US 20070016022A1

(19) United States
(12) Patent Application Publication (10) Pub. No.: US 2007/0016022 A1
Blalock et al. (43) Pub. Date: Jan. 18, 2007

(54) **ULTRASOUND IMAGING BEAM-FORMER APPARATUS AND METHOD**

(75) Inventors: **Travis N. Blalock**, Charlottesville, VA (US); **William F. Walker**, Barboursville, VA (US); **John A. Hossack**, Charlottesville, VA (US)

Correspondence Address:
NOVAK DRUCE & QUIGG, LLP
1300 EYE STREET NW
400 EAST TOWER
WASHINGTON, DC 20005 (US)

(73) Assignee: **UNIVERSITY OF VIRGINIA PATENT FOUNDATION**, Charlottesville, VA (US)

(21) Appl. No.: **11/160,915**

(22) Filed: **Jul. 14, 2005**

(30) **Foreign Application Priority Data**

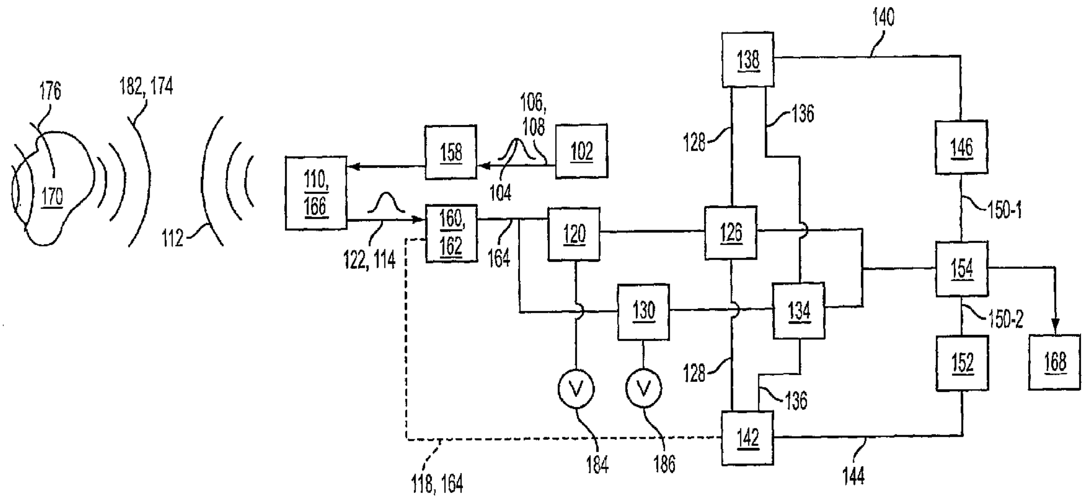
Jan. 14, 2004 (WO) PCT/US04/00887

Publication Classification

(51) **Int. Cl.**
A61B 8/00 (2006.01)
(52) **U.S. Cl.** **600/437**

(57) **ABSTRACT**

In some illustrative embodiments, an incoming signal from a transducer in an ultrasound imaging beam-former apparatus is applied to an in-phase sample-and-hold and a quadrature sample-and-hold. The quadrature sample-and-hold may be clocked a quarter period behind the in-phase sample-and-hold. The output of the sample-and-holds are applied to in-phase and quadrature analog-to-digital converters. A magnitude calculator receives the in-phase and quadrature digital values, and outputs a magnitude. A phase calculator receives the in-phase and quadrature digital values, and outputs a phase. An apodizer applies a difference between an amplitude of the outgoing signal and the magnitude and applies a first illumination to a image point in substantial proportion to the difference, and a phase rotator applies a second illumination to the image point in substantial proportion to the phase.



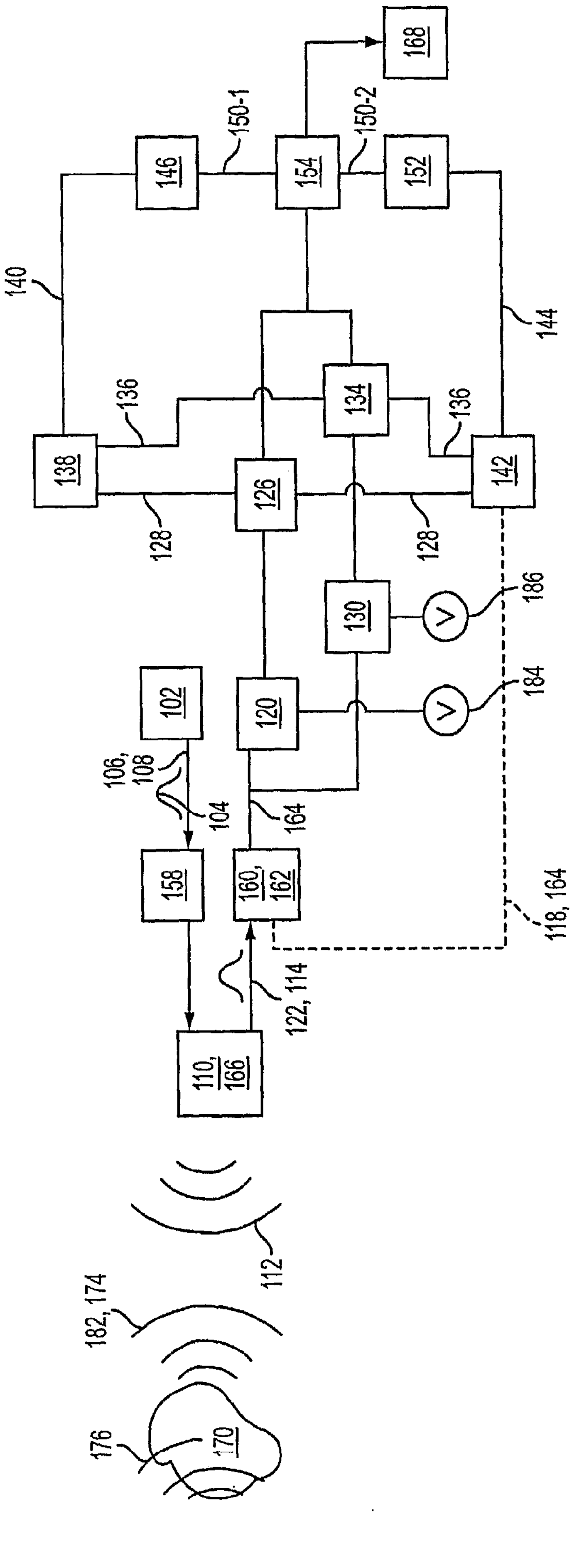

168
150-1
150-2
146
154
152
140
144
136
134
136
138
126
142
128
128
130
186
102
120
184
106,
108
104
164
158
160,
162
118, 164
122, 114
110,
166
112
182, 174
176
170

