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(54) **TRANSMIT BEAMFORMING IN 3-DIMENSIONAL ULTRASOUND**

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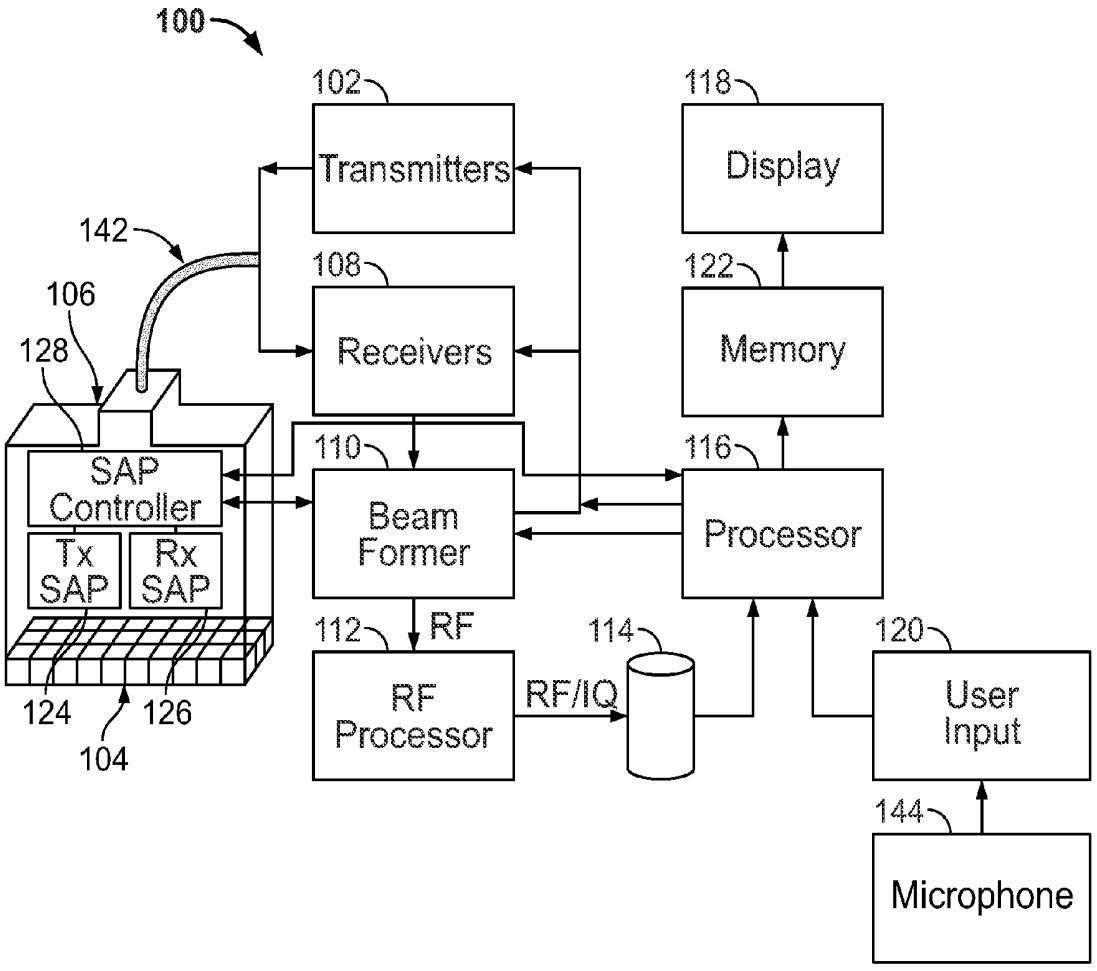
(57) **ABSTRACT**

An ultrasound system comprises a probe including a two-dimensional (2D) array of transducer elements that form an aperture having a plurality of receive elements that are configured to receive ultrasound signals. The transducer elements form at least one transmit sub-aperture that is configured to be interconnected with a fixed group of the transducer elements within the aperture. Transmitters generate electrical transmit signals, and at least one transmit sub-aperture processor (tx SAP) maps the transducer elements within the fixed group of the transducer elements to the transmitters in a transmit configuration based on a beam steering direction.



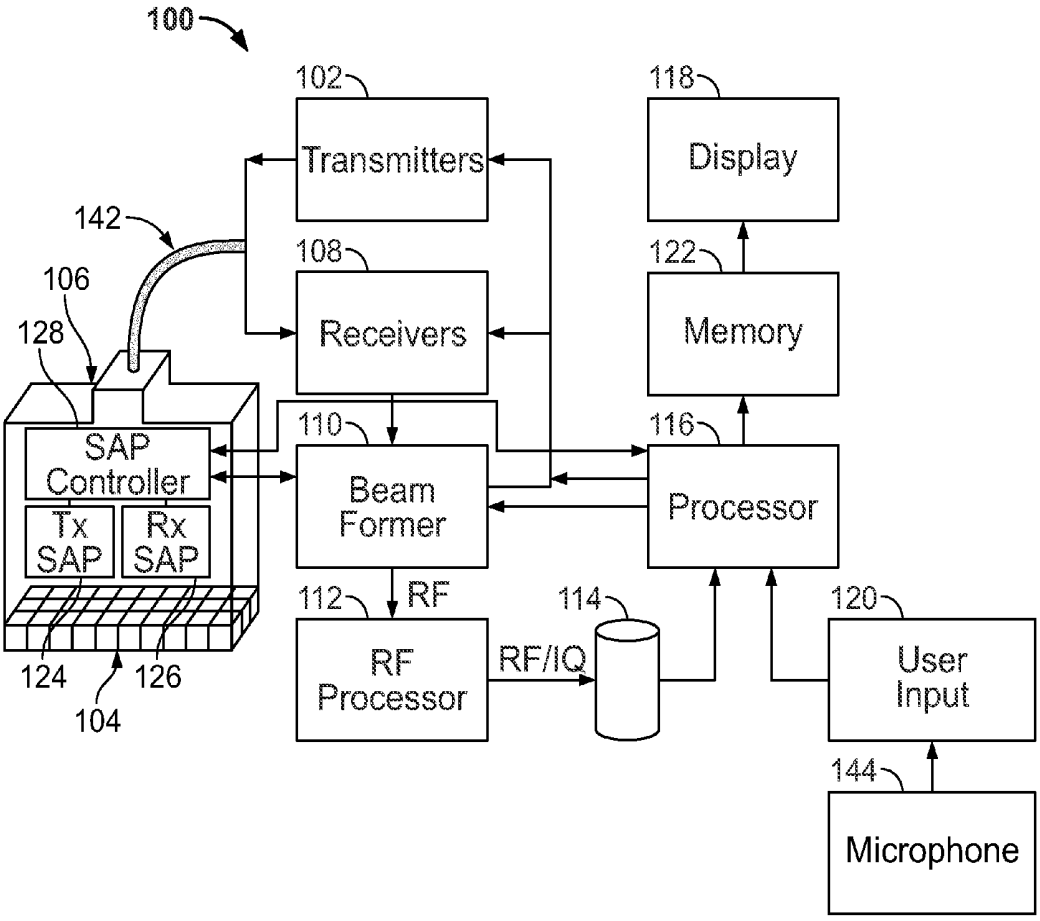

100
102
Transmitters
118
Display
142
108
Receivers
122
Memory
106
128
SAP
Controller
Tx
SAP
Rx
SAP
110
Beam
Former
116
Processor
112
RF
RF
Processor
RF/IQ
114
120
User
Input
144
Microphone
124
126
104

