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Pandey et al.

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(54) **SYSTEM AND METHOD FOR PHASED ARRAY MATERIAL IMAGING**

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(Continued)

(51) **Int. Cl.**
A61B 8/00 (2006.01)
G01S 15/89 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***G01S 15/8925*** (2013.01); ***G01N 29/00*** (2013.01); ***G01N 29/0654*** (2013.01);
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(58) **Field of Classification Search**
CPC G01N 2291/044; G01N 29/00; G01N 29/0654; G01N 29/262; G01S 15/89;
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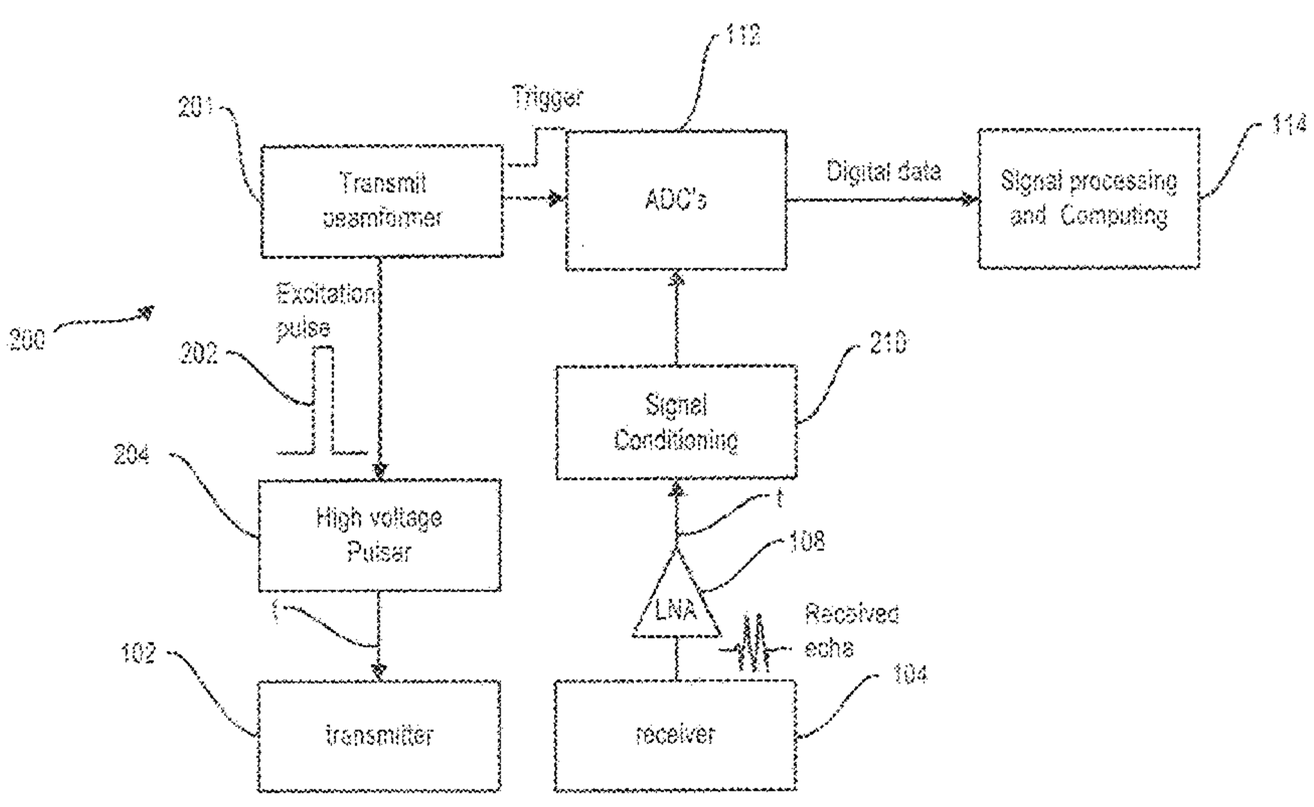
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(57) **ABSTRACT**

A probe is described for analyzing a target using an array of transceivers formed of transmitter/receiver pairs. As opposed to the prior art, the high voltage trigger signals from used to trigger the transmitters are separated from the output signals of the receivers thereby resulting in a simpler and more efficient circuitry. Moreover, the output signals are delayed to compensate for the delays in the echo signals from the target due to the varying distance between the different transceivers and the target. The probe can be used for analyzing pathological organs, as well as many other objects such as gas pipes, airplane wings, etc.

19 Claims, 9 Drawing Sheets



Integrated transmit and receive beamforming

Related U.S. Application Data

(60) Provisional application No. 62/129,344, filed on Mar. 6, 2015.

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G01N 29/00	(2006.01)
G01S 7/52	(2006.01)
G10K 11/34	(2006.01)
G01N 29/06	(2006.01)
G01N 29/26	(2006.01)

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

CPC ***G01N 29/262*** (2013.01); ***G01S 7/5202*** (2013.01); ***G01S 15/89*** (2013.01); ***G01S 15/8913*** (2013.01); ***G01S 15/8915*** (2013.01); ***G10K 11/346*** (2013.01); *A61B 8/4488* (2013.01); *G01N 2291/044* (2013.01)

(58) **Field of Classification Search**

CPC G01S 15/8913; G01S 15/8915; G01S 15/8925; G01S 7/5202; G10K 11/34

USPC 342/90

See application file for complete search history.