FIG. 1

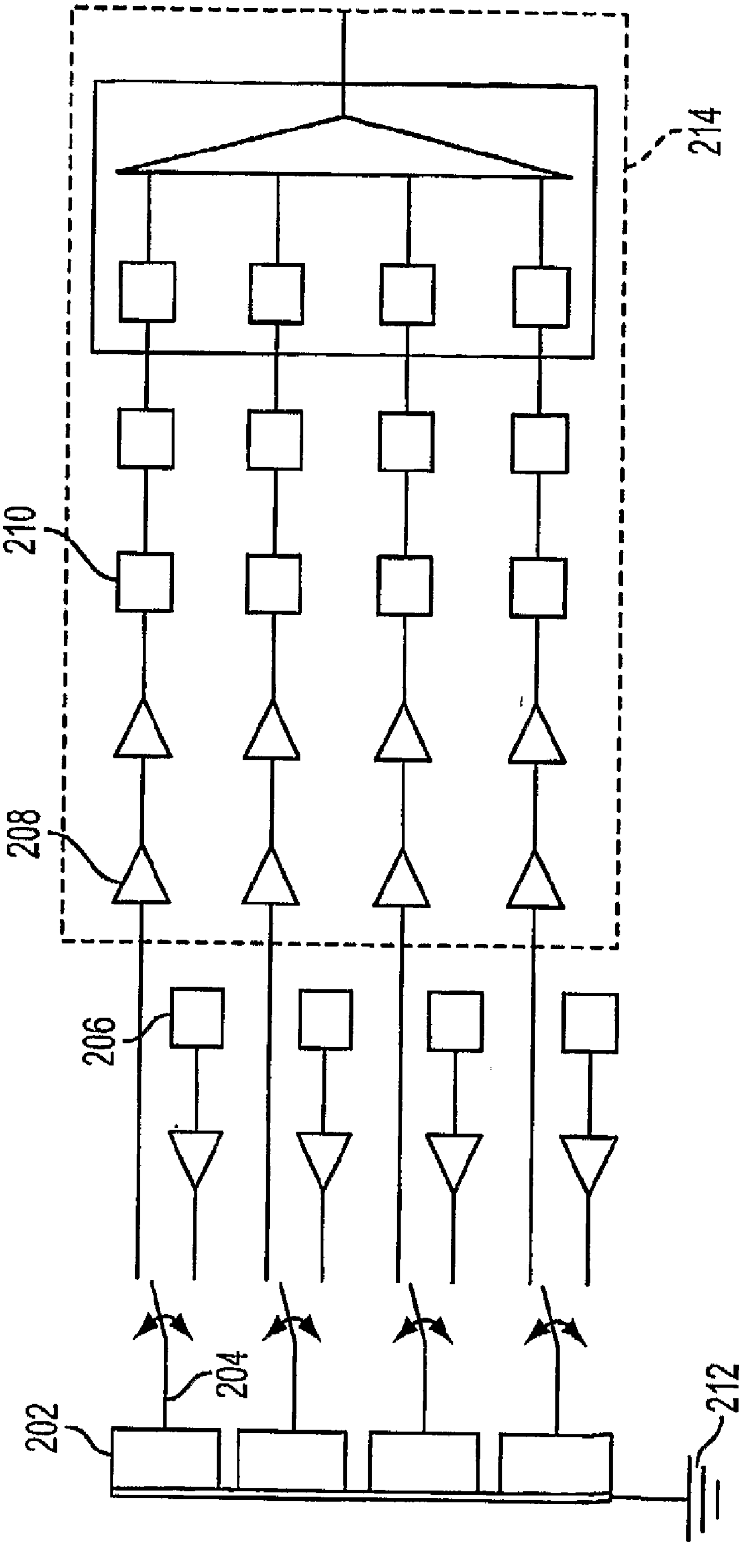


FIG. 2

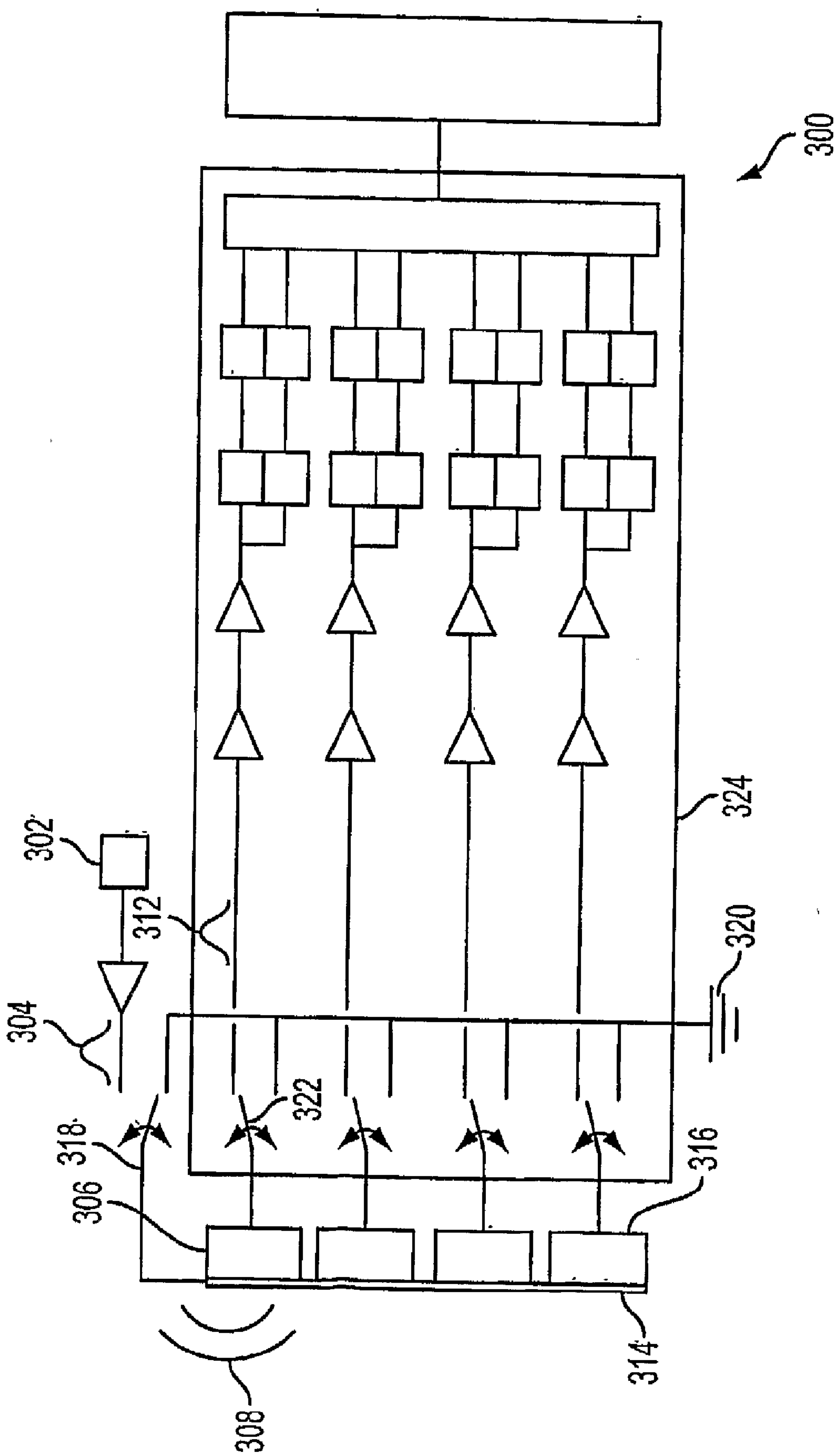


FIG. 3

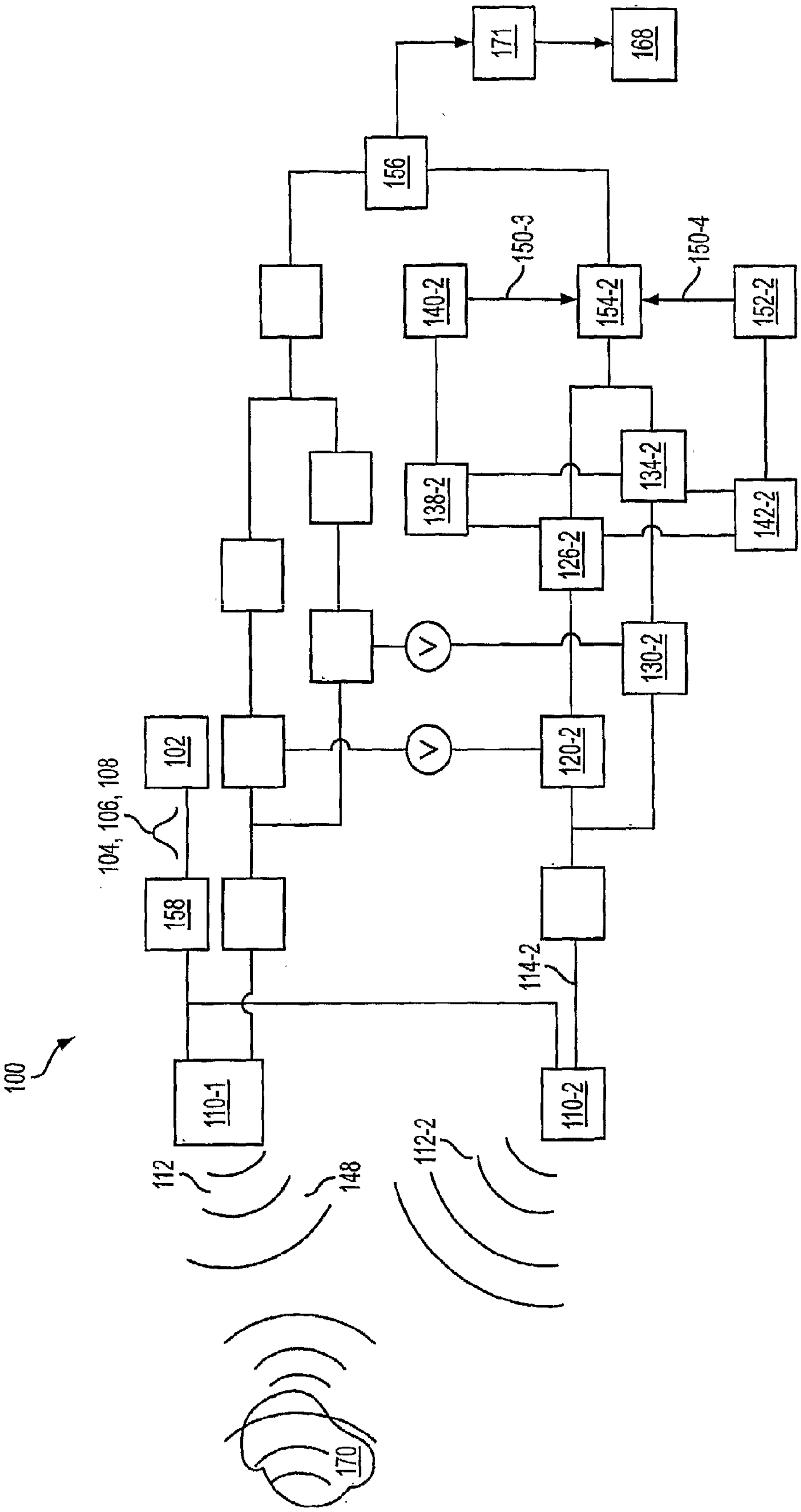
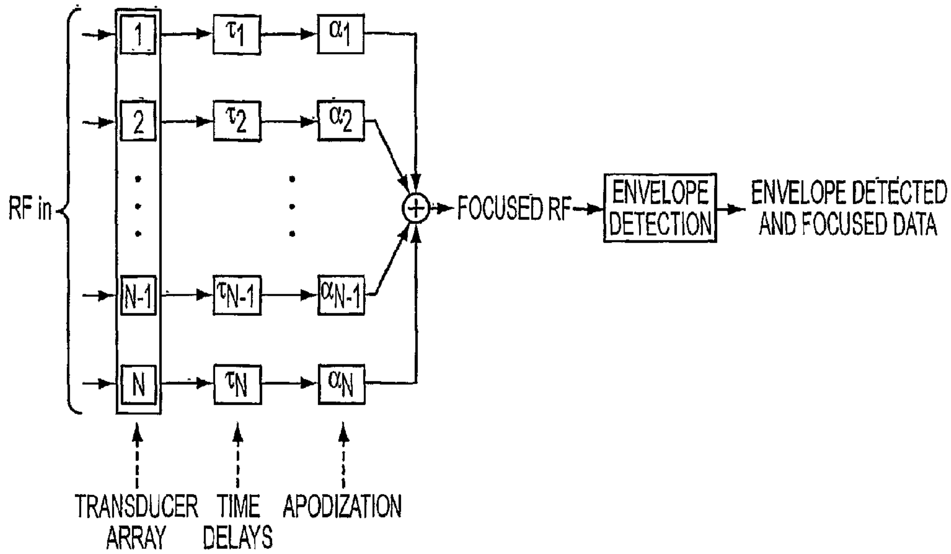
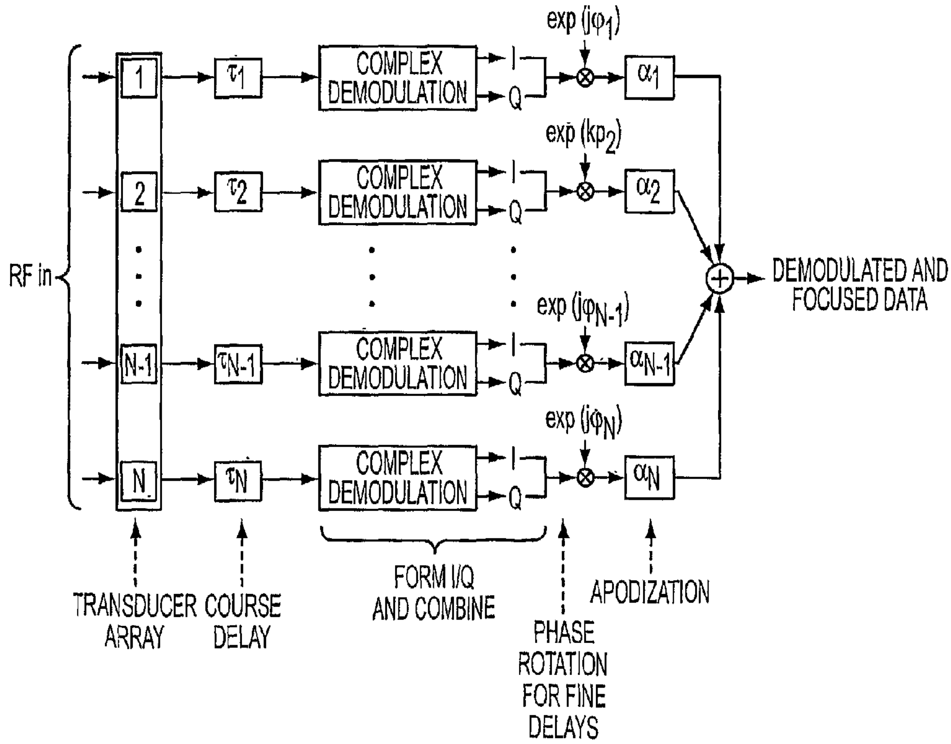

100
110-1
110-2
112
148
112-2
170
158
102
104, 106, 108
114-2
120-2
130-2
126-2
134-2
138-2
142-2
140-2
154-2
152-2
150-3
150-4
156
171
168

