ultrasonic transducer array undergo

constructive interference at multiple locations where the plurality of active implantable devices is positioned.

21. The method of claim 20, wherein each of the plurality of active implantable devices is selectively responsive to a range of frequencies for selectively activating the one or more active implantable devices.
22. A method of transmitting ultrasonic energy from an ultrasonic transducer array having a plurality of ultrasonic transducers to an active implantable device by time-delay focusing, the method comprising the steps of:
 - generating a first ultrasonic wave having at least one frequency and at least one amplitude by at least one ultrasonic transducer;
 - transmitting the first ultrasonic wave to the implantable device, wherein the first ultrasonic wave is received by a built-in transducer in the implantable device;
 - converting the first ultrasonic wave into electrical energy;
 - generating a second ultrasonic wave based on the first ultrasonic wave, wherein the second ultrasonic wave is transmitted in an opposite direction to the first ultrasonic wave;
 - receiving the second ultrasonic wave by the ultrasonic transducer array such that the plurality of ultrasonic transducers acquires a plurality of received signals based on the second ultrasonic wave;
 - coupling the received signals to a processor for generating phase delay signals; and
 - applying a phase delay focusing equation to the plurality of ultrasonic transducers based on the phase delay signals such that the ultrasonic energy can be focused onto the active implantable device with a desired waveform, wherein the ultrasonic energy is focused onto the active implantable device with constructive interference at a location of the active implantable device.
23. The method of claim 22, wherein the processor is configured to perform an image analysis and an image focusing for reconstructing an image of the active implantable device.

24. The method of claim 22, wherein the image focusing comprises a time-delay focusing and a simulated scatter-corrected focusing.
25. The method of claim 22, wherein the phase delay focusing equation is based on a relative position and a relative orientation between the one or more ultrasonic transducers.
26. The method of claim 22, wherein the ultrasonic energy is converted into electrical currents through piezoelectric elements, capacitive micromachined ultrasonic transducers (CMUTs), optical based transducers, or other materials.
27. A method for transmitting ultrasonic energy to a plurality of active implantable devices in a living body simultaneously by time-delay focusing, wherein each of the plurality of active implantable devices is configured to receive the ultrasonic energy from an ultrasonic transducer array in accordance with the method of claim 22, and wherein the ultrasonic energy is focused onto the plurality of active implantable devices with constructive interference at multiple locations where the plurality of active implantable devices is positioned.
28. The method of claim 27, wherein each of the plurality of active implantable devices is selectively responsive to a range of frequencies for selectively activating the one or more active implantable devices.