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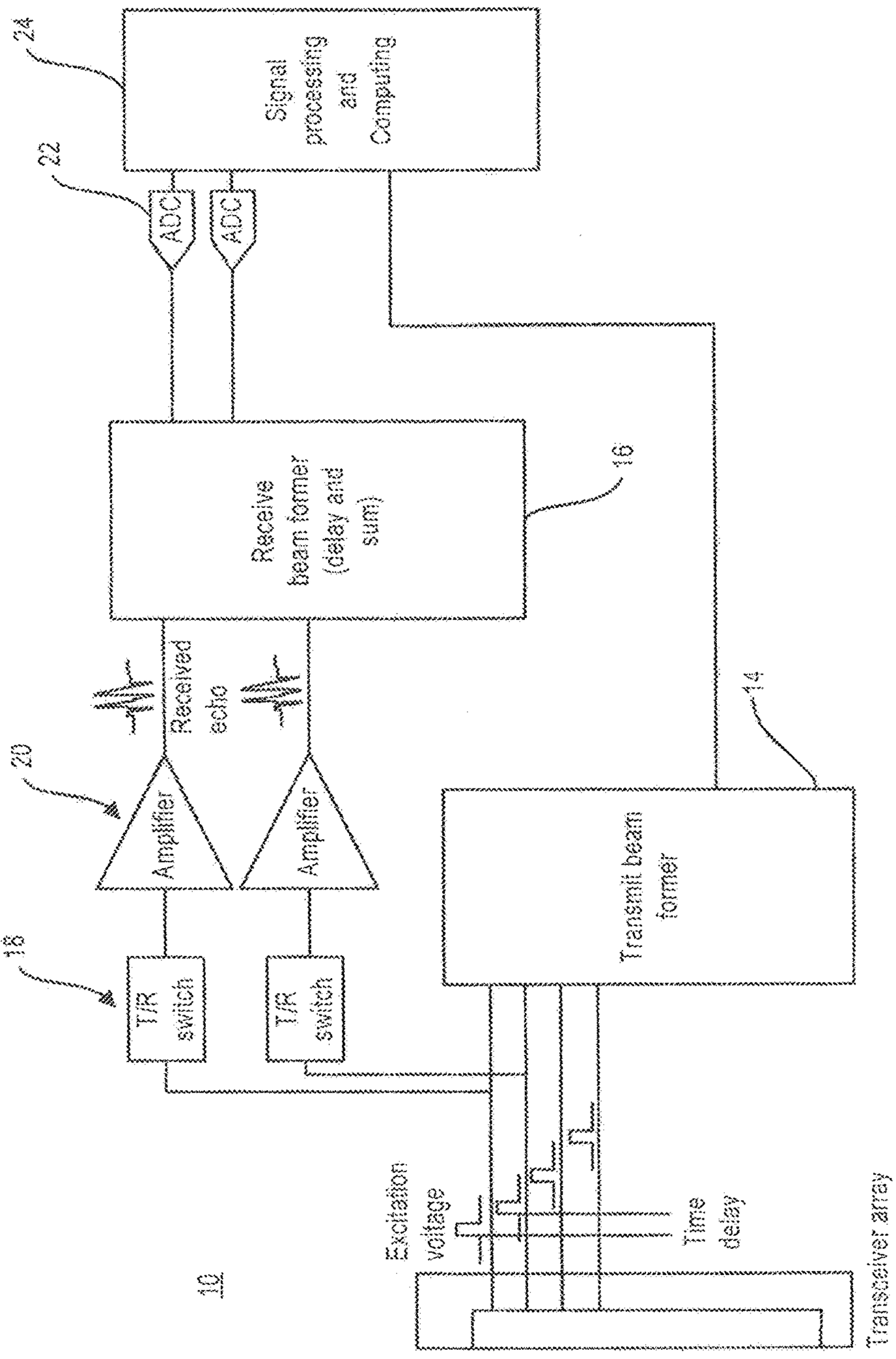
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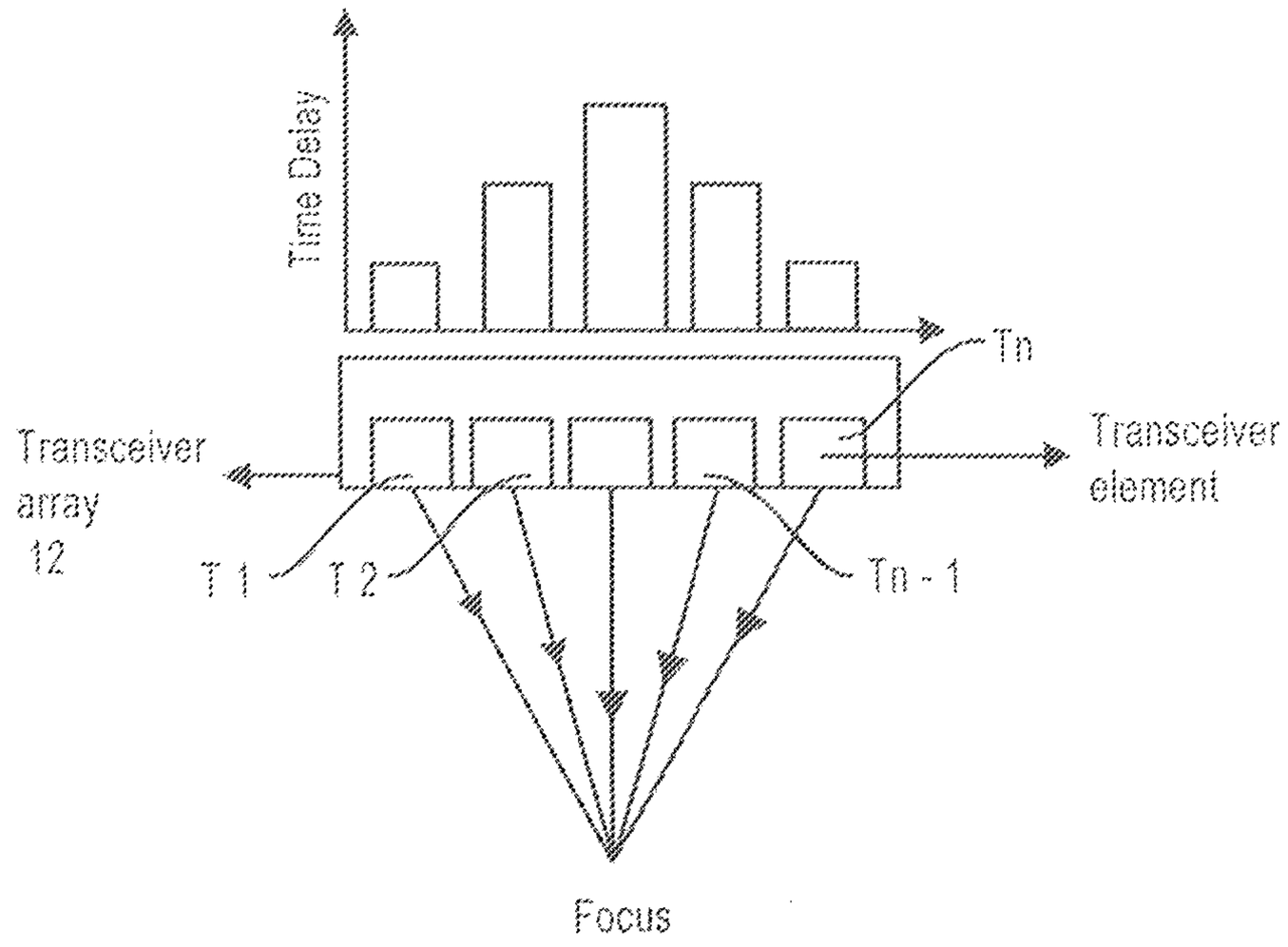
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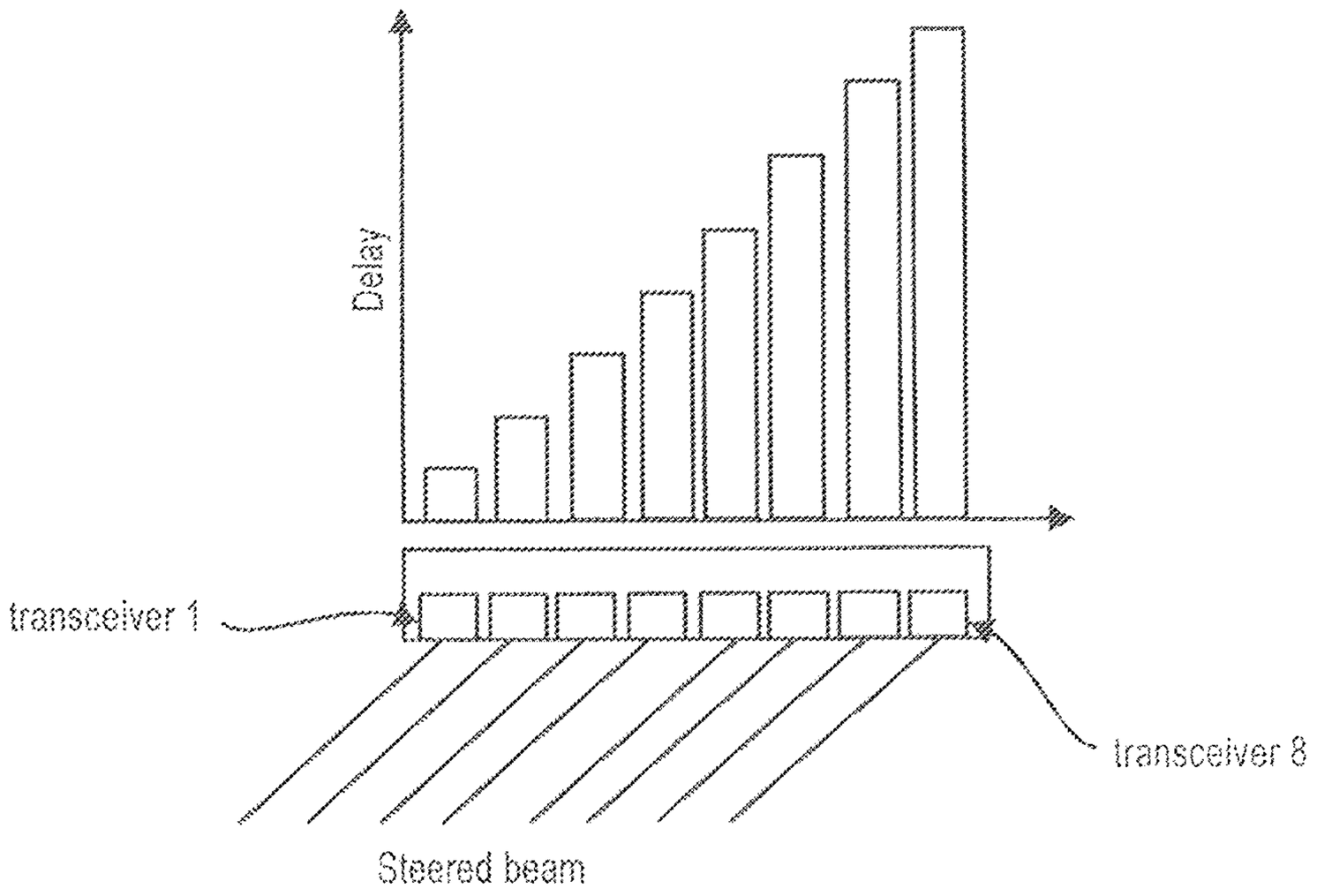
(PRIOR ART)

FIG. 1



(PRIOR ART)

FIG. 2



(PRIOR ART)

FIG. 3

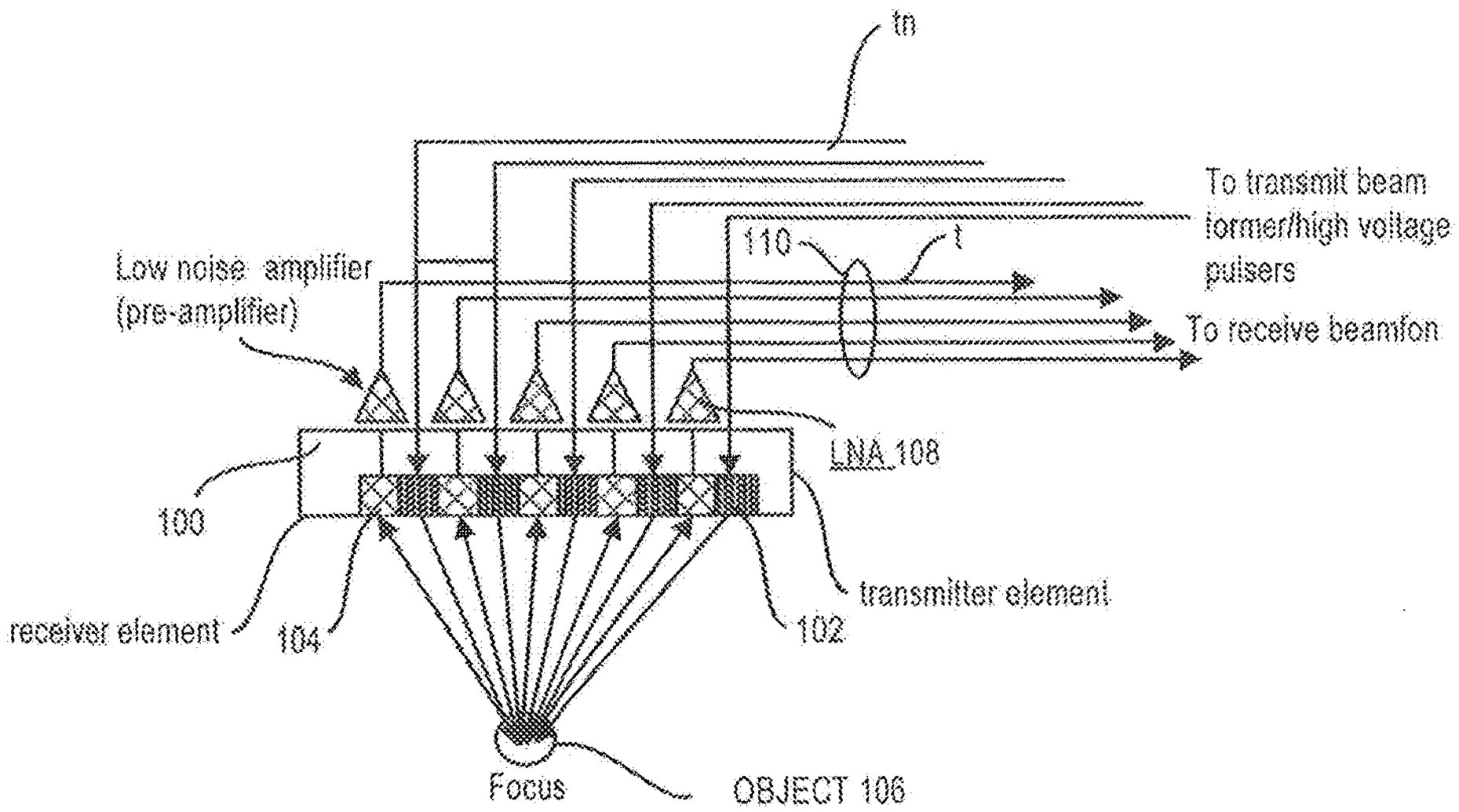
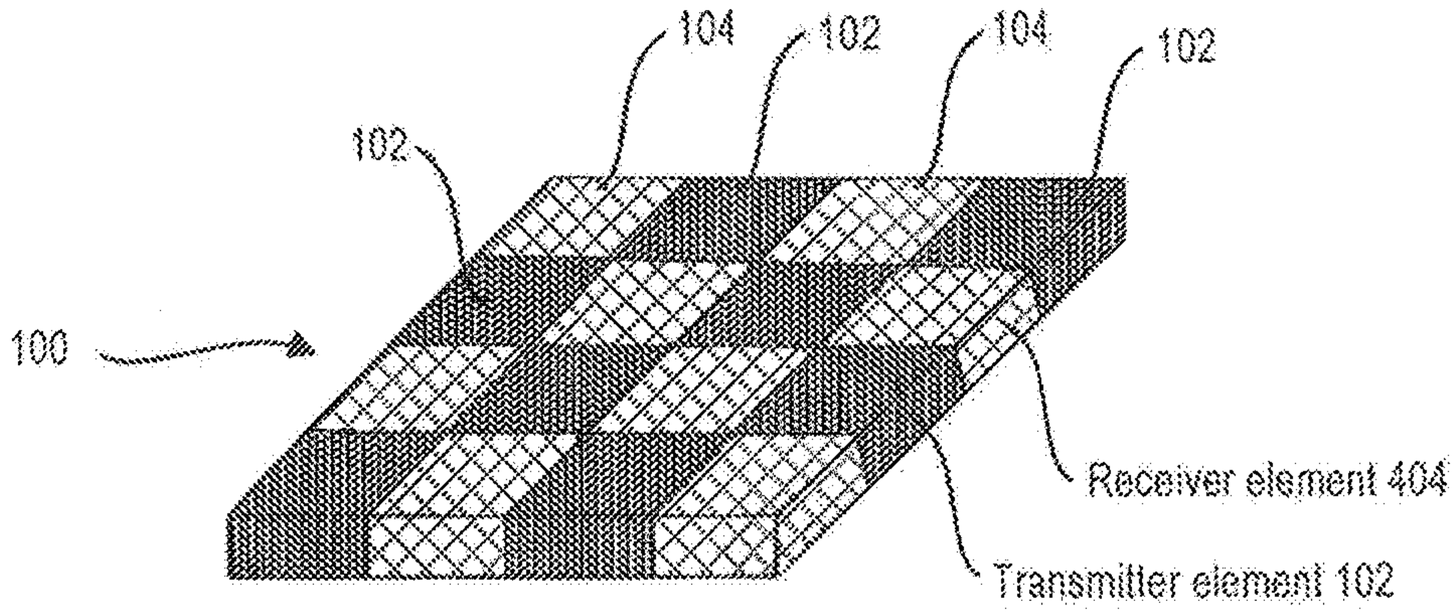