FIG. 4



CONVENTIONAL ART
FIG. 5A



CONVENTIONAL ART
FIG. 5B

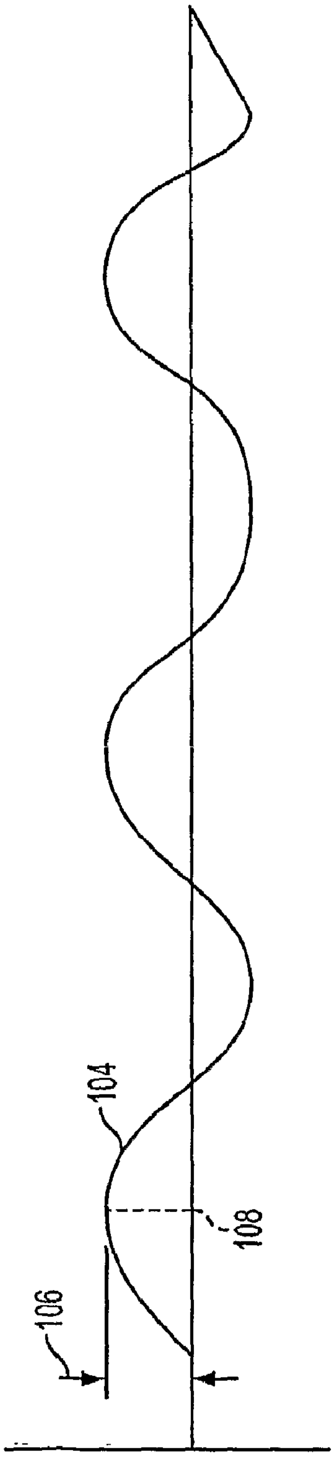


FIG. 6A

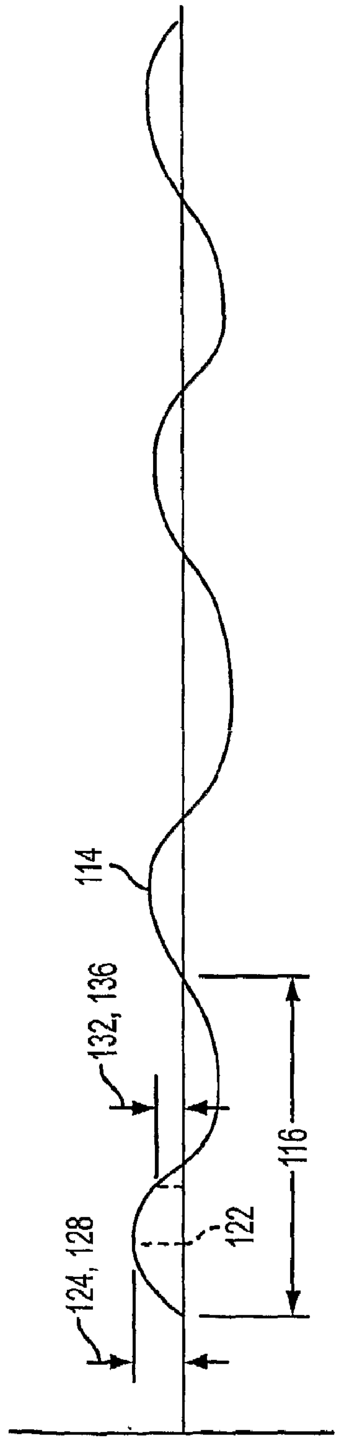


FIG. 6B

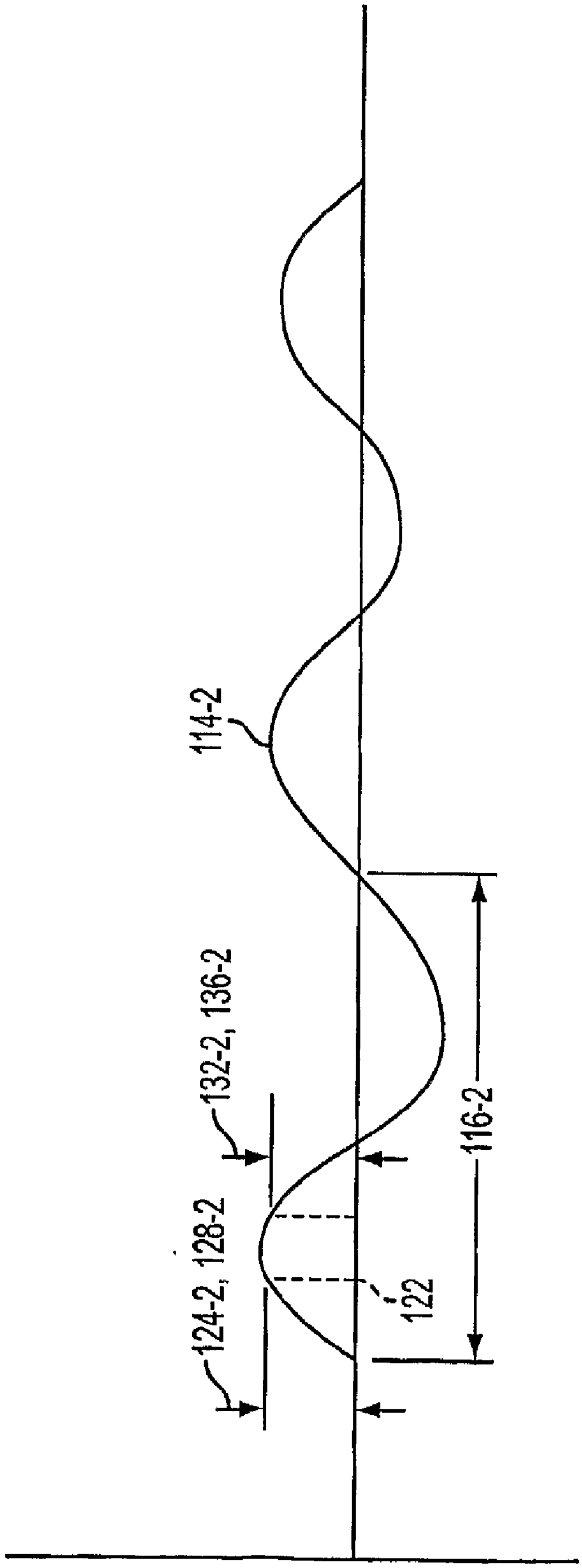


FIG. 6C

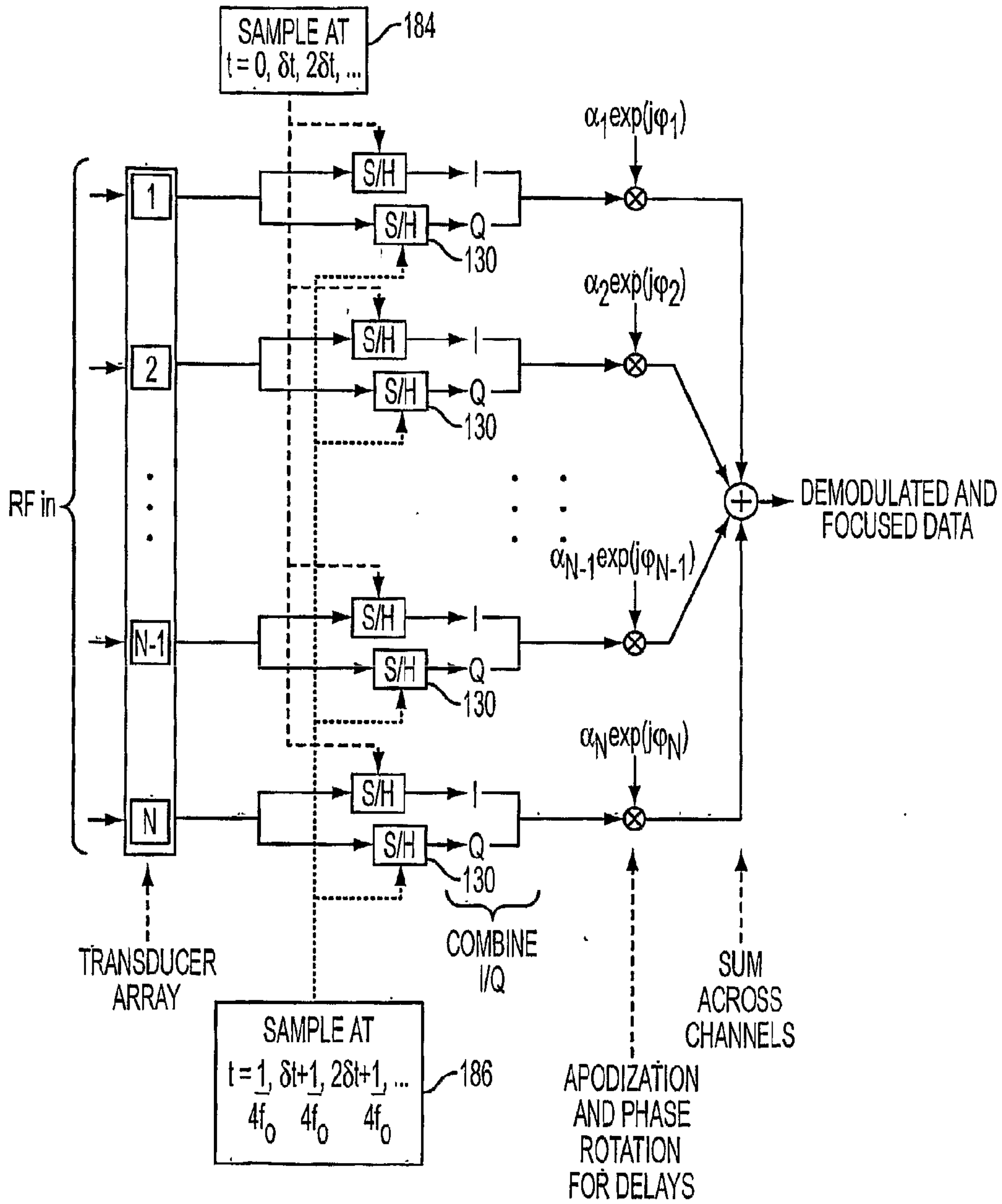

SAMPLE AT
t = 0, δt, 2δt, ...
184
$\alpha_1 \exp(j\varphi_1)$
$\alpha_2 \exp(j\varphi_2)$
$\alpha_{N-1} \exp(j\varphi_{N-1})$
$\alpha_N \exp(j\varphi_N)$
1
2
N-1
N
S/H
I
Q
130
RF in
DEMODULATED AND FOCUSED DATA
TRANSDUCER ARRAY
COMBINE I/Q
SUM ACROSS CHANNELS
APODIZATION AND PHASE ROTATION FOR DELAYS
SAMPLE AT
$t = \frac{1}{4f_0}, \delta t+\frac{1}{4f_0}, 2\delta t+\frac{1}{4f_0}, \ldots$
186

FIG. 7

ULTRASOUND IMAGING BEAM-FORMER APPARATUS AND METHOD

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application is National Stage filing under 35 U.S.C. 371 of International Applications No. PCT/US2004/000887 which claims priority to U.S. Provisional Application Ser. Nos. 60/440,020 filed on Jan. 14, 2003, 60/439,990 filed on Jan. 14, 2003, and 60/440,262 filed on Jan. 15, 2003 the entire disclosures of which are incorporated herein by reference.

BACKGROUND

[0002] 1. Field of the Invention

[0003] The present invention relates to ultrasonic diagnostic imaging systems and methods. More specifically, the preferred embodiments relate to a device and method for ultrasound imaging beam-forming that may be incorporated in a substantially integrated hand-held ultrasonic diagnostic imaging instrument.

[0004] 2. Introduction

[0005] Medical imaging is a field dominated by high cost systems that may be so complex as to require specialized technicians for operation and the services of experienced medical doctors and nurses for image interpretation. Medical ultrasound, which is considered a low cost modality, utilizes imaging systems costing as much as $250K. These systems may be operated by technicians with two years of training or specialized physicians. This high-tech, high-cost approach works very well for critical diagnostic procedures. However it makes ultrasound impractical for many of the routine tasks for which it would be clinically useful.

[0006] A number of companies have attempted to develop low cost, easy to use systems for more routine use. The most notable effort is that by Sonosite. Their system produces very high quality images at a system cost of approximately $20,000. While far less expensive than high-end systems, these systems are still very sophisticated and require a well-trained operator. Furthermore, at this price few new applications may be opened.

[0007] Many ultrasonic imaging systems utilize an array transducer that is connected to beamformer circuitry through a cable, and a display that is usually connected directly to or integrated with the beam-former. This approach is attractive because it allows the beamformer electronics to be as large as is needed to produce an economical system. In addition, the display may be of a very high quality.

[0008] Some conventional system architectures have been improved upon through reductions in beam-former size. One of the most notable efforts has been undertaken by Advanced Technologies Laboratories and then continued by a spin-off company, Sonosite. U.S. Pat. No. 6,135,961 to Pflugrath et al., entitled "Ultrasonic Signal Processor for a Hand Held Ultrasonic Diagnostic Instrument," hereby incorporated by reference herein in its entirety, describes some of the signal processing employed to produce a highly portable ultrasonic imaging system. The Pflugrath '961 patent makes reference to an earlier patent, U.S. Pat. No. 5,817,024 to Ogle et al., entitled, "Hand Held Ultrasonic Diagnostic instrument with Digital Beamformer," hereby incorporated by reference herein in its entirety. In U.S. Pat. No. 6,203,498 to Bunce et al., entitled "Ultrasonic Imaging Device with Integral Display," hereby incorporated by reference herein in its entirety, however, the transducer, beamformer, and display may be all integrated to produce a very small and convenient imaging system.

[0009] Other references of peripheral interest are U.S. Pat. No. 6,669,641 to Poland, et al., entitled "Method of and system for ultrasound imaging," which describes an ultrasonic apparatus and method in which a volumetric region of the body is imaged by biplane images. One biplane image has a fixed planar orientation to the transducer, and the plane of the other biplane image can be varied in relation to the fixed reference image.

[0010] U.S. Pat. No. 6,491,634 to Leavitt, et al., entitled "Sub-beam-forming apparatus and method for a portable ultrasound imaging," describes a sub-beam-forming method and apparatus that is applied to a portable, one-dimensional ultrasonic imaging system. The sub-beam-forming circuitry may be included in the probes assembly housing the ultrasonic transducer, thus minimizing the number of signals that are communicated between the probe assembly and the portable processor included in the imaging system.

[0011] U.S. Pat. No. 6,380,766 to Savord, entitled "Integrated circuitry for use with transducer elements in an imaging system," describes integrated circuitry for use with an ultrasound transducer of an ultrasound imaging system.

[0012] U.S. Pat. No. 6,013,032 to Savord, entitled "Beamforming methods and apparatus for three-dimensional ultrasound imaging using two-dimensional transducer array," describes an ultrasound imaging system including a two-dimensional array of ultrasound transducer elements that define multiple sub-arrays, a transmitter for transmitting ultrasound energy into a region of interest with transmit elements of the array, a sub-array processor and a phase shift network associated with each of the sub-arrays, a primary beam-former and an image generating circuit.