FIG. 1

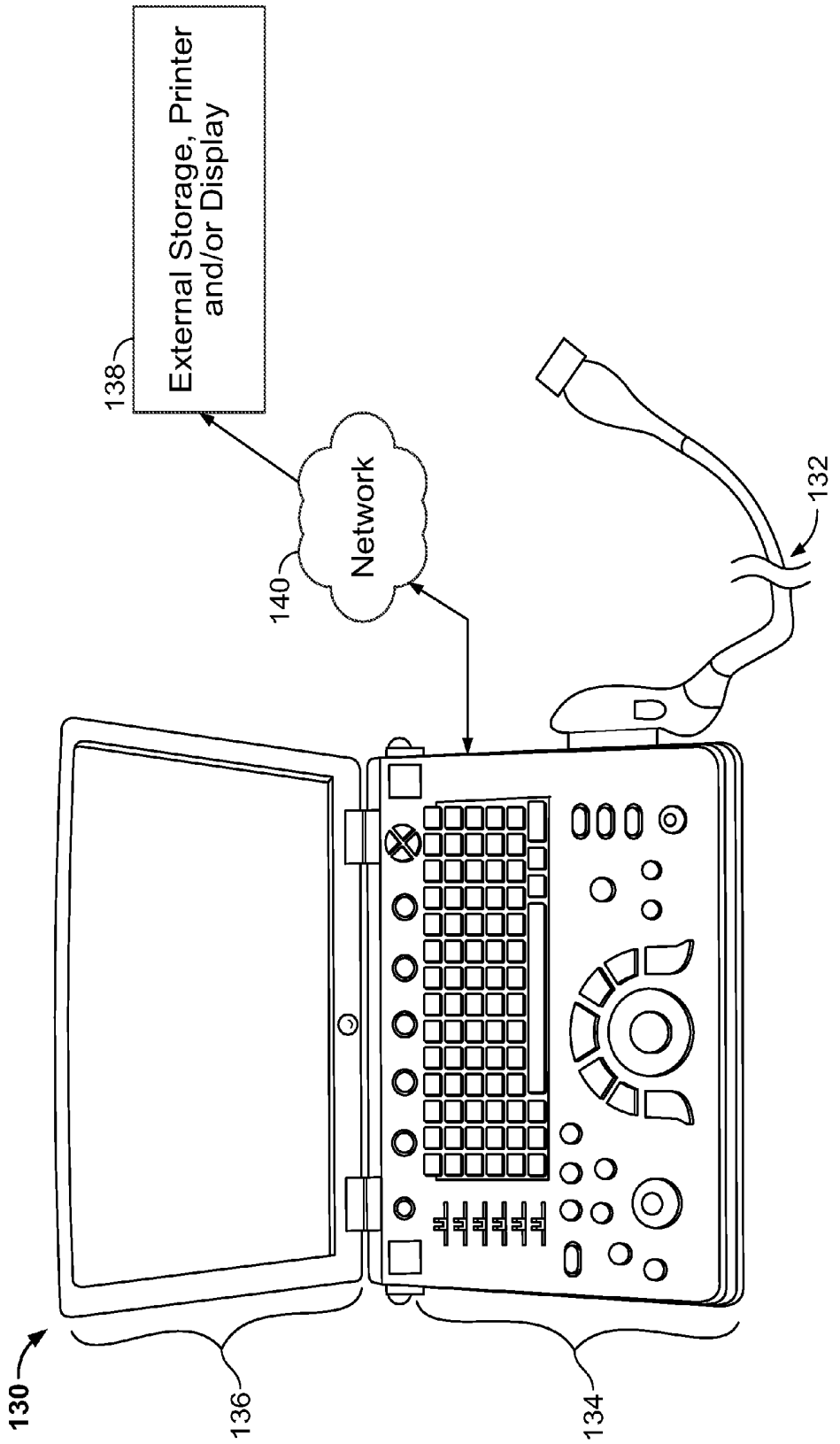

External Storage, Printer and/or Display
138
Network
140
132
130
136
134

FIG. 2

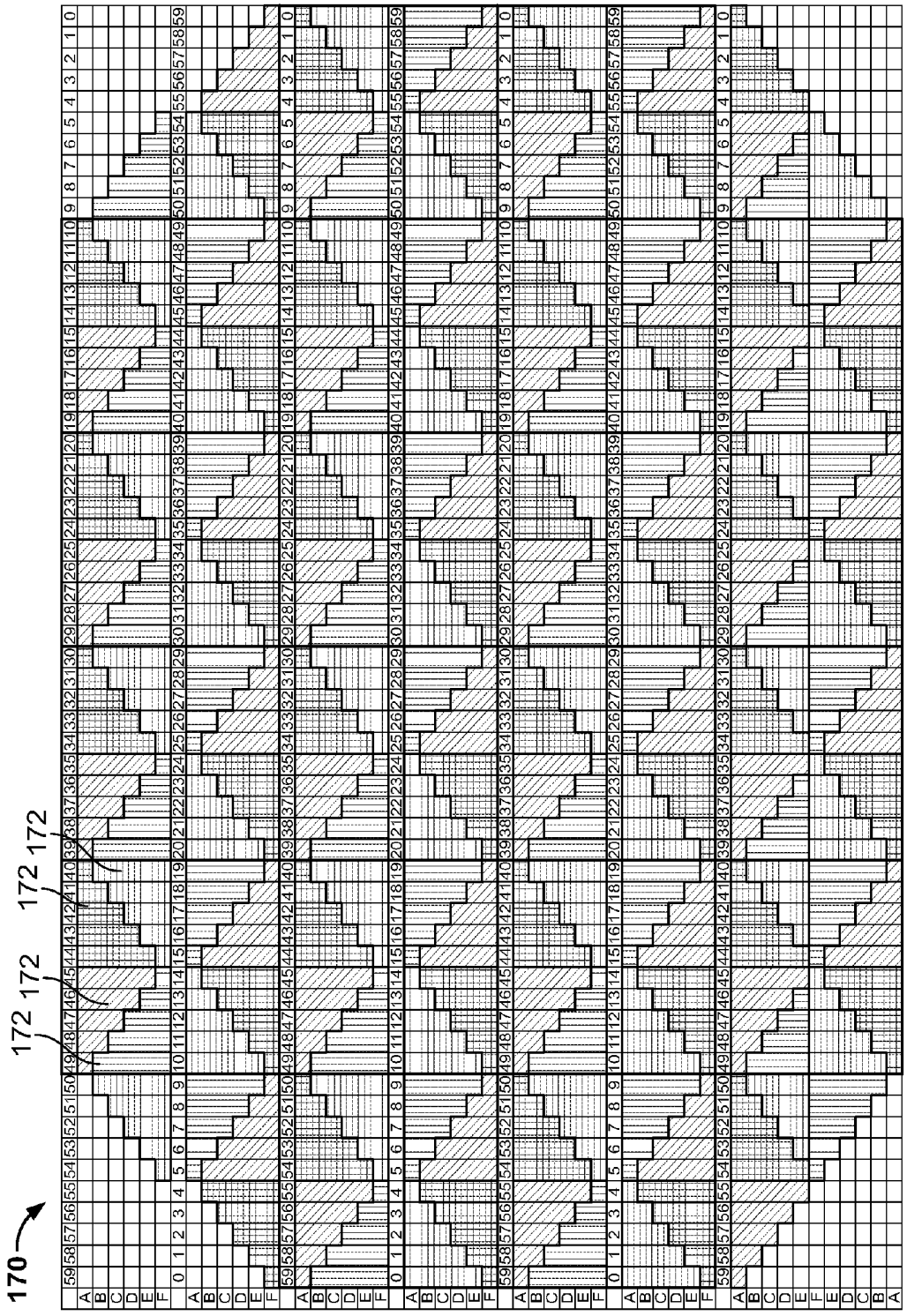


FIG. 3

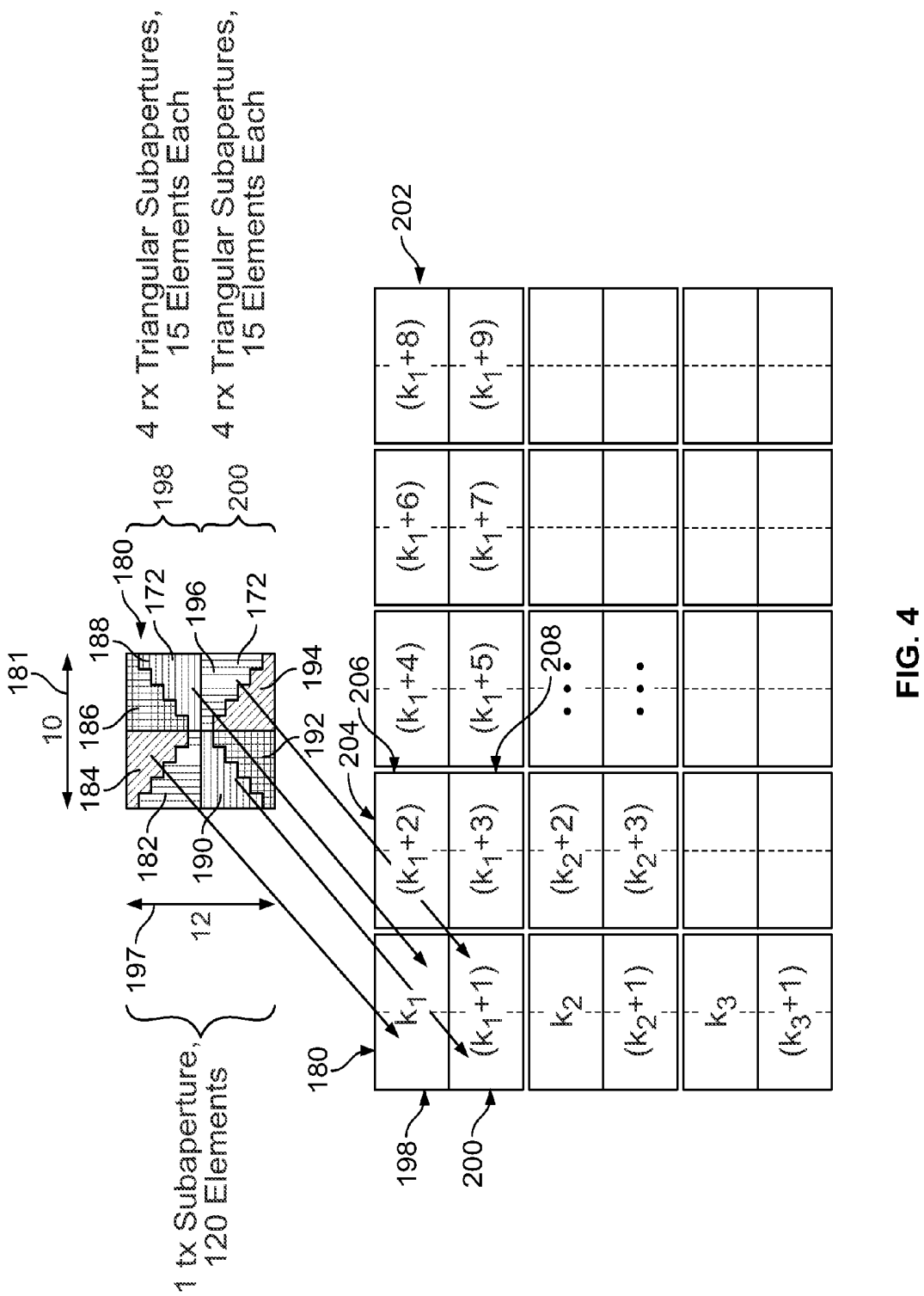

4 rx Triangular Subapertures, 15 Elements Each
4 rx Triangular Subapertures, 15 Elements Each
1 tx Subaperture, 120 Elements
181
10
184
186
188
180
172
196
172
194
192
182
190
197
12
198
200
202
204
206
208
180
198
200