FIG. 4A



Novel phased array probe with alternate transmitter and receiver elements – a) one dimensional probe b) two-dimensional probe. Pre-amplifiers/low noise amplifiers and cables for transmit and receive signals are not shown for two dimensional probe.

FIG. 4B

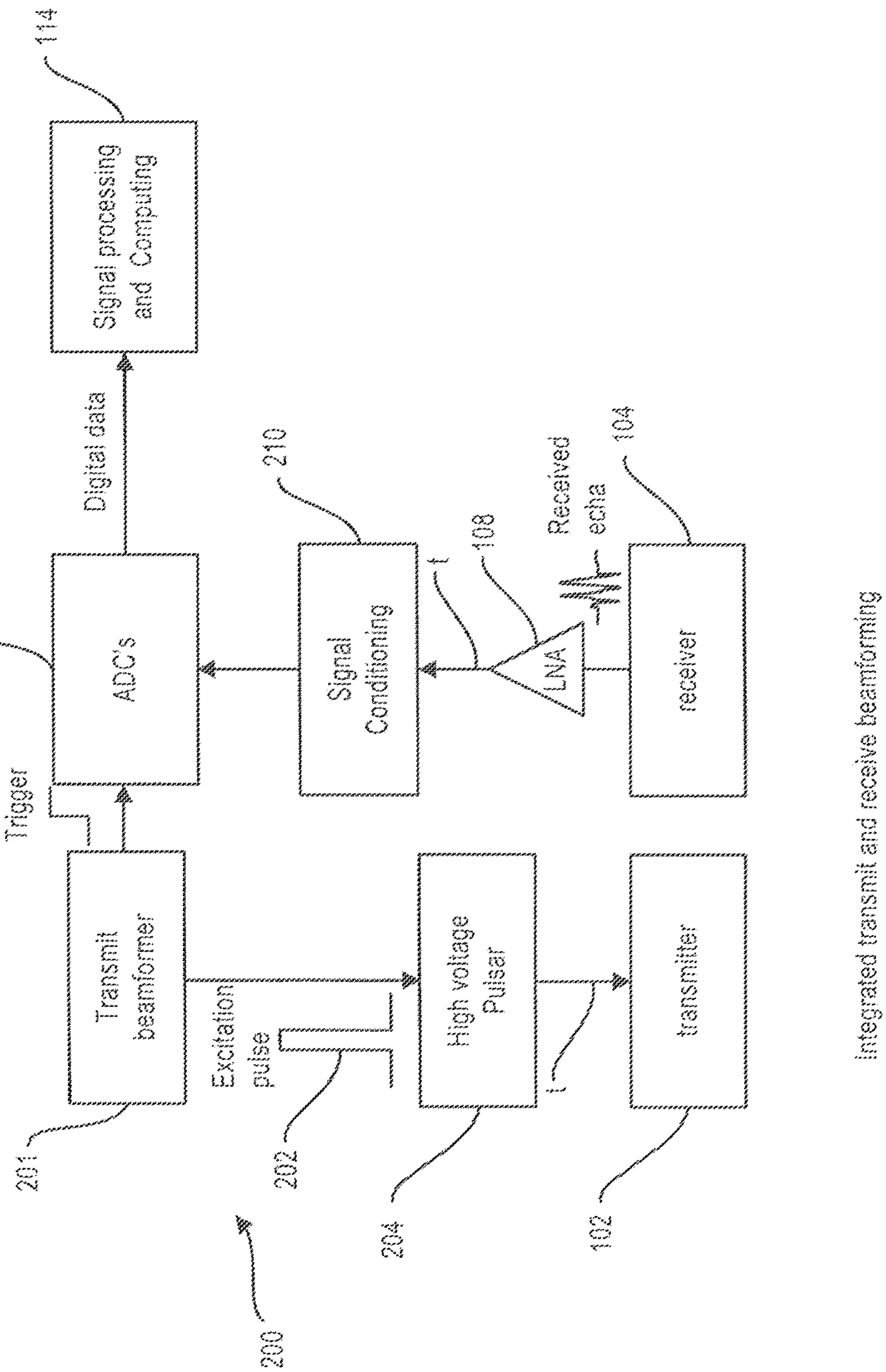

114
Signal processing and Computing
Digital data
112
ADC's
Trigger
210
Signal Conditioning
t
108
LNA
Received echa
104
receiver
Transmit beamformer
Excitation pulse
High voltage Pulsar
transmitter
201
202
204
102
200
integrated transmit and receive beamforming