[0013] U.S. Pat. No. 6,126,602 to Savord, et al., entitled "Phased array acoustic systems with intra-group processors," describes an ultrasound imaging apparatus and method that uses a transducer array with a very large number of transducer elements or a transducer array with many more transducer elements than beam-former channels.

[0014] U.S. Pat. No. 5,997,479 to Savord, et al., entitled "Phased array acoustic systems with intra-group processors," describes an ultrasound imaging apparatus and method that uses a transducer array with a very large number of transducer elements or a transducer array with many more transducer elements than beam-former channels.

[0015] U.S. Pat. No. 6,582,372 to Poland, entitled "Ultrasound system for the production of 3-D images," describes an ultrasound system that utilizes a probe in conjunction with little or no specialized 3-D software/hardware to produce images having depth cues.

[0016] U.S. Pat. No. 6,179,780 to Hossack, et al., entitled "Method and apparatus for medical diagnostic ultrasound real-time 3-D transmitting and imaging," describes a medical diagnostic ultrasound real-time 3-D transmitting and imaging system that generates multiple transmit beam sets using a 2-D transducer array.

[0017] U.S. Pat. No. 6,641,534 to Smith, et al., entitled "Methods and devices for ultrasound scanning by moving sub-apertures of cylindrical ultrasound transducer arrays in two dimensions," describes methods of scanning using a two dimensional (2-D) ultrasound transducer array.

[0018] U.S. Pat. No. 4,949,310 to Smith, et al., entitled "Maltese cross processor: a high speed compound acoustic imaging system," describes an electronic signal processing device which forms a compound image for any pulse-echo ultrasound imaging system using a two-dimensional array transducer.

[0019] U.S. Pat. No. 6,276,211 to Smith, entitled "Methods and systems for selective processing of transmit ultrasound beams to display views of selected slices of a volume," describes the selection of a configuration of slices of a volume, such as B slices, I slices, and/or C slices.

[0020] Commercial ultrasound systems have been limited to one-dimensional (1-D) or linear transducer arrays until fairly recently. A typical number of transducers in such an array may be 128. Providing separate multiplex and receive circuitry is manageable with this many transducers, albeit with significant use of expensive high-voltage switches. Newer arrays, however, may be likely to be two-dimensional (2-D) or square arrays. The number of transducers in a two-dimensional array may range up to 128×128 or 16,384, and is often in the thousands. Maintaining separate receive, transmit, and multiplex partitioning for the transducers in such an array creates a tremendous burden in terms of cost, space, and complexity. The power consumption and heat dissipation of thousands high-voltage multiplexers is enough to discourage the use of two-dimensional arrays in portable ultrasound imaging systems.

[0021] Current beam-forming strategies can be broadly classified into the two approaches depicted in FIG. **5**. One approach is to use digital time delays to focus the data, as illustrated in **5** (*a*). Geometric delays are calculated and applied to the digitized data on each channel. In such beam-formers, the data needs to either be sampled at a very high sampling rate or interpolated. Implementation of time delays requires sufficient memory to hold a few hundred samples per channel to implement an adequate delay envelope, constraining system complexity.

[0022] In the second approach, systems combine time delays with complex phase rotation, as depicted in **5** (*b*). Coarse focusing is implemented by delaying the digitized data on each channel. Fine focusing is accomplished by phase rotation of data that has undergone complex demodulation at the center frequency. Such systems require circuitry to perform complex demodulation on every channel. Time delay beam-forming requires significant fast memory to implement a reasonable delay envelope.

[0023] Conventional approaches to generating I/Q data may also include analog/digital baseband demodulation, or use a Hilbert transform. Using a demodulation based approach to generate I/Q data may necessitate significant extra circuitry on each channel, while use of the Hilbert transform may require a significant amount of memory to hold the raw RF data.

[0024] Accordingly, existing ultrasound systems with thousands of separate transmit and receive switches may be too expensive for many applications. While a variety of systems and methods may be known, there remains a need for improved systems and methods.

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] The preferred embodiments of the present invention are shown by a way of example, and not limitation, in the accompanying figures, in which:

[0026] FIG. **1** is a schematic diagram of an ultrasound imaging beam-forming apparatus according to a first embodiment of the invention;

[0027] FIG. **2** is a schematic diagram of a protection circuit for use with an embodiment of the invention;

[0028] FIG. **3** is a schematic diagram of a protection circuit for use with an embodiment of the invention;

[0029] FIG. **4** is a schematic diagram of an ultrasound imaging beam-forming apparatus according to a second embodiment of the invention;

[0030] FIG. **5** is a schematic diagram of a conventional ultrasound imaging beam-forming apparatus;

[0031] FIG. **6** are graphs of signals for use with an embodiment of the invention; and

[0032] FIG. **7** is a schematic diagram of a signal receiver for use with an embodiment of the invention.

SUMMARY OF THE INVENTION

[0033] The present invention ultrasound imaging beam-former may be incorporated in an ultrasonic imaging system convenient enough to be a common component of nearly every medical examination and procedure. The present invention ultrasound imaging beam-former provides the potential to have a broad and significant impact in health-care. The instant document identifies various clinical applications of the present invention ultrasound imaging beam-forming apparatus, but should not be limited thereto, and other applications will become attained as clinicians gain access to the system and method.

[0034] The preferred embodiments of the present invention may improve significantly upon existing methods and/or apparatuses. In particular, the present invention comprises an ultrasound imaging beam-former that may be used in a hand held ultrasonic instrument such as one provided in a portable unit which performs B-mode or C-Mode imaging and/or collects three dimensional (3-D) image data.

[0035] According to some embodiments, an ultrasound imaging beam-former is provided that includes, in a first aspect of the invention, an ultrasound imaging beam-former apparatus includes a signal generator for producing an outgoing signal, a transducer for converting the outgoing signal to outgoing ultrasound and for converting at least a portion of the outgoing ultrasound that is reflected to an incoming signal, the incoming signal having a period, and a signal receiver for processing the incoming signal, the signal receiver including, an in-phase sample- and-hold connected receivably to the transducer for sampling the incoming signal at an incoming time and outputting an in-phase amplitude of the incoming signal at substantially the incoming time, a quadrature sample-and-hold connected receivably to the transducer for sampling the incoming signal at substantially one-quarter of the period after the incoming time, the quadrature sample-and-hold outputting a quadrature amplitude of the incoming signal at substantially one-quarter of the period after the incoming time, a phase calculator connected receivably to the in-phase sample-and-hold and the quadrature sample-and-hold for receiving the incoming time, the in-phase amplitude, and the quadrature amplitude and outputting a phase, and a phase rotator for applying an illumination to the image point in substantial proportion to the phase.

[0036] In a second aspect, a method of beam-forming for ultrasound imaging includes generating an outgoing signal, transducing the outgoing signal to outgoing ultrasound, receiving at least a portion of reflected outgoing ultrasound, transducing the reflected ultrasound to an incoming signal having a period, sampling the incoming signal at an incoming time to produce an in-phase amplitude of the incoming signal, sampling the incoming signal at substantially one-quarter of the period after the incoming time to produce a quadrature amplitude of the incoming signal, calculating a phase at the incoming time based on the in-phase amplitude and the quadrature amplitude, and applying an illumination to the image point in substantial proportion to the phase.

[0037] In a third aspect, a system for beam-forming for ultrasound imaging includes means for generating an outgoing signal, means for transducing the outgoing signal to outgoing ultrasound, means for transducing at least a portion of reflected outgoing ultrasound to an incoming signal having a period, means for sampling the incoming signal at an incoming time and outputting an in-phase amplitude of the incoming signal, means for sampling the incoming signal at substantially one-quarter of the period after the incoming time and outputting a quadrature amplitude of the incoming signal, means for calculating a phase at the incoming time, based on the in-phase amplitude and the quadrature amplitude and outputting the phase, means for measuring a difference between the outgoing amplitude and the magnitude, means for applying a first illumination to a image point in substantial proportion to the difference, and means for applying a second illumination to the image point in substantial proportion to the phase.

[0038] The above and/or other aspects, features and/or advantages of various embodiments will be further appreciated in view of the following description in conjunction with the accompanying figures. Various embodiments can include and/or exclude different aspects, features and/or advantages where applicable. In addition, various embodiments can combine one or more aspect or feature of other embodiments where applicable. The descriptions of aspects, features and/or advantages of particular embodiments should not be construed as limiting other embodiments or the claims.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0039] The device and method for ultrasound imaging beam-forming may be utilized with various products and services as discussed below, but is not limited thereto. Technicians may attempt to insert needles into a vein based on the surface visibility of the vein coupled with their knowledge of anatomy. While this approach works quite well in thin, healthy individuals, it can prove extremely difficult in patients who may be ill or obese. It may be desirable to have a relatively small, inexpensive, and portable ultrasound imaging system for guiding the insertion of intravenous (IV) devices like needles and catheters into veins, or for drawing blood.

[0040] Sleep apnea (obstruction of the air passage in the of the throat) may affect more than eighteen million Americans. Obstructive sleep apnea may be among the most common variants of sleep apnea. Obstructive sleep apnea may represent a significant risk to the patient. It is difficult and expensive to diagnose obstructive sleep apnea. Typical diagnostic methods require an overnight hospital stay in an instrumented laboratory. Many at-risk patients refuse this inconvenient testing regime and thus go undiagnosed. It may be desirable to have a relatively small, inexpensive, and portable ultrasound imaging system to aid in the diagnosis of obstructive sleep apnea in a minimally obtrusive manner.

[0041] Manual palpation is an exceedingly common diagnostic procedure. Clinicians use their sense of touch to feel for subcutaneous lumps or even to estimate the size of lymph nodes or other masses. While palpation undoubtedly yields valuable qualitative information, numerous studies have shown it to have extremely poor sensitivity and that quantitative size estimates may be completely unreliable. It may be desirable to have a relatively small, inexpensive, and portable ultrasound imaging system to aid in observing subcutaneous tissues.

[0042] It may be desirable to place an image display at a transducer. It may be desirable to have a relatively small, inexpensive, and portable ultrasound imaging system to aid in placing the image display at the transducer.

[0043] Ultrasound may be used to search for internal defects in metallic or ceramic parts in a broad variety of industrial applications. Current systems may be cost effective, but may be unwieldy and acquire limited data, making it difficult to ensure that a thorough search has been performed. It may be desirable to have a relatively small, inexpensive, and portable ultrasound imaging system to aid in non-destructive evaluation.

[0044] Furthermore, new users may expect ultrasound images to produce representations parallel to the skin's surface, i.e. C-Scan images. It would be desirable for a low cost, system to be capable of producing C-Scan images. It may further be desirable to display data in the intuitive C-scan format to allow clinicians with little or no training in reviewing ultrasound images to make use of the device.

[0045] Ultrasound imaging devices may be too expensive for some applications. It may be desirable for an ultrasound imaging device to rely primarily or exclusively on receive side beam-forming to reduce or eliminate transmit-side circuitry, enabling the beam-former to be implemented using large scale integration or as software, and enabling system to be produced at a lower cost.

[0046] It may further be desirable for an ultrasound imaging device to rely primarily or exclusively on phase rotation for focusing, enabling the beam-former to be implemented using large scale integration or as software, and enabling system to be produced at a lower cost.

[0047] Ultrasound imaging devices may be insufficiently portable for some applications. It may be desirable for an ultrasonic imaging device to be of a small size to make it easy to carry the device in a pocket or on a belt attachment. This may make the device as convenient as a stethoscope and will thus open new applications. It may be desirable for an ultrasound imaging device to rely primarily or exclusively on receive side beam-forming to reduce or eliminate transmit-side circuitry, enabling the beam-former to be implemented using large scale integration or as software, and enabling the system to be made portable. It may further be desirable for an ultrasound imaging device to rely primarily or exclusively on phase rotation for focusing to reduce or eliminate transmit-side circuitry, enabling the beam-former to be implemented using large scale integration or as software, and enabling the system to be made portable.

[0048] Since it would be desirable for a beam-former to be simple, small, and low cost, it would be further desirable for the size and speed requirements of digital memory in such a beam-former to be minimized. It would be further desirable for focusing to be performed solely by phase rotation of I/Q data, thus eliminating the need for some circuitry, and allowing some of the remaining circuitry to be implemented as an integrated circuit. This may also allow the use of slower memory and reduce the computational complexity of the beam-former.