k_1
(k_1+1)
(k_1+2)
(k_1+3)
(k_1+4)
(k_1+5)
(k_1+6)
(k_1+7)
(k_1+8)
(k_1+9)
k_2
(k_2+1)
(k_2+2)
(k_2+3)
k_3
(k_3+1)

FIG. 4

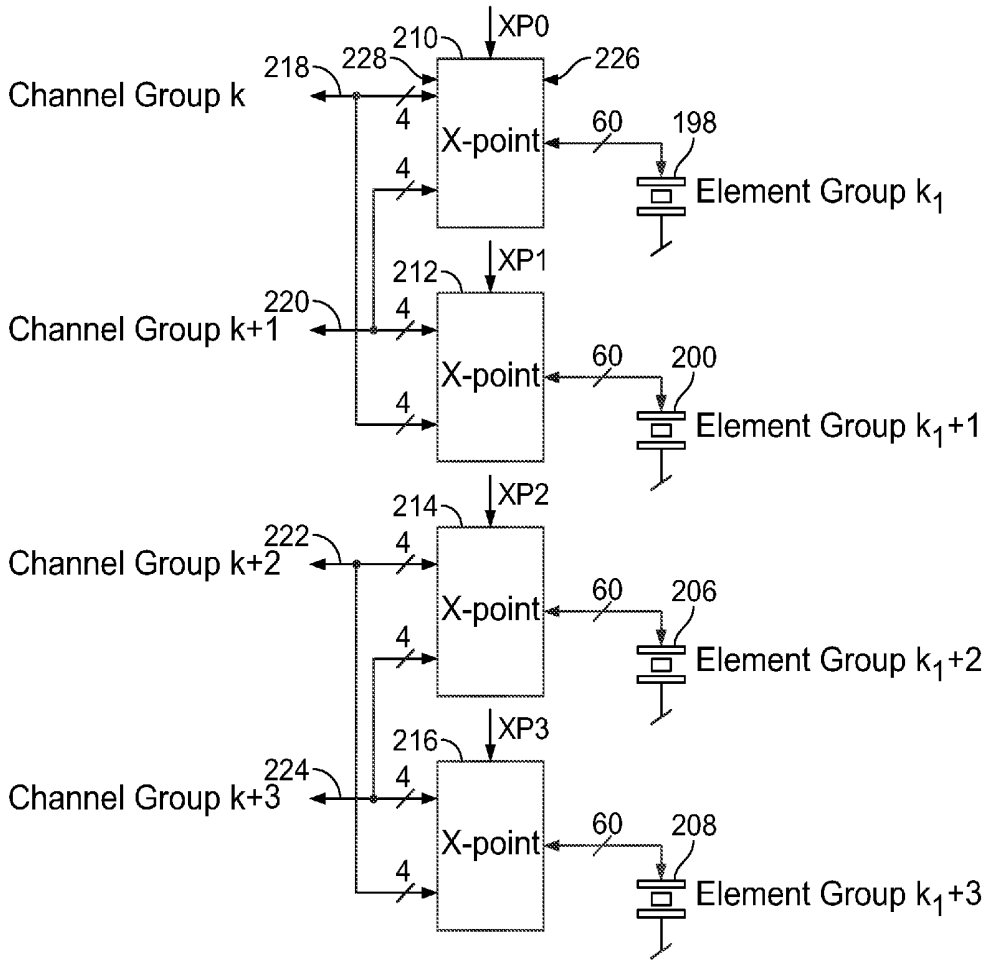

XP0
210
218
228
226
Channel Group k
4
X-point
60
198
4
Element Group k1
XP1
212
220
4
Channel Group k+1
X-point
60
200
4
Element Group k1+1
XP2
214
222
4
Channel Group k+2
X-point
60
206
4
Element Group k1+2
XP3
216
224
4
Channel Group k+3
X-point
60
208
4
Element Group k1+3