FIG. 5

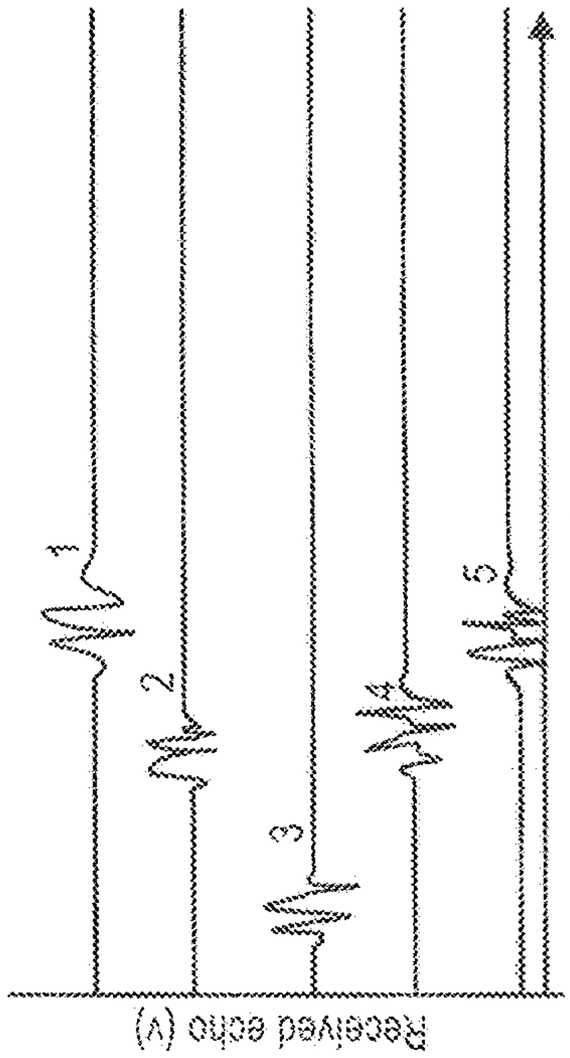


FIG. 6B

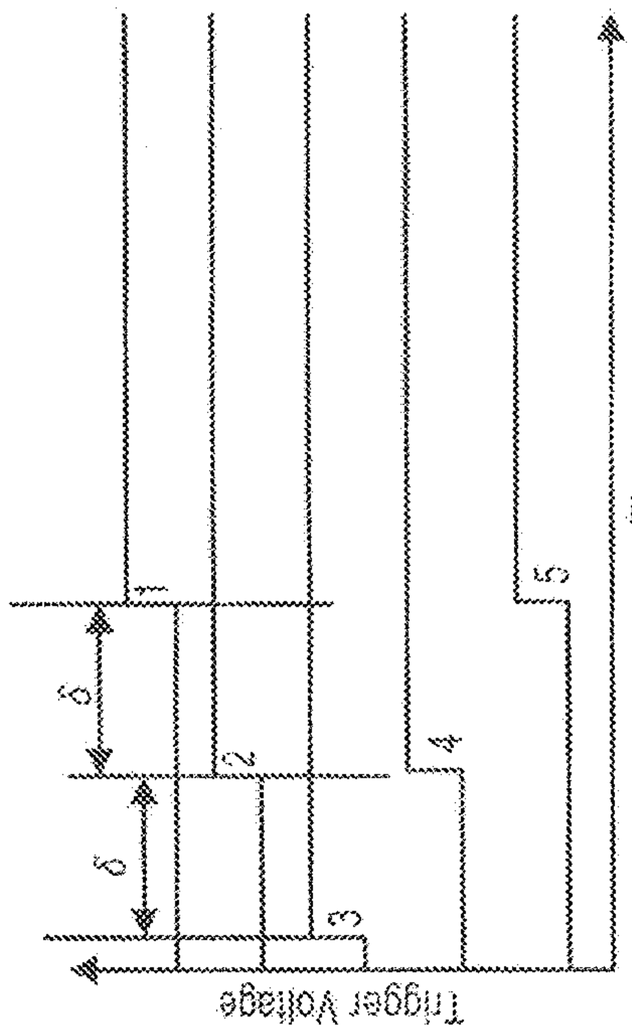


FIG. 6D

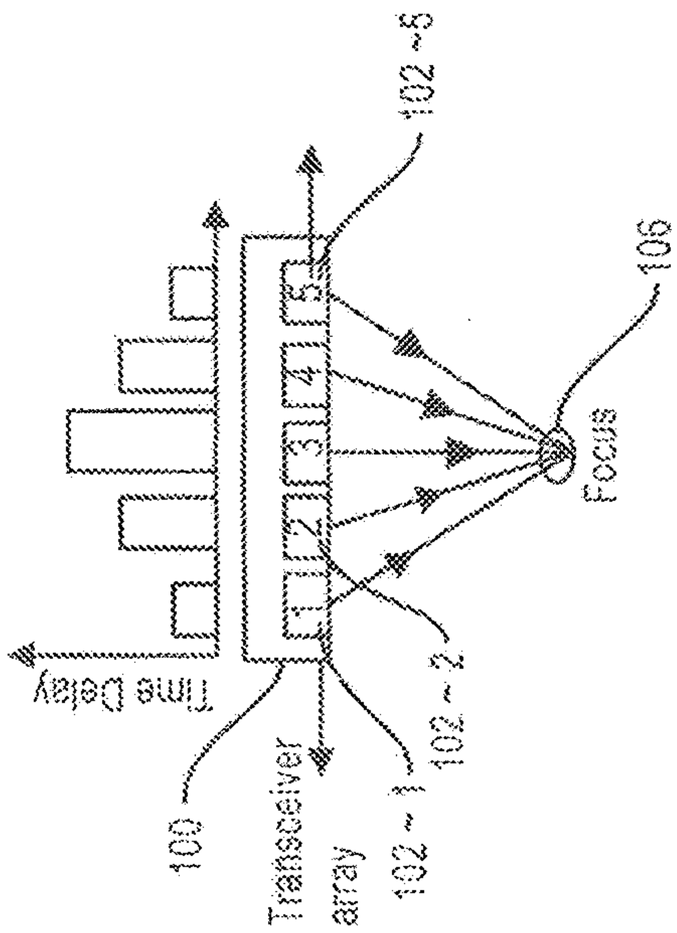


FIG. 6A

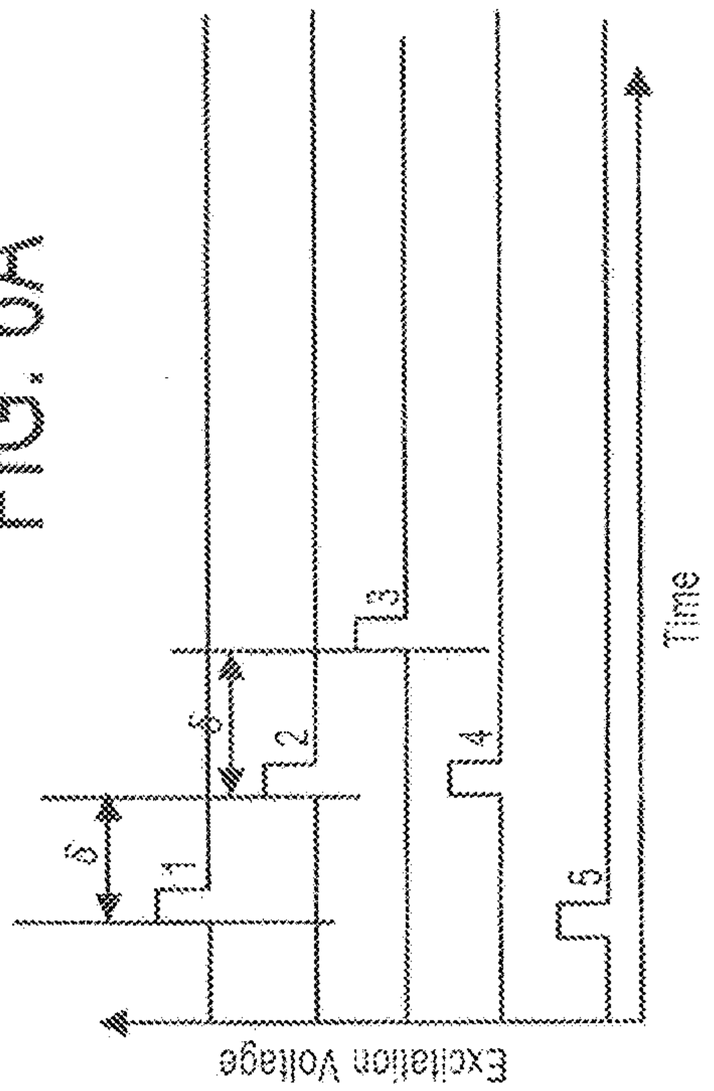


Illustration of novel beamformer architecture using a five element phased array.

FIG. 6C

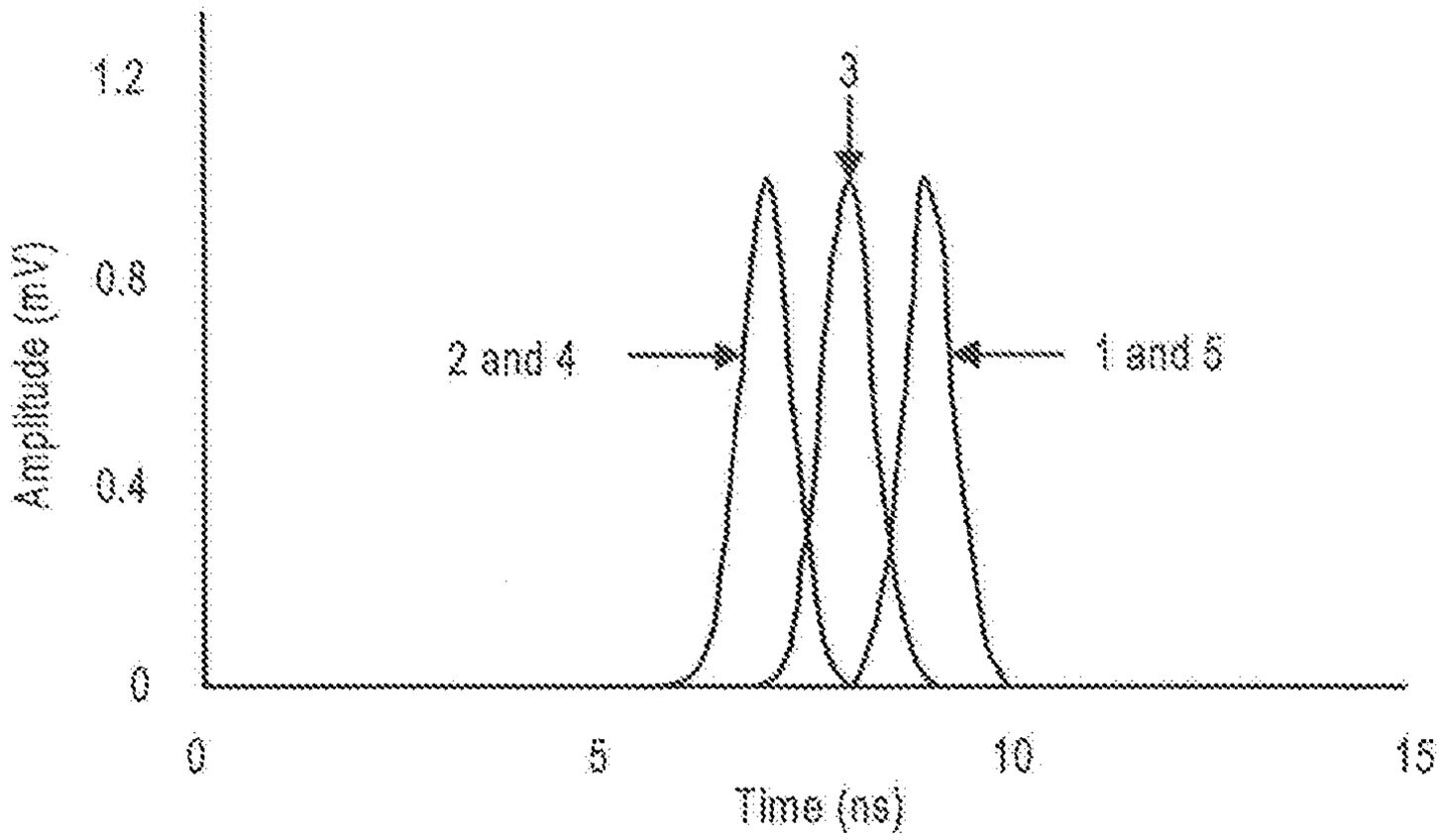
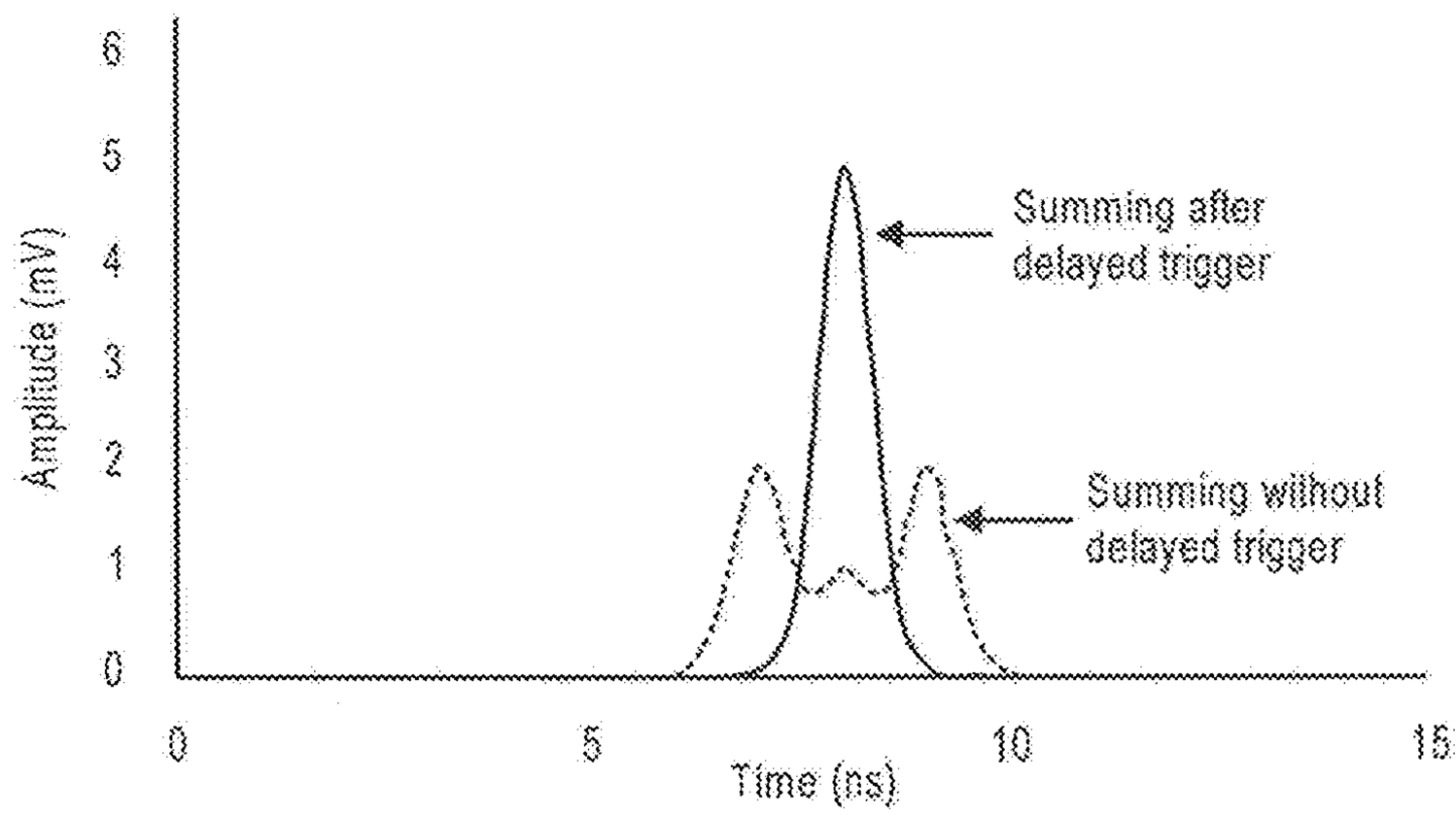