[0049] It would be further desirable for I/Q data to be generated by sampling an RF signal directly. In one embodiment, an analytic signal (I/Q data) is generated by sampling the received RF signal directly, in a manner analogous to the Hilbert transform. In one embodiment, focusing is implemented via phase rotation of this I/Q data.

[0050] In FIG. **1** is shown an ultrasound imaging beam-former apparatus **100** according to a first embodiment of the invention. Ultrasound imaging beam-former apparatus **100** may include a signal generator **102** for producing an outgoing signal **104** having an outgoing amplitude **106** at an outgoing time **108**, as shown in FIG. **6**A. In several embodiments, outgoing signal **104** may be an electrical signal, an electro-magnetic signal, or an optical signal.

[0051] If outgoing signal **104** is an optical signal, cross-talk between the circuits of ultrasound imaging beam-former apparatus **100** may be reduced or eliminated, since optical signals do not, in general, interfere with one another. This may allow ultrasound imaging beam-former apparatus **100** to be made smaller than an equivalent electronic device by increasing the density of the circuits. In one case, outgoing signal **104** may be processed as an optical signal and converted to an electrical signal to drive a transducer. An integrated circuit comprising ultrasound imaging beam-forming apparatus **100** may be implemented out of gallium-arsenide (GaAs) so that the both the optical circuits and the electrical circuits can be implemented on the same device. In another case, a transducer utilizing sono-luminescence to convert light directly into sound may be used, dispensing entirely with any need for an electrical-optical interface.

[0052] In several embodiments, signal generator **102** may be a storage device, such as a read-only memory (ROM), an oscillator such as a crystal oscillator, a resonant circuit such as a resistor-inductor-capacitor (RLC) or tank circuit, a resonant cavity such as a ruby laser or a laser diode or a tapped delay line.

[0053] In the event that signal generator **102** is a storage device, outgoing signal **104** may have been stored previously, to be read out when needed. In this embodiment, several versions of outgoing signal **104** may be stored for use with various objects **170** to be imaged. Ultrasound imaging beam-forming apparatus **100** may thus be set to produce a signal appropriate for a particular object **170** to be imaged by choosing one of the stored versions of outgoing signal **104**.

[0054] In the event that signal generator **102** is an oscillator, outgoing signal **104** may be a sinusoid of varying frequencies. In this case, outgoing signal **104** may be generated at an arbitrarily high clock speed and still be forced through filters of arbitrarily small bandwidth. This may be advantageous, for example, if a wide band signal is inconvenient. A resonant circuit or a resonant cavity may work in a similar manner. Furthermore, an oscillator may be used to produce a range of frequencies, from which a frequency that generates an optimum response may be selected.

[0055] In the event that signal generator **102** is tapped delay line, outgoing signal **104** could be generated in a manner similar to a spreading code in a code division multiple access (CDMA) format cell phone system. In this case outgoing signal **104** would not need to be a pure sinusoid, but may be a code with a fixed repetition length, such as a Walsh or a Gold code. This may, for example, allow an autocorrelation length of outgoing signal **104** to be adjusted to enhance or suppress coded excitation of an incoming signal.

[0056] If signal generator **102** is a tapped delay line it may be followed by an equalizer to bias or pre-emphasize a range of frequencies in outgoing signal **104**. In one embodiment, the equalizer may be an adaptive equalizer that operates on an incoming signal analogous to the sound reflected by the imaged object **170**. In this case, the incoming signal could be measured and the result applied to the adaptive equalizer to compensate for frequency attenuation of the sound by amplifying one or more frequencies of the incoming signal or outgoing signal **104** as necessary. This may be useful if, for example, object **170** attenuates or absorbs sound to the point that no return signal is available for imaging. In one embodiment, the adaptive equalizer could be placed in parallel with signal generator **102** and in series with the incoming signal.

[0057] In one embodiment, an equalizer could be placed in series with signal generator **102**. In this case the equalizer could emphasize a particular frequency or frequencies in outgoing signal **104**. The equalizer may, for example, place a bias or pre-emphasis toward lower frequencies on outgoing signal **104**. This embodiment may be appropriate if, for example, object **170** to be imaged is expected to have features that attenuate lower frequencies significantly more than higher frequencies to the extent that imaging may be difficult. The converse may be true as well, in that the equalizer may have a bias or pre-emphasis toward higher frequencies.

[0058] In one embodiment, outgoing signal **104** may be amplified. In one embodiment, signal generator **102** may include a generator amplifier **158** for amplifying outgoing signal **104**. Generator amplifier **158** may pre-emphasize certain frequencies of outgoing signal **104** to suit the attenuation characteristics of object **170** to be imaged as well. Signal generator **102** may also include an oscillator to produce an appropriate modulation frequency, such as a radio frequency (RF) signal, with which to modulate outgoing signal **104**.

[0059] A transducer **110** may convert outgoing signal **104** to outgoing ultrasound **112**. In several embodiments, transducer **110** may be a piezoelectric element, a voice coil, a crystal oscillator or a Hall effect transducer **110**. In one embodiment, reversals of outgoing signal **104** produce vibration of a surface of transducer **110** at substantially the frequency of outgoing signal **104**. In another embodiment, reversals of outgoing signal **104** produce vibrations of a surface of transducer **110** at frequencies that are significantly higher or lower than the frequency of outgoing signal **104**, such as harmonics of outgoing signal **104**. This vibration may, in turn, produce successive compressions and rarefactions of an atmosphere surrounding the surface of transducer **110**, also at substantially the frequency of outgoing signal **104**. If the frequency of outgoing signal **104** is substantially higher than a frequency at which sound may be heard, the successive compressions and rarefactions of the atmosphere may be termed ultrasound.

[0060] In one embodiment, transducer **110** may include a plurality of transducers **110**. In one embodiment, plurality of transducers **110** may be arranged in an array **166**. In several embodiments, array **166** may be a linear array, a phased array, a curvilinear array, an unequally sampled 2-D array, a 1.5-D array, an equally sampled 2D array, a sparse 2D array, or a fully sampled 2D array.

[0061] If outgoing ultrasound **112** is reflected by object **170**, some of outgoing ultrasound **112** may return to ultrasound imaging system **100** as reflected ultrasound **182**. Reflected ultrasound **182** may be converted to an incoming signal **114** having a period **116**, as shown in FIG. **6**B. In several embodiments, incoming signal **114** may be an electro-magnetic signal, an electrical signal or an optical signal. In several embodiments, incoming signal **114** may be amplified, pre-amplified, or stored.

[0062] In one embodiment, outgoing ultrasound **112** may be delayed or attenuated partially by object **170**. A first portion **174** of outgoing ultrasound **112**, for example, may be reflected immediately upon encountering a nearer surface **178** of object **170** while a second portion **176** of outgoing ultrasound **112** is not reflected until it encounters a further surface **180** of object **170**. A round trip of second portion **176** will thus be longer than a round trip of first portion **174**, resulting in a delay of second portion **176** relative to first portion **174**, as well as delays of both first and second portions **174**,**176** relative to outgoing ultrasound **112**. Furthermore, second portion **176** may be damped or attenuated by a material of object **170**. The delays may be measured for disparate points of object **170**, producing an image **168** of object **170**.

[0063] Apparatus **100** may include a signal receiver **118** for processing incoming signal **114**. In one embodiment, signal receiver **118** may be implemented as a digital signal processor **164**. In one embodiment, signal receiver **118** may be implemented as an integrated circuit.

[0064] Ultrasonic transducers associated with ultrasound imaging systems may be driven from a single terminal with the second terminal grounded. A transducer may be used to transmit ultrasound signals as well as receive reflected ultrasound. A signal received at a transducer may typically be several orders of magnitude smaller than the signal that was transmitted due to, inter alia, signal attenuation by the target tissue. Some of the signal may be lost due to transducer inefficiencies as well. It may be thus necessary to couple the transducer to a high-voltage transmit signal while the ultrasound is being transmitted, and then to a sensitive low-noise pre-amplifier while the reflected ultrasound is being received.

[0065] A switch that couples the transducer to the transmit and receive signals must be capable of withstanding high peak transmit voltages (typically 50-200 volts) while isolating the pre-amplifier input from those voltage levels, since they would otherwise destroy the pre-amplifier. If a receiver for the signals from the transducers is implemented as a high-density, low-voltage integrated circuit (IC), the switches themselves may need to be implemented off-chip in a separate package from materials and devices that can withstand the high voltage transmit pulses.

[0066] In one embodiment, ultrasound imaging system **100** may include a protection circuit **172** to allow both transmit and receive operations, as shown in FIG. **2**. A piezoelectric transducer array **202**, shown on the left, acts as an interface to a signal processor by converting electrical signals to acoustic pulses and vice versa. Images may be formed by transmitting a series of acoustic pulses from the transducer array **202** and displaying signals representative of the magnitude of the echoes received from these pulses. A beam-former **214** applies delays to the electrical signals to steer and focus the acoustic pulses and echoes.

[0067] Image formation begins when a state of a transmit/receive switch (TX/RX switch) **204** is altered to connect the transducer elements **202** to individual transmit circuits. Next, transmit generators **206** output time varying waveforms with delay and amplitude variations selected to produce a desired acoustic beam. Voltages of up to 200 Volts may be applied to the transducer elements **202**. Once transmission is complete, the state of the TX/RX switch **204** is altered again to connect the transducer elements **202** to individual receive circuitry associated with each element.

[0068] Signals representative of incoming echoes may be amplified by pre-amplifiers **208** and time gain control (TGC) **210** circuits to compensate for signal losses due to diffraction and attenuation. Note that the transducer array **202** shown in FIG. **2** has one common electrode **212**, and the non-common electrodes may be multiplexed between high-voltage transmit and low-voltage receive signals. This conventional TX/RX switch **204** is the source of considerable expense and bulk in typical ultrasound systems.

[0069] In FIG. **3** is shown an alternative ultrasound imaging beam-forming apparatus **300** with a protection circuit for use with an embodiment of the invention. Ultrasound imaging beam-forming apparatus **300** may include a signal generator **302** for producing an outgoing signal **304**.

[0070] Ultrasound imaging beam-forming apparatus **300** may also include a transducer **306** for converting outgoing signal **304** to outgoing ultrasound **308** at a frequency of outgoing signal **304**. In one embodiment, transducer **306** may have a transmit side **314** forming an interface with outgoing signal **304**.

[0071] In one embodiment, transmit side **314** may be connected operably to a transmit switch **318**. In several embodiments, transmit switch **318** may be an electronic switch, an optical switch, a micro-mechanical switch, a transistor, a field-effect transistor (FET), a bi-polar transistor, a metal-oxide-semiconductor (MOS) transistor, a complementary metal-oxide-semiconductor (CMOS) transistor, or a metal-oxide-semiconductor field-effect transistor (MOSFET). Transmit switch **318** may be connected switchably to signal generator **302** and a ground **320**.

[0072] In one embodiment, transducer **306** may convert at least a portion of reflected ultrasound **310** to an incoming signal **312**. In several embodiments, incoming signal **312** may be an electro-magnetic signal, an electrical signal, or an optical signal. In one embodiment, transducer **306** may have a receive side **316** forming an interface with incoming signal **312**.

[0073] In one embodiment, receive side **316** may be connected operably to a receive switch **322**. In several embodiments, receive switch **322** may be an electronic switch, an optical switch, a micro-mechanical switch, a transistor, a field-effect transistor, a bi-polar transistor, a MOS transistor, a CMOS transistor, or a MOSFET transistor. Receive switch **322** may be connected switchably to a signal receiver **324** and ground **320**.

[0074] In one embodiment, transmit switch **318** may connect transmit side **314** to signal generator **302** for a first predetermined period of time while signal generator **302** generates outgoing signal **304**. In this embodiment, receive switch **322** may connect receive side **316** to signal receiver **324** for a second predetermined period of time while signal receiver **324** receives incoming signal **312**. Transmit switch **318** may connect transmit side **314** to ground **320** during substantially second predetermined period of time while signal receiver **324** receives incoming signal **312**, and receive switch **322** may connect receive side **316** to ground **320** during substantially first predetermined period of time while signal generator **302** generates outgoing signal **304**. In one embodiment, transmit side **314** and receive side **316** are on separate transducers **306**.