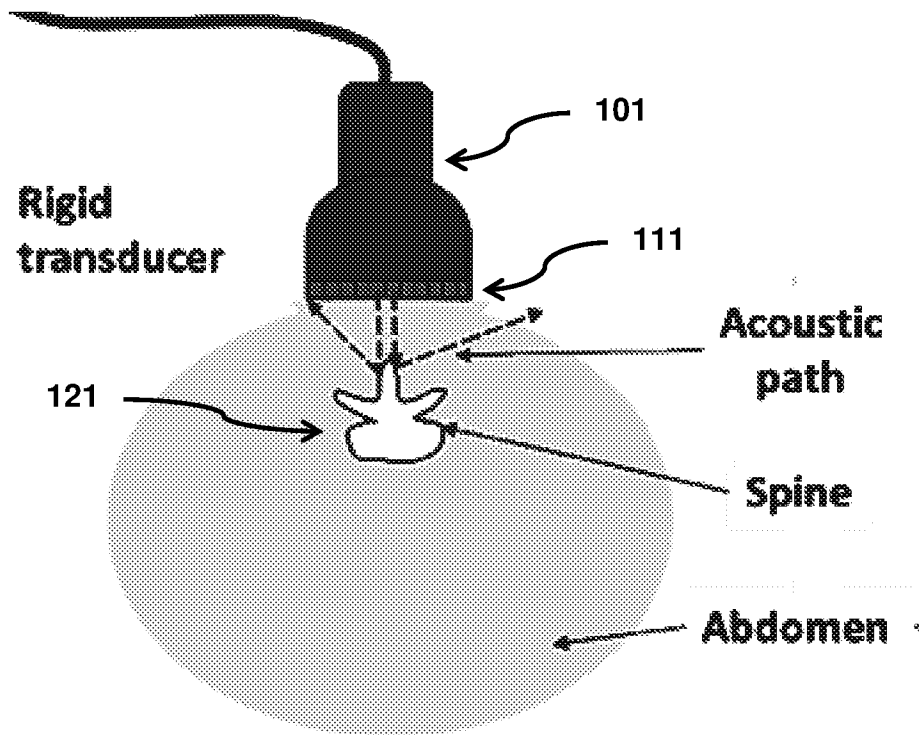


FIG. 1A

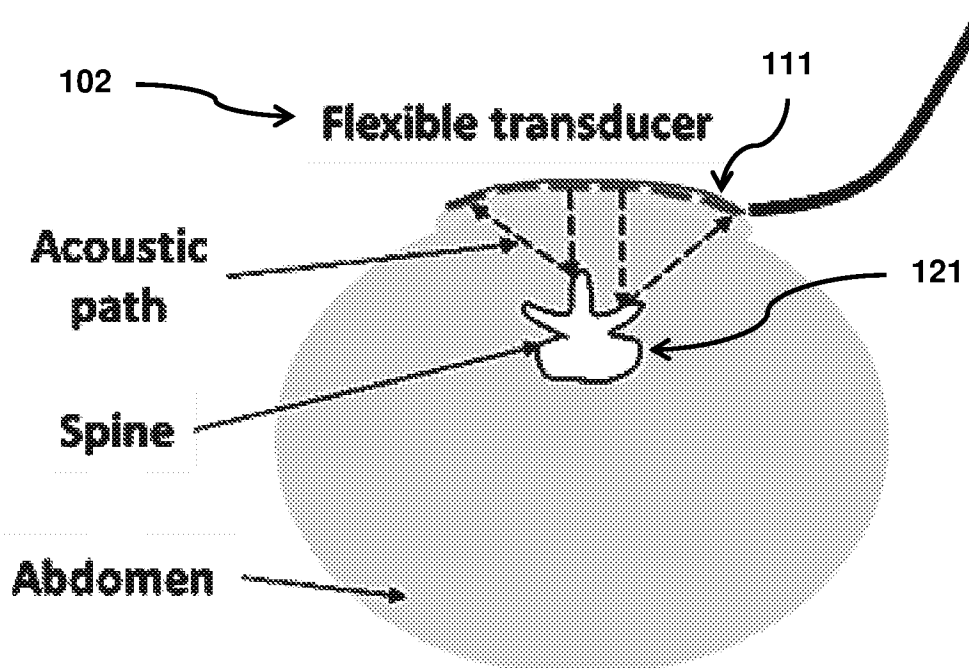


FIG. 1B

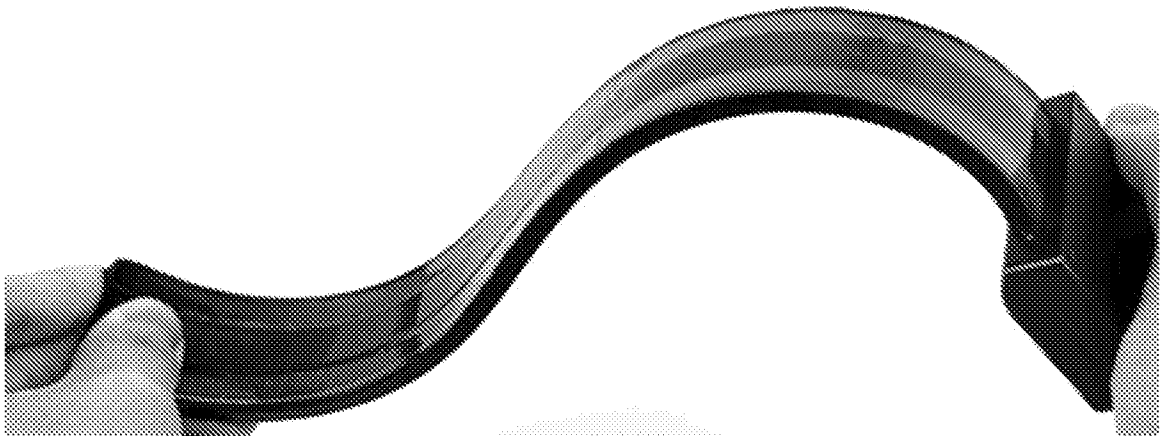


FIG. 2

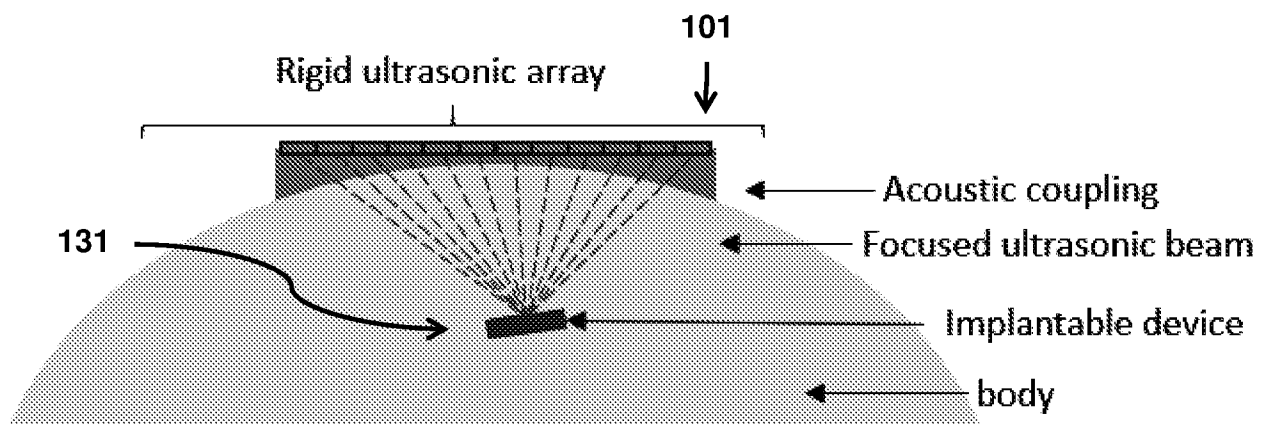


FIG. 3A

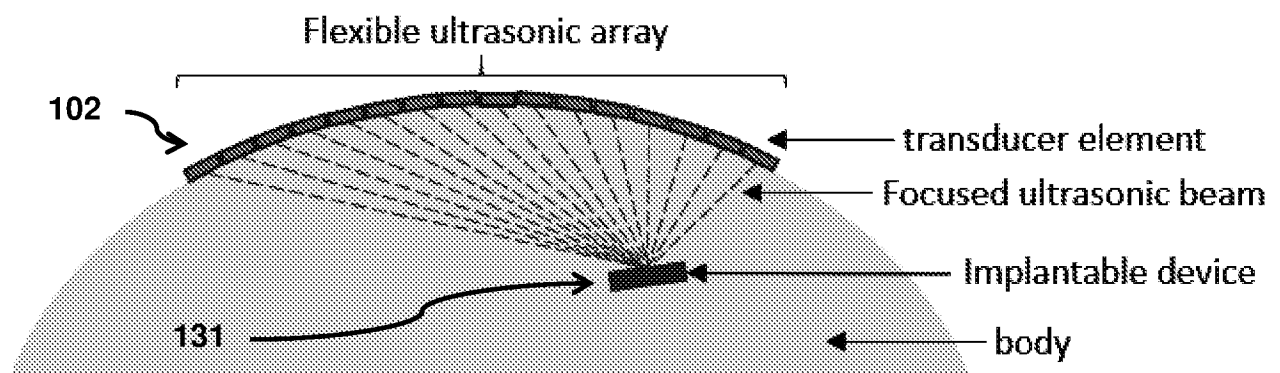