FIG. 7A



An illustration of the improvement in resolution using the novel delayed trigger technique. A) Reflected echoes resulting from transceivers in Figure 6. B) Comparison of delayed trigger technique with sampling without delayed trigger.

FIG. 7B

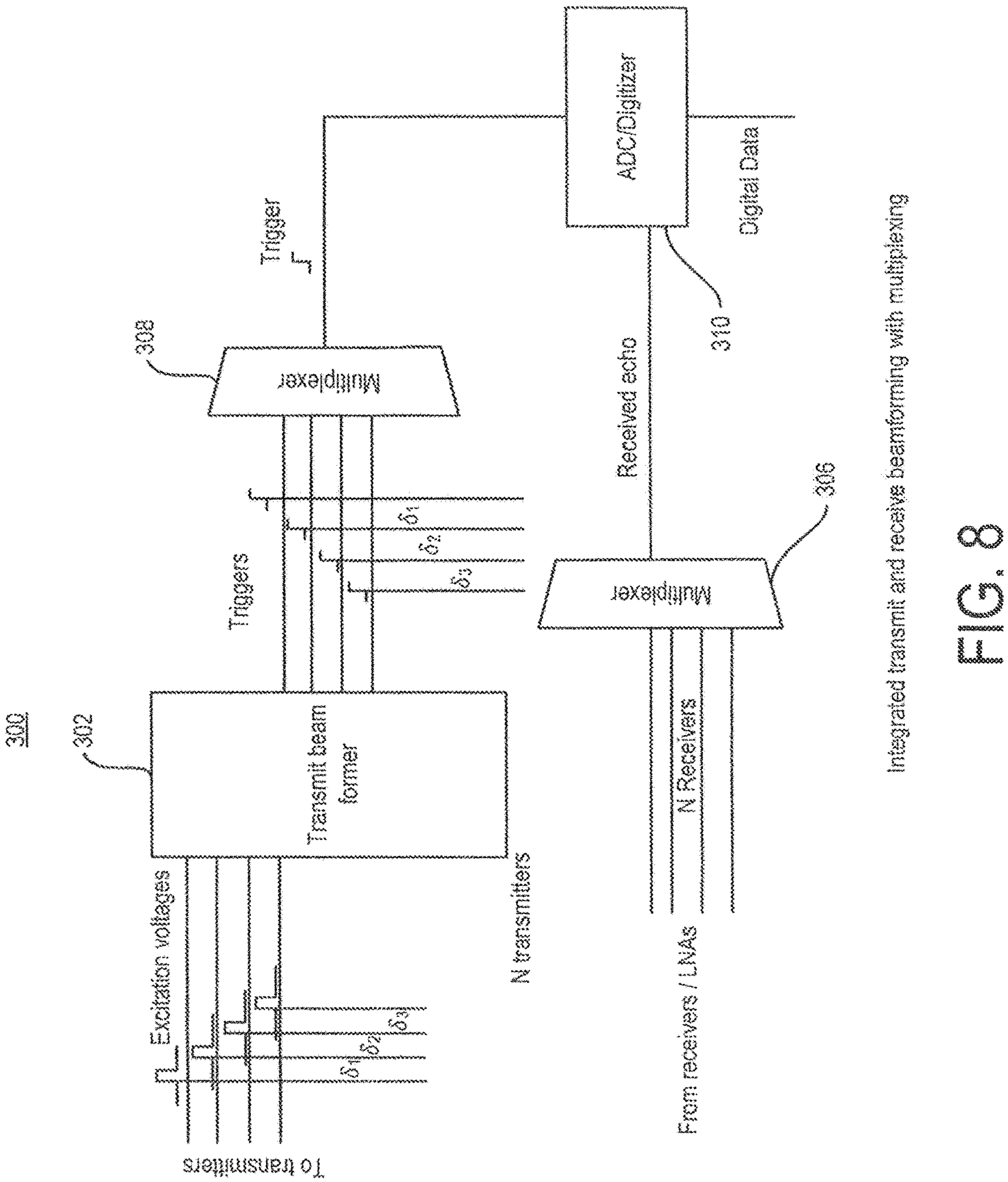

300
302
Transmit beam former
Excitation voltages
To transmitters
Triggers
δ_1
δ_2
δ_3
308
Multiplexer
Trigger
ADC/Digitizer
Digital Data
310
Received echo
306
Multiplexer
N Receivers
From receivers / LNAs
N transmitters
Integrated transmit and receive beamforming with multiplexing

FIG. 8

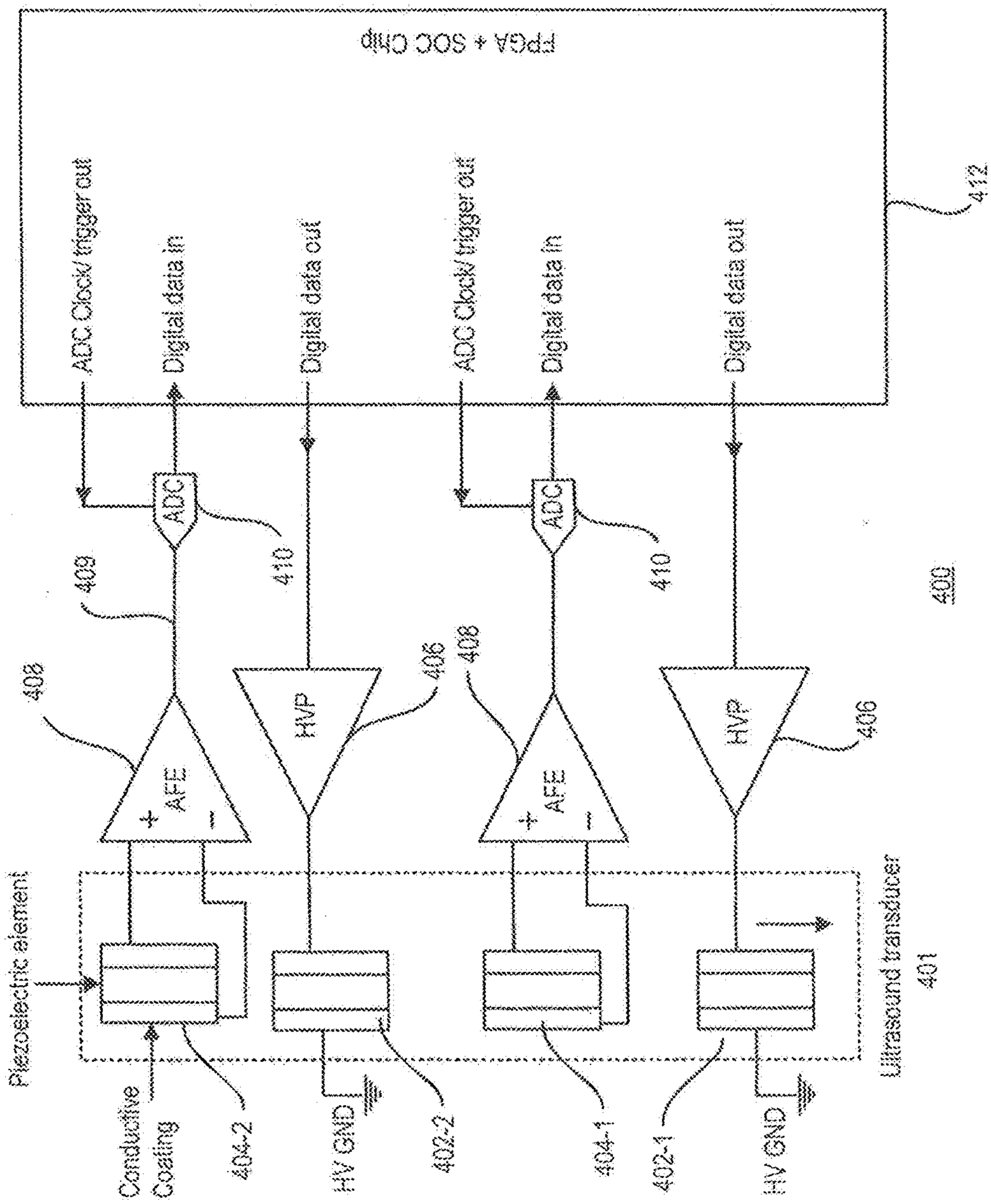

FPGA + SOC Chip
ADC Clock/ trigger out
Digital data in
Digital data out
ADC Clock/ trigger out
Digital data in
Digital data out
412
ADC
409
410
ADC
410
408
406
AFE
HVP
408
406
AFE
HVP
400
Piezoelectric element
Conductive Coating
404-2
HV GND
402-2
404-1
402-1
HV GND
Ultrasound transducer
401