FIG. 5

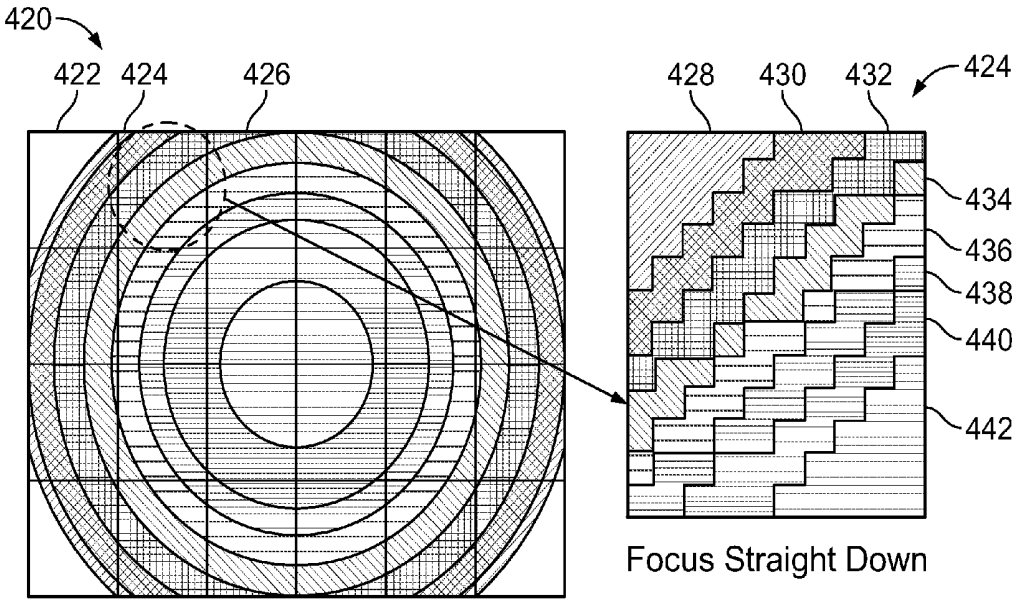

420
422
424
426
428
430
432
424
434
436
438
440
442
Focus Straight Down

FIG. 6

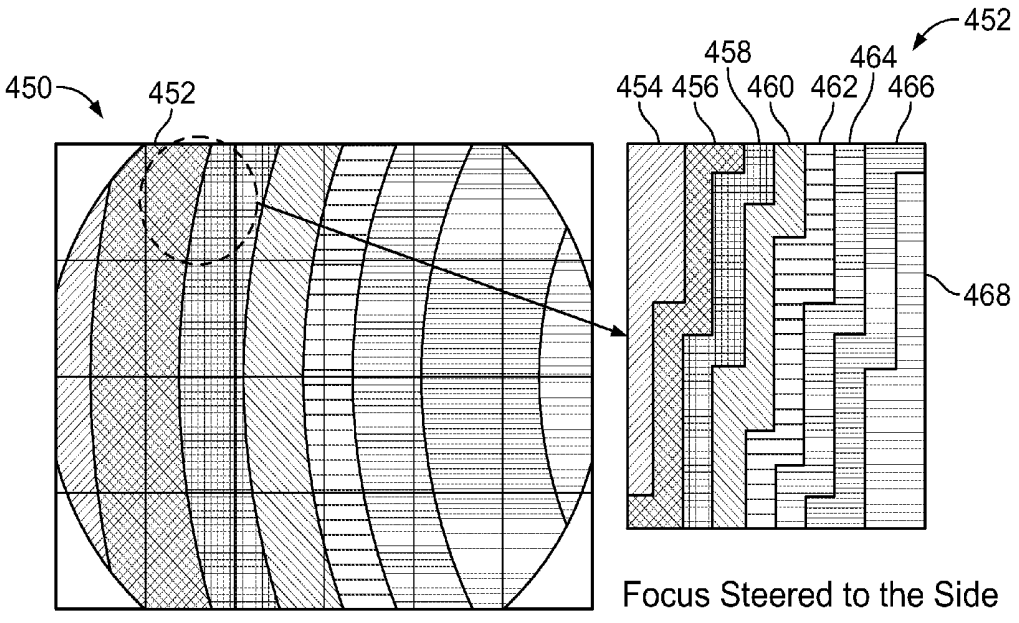

450
452
452
458
464
454
456
460
462
466
468
Focus Steered to the Side

FIG. 7

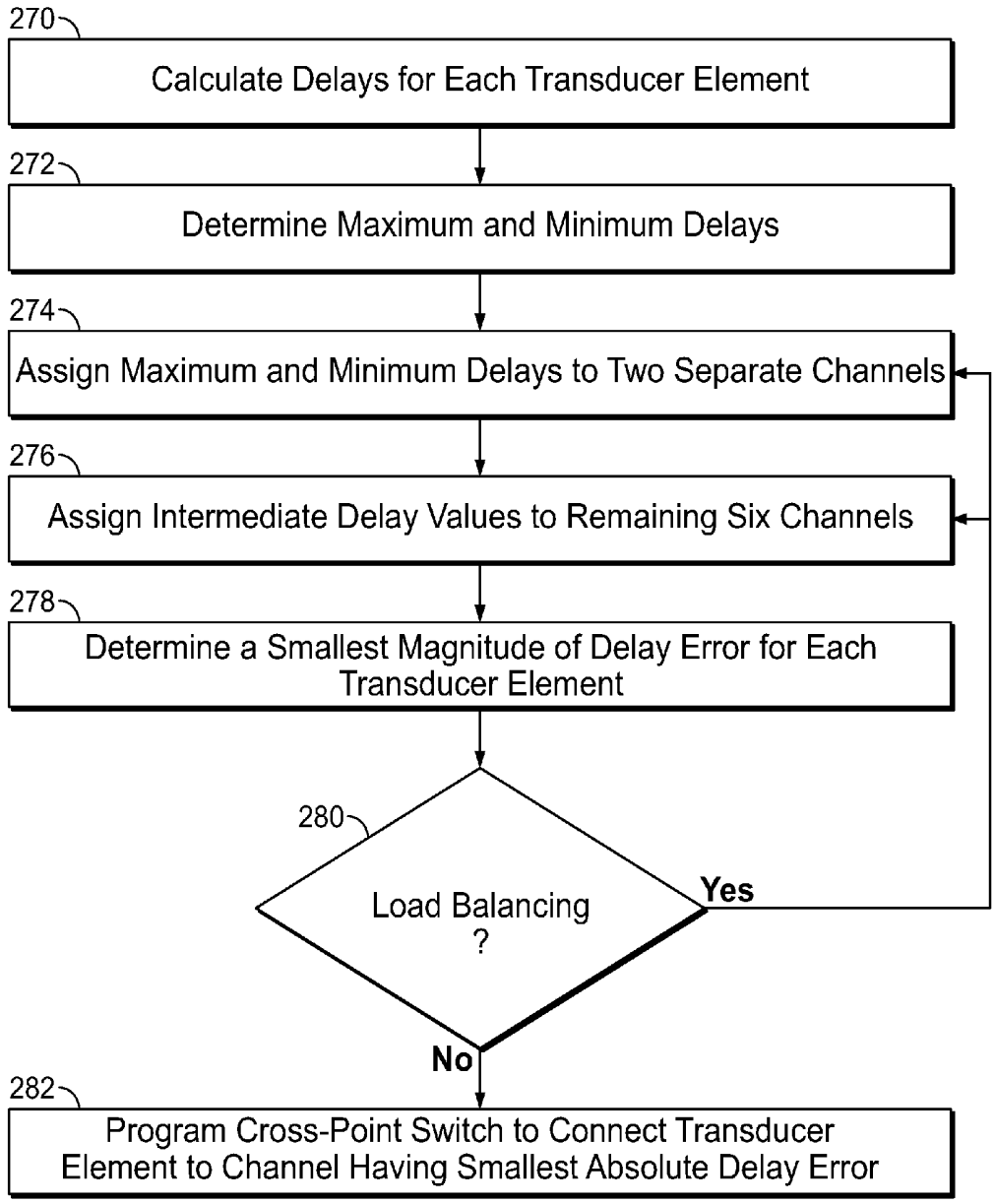

270
Calculate Delays for Each Transducer Element
272
Determine Maximum and Minimum Delays
274
Assign Maximum and Minimum Delays to Two Separate Channels
276
Assign Intermediate Delay Values to Remaining Six Channels
278
Determine a Smallest Magnitude of Delay Error for Each Transducer Element
280
Load Balancing ?
Yes
No
282
Program Cross-Point Switch to Connect Transducer Element to Channel Having Smallest Absolute Delay Error