FIG. 3B

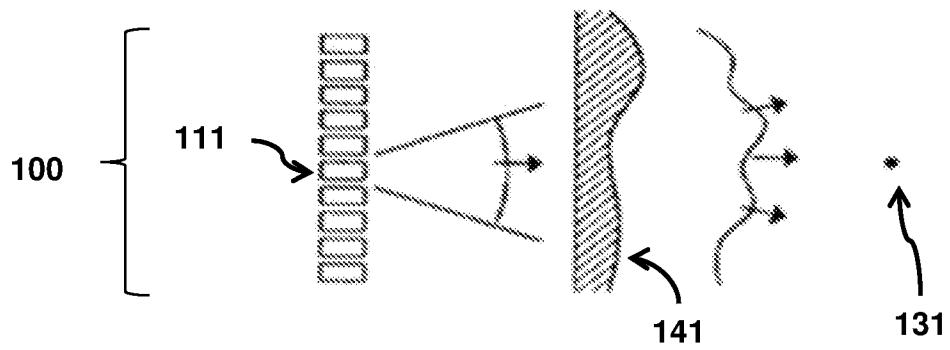


FIG. 4A

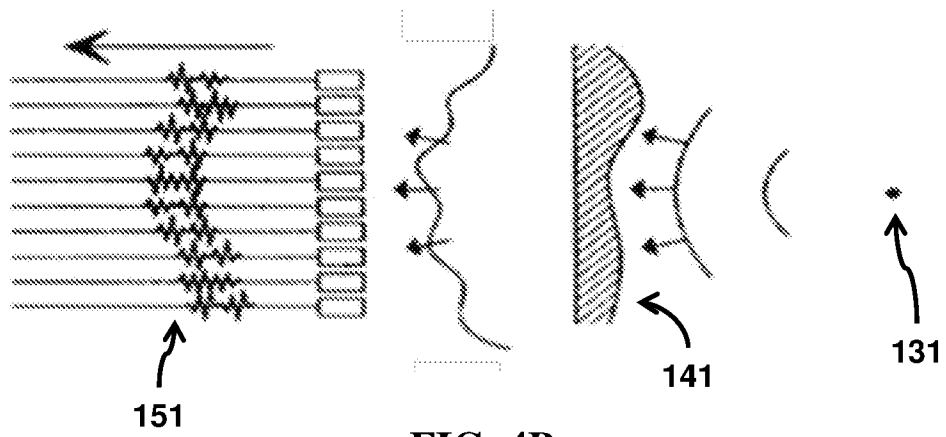


FIG. 4B

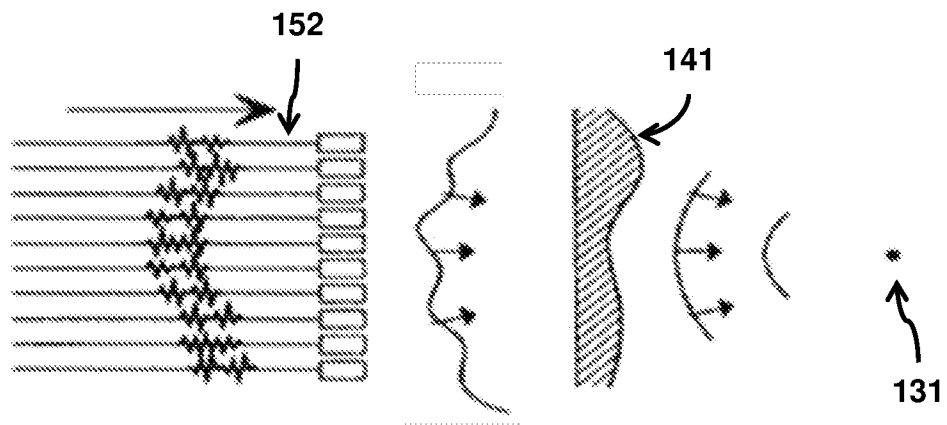


FIG. 4C

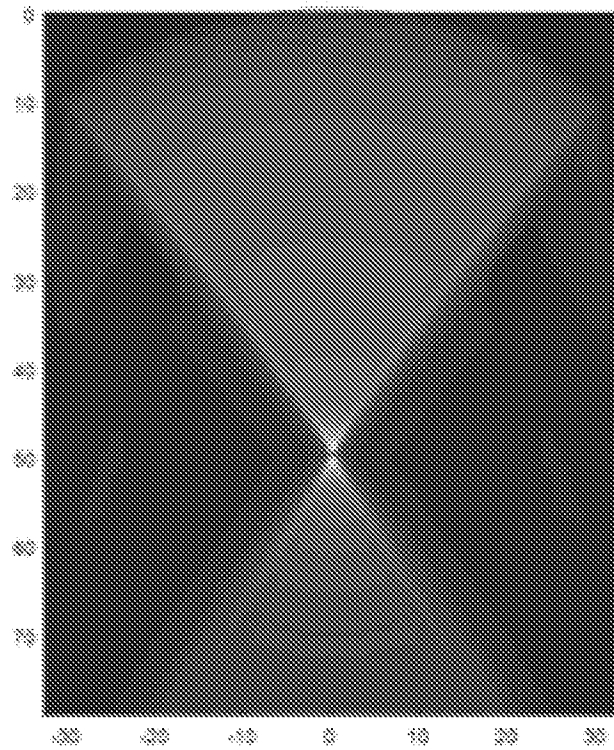


FIG. 5A

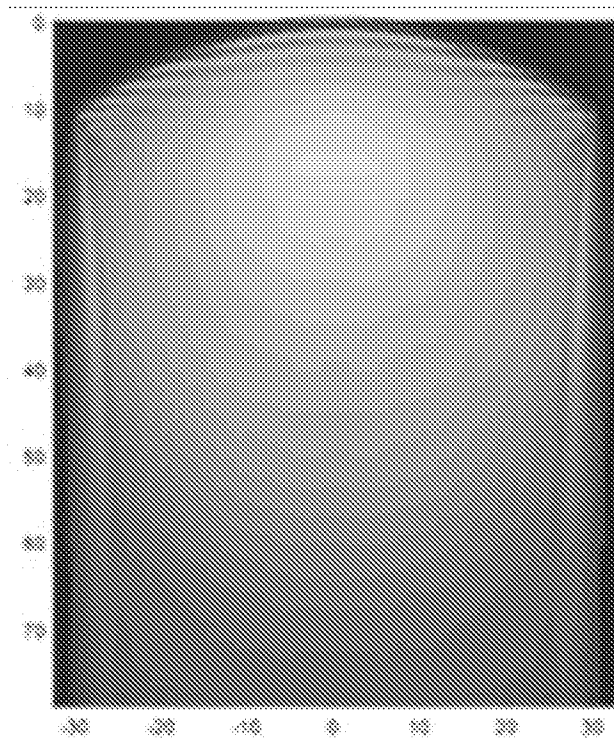