FIG. 9

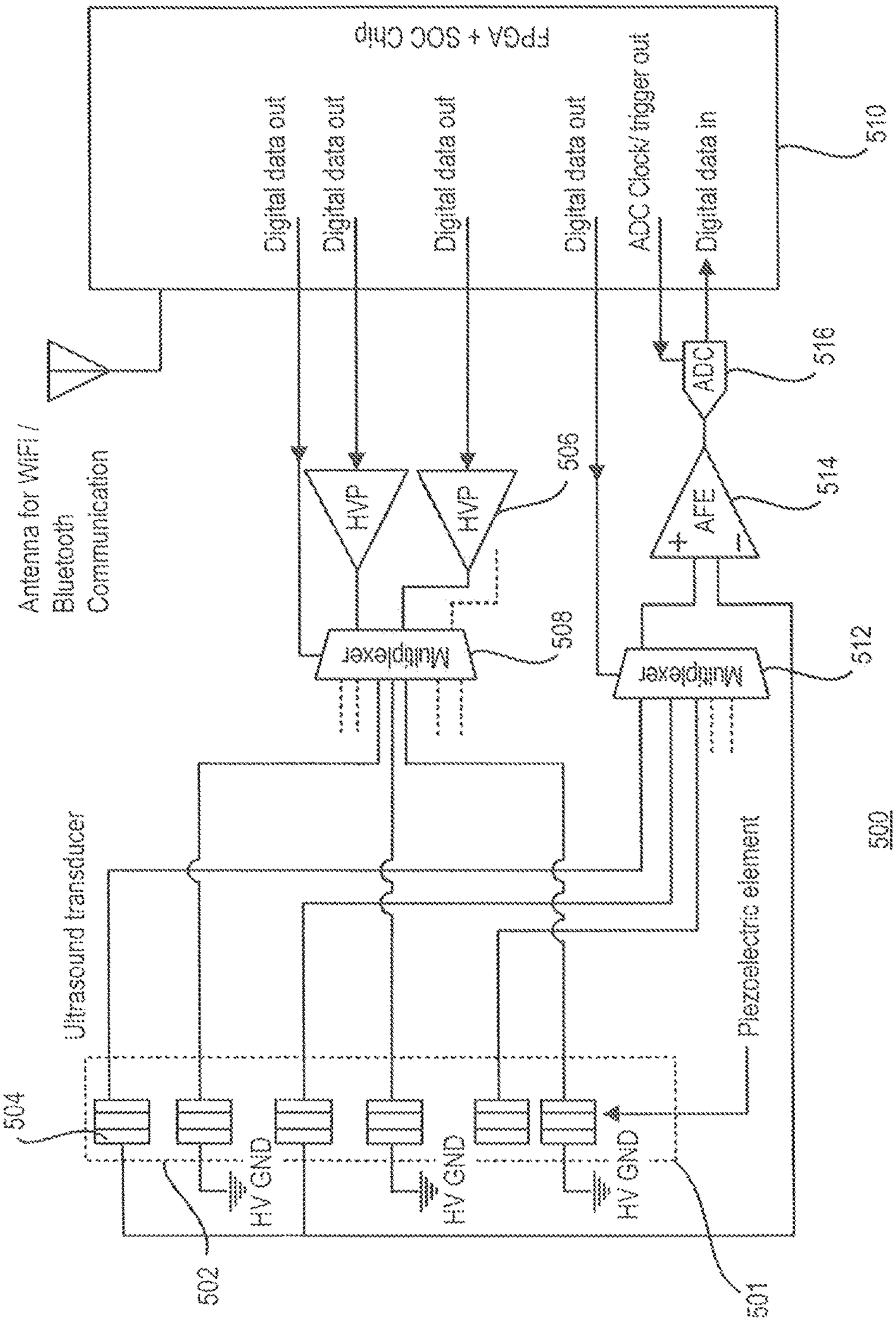

FPGA + SOC Chip
Digital data out
Digital data out
Digital data out
Digital data out
ADC Clock/ trigger out
Digital data in
510
Antenna for WiFi / Bluetooth Communication
HVP
HVP
506
Multiplexer
508
ADC
516
AFE
514
Multiplexer
512
500
Ultrasound transducer
Piezoelectric element
504
HV GND
HV GND
HV GND
502
501

FIG. 10

SYSTEM AND METHOD FOR PHASED ARRAY MATERIAL IMAGING

CROSS-REFERENCE TO RELATED APPLICATIONS

Related Applications

Related applications: This application is a continuation application of application Ser. No. 15/061,116 filed on Mar. 4, 2016, which claims priority to U.S. provisional patent application Ser. No. 62/129,344 filed Mar. 6, 2016, each of which is incorporated herein in their entirety.

A. Field of Invention

A system and method for mapping a material, object or organ (pathology) is presented using improved Transmit/Receive (T/R) imaging techniques and a multiplicity of sensors. The sensors may be ultrasound, acoustic, electromagnetic or other type of sensors.

B. Description of Prior Art

Phased array imaging techniques have been applied to ultrasound, electromagnetic (RADAR), optical and acoustic (SONAR) sensors. Phased array systems are used extensively in non-destructive evaluation, biomedical imaging, underwater imaging and RADAR and others. The prior art techniques use an array or a matrix of waveform transceivers. Individual transceivers are designed to produce a far field pattern. A time delay or a phase shift pattern is introduced between individual transceivers resulting in an interference pattern. The interference pattern effectively steers the transmitted beam in a desired direction or at a focal point.

As shown in FIG. **1**, a conventional phased array imaging system **10** may consist of the following major components:

1) a transceiver array **12**;

2) a transmit beam-former **14**;

3) a receive beam former **16**,

4) SPDT (Single Pole Double Throw) Transmit/receive switches **18** (one for each transceiver of the array **12**,

5) Amplifiers **20**,

6) Analog to digital converters (ADCs) **22**

7) at least one signal processing and computing device **24**.

The transmit beam former **14** and/or switches **18** excite (turns on/off) the transmitter elements in the transceiver array **12** at precisely timed intervals. In FIG. **2** the transmitter elements T**1**, T**2**, . . . Tn-**1**, Tn of array **12** are shown with transmitters T**1** and Tn being the farthest from a focal point or focus F, transmitter elements T**2** and Tn-**1** being closer to the focal point F, and so on. The transmitter elements T**1**, Tn are excited (and/or switched on/off) first, transmitter elements closer to the focal point (**2**, Tn-**1** are excited after a predetermined time delay, and so on.

Alternatively, as shown in FIG. **3** directional steering may be used, in which case the transmitter elements T**1** . . . T**8** are excited by respective excitation wave or pulses that are provided either with time delays or phase shifts or a combination of both time delays and phase shifts. Phase shifts for directional steering of beam are most common in RADAR (electromagnetic) phased arrays. All these excitation signals are produced by the transmit beam former **14**.

When the beams from transmitters hit a target, the resulting interference pattern produces echoes from the region under observation. These echoes are detected and collected

by individual receiver elements Time delays that are introduced during the excitation phase of the process are taken into account in summing the received waveforms. The receive beam former **16** performs the task of delaying the received waveforms and summing them.

Because often the received waveforms are highly attenuated, an 'analog front end' amplifiers **20** are needed before the receive beam former **16** can delay and sum the waveforms. Often high voltages are involved during the excitation or transmit mode and hence SPAT transmit-receive switches **18** are required to protect the analog front end amplifiers **20** and the receive beam former **16** from damaging high voltages. Analog to digital converters **22** interface the receive beam former **16** to a signal processing and computing device **24**. The computing device **24** also includes a graphic user interface (not shown) and further means (not shown) to present the received echoes in human understandable format.

Due to electronic focusing and beam steering, phased array based ultrasound, SONAR and RADAR systems generate outputs with sharper focus, a variable depth of field and reduced mechanical complexity as compared to prior technology. However, the present state of the art suffers from significant technological and functional drawbacks which result in:

1. High cost of phased array imaging systems
2. Noise due to power supply.
3. Ringing and blind zone distances.
4. Reduced accuracy and resolution of phased array imaging systems.
5. Due to the above and other technological drawbacks, the miniaturization of phased array systems is hindered.

More specifically, the disadvantages of current phased array imaging systems such as the ones illustrated in FIGS. **1-3** include:

1) The requirement for SPDT T/R switches **18**: As discussed above, these T/R switches **18** are used to protect the receive amplifiers **20** and the receiver beam former **16** from destructive high excitation transmit pulse voltages. T/R switches have a switching time delay, typically in range of tens of nanoseconds. For the beam former **16** typical delay times are in range of few nanoseconds. Hence, the T/R switches **18** introduce significant electrical and electronic complexities in phased array imaging systems. Additionally, many advanced T/R switches **18** often need a digital programming signal to either enable them or to control bias currents. Due to this requirement for T/R switches, amplifiers are not integrated directly with transceivers. This is especially a problem in ultrasound phased array systems. Since the amplifiers are not physically close to the transceivers, noise and time delays are introduced as the received (very low level) echo signals travel through cables from the transceivers to T/R switches. Further, T/R switches have their own electrical characteristics which convolute (distort) the received echoes with 'noise', thereby introducing further inaccuracy.

2) Large number of ADCs **22**: Current phased array systems require analog to digital converters of the order of the number of transceiver elements. This increases the cost and complexity of the current phased array imaging systems.

3) High performance ADCs **22**: Current phased array imaging systems require a very precise time delay from the transmit beam former. For example, in a current ultrasound phased array system, a typical time delay could be as small as 1-2.5 ns. Since the received echoes need to be time delayed as well, this would mean an ADC capable of sampling at 1 GHz or faster. Ultrasound signals are typically

only 1-50 MHz; hence a much higher speed ADC is required to process the time delay. Therefore, using high performance ADCs drastically increases the cost and complexity of the current phased array systems. It further increases the memory requirement in signal processing by up to 1000 times for phased array ultrasound systems. Additionally, due to the high computing resources required, the imaging frame rate is extremely slow, causing blurry images, and less accurate final imaging.