[0075] In one embodiment, signal receiver **118** may include a receiver amplifier **160** for amplifying incoming signal **114**. In one embodiment, signal receiver **118** may include a receiver pre-amplifier **162** for amplifying incoming signal **114**. In one embodiment, signal receiver **118** may include a band-pass filter **164** for filtering incoming signal **114**.

[0076] In one embodiment, signal receiver **118** may include an in-phase sample- and-hold **120** connected receivably to transducer **110** for sampling incoming signal **114** at an incoming time **122** and outputting an in-phase amplitude **124** of incoming signal **114** at substantially incoming time **122**. In one embodiment, signal receiver **118** may include an in-phase analog-to-digital converter **126** connected receivably to in-phase sample-and-hold **120** for assigning an in-phase digital value **128** to in-phase amplitude **124** and outputting in-phase digital value **128**.

[0077] In one embodiment, signal receiver **118** may include a quadrature sample-and-hold **130** connected receivably to transducer **110** for sampling incoming signal **114** at substantially one-quarter of period **116** after incoming time **122**, quadrature sample-and-hold **130** outputting a quadrature amplitude **132** of incoming signal **114** at substantially one-quarter of period **116** after incoming time **122**. One-quarter of period **116** is merely exemplary. Incoming signal **114** may be sampled at any appropriate interval or fraction of period **116**. In one embodiment, signal receiver **118** may include a quadrature analog-to-digital converter **134** connected receivably to quadrature sample-and-hold **130** for assigning a quadrature digital value **136** to quadrature amplitude **132** and outputting quadrature digital value **136**.

[0078] In one embodiment, signal receiver **118** may include a magnitude calculator **138** connected receivably to in-phase analog-to-digital converter **126** and quadrature analog-to-digital converter **134** for receiving incoming time **122**, in-phase digital value **128**, and quadrature digital value **136** and outputting a magnitude **140**. In one embodiment, signal receiver **118** may include a phase calculator **142** connected receivably to in-phase analog-to-digital converter **126** and quadrature analog-to-digital converter **134** for receiving incoming time **122**, in-phase digital value **128**, and quadrature digital value **136** and outputting a phase **144**.

[0079] In one embodiment, incoming signal **114** may be band-pass filtered by band-pass filter **164** and diverted to in-phase sample-and-hold **120** and quadrature sample-and-hold **130**. An in-phase clock signal **184** driving in-phase sample-and-hold **120** may be of the same frequency as a quadrature clock signal **186** driving quadrature sample-and-hold **130**. Quadrature clock signal **186** may, however, be offset by a quarter of period **116** with respect to in-phase clock signal **184** at an assumed center frequency of incoming signal **114**. An output of in-phase sample-and-hold **120** may be digitized by in-phase analog-to-digital converter **126** while an output of quadrature sample-and-hold **130** is digitized in quadrature analog-to-digital converter **134**, forming I and Q channel data.

[0080] Reflected ultrasound **182** may be considered to be real part of an amplitude and phase modulated complex exponential signal, or analytic signal. The modulating signal may be expressed mathematically as:

[0081] , $A(t)e^{j\phi(t)}$ with instantaneous amplitude A(t) and phase $\phi(t)$. This is superimposed on a carrier signal $e^{-j\omega_0 t}$, where $\omega_0=2\pi f_0$ and f_0 is the frequency of the signal. Therefore the analytic signal S(t) can be written as,

$$
\begin{aligned}
S(t) &= A(t)e^{-j(\omega_0 t-\phi(t))} \qquad (1)\\
&= A(t)\cos(\omega_0 t-\phi(t)) - jA(t)\sin(\omega_0 t-\phi(t))
\end{aligned}
$$

[0082] Only the real part of S (t), which is equivalent to reflected ultrasound **182**, is able to be acquired experimentally.

$$I(t)=Re\{S(t)\}=A(t)\cos(\omega_0 t-\phi(t)) \qquad (2)$$

[0083] The output of in-phase analog-to-digital converter **126** is the signal in equation 2 after sampling, or

$$\hat{I}(nT)=InT)=A(nT)\cos(\omega_0 nT-\phi(nT)),\ n=0, 1, 2, 3 \ldots \qquad (3)$$

[0084] where T is the sample interval. However, we also require the imaginary component of S (t), shown below in equation 4, to perform beam-forming.

$$Q(t)=Im\{S(t)\}=-A(t)\sin(\omega_0 t-\phi(t)) \qquad (4)$$

[0085] Quadrature clock signal **186** has a time lag of a quarter period at the assumed center frequency relative to the in-phase clock signal **184**, as shown **1** schematically in FIG. **7**. Therefore the relative time lag is:

$$\frac{1}{4f_0}, \text{ or } \frac{\pi}{2\omega_0}.$$

[0086] The output of quadrature sample-and-hold **130** is,

$$\begin{aligned}\hat{Q}(nT) &= 1\left\{nT + \frac{\pi}{2\omega_0}\right\} \\ &= A\left(nT + \frac{\pi}{2\omega_0}\right)\cos\left(\omega_0\left(nT + \frac{\pi}{2\omega_0}\right) - \phi\left(nT + \frac{\pi}{2\omega_0}\right)\right)\end{aligned} \tag{5}$$

[0087] We assume that the modulating signal $A(t)e^{j\Phi(t)}$ varies slowly with time and approximate,

$$A\left(nT + \frac{\pi}{2\omega_0}\right) \approx A(nT) \tag{6}$$

and

$$\phi\left(nT + \frac{\pi}{2\omega_0}\right) \approx \phi(nT) \tag{7}$$

[0088] Equation 5 can now be rewritten as follows.

$$\begin{aligned}\hat{Q}(nT) &\approx A(nT)\cos\left(\omega_0\left(nT + \frac{\pi}{2\omega_0}\right) - \phi(nT)\right), n = 0,1,2,3\ldots \\ &\approx -A(nT)\sin(\omega_0 nT - \phi(nT)) \\ &\approx Q(nT)\end{aligned} \tag{8}$$

[0089] We therefore approximate the imaginary component of S (t), or Q(t) in equation 4, by estimating it to be the output of quadrature sample-and-hold **130**.

[0090] Geometric time delays may be calculated and converted to phase delays at the assumed center frequency. Complex weights that implement apodization and focus with the calculated phase delays may be applied to the I/Q data. In one embodiment, signal receiver **118** may include an apodizer **146** for applying a difference **148** between outgoing amplitude **106** and magnitude **140** and applying a first illumination **150-1** to an image points **154** in substantial proportion to difference **148**. In one embodiment, signal receiver **118** may include a phase rotator **152** for applying a second illumination **150-2** to image point **154** in substantial proportion to phase **144**.

[0091] In a second embodiment of the invention, shown in FIG. **4**, apparatus **100** may include a second transducer **110-2** for converting outgoing signal **104** to second outgoing ultrasound **112-2**. Some of second outgoing ultrasound **112-2** may return to second transducer **110-2** if it is reflected by object **170** as well. Second transducer **110-2** may convert at least a portion of outgoing ultrasound **112** and second outgoing ultrasound **112-2** to a second incoming signal **114-2** having a second period **116-2**, as shown in FIG. **6**C.

[0092] In one embodiment, signal receiver **118** may include a second in-phase sample-and-hold **120-2** connected receivably to second transducer **110-2** for sampling second incoming signal **114-2** at incoming time **122** and outputting a second in-phase amplitude **124-2** of second incoming signal **114-2** at substantially incoming time **122**. In one embodiment, signal receiver **118** may include a second in-phase analog-to-digital converter **126-2** connected receivably to second in-phase sample-and-hold **120-2** for assigning a second in-phase digital value **128-2** to second in-phase amplitude **124-2** and outputting second in-phase digital value **128-2**.

[0093] In one embodiment, signal receiver **118** may include a second quadrature sample-and-hold **130-2** connected receivably to second transducer **110-2** for sampling second incoming signal **114-2** at substantially one-quarter of second period **116-2** after incoming time **122**, second quadrature sample-and-hold **130-2** outputting a second quadrature amplitude **132-2** of second incoming signal **114-2** at substantially one-quarter of second period **116-2** after incoming time **122**. In one embodiment, signal receiver **118** may include a second quadrature analog-to-digital converter **134-2** connected receivably to second quadrature sample-and-hold **130-2** for assigning a second quadrature digital value **136-2** to second quadrature amplitude **132-2** and outputting second quadrature digital value **136-2**.—[0085] In one embodiment, signal receiver **118** may include a second magnitude calculator **138-2** connected receivably to second in-phase analog-to-digital converter **126-2** and second quadrature analog-to-digital converter **134-2** for receiving incoming time **122**, second in-phase digital value **128-2**, and second quadrature digital value **136-2** and outputting a second magnitude **140-2**. In one embodiment, signal receiver **118** may include a second phase calculator **142-2** connected receivably to second in-phase analog-to-digital converter **126-2** and second quadrature analog-to-digital converter **134-2** for receiving incoming time **122**, second in-phase digital value **128-2**, and second quadrature digital value **136-2** and outputting a second phase **144-2**.

[0094] In one embodiment, signal receiver **118** may include a second apodizer **146-2** for applying a second difference **148-2** between outgoing amplitude **106** and second magnitude **140-2** and applying a third illumination **150-3** to an image point **154** in substantial proportion to second difference **148-2**. In one embodiment, signal receiver **118** may include a second phase rotator **152-2** for applying a fourth illumination **150-4** to image point **154** in substantial proportion to second phase **144-2**. In one embodiment, signal receiver **118** may include a summer **156** for combining difference **148**, second difference **148-2**, phase **144**, and second phase **144-2** before first, second, third, and fourth illuminations **150-1-150-4** are applied to image point **154**.

[0095] In a third embodiment, a method of beam-forming for ultrasound imaging may include the steps of generating an outgoing signal **104** having an outgoing amplitude **106** at an outgoing time **108**, transducing outgoing signal **104** to outgoing ultrasound **112**, receiving at least a portion of reflected outgoing ultrasound **112**, transducing reflected ultrasound to an incoming signal **114** having a period **116**, sampling incoming signal **114** at an incoming time **122** to produce an in-phase amplitude **124** of incoming signal **114**, assigning an in-phase digital value **128** to in-phase amplitude **124** sampling incoming signal **114** at substantially one-quarter of period **116** after incoming time **122** to produce a quadrature amplitude **132** of incoming signal **114**, assigning a quadrature digital value **136** to quadrature amplitude **132**, calculating a magnitude **140** at incoming time **122** based on in-phase digital value **128** and quadrature digital value **136**, calculating a phase **144** at incoming time **122** based on in-phase digital value **128** and quadrature digital value **136**, measuring a difference **148** between outgoing amplitude **106** and magnitude **140**, applying a first illumination **150-1** to an image point **154** in substantial proportion to difference **148**, and applying a second illumination **150-2** to image point **154** in substantial proportion to phase **144**.

[0096] In one embodiment, the method of beam-forming for ultrasound imaging may further include the steps of transducing outgoing signal **104** to second outgoing ultrasound **112-2**, receiving at least a portion of reflected outgoing ultrasound **112** and second outgoing ultrasound **112-2**, transducing reflected outgoing ultrasound **112** and second outgoing ultrasound **112-2** to a second incoming signal **114-2** having a second period **116-2**, sampling second incoming signal **114-2** at incoming time **122** to produce a second in-phase amplitude **124-2** of second incoming signal **114-2**, assigning a second in-phase digital value **128-2** to second in-phase amplitude **124-2**, sampling second incoming signal **114-2** at substantially one-quarter of second period **116-2** after incoming time **122** to produce a second quadrature amplitude **122-2** of second incoming signal **114-2**, assigning a second quadrature digital value **136-2** to second quadrature amplitude **122-2**, calculating a second magnitude **140-2** at incoming time **122** based on second in-phase digital value **128-2** and second quadrature digital value **136-2**, calculating a second phase **144-2** at incoming time **122** based on second in-phase digital value **128-2** and second quadrature digital value **136-2**, measuring a second difference **148-2** between outgoing amplitude **106** and second magnitude **140-2**, summing difference **148**, second difference **148-2**, phase **144**, and second phase **144-2**, applying a third illumination **150-3** to image point **154** in substantial proportion to second difference **148-2**, and applying a fourth illumination **150-4** to image point **154** in substantial proportion to second phase **144-2**.