FIG. 5B

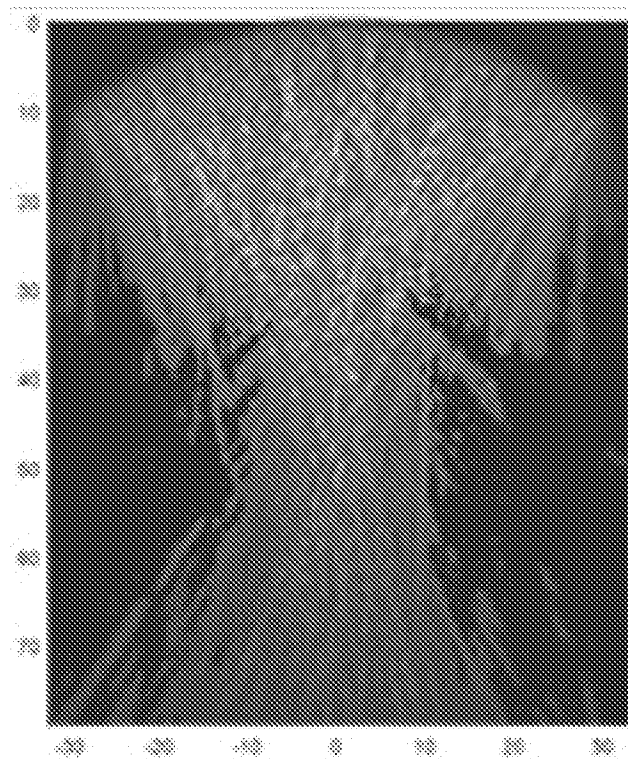


FIG. 5C

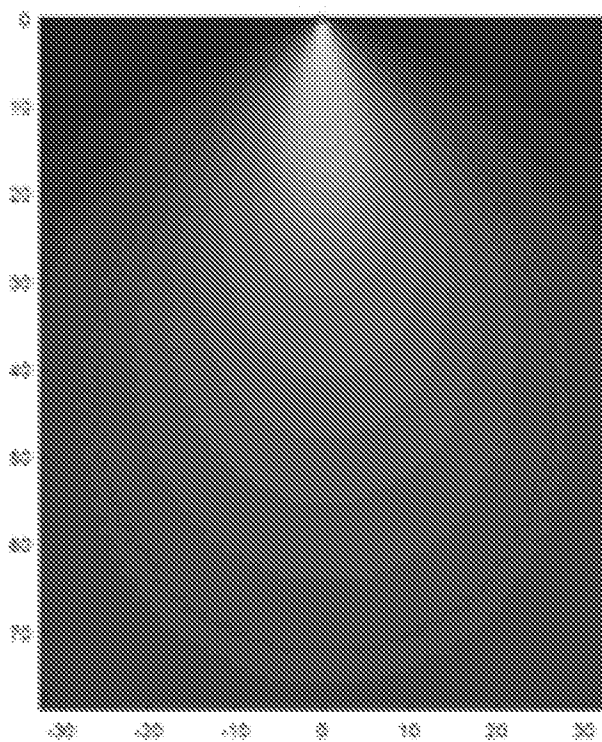


FIG. 5D

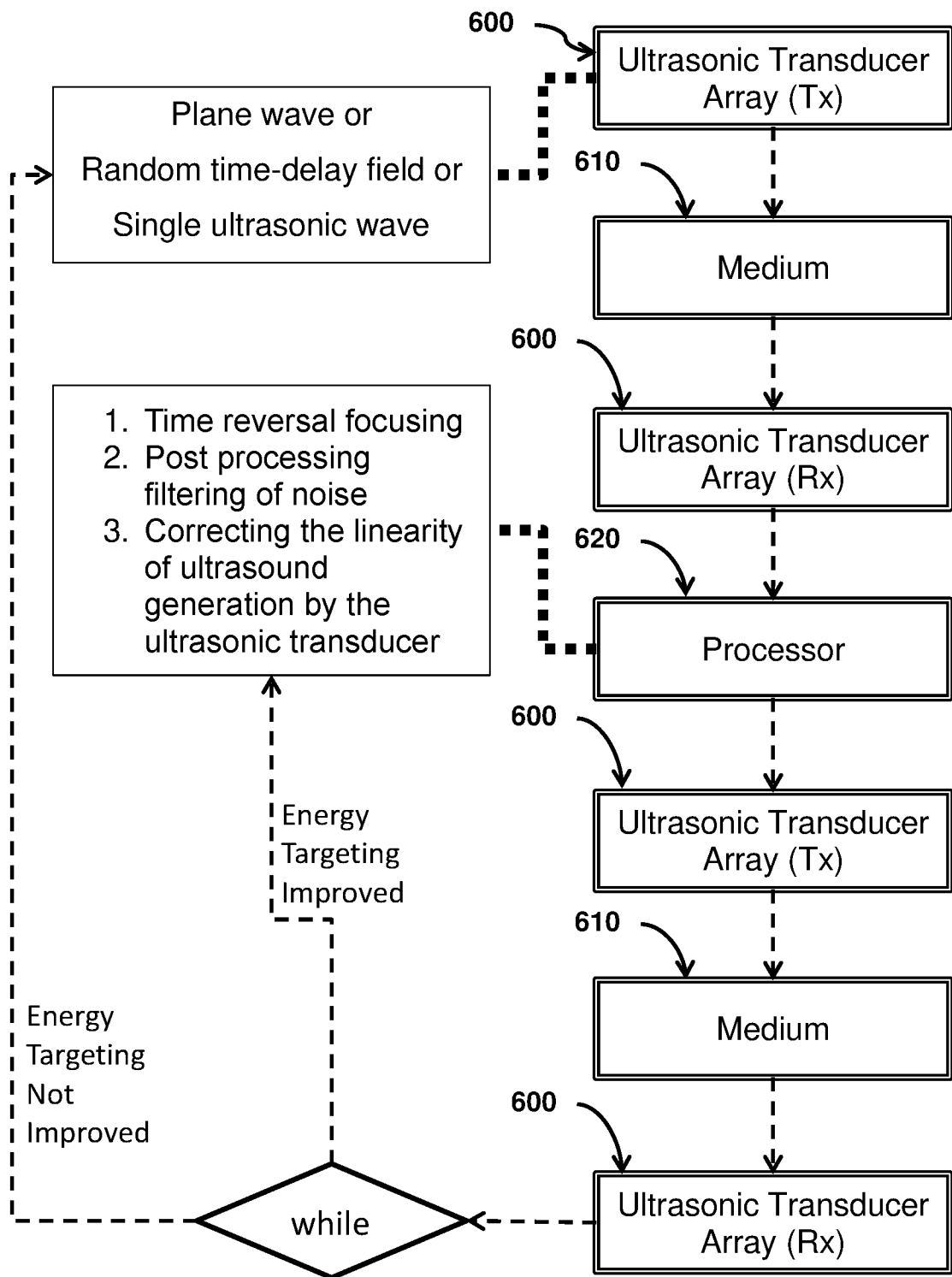
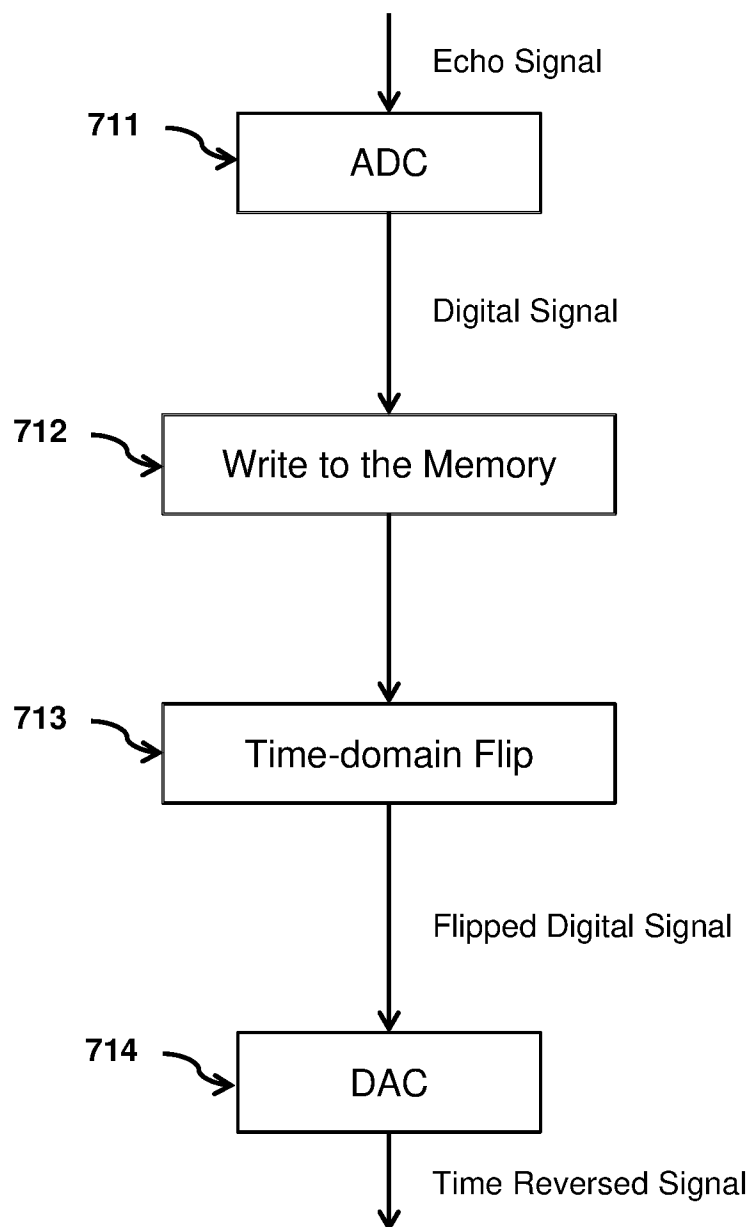
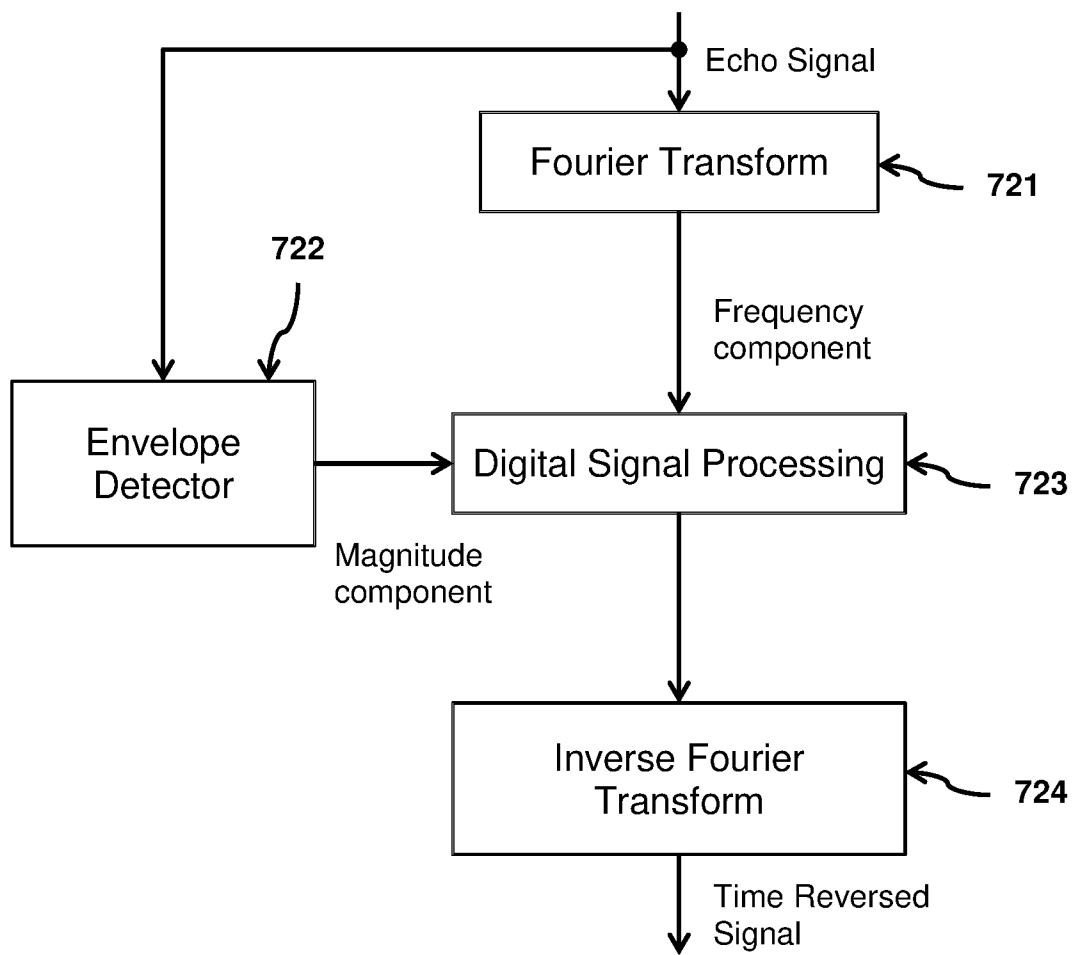