4) High performance computing and signal processing device **24**: Due to the above discussed high cost of high performance ADC's, an alternate to using high performance ADCs is to use 'interpolation filtering' or some other computational technique to sum and delay the received echoes. However, this still requires large memory and computational power, reduces accuracy/resolution as well as increases cost due to the need for high computing resources.

5) Significant electrical noise introduced by the high voltage power supply: Either electromagnetic or ultrasonic, the received voltages in the present state-of-art phased array imaging signals are several orders of magnitude smaller than the transmitter pulsing voltages. In present state-of-art systems, the high voltage components (50-200 volts for ultrasound) are electrically connected to low voltage receiver elements (for ultrasound, received voltages are a few millivolts). This is because both transmitter and receiver elements are not electrically isolated (share a common electrical point (ground)), as illustrated for example in US Patent Application Publication 2010/00274139. Hence even a small noise in high voltage power supply leads to significantly larger noises in analog front end, low noise amplifier etc. The additional noise in the received waveforms/echoes means that—1) additional computational resources or analog electronics has to be dedicated to reduce the noise 2) High pulsing voltages need to be used to excite the transmitter. Both of these have a detrimental effect on image quality, miniaturization, cost as well as health hazard (in case of ultrasound, high pulsing voltages cause tissue heating and damage).

6) Ringing and blind distance: As a result of 1) transmitter and receiver elements not being electrically isolated and 2) the transmitter continuing to vibrate even after the pulsing voltage is removed, near surface object objects cannot be imaged.

SUMMARY OF THE INVENTION

The present invention is concerned with the design of an efficient phased array imaging/material mapping system without T/R switches and with a lesser number of low sampling speed ADCs. The invention further provides for electrical isolation between LNA (Low Noise Amplifiers) and high voltage power supply, different ground electrical reference point, dramatically reduced noise.

The invention also reduces the required memory size and therefore reduces the need for computing resources and costs. The invention includes dedicated transmitters and receivers instead of using the same phased array element (piezoelectric/capacitive/magnetostrictive/antennae etc.) as both the transmitter and the receiver (transceiver).

In one embodiment, a phased array probe is presented that includes

a plurality of transmitters and receivers wherein at least one of said transmitter is a reference transmitter and all other transmitters are laterally offset from said reference transmitter, and wherein at least one receiver is a reference receiver with all the other receivers being laterally offset from said reference receiver;

a beam former generating control signals for exciting each said transmitter,

a pulse generator generating excitation pulses to said transmitter in response to said control signals, in response said transmitters sending respective probe signals to a target or other object of interest, the excitation pulses to all other transmitters being delayed by a period related to said lateral offset;

a receiving module receiving echo signals from said receivers corresponding to said probe signals, said receiving module delaying echo signals from said all other receivers by delays related to said lateral offset; and

an analyzer analyzing said echo signals.

The transmitters are one of piezoelectric, capacitive, magnetostrictive, acoustic, electromagnetic and any other transducer elements converting electrical voltage pulses into acoustic, ultrasonic or electromagnetic waves.

The probe may include low noise amplifiers amplifying signals from said receivers to generate said echo signals. The receiving module may include ADCs converting the echo signals into corresponding digital output signals.

Preferably, echo signals are delayed by respective amounts with said echo signals from all the receivers occurring simultaneously. Once they processed, the echo signals can be summed or added resulting a single well defined, clean signal.

In one embodiment multiplexers may be used to reduce the number of components.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a block diagram of a known system using a phased transceiver array;

FIG. **2** shows a plurality of beams transmitted from transmitters to single focal point;

FIG. **3** shows a plurality of parallel beams from transmitters directed at an angle with respect to a surface of an object;

FIGS. **4**A and **4**B a block diagram and a two-dimensional layout of a sensor array configured in accordance with this invention;

FIG. **5** shows a block diagram of a sensor system using the array of FIG. **4**;

FIGS. **6**A, **6**B, **6**C and **6**D show respectively the sequence of responses from a group of linear receivers in accordance with this invention, the sequence of excitation pulses sent to the linear receivers, the timing of the received waveforms from the receivers, and the sequence of delays applied each trigger signal to achieve shapeforming;

FIG. **7**A shows the waveshapes from the linear receivers with no delay;

FIG. **7**B shows the wave shapes of the linear receivers with the delays shown in FIG. **6**D;

FIG. **8** shows a block diagram of a sensor system constructed in accordance with this invention using multiplexers;

FIG. **9** shows a block diagram for a real time, small size, high resolution ultrasound imaging system for biomedical or industrial imaging constructed in accordance with this invention; and

FIG. **10** shows a block diagram of a high resolution, low cost ultrasound system for structural condition monitoring constructed in accordance with this invention.

DETAILED DESCRIPTION OF THE INVENTION

FIGS. **4**A and **4**B shows a novel configuration of transceiver array **100** with alternate (separate) transmitters **102** and receivers **104**. The transmitters **102** are excited by high trigger signals t from a beam forming circuitry (not shown) in this figure. Both transmiters **102** and receivers are aimed a target or object **106**. The reflected signals are sensed by receivers **104** and corresponding received signal r (after amplification by amplifiers **108** are sent by a separate set of lines to a signal processor (not shown in this drawings).

As T/R switches used in prior art systems are not required, a low noise amplifier (LNA) and/or preamplifier **108** can be placed physically close to the respective receiver **104**, eliminating noise, time delays and possibly fragile cables. The LNA **108** is an analog electronic device that is easily integrated with the phased array **100** using well known solid state integration technology at low cost. Since the received signals r are amplified at a considerably reduced connection distance, the signal to noise ratio improves significantly and little, if any, additional noise is picked up in the cables **110** between the LNA and the receive beam former circuitry due to the higher signal levels. The receive beam former circuitry could be provided on a separate chip disposed near array **100** or could be integrated on the same IC chip. This would also result in a significantly improved accuracy, resolution and lower costs as compared to the prior art.

FIG. **4**A shows the novel phased array sensor **100** in a one dimensional near configuration. However similar arrangement is possible in a two dimensional matrix form as well as shown in FIG. **4**B. Even though the amplitude of the received signals may be reduced by half, the LNA can have gain in the range of 10-100 so that the resultant signal to noise ratio is still much higher than prior art. This novel phased array sensor shown in FIGS. **4**A and **4**B may be integrated (and may be substituted in conventional system) with existing phased array instrumentation without any major changes to existing hardware or software.

However, in the present application a transmit and receive beam former circuit is presented in order to reduce both the number and the sampling frequency of ADCs. In the proposed new circuit shown in FIG. **5**, the receive beam former used in conventional systems (such as the one described in the US Patent Publication identified above) is eliminated. In conventional systems, the transmit beam former consists of a type of programmable logic device such as a field programmable gate array (FPGA) or a phase shifter. As shown in FIG. **5**, the transmit beam former initiates high voltage excitation pulses, it also generates appropriately delayed 'trigger' pulses for ADC digitizer "programming" in such a way that the received echoes (or received signals) are aligned properly so as to increase resolution. This further serves to increase system accuracy and reduce costs.

More specifically, referring to FIG. **5**, the complete system **200** includes a transmit beam former **201** that generates control signals to a high voltage pulser **202**. In response, the pulser **202** generates high voltage excitation pulses (of an appropriate magnitude and duration) to each of the transmitters **102**. In response, the transmitters **102** generate a signal to the target or object of interest **106**. The signals reflected from the target **106** (or echoes) are sensed by receivers **104**. The received signal from each receiver is amplified by amplifier **108**, conditioned (e.g., filtered, etc., by a signal conditioner **210** and provided to a bank of ADC (analog to digital converters) **212**. The beam former **201** also sends a set of trigger or delay signals to the ADC bank **212** to delay all or some of the received signals. The ADCs start sampling the received signals only after they receive their respective trigger. These signals are therefore appropriately delayed and hence can be summed (or a weighted average operation can be performed) by the signal processing and computing module **214**.

FIGS. **6**A-D illustrates the use of delay signals to align received echoes. For simplicity, let us assume a five element phased array **100** (with equally spaced transmit elements **102-1**, **102-2** . . . **102-5**) is used to focus on target **106** disposed at a focal point which lies on the perpendicular bisector of the phased array. Since transmitter **102-1** and **102-5** are farthest from the focal point, they are excited first. Transmitter **102-3** is excited after a time delay σ from transmitters **102-1** and **102-5**. Transmitter **102-2** and **102-4** are excited after a time delay of σ from transmitter **102-3** as shown in FIG. **6**B.

This results in all the waveforms/pulses interfering constructively at the focus. The resultant echoes from the focus arrive at the respective receivers (which have been omitted from FIG. **6**A for the sake of clarity) at different times as shown in FIG. **6**C with the echoes from the receiver associated with transmitter **102-3** arriving at the earliest. To sample the received echoes, we can use trigger signals as shown in FIG. **6**D, so as to compensate for the time difference due to the path difference for different transceiver elements.

FIGS. **7**A and **7**B show the echo pulses from transceivers and the effect of sampling using our novel technique (delayed trigger) versus sampling without using delayed triggers (current state of art). Notice that there is a marked improvement in accuracy. As described in section B (prior art), an alternate to using the delayed triggers is to use either high sampling frequency ADCs or to use interpolation filtering. Both these techniques used in present art result in either high cost, reduced resolution or both.

The illustration in FIGS. **7**A and B show the improvement in resolution/accuracy just for 5 element phased array. FIG. **7**A shows five signals received from the five receivers. Obviously it is difficult to analyze these signals to get information about the target **106**. FIG. **7**B shows the combined with and without the delays. Obviously delaying and summing the signals results in a combined signal that is much easier to analyze.

However, in practice, the number of transceiver elements in the phased array can be in several hundreds and hence the resolution/accuracy without delayed trigger will be very poor as the number of transceiver elements increases.

The digital data from all the receivers is already offset by a suitable delay originating from the transmit beam former and hence can be added as such without any interpolation. Hence, for a 10 MHz ultrasound signal with 1 ns delay, an ADC/Digitizer with 10 MHz sampling frequency can be used instead of possibly a 1 GHz sampling ADC. Hence, less computing resources are required to process the received ultrasound echo signal.

Further, a multiplexer can be used to reduce the number of ADCs as well, further reducing the cost. AnN:1 multiplexing architecture **300** (with N being the number of receivers) is shown in FIG. **8**. During the transmit stage, all the transmitters are excited by the transmit beam former **302**. However, during the receive stage, both the trigger signals as well as received echoes from the receivers are multiplexed using two multiplexers **306**, **308**. Only one received echo goes to the analog front end and ADC/Digitizer at a time and the corresponding trigger signal switches on the ADC/digitizer. Once an echo is digitized, it is stored in the

computer memory and the next echo is digitized, keeping the delay law pattern in the transmit beam former identical. Since all the echoes are appropriately offset and properly 'referenced', all the echoes can be added up within the ADC/digitizer **310** after all the receiver data have been acquired.