FIG. 8

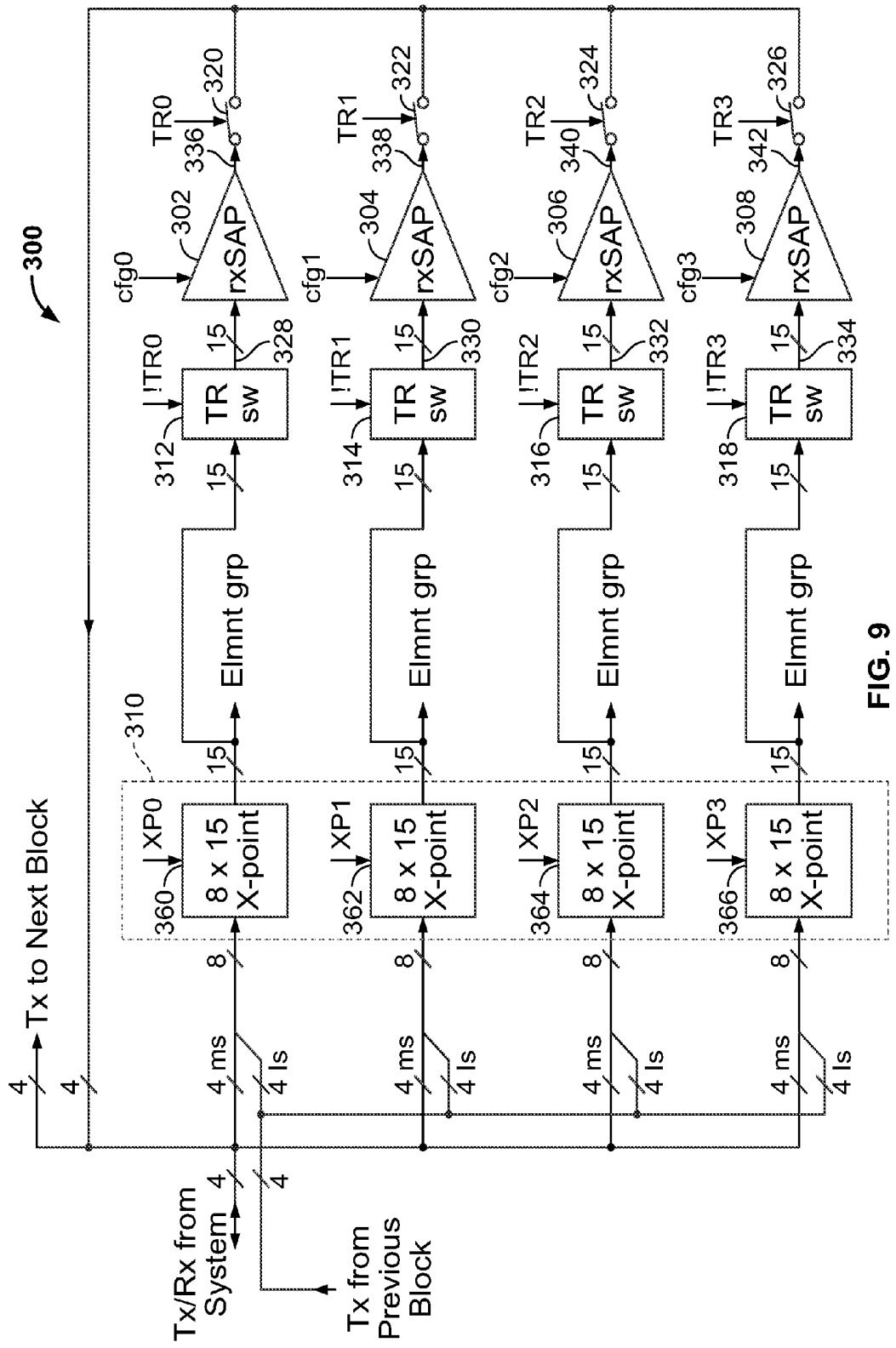

300
Tx to Next Block
Tx/Rx from System
Tx from Previous Block
4
4 ms
4 ls
8
15
310
XP0
XP1
XP2
XP3
8 x 15 X-point
360
362
364
366
Elmnt grp
!TR0
!TR1
!TR2
!TR3
TR sw
312
314
316
318
328
330
332
334
cfg0
cfg1
cfg2
cfg3
rxSAP
302
304
306
308
TR0
TR1
TR2
TR3
320
322
324
326
336
338
340
342

FIG. 9

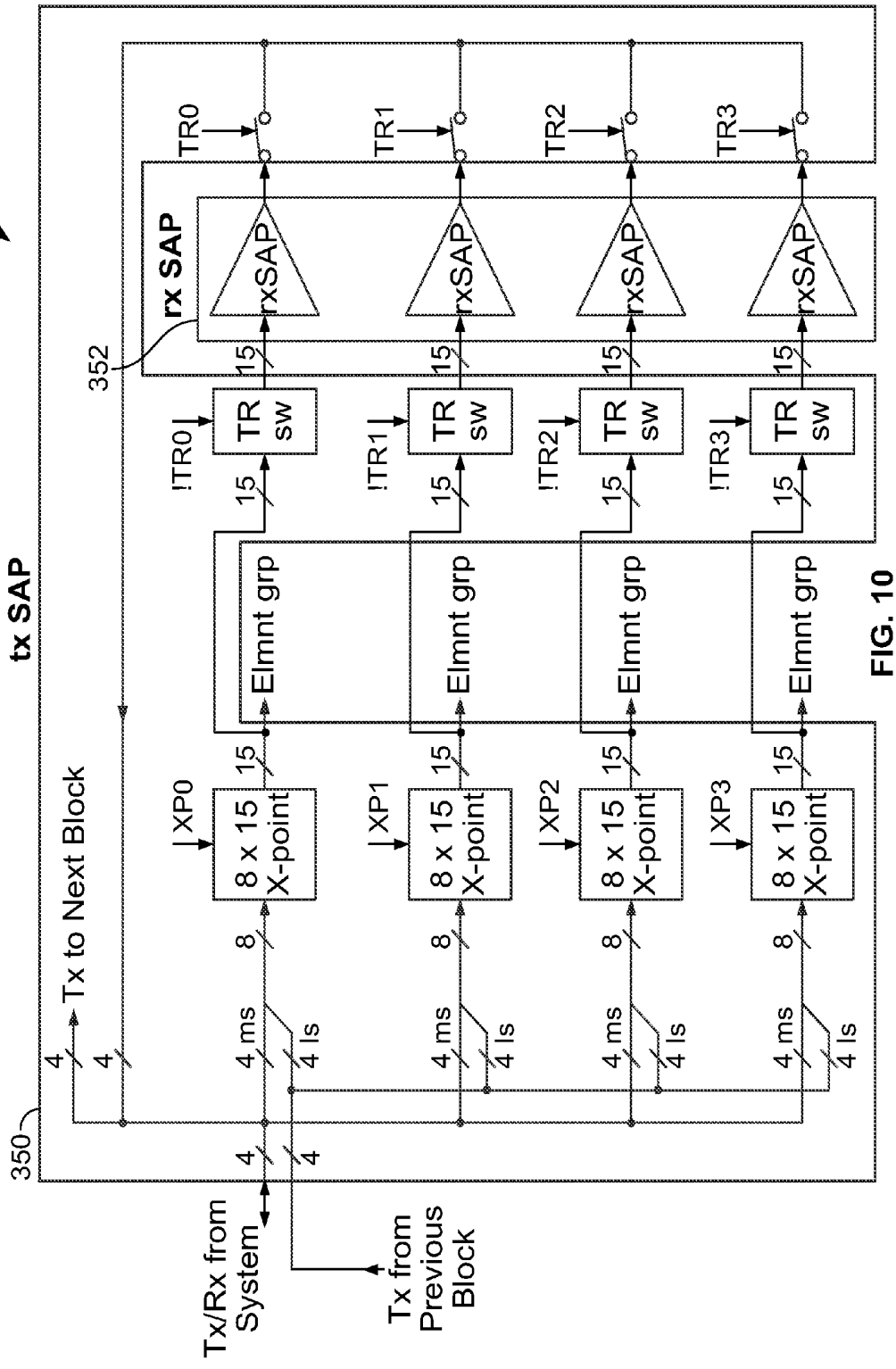

300
tx SAP
rx SAP
352
350
TR0
TR1
TR2
TR3
rxSAP
!TR0
!TR1
!TR2
!TR3
TR sw
Elmnt grp
XP0
XP1
XP2
XP3
8 x 15 X-point
Tx to Next Block
4 ms
4 ls
Tx/Rx from System
Tx from Previous Block