[0097] In one embodiment, the method of beam-forming may be repeated to produce a plurality of image points **154** forming an image **168**. In several embodiments, image **168** may be viewed, used to guide insertion of a needle, used to guide insertion of a catheter, used to guide insertion of an endoscope, used to estimate blood flow, or used to estimate tissue motion. In one embodiment, plurality of image points **154** may be focused. In one embodiment, focusing may be repeated on reflected outgoing ultrasound **112** at plurality of image points **154**.

[0098] In one embodiment, plurality of image points **154** may be along a line at a range of interest. In one embodiment, a line may be formed at a plurality of ranges to form a planar image. In one embodiment, the planar image may be a B-mode image. In one embodiment, plurality of image points **154** may lie within a plane at a range of interest. In one embodiment, plurality of image points **154** may form a C-scan. In one embodiment, the plane may be formed at multiple ranges. In one embodiment, several planes may form a complex 1-D image.

[0099] In one embodiment, an envelope of magnitude **140** may be displayed. In one embodiment, phase **144** may be used to compensate for a path difference **148** between various transducers and object **170**. In one embodiment, a main lobe resolution and a side lobe level may be balanced based on magnitude **140**. In one embodiment, a sum squared error between a desired system response and a true system response may be minimized.

[0100] One skilled in the art would appreciate that a variety of tissue information may be obtained through judicious pulse transmission and signal processing of received echoes with the current invention. Such information could be displayed in conjunction with or instead of the aforementioned echo information.

[0101] One such type of information is referred to as color flow Doppler as described in U.S. Pat. No. 4,573,477 to Namekawa et al., entitled "Ultrasonic Diagnostic Apparatus," hereby incorporated by reference herein in its entirety. Another useful type of information is harmonic image data as described in U.S. Pat. No. 6,251,074 to Averkiou et al., entitled "Ultrasonic Tissue Harmonic Imaging" and U.S. Pat. No. 5,632,277 to Chapman et al., entitled "Ultrasound Imaging System Employing Phase Inversion Subtraction to Enhance the Image," both of which are hereby incorporated by reference herein in their entirety. Yet another type of information that may be obtained and displayed is known as Power Doppler as described in U.S. Pat. No. 5,471,990 to Thirsk, entitled "Ultrasonic Doppler Power Measurement and Display System," hereby incorporated by reference herein in its entirety.

[0102] Angular scatter information might also be acquired using a method described in a co-pending U.S. patent application Ser. No. 10/030,958, entitled "Angular Scatter Imaging System Using Translating Apertures Algorithm and Method Thereof," filed Jun. 3, 2002, of which is hereby incorporated by reference herein in its entirety. Speckle is a common feature of ultrasound images. While it is fundamental to the imaging process, many users find its appearance confusing and it has been shown to limit target detectability. A variety of so called compounding techniques have been described which could be valuable for reducing the appearance of speckle in ultrasound transducer drive images. These techniques include spatial compounding and frequency compounding, both of which are well described in the literature.

[0103] One skilled in the art would appreciate that the common practice of frequency compounding could be readily applied to the current invention. By transmitting a plurality of pulses at different frequencies and forming separate detected images using the pulses one may obtain multiple unique speckle patterns from the same target. These patterns may then be averaged to reduce the overall appearance of speckle.

[0104] The well known techniques of spatial compounding may also be applied to the current invention. The most conventional form of spatial compounding, which we call two-way or transmit-receive spatial compounding, entails the acquisition of multiple images with the active transmit and receive apertures shifted spatially between image acquisitions. This shifting operation causes the speckle patterns obtained to differ from one image to the next, enabling image averaging to reduce the speckle pattern.

[0105] In another technique, which we term one-way or receive-only spatial compounding, the transmit aperture is held constant between image acquisitions while the receive aperture is shifted between image acquisitions. As with two-way spatial compounding, this technique reduces the appearance of speckle in the final image.

[0106] In many ultrasound applications the received echoes from tissue have very small amplitude, resulting in an image with poor signal to noise ratio. This problem may be addressed through the use of a technique known as coded excitation. In this method the transmitted pulse is long in time and designed so that it has a very short auto-correlation length. In this manner the pulse is transmitted and received signals are correlated with the transmitted pulse to yield a resultant signal with good signal to noise ratio, but high axial resolution (short correlation length). This method could be readily applied in the present invention ultrasound transducer drive device and method to improve the effective signal to noise ratio. The coded excitation technique is described in U.S. Pat. No. 5,014,712 to O'Donnell, entitled "Coded Excitation for Transmission Dynamic Focusing of Vibratory Energy Beam," hereby incorporated by reference herein in its entirety.

[0107] An aspect in fabricating a system like the present invention ultrasound imaging beam-forming apparatus is in construction of the transducer array. Both cost and complexity could be reduced by incorporating a transducer implemented using photolithographic techniques, i.e. the transducer is formed using micro electro mechanical systems (MEMS). One particularly attractive approach has been described in U.S. Pat. No. 6,262,946 to Khuri-Yakub et al., entitled "Capacitive Micromachined Ultrasonic Transducer Arrays with Reduced Cross-Coupling," hereby incorporated by reference herein in its entirety.

[0108] While the present invention may be embodied in many different forms, a number of illustrative embodiments are described herein with the understanding that the present disclosure is to be considered as providing examples of the principles of the invention and such examples are not intended to limit the invention to preferred embodiments described herein and/or illustrated herein.

Broad Scope of the Invention:

[0109] While illustrative embodiments of the invention have been described herein, the present invention is not limited to the various preferred embodiments described herein, but includes any and all embodiments having equivalent elements, modifications, omissions, combinations (e.g., of aspects across various embodiments), adaptations and/or alterations as would be appreciated by those in the art based on the present disclosure. The limitations in the claims are to be interpreted broadly based on the language employed in the claims and not limited to examples described in the present specification or during the prosecution of the application, which examples are to be construed as non-exclusive. For example, in the present disclosure, the term "preferably" is non-exclusive and means "preferably, but not limited to." In this disclosure and during the prosecution of this application, means-plus-function or step-plus-function limitations will only be employed where for a specific claim limitation all of the following conditions are present in that limitation: a) "means for" or "step for" is expressly recited; b) a corresponding function is expressly recited; and c) structure, material or acts that support that structure are not recited. In this disclosure and during the prosecution of this application, the terminology "present invention" or "invention" may be used as a reference to one or more aspect within the present disclosure. The language present invention or invention should not be improperly interpreted as an identification of criticality, should not be improperly interpreted as applying across all aspects or embodiments (i.e., it should be understood that the present invention has a number of aspects and embodiments), and should not be improperly interpreted as limiting the scope of the application or claims. In this disclosure and during the prosecution of this application, the terminology "embodiment" can be used to describe any aspect, feature, process or step, any combination thereof, and/or any portion thereof, etc. In some examples, various embodiments may include overlapping features. In this disclosure, the following abbreviated terminology may be employed: "e.g." which means "for example;" and "NB" which means "note well."

What is claimed is:

1. An ultrasound imaging beam-former apparatus, comprising:

a signal generator for producing an outgoing signal;

a transducer for converting said outgoing signal to outgoing ultrasound and for converting at least a portion of said outgoing ultrasound that is reflected to an incoming signal, said incoming signal having a period; and

a signal receiver for processing said incoming signal, said signal receiver comprising:

an in-phase sample-and-hold connected receivably to said transducer for sampling said incoming signal at an incoming time and outputting an in-phase amplitude of said incoming signal at substantially said incoming time;

a quadrature sample-and-hold connected receivably to said transducer for sampling said incoming signal at substantially one-quarter of said period after said incoming time, said quadrature sample-and-hold outputting a quadrature amplitude of said incoming signal at substantially one-quarter of said period after said incoming time;

a phase calculator connected receivably to said in-phase sample-and-hold and said quadrature sample-and-hold for receiving said incoming time, said in-phase amplitude, and said quadrature amplitude and outputting a phase; and

a phase rotator for applying an illumination to said image point in substantial proportion to said phase.

2. The ultrasound imaging beam-former apparatus of claim 1, comprising further:

an in-phase analog-to-digital converter connected receivably to said in-phase sample-and-hold for assigning an in-phase digital value to said in-phase amplitude and outputting said in-phase digital value.

3. The ultrasound imaging beam-former apparatus of claim 1, comprising further:

a quadrature analog-to-digital converter connected receivably to said quadrature sample-and-hold for assigning a quadrature digital value to said quadrature amplitude and outputting said quadrature digital value.

4. The ultrasound imaging beam-former apparatus of claim 1, wherein signal has an outgoing amplitude;

a magnitude calculator connected receivably to said in-phase analog-to-digital converter and said quadrature analog-to-digital converter for receiving said incoming time, said in-phase digital value, and said quadrature digital value and outputting a magnitude; and

an apodizer for applying a difference between an outgoing amplitude of said outgoing signal at an outgoing time and said magnitude and applying a second illumination to a image point in substantial proportion to said difference.

5. The ultrasound imaging beam-former apparatus of claim 1, comprising further:

a second transducer for converting said outgoing signal to second outgoing ultrasound and for converting at least a portion of said outgoing ultrasound and said second outgoing ultrasound that is reflected to a second incoming signal, said second incoming signal having a second period; and

a second signal receiver for processing said second incoming signal, said second signal receiver comprising:

a second in-phase sample-and-hold connected receivably to said second transducer for sampling said second incoming signal at a second incoming time and outputting a second in-phase amplitude of said second incoming signal at substantially said second incoming time;

a second quadrature sample-and-hold connected receivably to said second transducer for sampling said second incoming signal at substantially one-quarter of said second period after said second incoming time,

said second quadrature sample-and-hold outputting a second quadrature amplitude of said second incoming signal at substantially one-quarter of said second period after said second incoming time;

a second phase calculator connected receivably to said second in-phase sample-and-hold and said second quadrature sample-and-hold for receiving said second incoming time, said second in-phase amplitude, and said second quadrature amplitude and outputting a second phase; and

a second phase rotator for applying a second illumination to said second image point in substantial proportion to said second phase; and

a summer for combining said difference, said second difference, said phase, and said second phase before said illumination and said second illumination are applied to said image point.

6. The ultrasound imaging beam-former apparatus of claim 1, wherein said signal generator comprises further a generator amplifier for amplifying said outgoing signal.

7. The ultrasound imaging beam-former apparatus of claim 1, wherein said signal receiver comprises further a receiver amplifier for amplifying said incoming signal.

8. The ultrasound imaging beam-former apparatus of claim 1, wherein said signal receiver comprises further a receiver pre-amplifier for amplifying said incoming signal.

9. The ultrasound imaging beam-former apparatus of claim 1, wherein said signal receiver comprises further a band-pass filter for filtering said incoming signal.

10. The ultrasonic imaging beam-former apparatus of claim 1, wherein said signal receiver comprises a digital signal processor.

11. The ultrasonic imaging beam-former apparatus of claim 1, wherein said outgoing signal is selected from the group consisting of:

an electro-magnetic signal,

an electrical signal, and

an optical signal.

12. The ultrasonic imaging beam-former apparatus of claim 1, wherein said incoming signal is selected from the group consisting of:

an electro-magnetic signal,

an electrical signal, and

an optical signal.

13. The ultrasonic imaging beam-former apparatus of claim 1, wherein said transducer is selected from the group consisting of:

a piezoelectric element,

a voice coil,

a MEMS device,

a capacitive micro-machined transducer,

a crystal oscillator, and

a Hall effect transducer.

14. The ultrasonic imaging beam-former apparatus of claim 1, wherein said signal receiver is implemented as an integrated circuit.

15. The ultrasonic imaging beam-former apparatus of claim 1, wherein the transducer comprises further a plurality of transducers.

16. The ultrasonic imaging beam-former apparatus of claim 12, wherein said plurality of transducers forms an array selected from the group consisting of:

a linear array,

a phased array a curvilinear array,

an unequally sampled 2-D array,

a 1.5-D array,

a catheter based array,

an intra-cavity array,

an equally sampled 2D,

a sparse 2D array, and

fully sampled 2D array.

17. The ultrasonic imaging beam-former apparatus of claim 1, comprising further a protection circuit to allow both transmit and receive operations.

18. A method of beam-forming for ultrasound imaging, comprising:

generating an outgoing signal;

transducing said outgoing signal to outgoing ultrasound;

receiving at least a portion of reflected outgoing ultrasound;

transducing said reflected ultrasound to an incoming signal having a period;

sampling said incoming signal at an incoming time to produce an in-phase amplitude of said incoming signal;

sampling said incoming signal at substantially one-quarter of said period after said incoming time to produce a quadrature amplitude of said incoming signal;

calculating a phase at said incoming time based on said in-phase amplitude and said quadrature amplitude; and

applying a illumination to an image point in substantial proportion to said phase.