FIG. 6

**FIG. 7A**

**FIG. 7B**

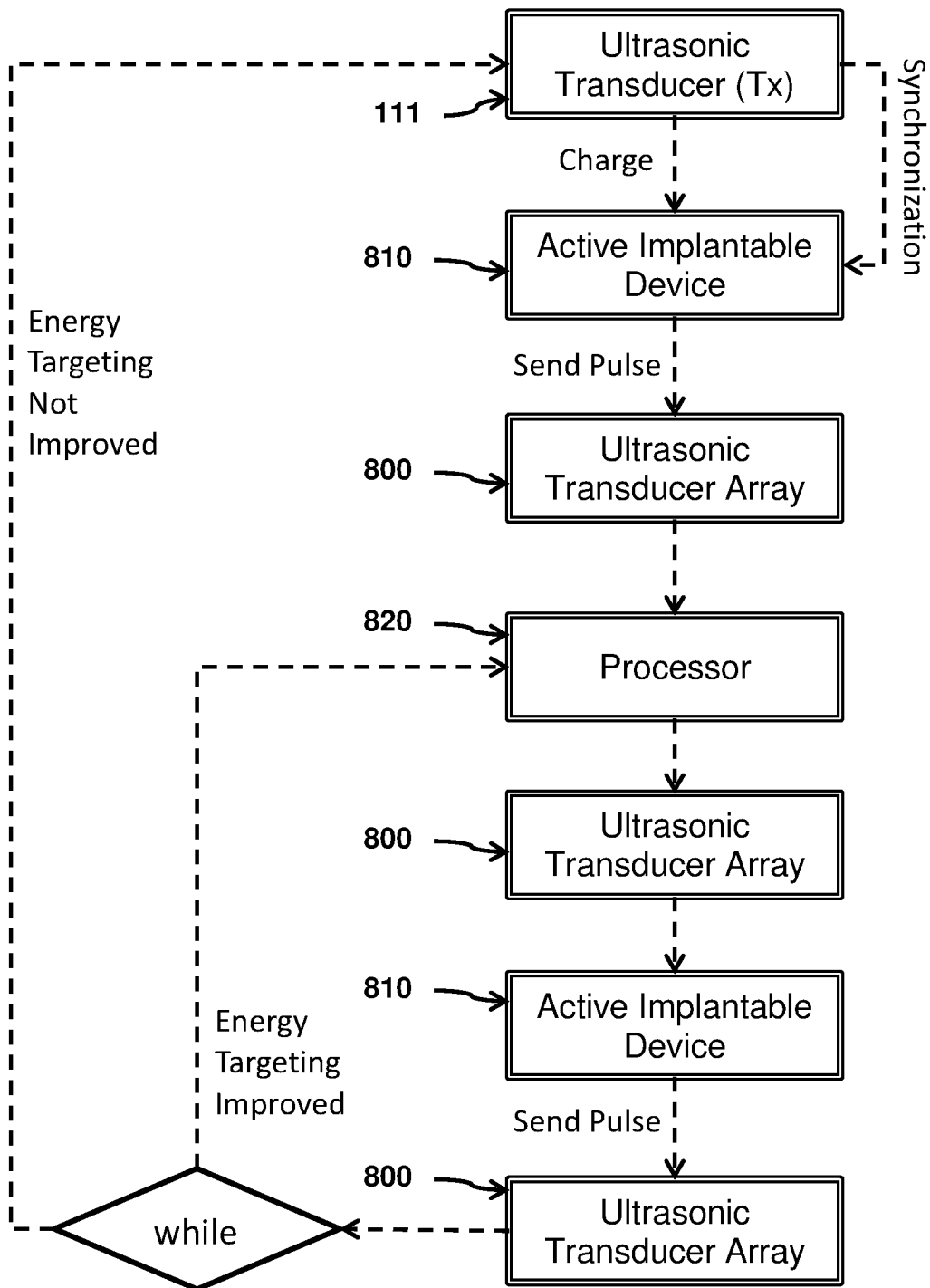


FIG. 8

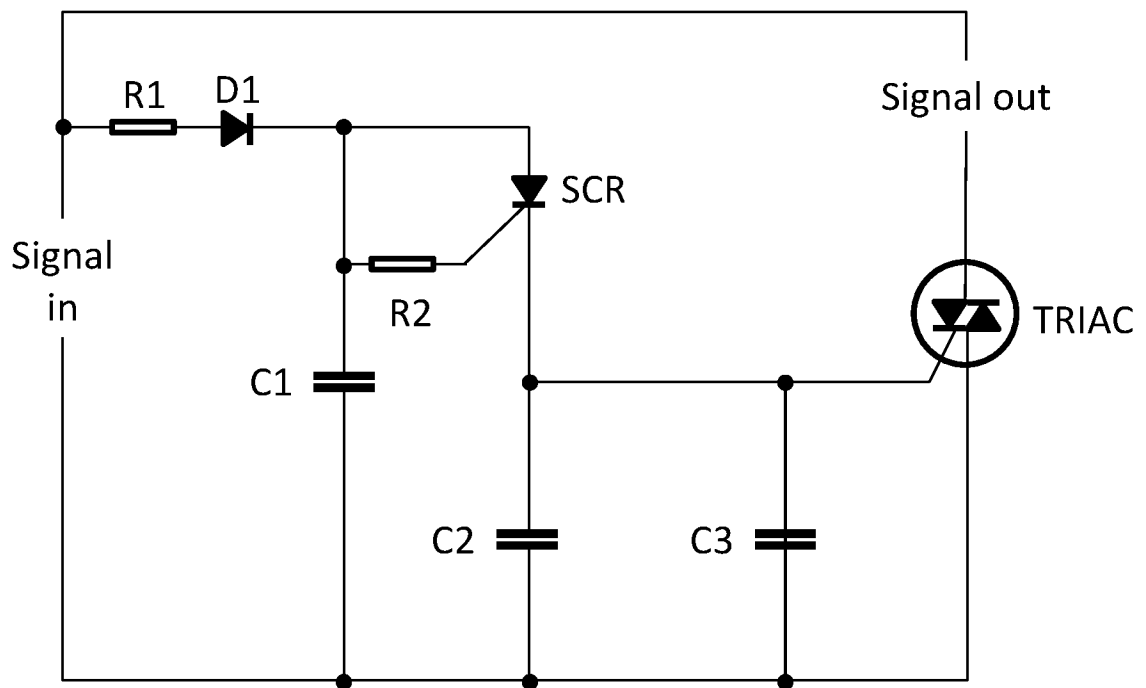
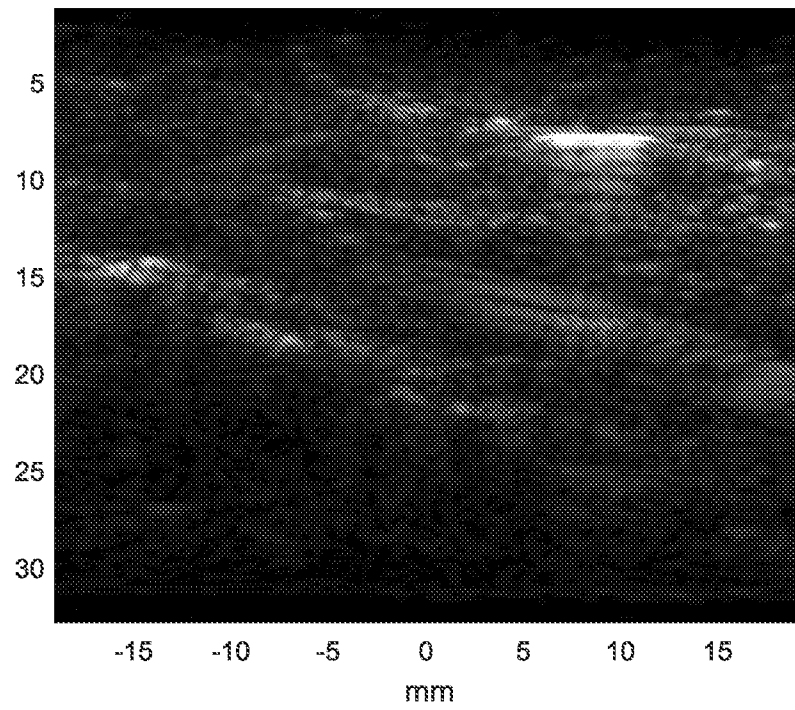
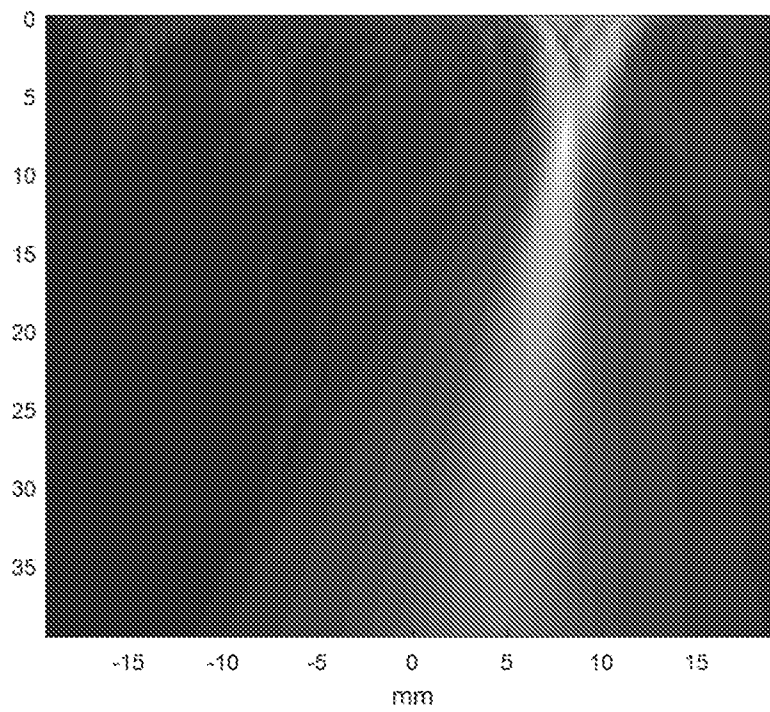