FIG. 10

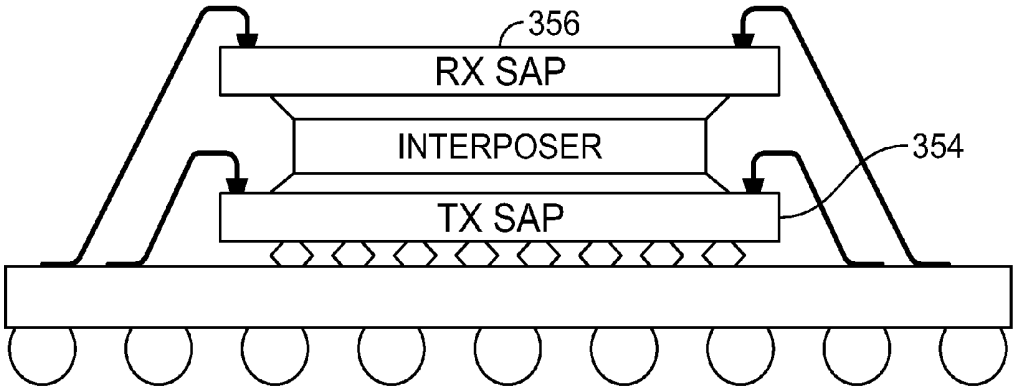


FIG. 11

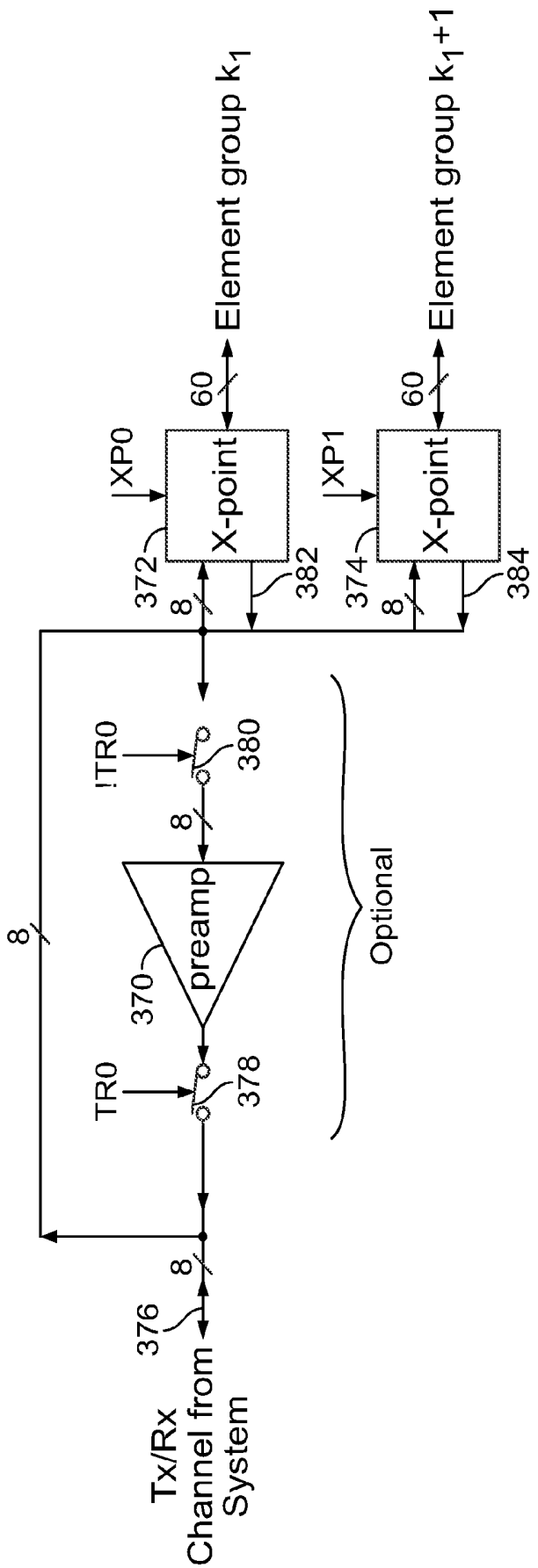

Element group k_1
Element group k_1+1
60
60
XP0
XP1
X-point
X-point
372
374
382
384
8
8
8
8
8
8
!TR0
TR0
380
378
preamp
370
Optional
376
Tx/Rx
Channel from
System

FIG. 12

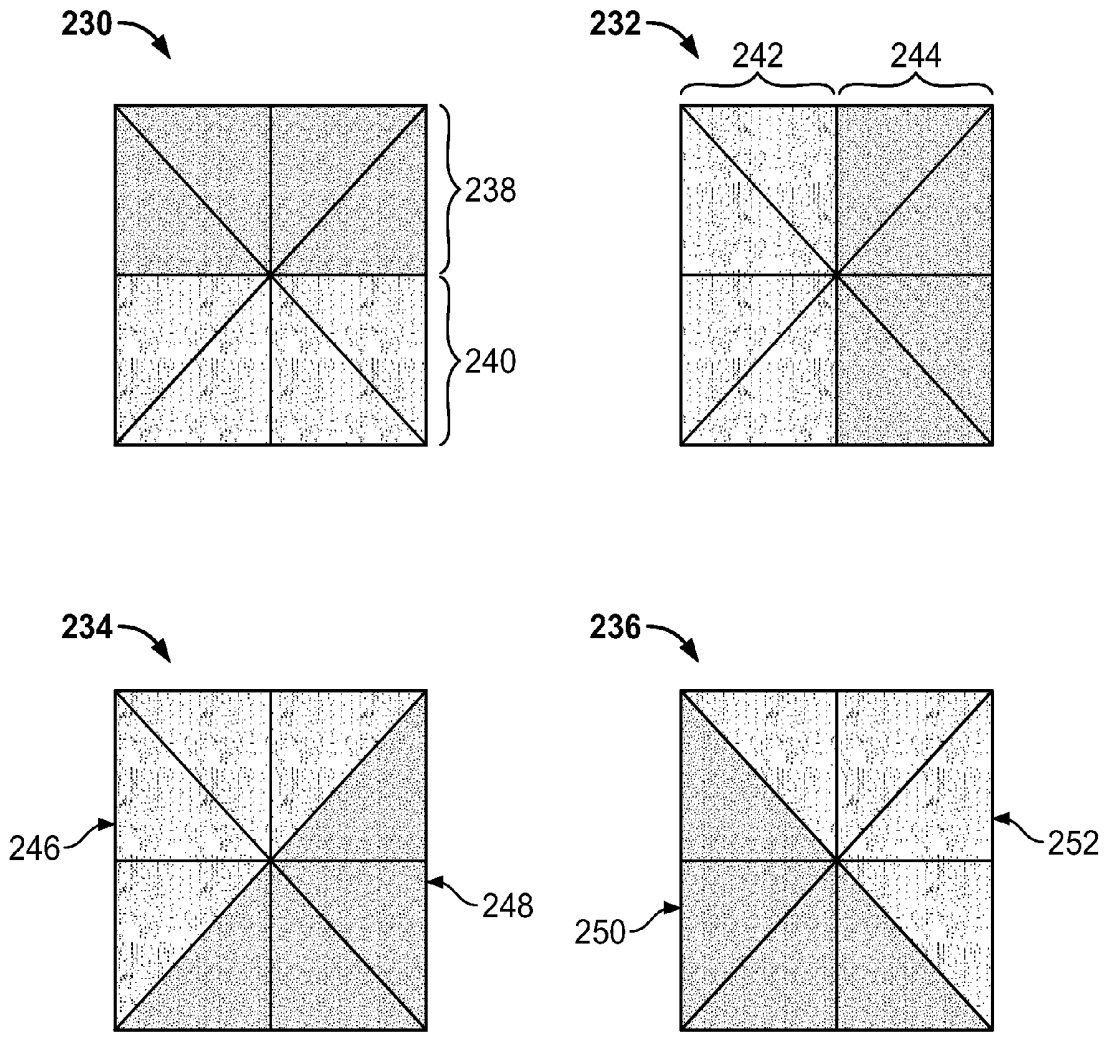
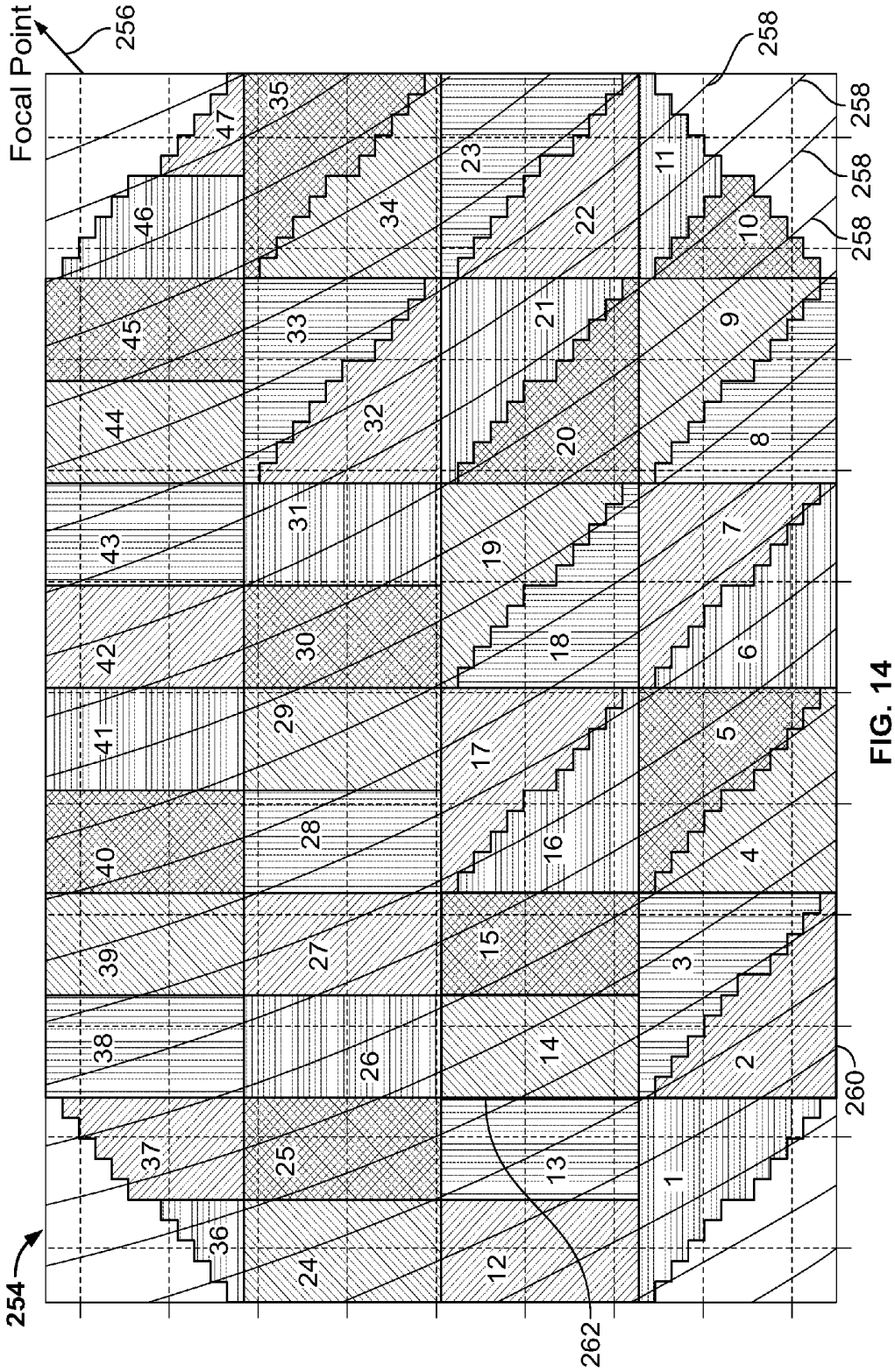