19. The method of beam-forming for ultrasound imaging of claim 18, comprising further:

assigning an in-phase digital value to said in-phase amplitude.

20. The method of beam-forming for ultrasound imaging of claim 18, comprising further:

assigning a quadrature digital value to said quadrature amplitude.

21. The method of beam-forming for ultrasound imaging of claim 18, comprising further:

calculating a magnitude at said incoming time, based on said in-phase amplitude and said quadrature amplitude;

measuring a difference between an outgoing amplitude of said outgoing signal and said magnitude; and

applying a second illumination to said image point in substantial proportion to said difference.

22. The method of beam-forming for ultrasound imaging of claim 18, comprising further:

transducing said outgoing signal to second outgoing ultrasound;

receiving at least a portion of reflected outgoing ultrasound and second outgoing ultrasound;

transducing said reflected outgoing ultrasound and second outgoing ultrasound to a second incoming signal having a second period;

sampling said second incoming signal at said incoming time to produce a second in-phase amplitude of said second incoming signal;

sampling said second incoming signal at substantially one-quarter of said second period after said incoming time to produce a second quadrature amplitude of said second incoming signal;

calculating a second phase at said incoming time based on said second in-phase amplitude and said second quadrature amplitude;

summing said phase and said second phase; and

applying a second illumination to said image point in substantial proportion to said second phase.

23. The method of beam-forming for ultrasound imaging of claim 18, comprising further amplifying said outgoing signal.

24. The method of beam-forming for ultrasound imaging of claim 18, comprising further an operation selected from the group consisting of:

amplifying said incoming signal,

pre-amplifying said incoming signal, and

storing said incoming signal.

25. The method of beam-forming for ultrasound imaging of claim 18, comprising further repeating the method of beam-forming to produce a plurality of image points forming an image.

26. The method of beam-forming for ultrasound imaging of claim 25, comprising further an operation selected from the group consisting of:

viewing said image,

guiding insertion of a needle based on said image,

guiding insertion of a catheter based on said image,

guiding insertion of an endoscope based on said image,

estimating blood flow based on said image, and

estimating tissue motion based on said image.

27. The method of beam-forming for ultrasound imaging of claim 25, further comprising focusing said plurality of image points.

28. The method of beam-forming for ultrasound imaging of claim 25, wherein said focusing is repeated on said reflected outgoing ultrasound at said plurality of image points.

29. The method of beam-forming for ultrasound imaging of claim 25, wherein the plurality of image points are along a line at a range of interest.

30. The method of beam-forming for ultrasound imaging of claim 29, wherein the line is formed at a plurality of ranges to form a planar image.

31. The method of beam-forming for ultrasound imaging of claim 30, wherein the planar image is a B-mode image.

32. The method of beam-forming for ultrasound imaging of claim 25, wherein the plurality of image points lie within a plane at a range of interest.

33. The method of beam-forming for ultrasound imaging of claim 32, wherein the plurality of image points form a C-scan.

34. The method of beam-forming for ultrasound imaging of claim 32, wherein the plane is formed at multiple ranges.

35. The method of beam-forming for ultrasound imaging of claim 32, wherein the planes form a complex 3D image.

36. The method of beam-forming for ultrasound imaging of claim 18, wherein an envelope of the magnitude is displayed.

37. The method of beam-forming for ultrasound imaging of claim 18, further comprising compensating for a path difference based on the phase.

38. The method of beam-forming for ultrasound imaging of claim 18, wherein a main lobe resolution and a side lobe level is balanced based on the magnitude.

39. The method of beam-forming for ultrasound imaging of claim 18, wherein a sum squared error between a desired system response and a true system response is minimized.

40. A system for beam-forming for ultrasound imaging, comprising:

means for generating an outgoing signal having an outgoing amplitude at an outgoing time;

means for transducing said outgoing signal to outgoing ultrasound;

means for transducing at least a portion of reflected outgoing ultrasound to an incoming signal having a period;

means for sampling said incoming signal at an incoming time and outputting an in-phase amplitude of said incoming signal;

means for sampling said incoming signal at substantially one-quarter of said period after said incoming time and outputting a quadrature amplitude of said incoming signal;

means for calculating a phase at said incoming time, based on said in-phase amplitude and said quadrature amplitude and outputting said phase; and

means for applying a second illumination to said image point in substantial proportion to said phase;

means for calculating a magnitude at said incoming time, based on said in-phase amplitude and said quadrature amplitude and outputting said magnitude;

means for measuring a difference between an outgoing amplitude of said outgoing signal and said magnitude; and

means for applying a first illumination to a image point in substantial proportion to said difference.

41. The system for beam-forming for ultrasound imaging of claim 40, comprising further:

second means for transducing said outgoing signal to second outgoing ultrasound;

second means for transducing said reflected outgoing ultrasound and second outgoing ultrasound to a second incoming signal having a second period;

second means for sampling said second incoming signal at said incoming time and outputting a second in-phase amplitude of said second incoming signal;

second means for sampling said second incoming signal at substantially one-quarter of said second period after said incoming time and outputting a second quadrature amplitude of said second incoming signal;

second means for calculating a second phase at said incoming time based on said second in-phase amplitude and said second quadrature amplitude and outputting said second phase;

second means for summing said difference, said second difference, said phase, and said second phase; and

second means for applying a fourth illumination to said image point in substantial proportion to said second phase.

42. The system for beam-forming for ultrasound imaging of claim 40, comprising further means for amplifying said outgoing signal.

43. The system for beam-forming for ultrasound imaging of claim 40, comprising further means for amplifying said incoming signal.

44. The system for beam-forming for ultrasound imaging of claim 40, comprising further means for pre-amplifying said incoming signal.

45. The system for beam-forming for ultrasound imaging of claim 40, comprising further means for storing said incoming signal.

46. The system for beam-forming for ultrasound imaging of claim 40, comprising further means for viewing an image comprising said image point.

47. The system for beam-forming for ultrasound imaging of claim 40, comprising further means for guiding insertion of a needle, a catheter, or an endoscope based on an image comprising said image point.

48. An ultrasound beamformer apparatus, comprising:

a signal generator for producing an outgoing signal having an outgoing amplitude at an outgoing time;

a transducer for converting said outgoing signal to outgoing ultrasound;

a plurality of transducers for converting at least a portion of said outgoing ultrasound that is reflected to incoming signals, said incoming signals having oscillations in time;

a plurality of signal receivers for converting each of said incoming signals to a pair, or time series of pairs of in phase and quadrature samples; and

a focusing apparatus for combining said in phase and quadrature samples to yield a focused in phase/quadrature sample.

49. The ultrasound beamformer apparatus of claim 48, wherein:

complex demodulated echo data obtained from a single range from each transducer array element are sampled;

complex echo signals are multiplied by complex weightings; and

the results are summed to focus at a specific point at the range of interest.

50. The ultrasound beamformer apparatus of claim 48, wherein:

the complex demodulation is performed using an analog demodulation circuit on each element.

51. The ultrasound beamformer apparatus of claim 48, wherein:

the complex demodulation is performed by sampling the incoming signal at two points separated in time by approximately ¼ of a period.

52. The ultrasound beamformer apparatus of claim 48, wherein:

the complex demodulation is performed via digital means.

53. The ultrasound beamformer apparatus of claim 48, wherein:

the focusing operation is repeated on the same set of echo data at a plurality of points to form complex image data at that range.

54. The ultrasound beamformer apparatus of claim 53, wherein:

the plurality of image points are along a line at the range of interest.

55. The ultrasound beamformer apparatus of claim 53, wherein:

the plurality of image points lie within a plane at the range of interest and thereby form a complex c-scan.

56. The ultrasound beamformer apparatus of claim 53, wherein:

the process of forming image lines is repeated at numerous ranges to form a planar ultrasound image, possibly being a b-mode image.

57. The ultrasound beamformer apparatus of claim 53, wherein:

the process of forming image planes is repeated at multiple ranges to form a complex 3D image.

58. The ultrasound beamformer apparatus of claim 48, wherein:

the envelope of the magnitude of the complex image is taken for display to the user.

59. The ultrasound beamformer apparatus of claim 48, wherein:

the phases of the complex weightings used for focusing are determined so as to compensate for path length differences between different transducer array elements and the focal point.

60. The ultrasound beamformer apparatus of claim 48, wherein:

the magnitude of applied complex weightings are selected to maintain a reasonable balance between main-lobe resolution and side-lobe levels in the system response.

61. The ultrasound beamformer apparatus of claim 48, wherein:

the complex weightings used for focusing are determined so as to minimize the sum squared error between some desired system response and the true system response following the method described by Ranganathan and Walker in "A Novel Beamformer Design Method for Medical Ultrasound: Part I: Theory" a paper in press for IEEE Trans. Ultrason. Ferroelec. Freq. Contr.

62. The ultrasound beamformer apparatus of claim 48, wherein:

the transducer array employed for imaging consists of a plurality of array elements transducer elements placing in a linear configuration selected from the group consisting of:

a linear array,

a phased array, and

a curvilinear array.

63. The ultrasound beamformer apparatus of claim 48, wherein:

the transducer array employed for imaging consists of a plurality of elements arranged in an unequally sampled 2D configuration or a 1.5-D array.

64. The ultrasound beamformer apparatus of claim 48, wherein:

the transducer array employed for imaging consists of a plurality of elements that are placed in an equally sampled 2D configuration.

65. The ultrasound beamformer apparatus of claim 64, wherein a fraction of the elements of the array are utilized such that the resulting array is a sparse 2D array.

66. The ultrasound beamformer apparatus of claim 64, wherein:

all elements of the array are utilized such that the resulting array is a fully sampled 2D array.

67. The ultrasound beamformer apparatus of claim 48, wherein:

connections are made to individual array elements such that individual elements may be used for either transmission or reception, but not both, thereby eliminating the need for receive protection circuitry.

68. The ultrasound beamformer apparatus of claim 48, wherein:

only a fraction of elements are used to form any given image point.

69. The ultrasound beamformer apparatus of claim 48, wherein:

the focusing operation is repeated for different fractions of the aperture thereby obtaining multiple redundant views of the same target location.

70. The ultrasound beamformer apparatus of claim 48, wherein:

the multiple looks are averaged after taking their magnitudes so as to reduce the appearance of speckle in the resulting image.

71. The ultrasound beamformer apparatus of claim 48, wherein:

the complex image points are used over successive acquisitions to estimate blood flow or tissue motion.

72. The ultrasound beamformer apparatus of claim 48, wherein:

the sampling operation is performed at multiple ranges for a single transmit event, thereby increasing the image formation rate.

* * * * *

专利名称(译)	超声成像光束成形装置和方法		
公开(公告)号	US20070016022A1	公开(公告)日	2007-01-18
申请号	US11/160915	申请日	2005-07-14
[标]申请(专利权)人(译)	弗吉尼亚大学专利基金会		
申请(专利权)人(译)	VIRGINIA专利大学基金会		
当前申请(专利权)人(译)	VIRGINIA专利大学基金会		
[标]发明人	BLALOCK TRAVIS N WALKER WILLIAM F HOSSACK JOHN A		
发明人	BLALOCK, TRAVIS N. WALKER, WILLIAM F. HOSSACK, JOHN A.		
IPC分类号	A61B8/00 A61B A61B8/14 G01S15/89 G10K11/34		
CPC分类号	A61B8/00 G01S7/52028 G01S7/52034 G01S15/8915 G01S15/8959 G01S15/8995 G10K11/346 G01S7/5208 A61B8/4494 A61B8/145 A61B8/4483 A61B8/4488 A61B8/461 A61B8/5207 G01S7/52085		
优先权	PCT/US2004/000887 2004-01-14 WO		
其他公开文献	US20100312106A9		
外部链接	Espacenet USPTO		

摘要(译)

在一些说明性实施例中，来自超声成像波束形成器装置中的换能器的输入信号被应用于同相采样和保持以及正交采样和保持。正交采样保持可以在同相采样保持之后的四分之一周期内计时。采样保持器的输出应用于同相和正交模数转换器。幅度计算器接收同相和正交数字值，并输出幅度。相位计算器接收同相和正交数字值，并输出相位。变迹器应用输出信号的幅度与幅度之间的差值，并且将第一照度应用于与差值基本成比例的图像点，并且相位旋转器将第二照度应用于与相位基本成比例的图像点。