Alternately, the digitized echoes can be added up sequentially as they are acquired. Even though FIG. **8** shows N:1 multiplexing architecture however N:K multiplexing scheme can be adopted as well, where K is the number of analog-front end and ADC/digitizer pairs. The N:K multiplexing will be higher frame rate than N:1 multiplexing but the cost will be higher than N:1 multiplexing. By a suitable selection of N and K, the cost and frame-rate can both be optimized. The novel integrated beamforming architecture with or without multiplexing can be used either with existing phased array probes or with the novel phased array probes without T/R switches or with novel phased array probes with electrical isolation between transmitters and receivers.

The electrical isolation between transmitter and receiver elements will completely eradicate the noise from high voltage component of the system to cross over to the low noise amplifiers. In addition, blind distances will be completely eliminated through the electrical isolation of transmitters and receivers. This will enable the imaging of near surface artifacts as well as possible reduction in transmitter pulsing voltages.

Reduced voltages also will provide for safer "in body" medical imaging, meeting newer food and drug administration (FDA) restrictions on high voltage in medical examinations.

The multiplexed architecture is especially suitable for materials testing applications where the test specimen is 'static' or changes very slowly. For example, using the multiplexed architecture, a low cost real-time ultrasonic monitoring system for civil or energy infrastructure such as oil/gas pipelines can be designed and permanently fixed to the structure.

A 1-20 MHz high resolution and small sized phased array ultrasound system **400** constructed in accordance with this invention is now described in accordance with this invention in conjunction with FIG. **10**. The transducer **401** consists of a number of alternate transmitter **402-1** . . . and receiver elements **404-1**, . . . (only two each shown in Figure). The receiver elements **404-1**, . . . are connected to an analog front end (AFE **408**) chip such as MAX 2077 (Maxim Integrated) for amplification. The transmitter elements **402-1** . . . isolate the receivers from high voltage circuitry, effectively reducing noise in received ultrasound signals. The AFE **408** includes a number of low noise amplifiers, time gain amplifiers and low pass (anti-aliasing) filters. The transmitter elements **402-1**, . . . are connected to a high voltage pulser (HVP) **406** chip such as STHV748 (ST Microelectronics) or MAX4940 (Maxim Integrated). The HVP chip **406** produces an up-to 200 volt peak-peak pulse. The AFE output **409** is connected to a high speed ADC **410** such as AD-9248 (Analog Devices). A 200MSPS ADC will be sufficient for frequencies in range of 1-20 MHz. The ADC clocks obtained from am FPGA **412** are appropriately delayed (in steps of 1 ns) to enable receive beamforming. ADC clocks as well as the digital data to configure both HVP and AFE are generated by the FPGA **410** such a FPGA-SOC chip such as Altera Cyclone V SoC. The FPGA-SoC also collects the digital output from ADC to form a human readable ultrasonic image.

A high resolution and extremely low cost ultrasound system **500** for structural condition monitoring applications is shown in FIG. **11**.

In certain applications (mainly industrial) such as monitoring of wind turbine blades, oil and gas pipelines and aerospace structures, it will be very useful to have a low cost sensor system permanently attached to the structure which can monitor the structure. In such structural condition monitoring applications, instantaneous imaging is not necessary. However, the imaging resolution (typically micrometers) cannot be sacrificed. At the same time, cost saving becomes critical. Using the present invention, create a high resolution yet low cost system can be created. The system saves cost by reducing the number of ADCs significantly.

As an example, for an oil pipeline of the diameter of 32 inches, an ultrasound transducer (typically 1-5 MHz) of several hundred thousand elements will be required to cover the entire circumference of the pipeline over the cylindrical length of, say, 6 inches. For such an application, reduction in the sampling frequency and number of ADCs is the key to reducing the system cost. As discussed in previous sections, for a 5 MHz phased array transducer, our novel design enables the transmit beamforming with an accuracy of 1 ns while using ADCs in the range of 50-100 MSPS. This design has enormous cost savings as compared to using ADCs in 1 GHz MSPS for a 1 ns delay. Secondly, we reduce the number of ADCs by using an analog multiplexer after the receiver elements. Since the data from each ADC is precisely timed, the ADC digital output can be stored in FPGA-SoC memory and can be summed/processed at a later time. In addition to reducing the number of ADCs, we can also reduce the number of AFEs successfully. Similarly, the number of HVPs can be reduced by using a high voltage high speed analog switch such as MAX 4968 (Maxim Integrated). Alternately, HVPs can be replaced by high voltage field effect transistors (FETs) and the FETs can be integrated permanently with the ultrasound transducer. This will reduce the amount of noise and jitter during transmit beam forming improving resolution and accuracy.

The digital data acquired from ADCs can be communicated to another computer through a WiFi/Bluetooth or other suitable topology. Ultrasonic measurements in a given area can be compared over time. This can enable detection of subtle changes in the structure such as hydrogen cracking (for oil and gas pipelines) or matrix micro cracking (in fiber composite structures such as wind turbine blades or carbon fiber aircraft structures). Small changes such as these go undetected in normal ultrasonic measurements due to high background noise. Automated monitoring of such small changes using permanently mounted phased array ultrasonic sensors can enable early warning about catastrophic failure and can increase the service lifetime of structures.

The system **500** includes a sensor array **501** including transmitters **502** and receivers **504**. High voltage pulses are generated by pullers **506** and fed through multiplexers **508** to the transmitters **502**. The echoes or received signals from the receivers **504** are multiplexed by multiplexer **512**, amplified and conditioned by AFE's **514**, digitized by ADC's **516** and then fed to the FPGA **510** for analyses. As before clock signals for the ADCs **516** and pulsers **506** with suitable delays are generated by the FPGA **510**.

Present phased array ultrasound systems are extremely expensive and so are almost operated by skilled technicians and not affixed to the structure for automated monitoring. However, as the novel architecture embedded in equipment is expected to reduce the costs drastically, the phased array ultrasound device can be fixed to the monitored infrastruc-

ture at a particular spot. Alternately, 'smart pipelines' can be fabricated with built-in phase array transducers.

Numerous modifications may be made to the invention without departing from its scope as defined in the appended claims.

We claim:

1. A phased array probe, comprising:

a solid state array including a first transmitter, a second transmitter, a first receiver and a second receiver, each of the first transmitter, second transmitter, first receiver and second receiver being distinct and respectively coupled to distinct signal paths;

first and second amplifiers integrated with the solid state array and respectively coupled to the first and second receivers;

a transmit beam former configured to

generate control signals to respectively excite the first and second transmitters, a control signal associated with the second transmitter being delayed with respect to a control signal associated with the first transmitter, and

generate a trigger signal corresponding to the delay;

a pulser generator configured to generate excitation pulses to the transmitters in response to the control signals thereby causing a probe signal transmitted by the second transmitter to be delayed with respect to a probe signal transmitted by the first transmitter;

a receiving module configured to

receive signals from the first and second amplifiers corresponding to the probe signals, and

delay sampling of the received signal associated with the second receiver based on the trigger signal generated by the transmit beam former; and

an analyzer configured to analyze the received signals.

2. The probe of claim **1**, wherein the receiving module includes at least one analog-to-digital converter that converts the received signals into digital output signals.

3. The probe of claim **2**, wherein the trigger signal of the transmit beam former is coupled to the analog-to-digital converter to respectively delay sampling of the received signals.

4. The probe of claim **2**, further comprising a memory configured to store digital values output by the analog-to-digital converter.

5. The probe of claim **4**, wherein the receiving module is configured to perform a summation of the stored digital values.

6. The probe of claim **1**, wherein the delayed received signal associated with the second receiver overlaps with the received signal associated with the first receiver.

7. The probe of claim **1**, wherein the first transmitter and the second transmitter are coupled to a high voltage ground.

8. The probe of claim **7**, wherein the first receiver and the second receiver are coupled to a low voltage reference.

9. The probe of claim **1**, wherein the first transmitter includes a transmitter element selected from the group consisting of piezoelectric, capacitive, magnetostrictive, acoustic, and electromagnetic element that converts electrical voltage pulses into acoustic, ultrasonic or electromagnetic waves.

10. The probe of claim **1**, further comprising a multiplexer that multiplexes a plurality of trigger signals generated by the transmit beam former, and the transmit beam former provides a multiplexed trigger signal to an analog-to-digital converter.

11. The probe of claim **1**, wherein the receiving module includes a multiplexor that multiplexes the received signals and provides the multiplexed received signal to an analog-to-digital converter.

12. A method of probing a target with a probe including a solid state array including a first transmitter, a second transmitter, a first receiver and a second receiver, each of the first transmitter, second transmitter, first receiver and second receiver being distinct and respectively coupled to distinct signal paths, the method comprising:

generating, by a transmit beam former, a first transmit signal and a second transmit signal, the first transmit signal being delayed with respect to the second transmit signal, the first transmit signal and the second transmit signal being respectively provided to the first and second transmitters;

detecting a first echo signal with the first receiver and a second echo signal with the second receiver;

amplifying, respectively using first and second low noise amplifiers integrated with the solid state array, the first and second echo signals;

delaying, by a receiving module and based on a trigger signal generated by the transmit beam former, sampling the first amplified echo signal relative to the second amplified echo signal;

converting the first and second echo signals into digital signals based on the sampling; and

summing the digital signals.

13. The method of claim **12**, further comprising sending excitation signals to the transmitters by the transmit beam former to cause the generation of the transmit signals.

14. The method of claim **12**, further comprising multiplexing the first and second amplified echo signals.

15. The method of claim **14**, wherein the sampling is performed by an analog-to-digital converter, and a trigger signal of the transmit beam former is coupled to the analog-to-digital converter to respectively delay sampling of the received signals.

16. The method of claim **12**, wherein the first transmitter and the second transmitter are coupled to a high voltage ground.

17. The method of claim **16**, wherein the first receiver and the second receiver are coupled to a low voltage reference.

18. The method of claim **12**, further comprising multiplexing a plurality of trigger signals generated by the transmit beam former, and providing, by the transmit beam former, a multiplexed trigger signal to an analog-to-digital converter.

19. The method of claim **12**, further comprising multiplexing, by the receiving module, the first and second amplified echo signals providing the multiplexed received signal to an analog-to-digital converter.

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