FIG. 13


Focal Point
256
254
258
260
262
1
2
3
4
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6
7
8
9
10
11
12
13
14
15
16
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21
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FIG. 14

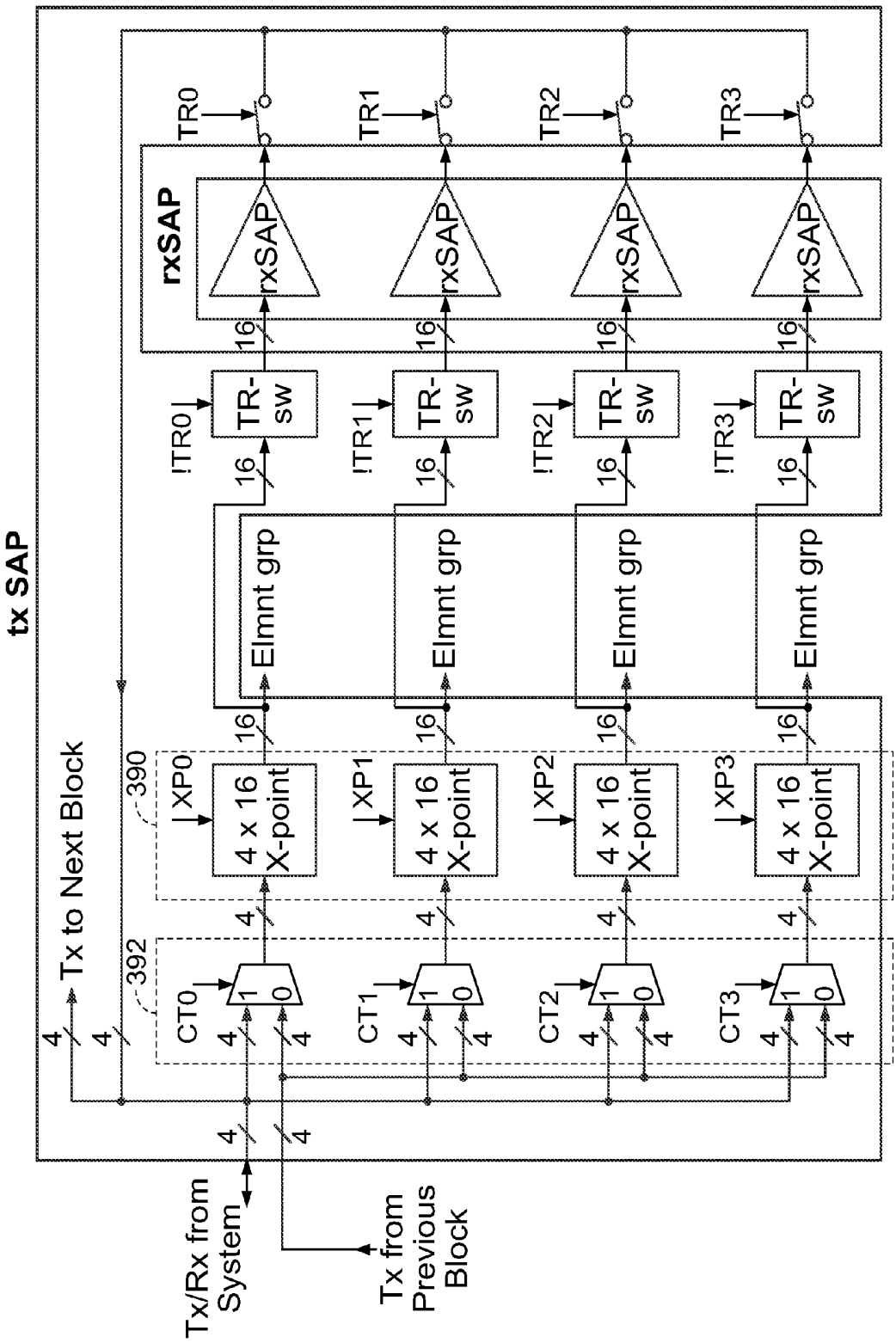
tx SAP
Tx to Next Block
392
390
CT0
CT1
CT2
CT3
XP0
XP1
XP2
XP3
4 x 16 X-point
Elmnt grp
!TR0
!TR1
!TR2
!TR3
TR-sw
rxSAP
TR0
TR1
TR2
TR3
Tx/Rx from System
Tx from Previous Block