FIG. 9

**FIG. 10A****FIG. 10B**

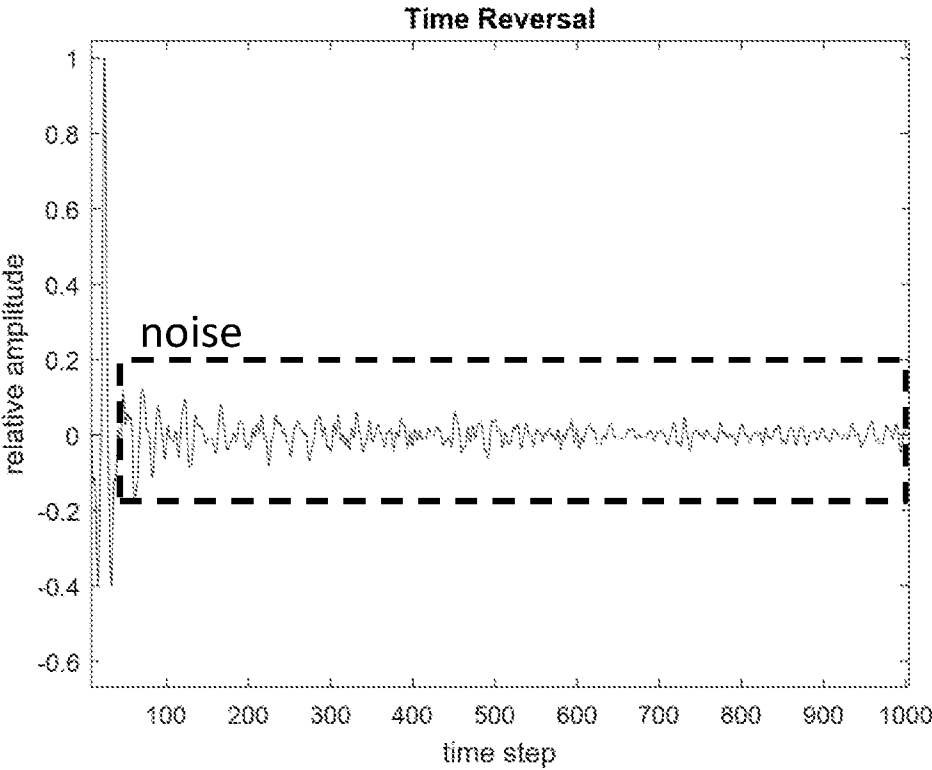


FIG. 11A

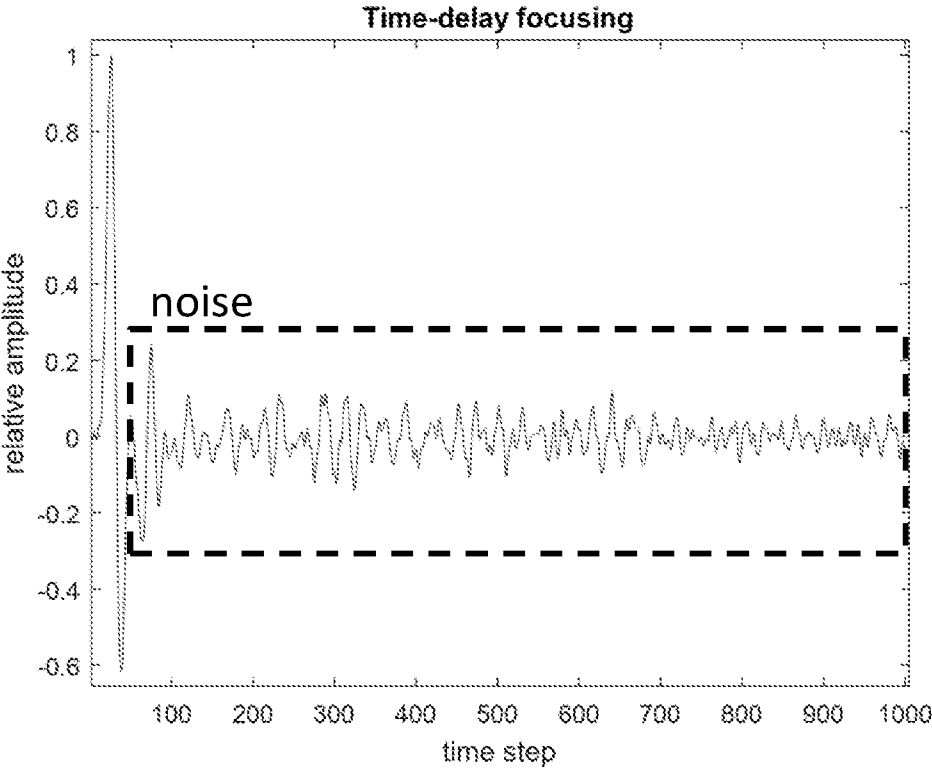
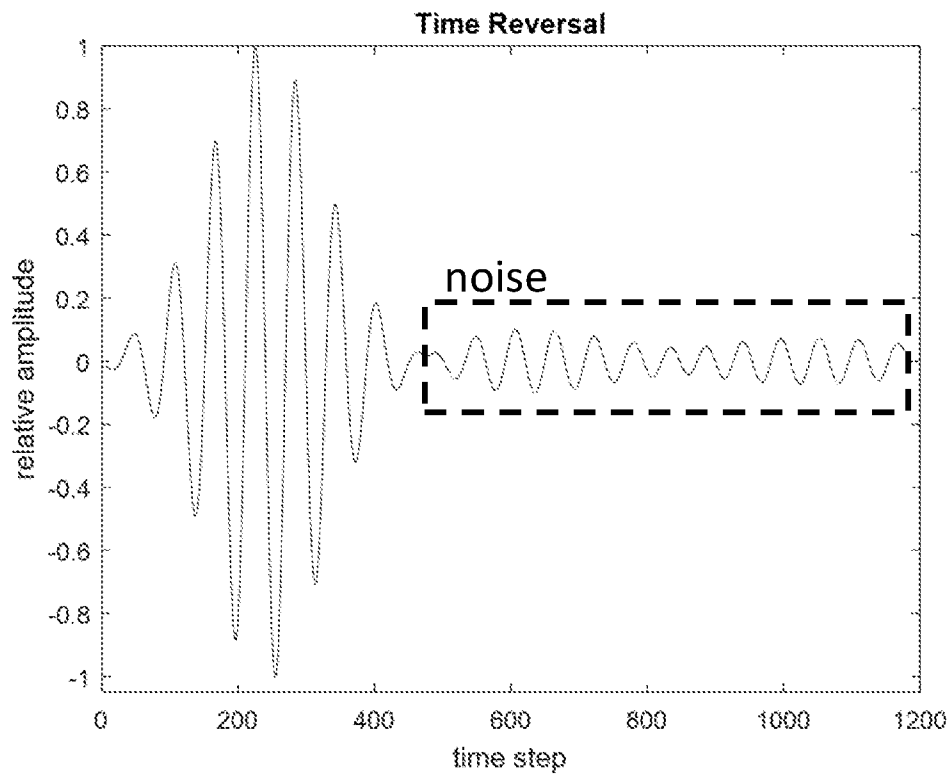
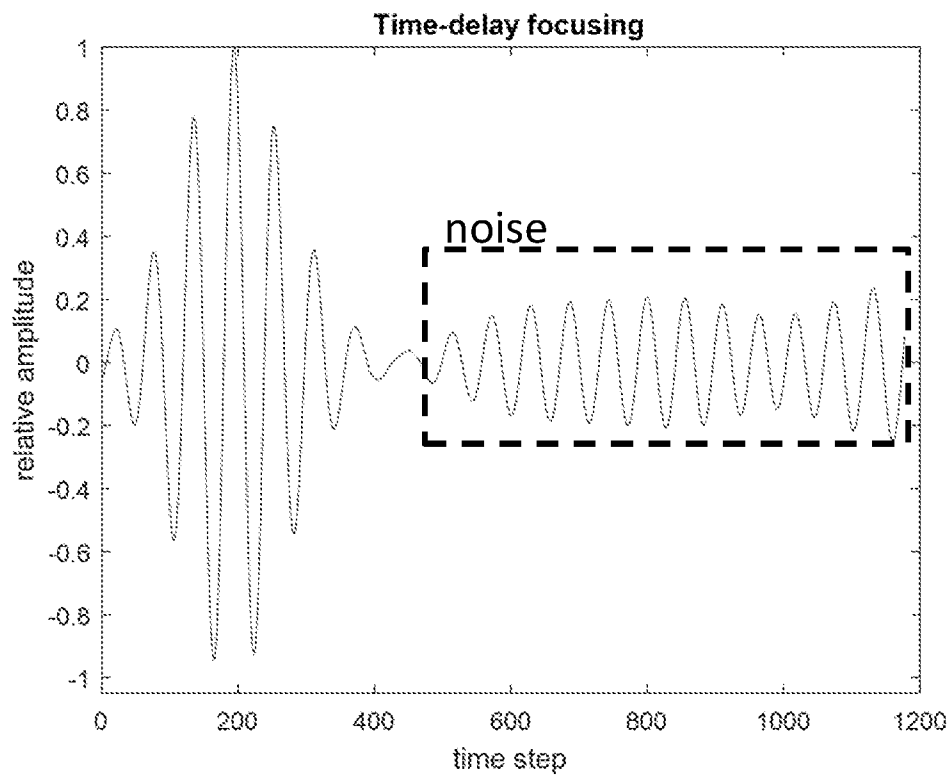
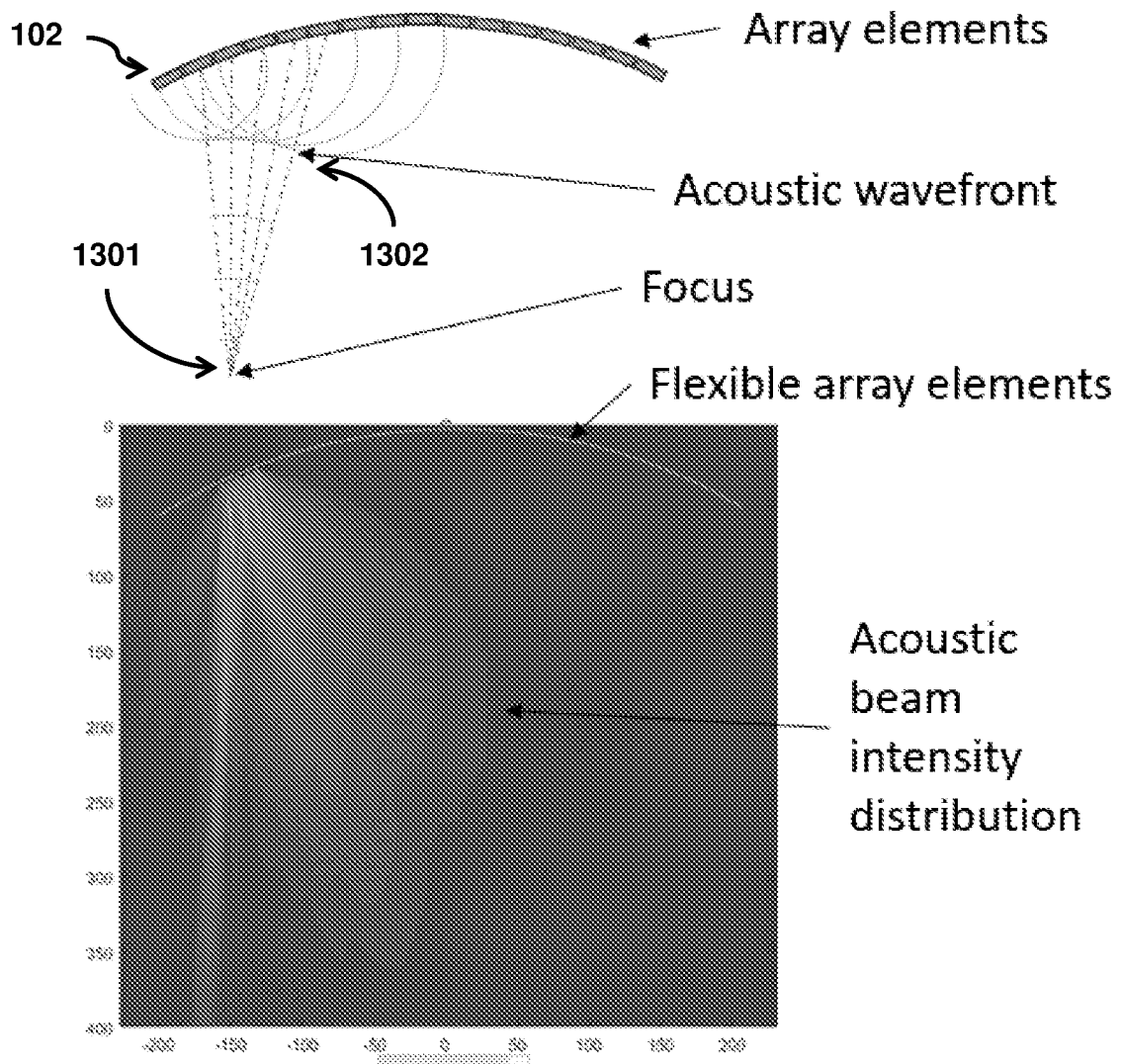
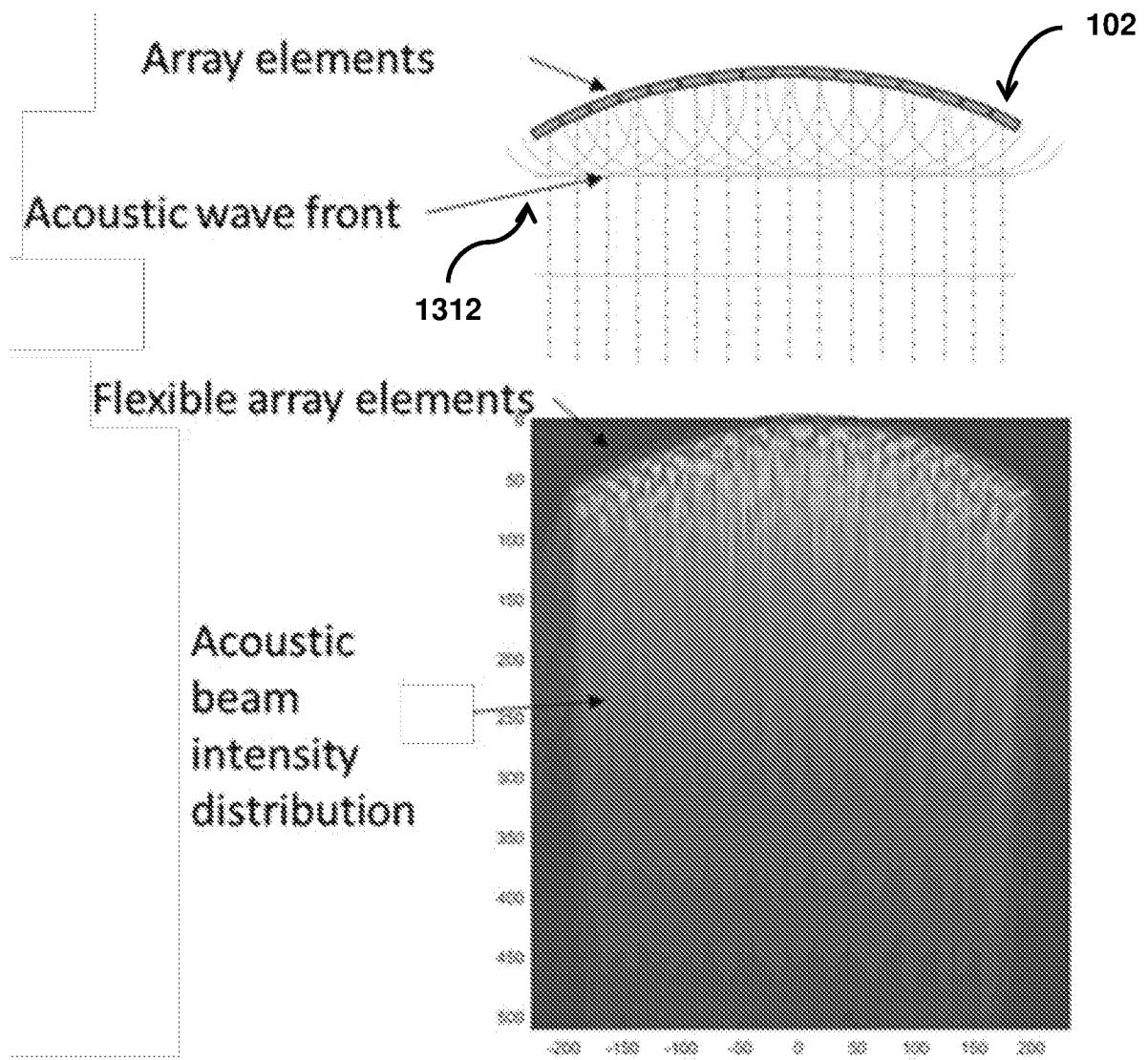


FIG. 11B

**FIG. 12A****FIG. 12B**

**FIG. 13A**

**FIG. 13B**

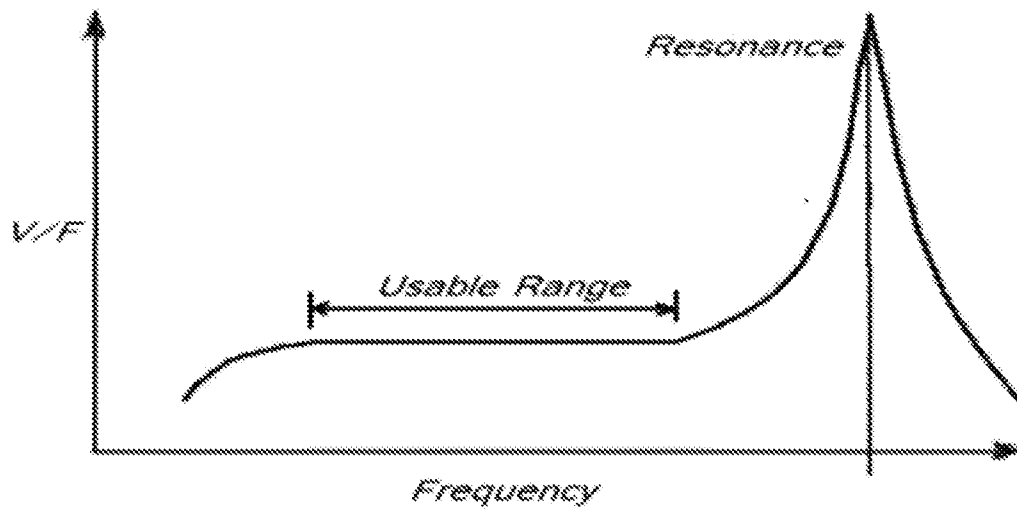


FIG. 14

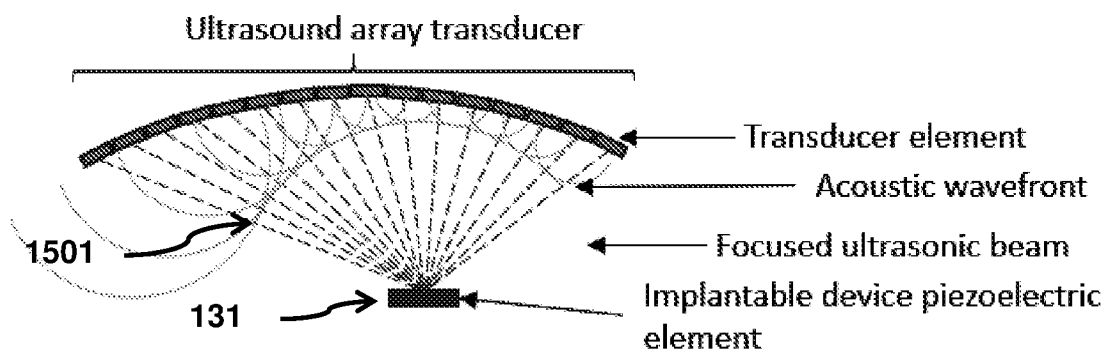


FIG. 15A

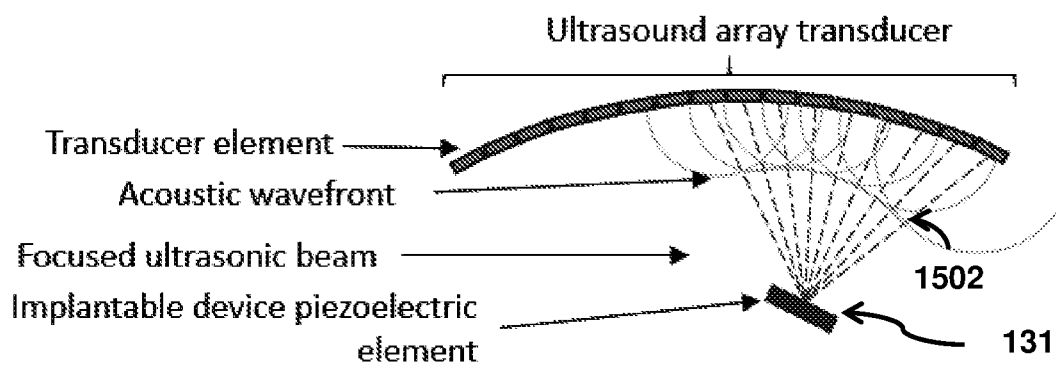


FIG. 15B

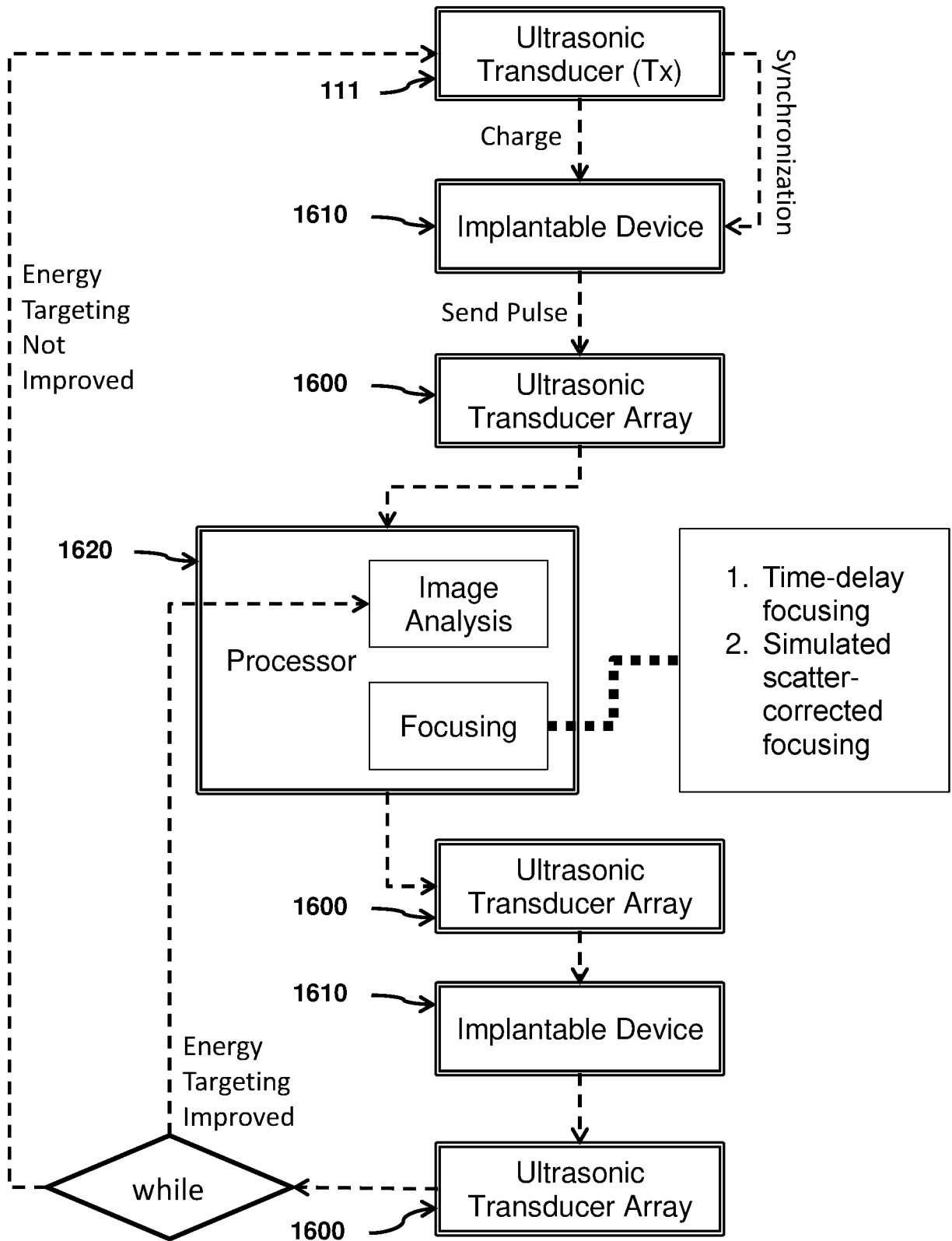
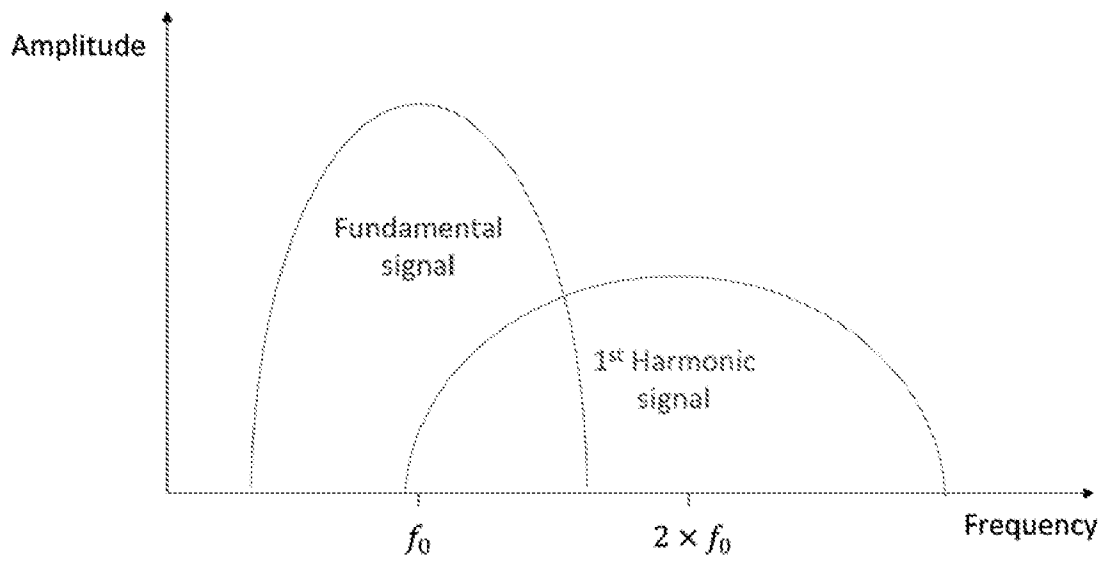
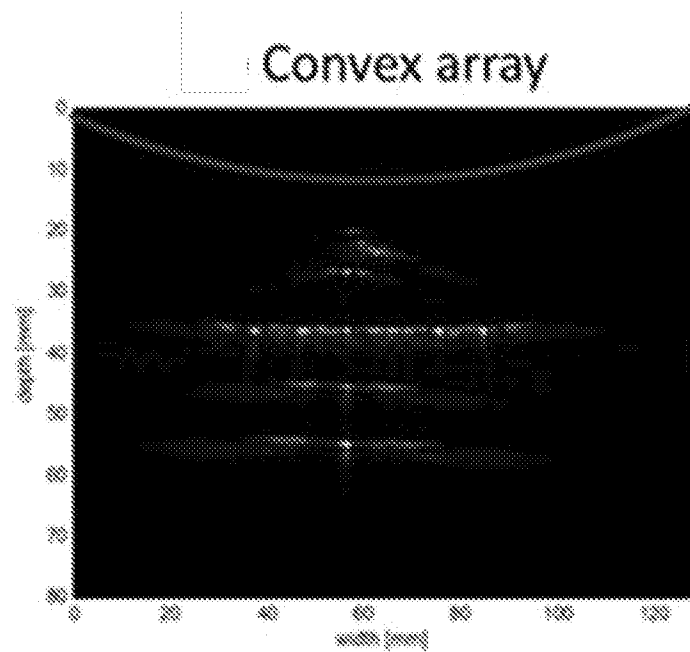


FIG. 16

**FIG. 17****FIG. 18A**

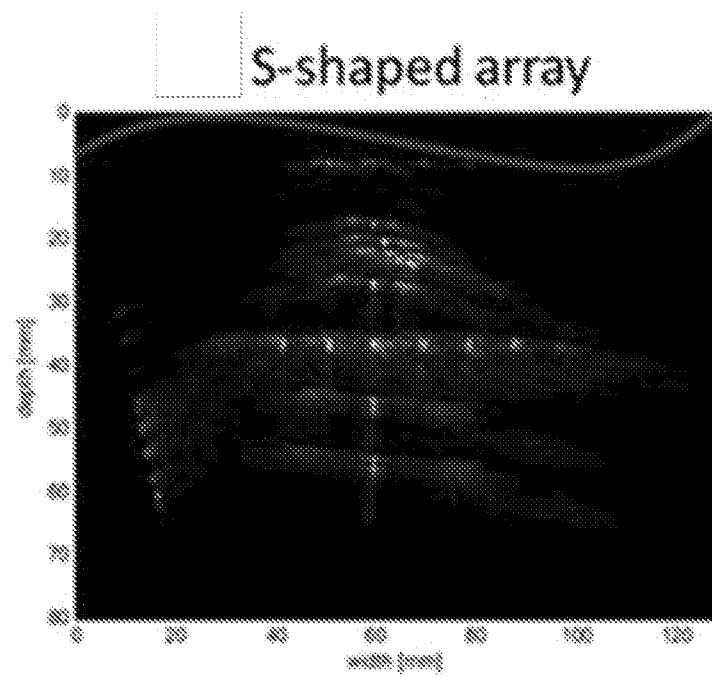


FIG. 18B

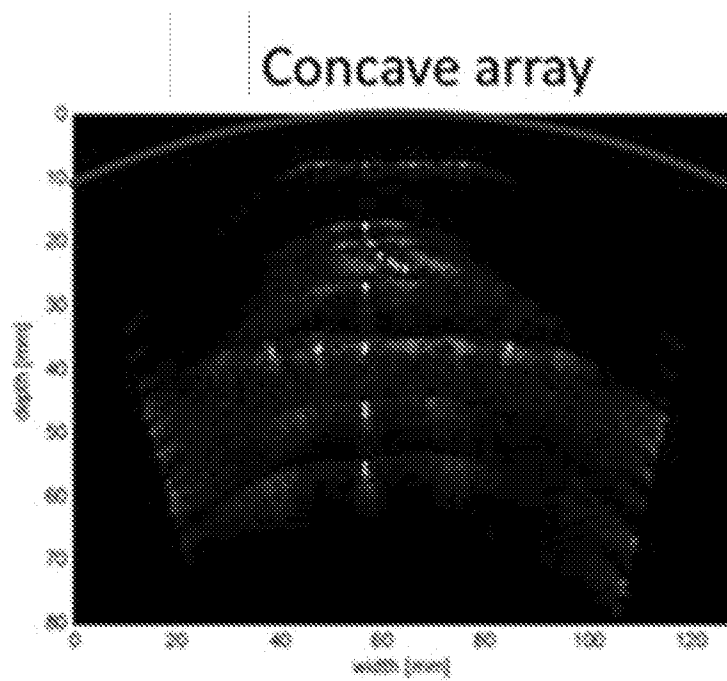


FIG. 18C

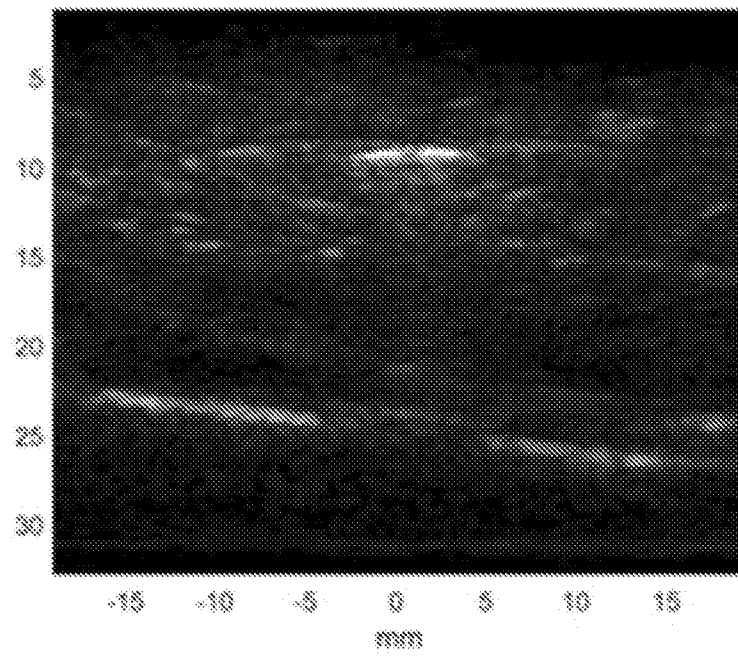


FIG. 19A

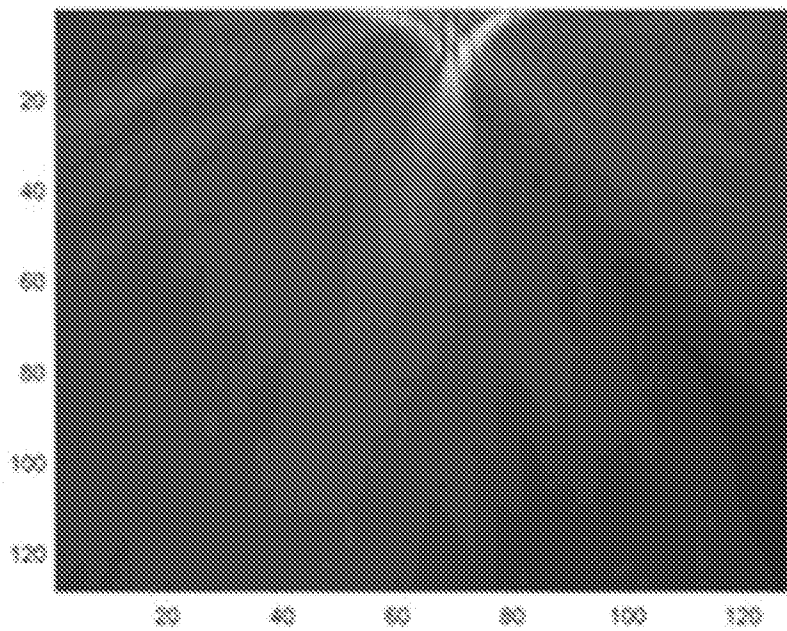


FIG. 19B

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2019/093038

A. CLASSIFICATION OF SUBJECT MATTER

A61N 1/00(2006.01)i; A61B 5/00(2006.01)i

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)

A61B; A61N; H02J

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

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

CNABS,CNTXT,CNKI,VEN,WUE,IEEE:ultrasound,ultrasonic,energy,charge,battery,implant+,time delay,phase delay,delay, time reversal focus+,constructive interference,echo,transmit,transducer

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CN 108173331 A (TSINGHUA UNIVERSITY) 15 June 2018 (2018-06-15) description** paragraphs 0002-0111 and figures 1-10	1-21
Y	CN 108173331 A (TSINGHUA UNIVERSITY) 15 June 2018 (2018-06-15) description** paragraphs 0002-0111 and figures 1-10	22-28
Y	US 10118054 B2 (UNIV CALIFORNIA) 06 November 2018 (2018-11-06) description, columns 11-24	22-28
A	CN 106849386 A (UNIV CHINA ELECTRONIC SCI & TECHNOLOGY) 13 June 2017 (2017-06-13) the whole document	1-28
A	US 9323397 B2 (UNIV CALIFORNIA) 26 April 2016 (2016-04-26) the whole document	1-28
A	US 2017311836 A1 (BRIGHAM AND WOMEN&#39S HOSPITAL INC) 02 November 2017 (2017-11-02) the whole document	1-28
A	US 2009270790 A1 (RAGHAVAN RAGHU) 29 October 2009 (2009-10-29) the whole document	1-28



Further documents are listed in the continuation of Box C.



See patent family annex.

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“O” document referring to an oral disclosure, use, exhibition or other means

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

“T” 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

“X” 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

“Y” 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

16 October 2019

Date of mailing of the international search report

28 October 2019

Name and mailing address of the ISA/CN

National Intellectual Property Administration, PRC
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100088
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Authorized officer

FAN, Wenyang

Facsimile No. (86-10)62019451

Telephone No. (86-10)62085628

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2019/093038**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2018250058 A1 (UNIV MINNESOTA ET AL.) 06 September 2018 (2018-09-06) the whole document	1-28
A	US 2014253435 A1 (UNIV CALIFORNIA) 11 September 2014 (2014-09-11) the whole document	1-28

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/CN2019/093038

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
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				BR	112019000287	A2	16 April 2019
				CN	109890267	A	14 June 2019
				CA	3029822	A1	11 January 2018
				AU	2017292929	A1	24 January 2019
				AU	2017292931	A1	24 January 2019
				JP	2019524230	A	05 September 2019
				US	2018085605	A1	29 March 2018
				EP	3481284	A1	15 May 2019
				US	2019022428	A1	24 January 2019
				CA	3029899	A1	11 January 2018
				WO	2018009912	A1	11 January 2018
				EP	3481285	A1	15 May 2019
				WO	2018009908	A1	11 January 2018
				US	2019022427	A1	24 January 2019
				WO	2018009911	A1	11 January 2018
				JP	2019524224	A	05 September 2019
				WO	2018009910	A1	11 January 2018
				AU	2017292924	A1	14 February 2019
				US	10300310	B2	28 May 2019
				BR	112018077435	A2	02 April 2019
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				WO	2018009905	A2	11 January 2018
				US	2019150883	A1	23 May 2019
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				US	10300309	B2	28 May 2019
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				CA	3029019	A1	11 January 2018
				US	2019150881	A1	23 May 2019
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				WO	2016081792	A1	26 May 2016
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				US	8545405	B2	01 October 2013
				WO	2010080701	A1	15 July 2010
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US	2014253435	A1	11 September 2014	US	9710111	B2	18 July 2017
				US	9323397	B2	26 April 2016
				US	2016291716	A1	06 October 2016