FIG. 15

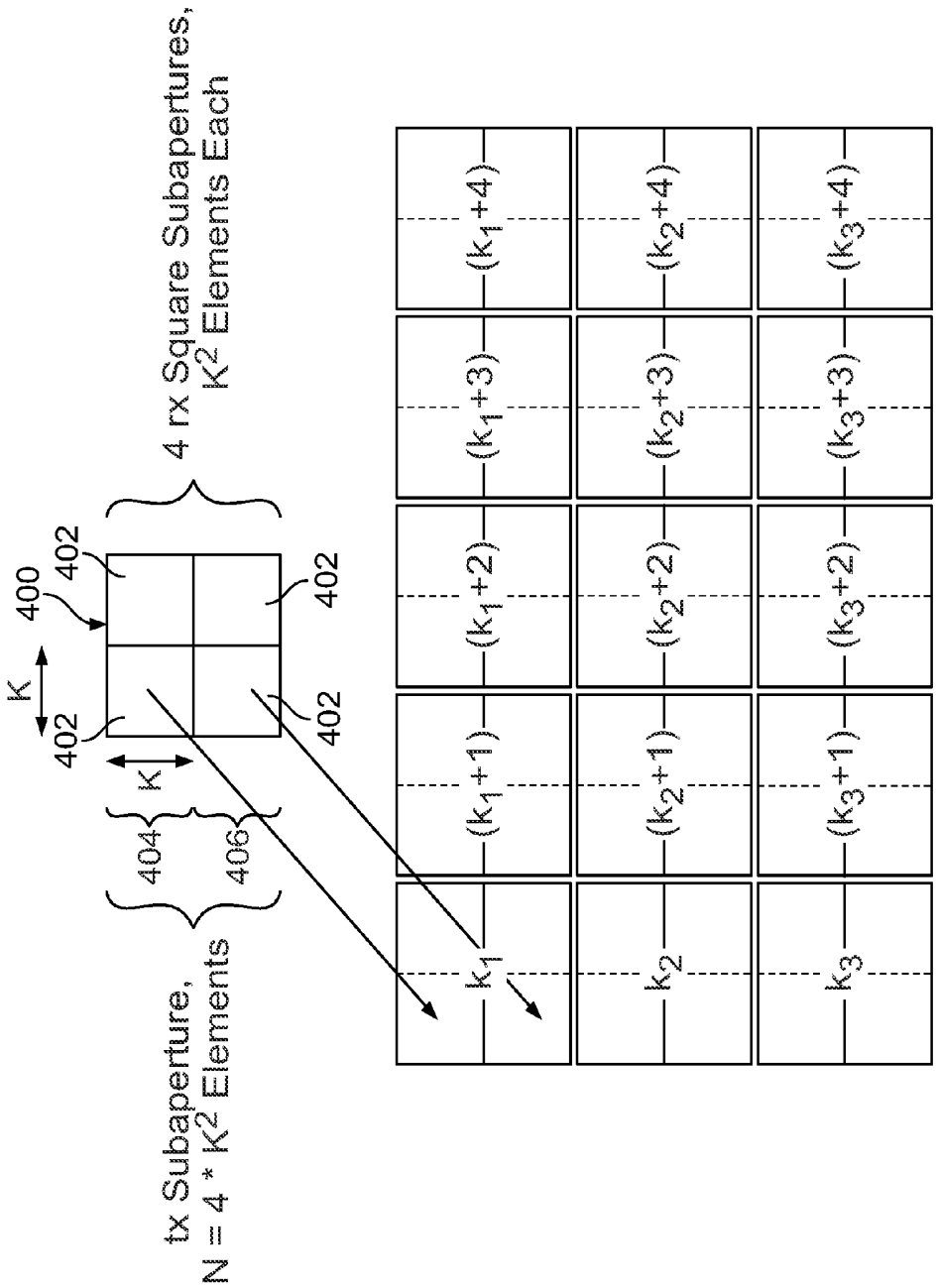
4 rx Square Subapertures,
K^2 Elements Each
400
402
402
402
402
K
K
404
406
tx Subaperture,
$N = 4 * K^2$ Elements
k_1
k_2
k_3
(k_1+1)
(k_2+1)
(k_3+1)
(k_1+2)
(k_2+2)
(k_3+2)
(k_1+3)
(k_2+3)
(k_3+3)
(k_1+4)
(k_2+4)
(k_3+4)

FIG. 16

TRANSMIT BEAMFORMING IN 3-DIMENSIONAL ULTRASOUND

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of and claims priority and the benefit of the filing date of U.S. application Ser. No. 11/770,126, filed Jun. 28, 2007 and entitled "TRANSMIT BEAMFORMING IN 3-DIMENSIONAL ULTRASOUND", the subject matter of which is hereby incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION

[0002] This invention relates generally to ultrasound medical imaging systems, and more specifically, to partitioning multiple transducer elements of an ultrasonic probe into non-overlapping sub-apertures for the transmission of an ultrasound signal.

[0003] Two key components of an ultrasound system are the ultrasound probe and the beamformer. The beamformer focuses and steers ultrasound energy transmitted by and received by the probe to acquire image data, and as one step in generating images of anatomic content on a display. Three-dimensional (3D) ultrasound imaging may be accomplished using a probe that has a two-dimensional (2D) matrix array of transducer elements. In many systems, the elements are used for both transmit and receive operations. Current systems achieve this dual operation of the transducer elements by multiplexing between the transmit and receive circuitry in the system. Each channel in the probe may be connected with one cable to the system and be used both for transmit and receive operations.

[0004] The transducer elements are typically arranged in a 2D array that may be divided into a plurality of sub-apertures (or subarrays) for both transmit and receive operations by grouping subsets of the transducer elements together. For example, each aperture may include at least one acoustic transducer element. The sub-aperture grouping may be different on transmit and receive. The layout and implementation of the sub-apertures for transmit and receive affects image quality. Some probes use transmitters located within the probe although this configuration can generate significant heat. It is therefore desirable to provide a transmit solution for a 2D array probe where a relatively small number of system channels (such as approximately 170 system channels) can drive an array with a large number of elements (such as approximately 2600 elements).

[0005] Therefore, a need exists for improved transmit beamforming of a 2D array for 3D ultrasound imaging that improves the aperture sub-grouping without the limitations discussed above.

BRIEF DESCRIPTION OF THE INVENTION

[0006] In one embodiment, an ultrasound system comprises a probe including a two-dimensional (2D) array of transducer elements that form an aperture having a plurality of receive elements that are configured to receive ultrasound signals. The transducer elements form at least one transmit sub-aperture that is configured to be interconnected with a fixed group of the transducer elements within the aperture. Transmitters generate electrical transmit signals, and at least one transmit sub-aperture processor (tx SAP) maps the transducer elements within the fixed group of the transducer elements to the transmitters in a transmit configuration based on a beam steering direction.

[0007] In another embodiment, a method for transmitting ultrasound signals using a 2D array of transducer elements comprises forming at least one transmit sub-aperture comprising a fixed group of transducer elements for transmitting ultrasonic transmit signals and at least two receive sub-apertures for receiving ultrasonic receive signals. The at least one transmit sub-aperture and the at least two receive sub-apertures are associated with a predetermined group of system channels. A delay is calculated for each of the transducer elements within the fixed group of transducer elements wherein the delay is based at least on a steering angle associated with the transducer element and a transmit operation. At least a portion of the transducer elements within the fixed group of transducer elements are connected to the predetermined group of system channels based at least on the delays associated with the transducer elements.

[0008] In yet another embodiment, an ultrasound system comprises a probe including a 2D array of transducer elements that form an aperture having a plurality of receive elements that are configured to receive ultrasound signals. At least one configurable cross-point switch has first and second sides and is interconnected on the first side with a fixed group of the transducer elements that forms a transmit sub-aperture configured to transmit ultrasound signals. System channels are configured to convey at least the transmit signals and interconnect with the at least one configurable cross-point switch on the second side. The at least one configurable cross-point switch further comprises at least one switch associated with each of the transducer elements within the fixed group of transducer elements, and the at least one configurable cross-point switch connects at least one of the transducer elements with one of the system channels. A sub-aperture processor (SAP) controller is configured to control the at least one configurable cross-point switch to map each of the transducer elements within the fixed group of transducer element to the system channels in a transmit configuration based on delays associated with the transmit signals.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. **1** is a block diagram of an ultrasound system formed in accordance with an embodiment of the present invention.

[0010] FIG. **2** illustrates a miniaturized ultrasound system formed in accordance with an embodiment of the present invention and having a probe configured to acquire ultrasonic data.

[0011] FIG. **3** is a diagram illustrating an aperture of an ultrasonic 2D array comprising transducer elements that is formed in accordance with an embodiment of the present invention.

[0012] FIG. **4** is a diagram illustrating many transmit sub-apertures and a portion of the transmit sub-aperture organization formed in accordance with an embodiment of the present invention.

[0013] FIG. **5** is a schematic block diagram illustrating the use of a cross-point switch to connect the transducer elements to system channels that are connected to the transmitters in accordance with an embodiment of the present invention.

[0014] FIG. **6** illustrates an example of mapping a transmit configuration for an aperture of a probe and a transmit sub-aperture within the aperture in accordance with an embodiment of the present invention.

[0015] FIG. **7** illustrates another example of mapping a transmit configuration in accordance with an embodiment of the present invention.

[0016] FIG. **8** is a flowchart of a method for determining a mapping of the transducer elements and channels during transmission in accordance with an embodiment of the present invention.

[0017] FIG. **9** is a schematic block diagram of an input/output architecture for a transmit sub-aperture processor (tx SAP) using a cross-point switch matrix that comprises switches formed in accordance with an embodiment of the present invention.

[0018] FIG. **10** is a schematic block diagram of the architecture of FIG. **9** separated into transmit and receive SAPs in accordance with an embodiment of the present invention.

[0019] FIG. **11** is an elevation view of the stacking of transmit and receive SAPs in accordance with an embodiment of the present invention.

[0020] FIG. **12** is a schematic block diagram of cross-point switches being used for both transmit and receive operations in accordance with an embodiment of the present invention.

[0021] FIG. **13** is a diagram illustrating four different sub-aperture configurations of the transmit sub-apertures that may be used to steer the ultrasound beams during transmission in accordance with an embodiment of the present invention.

[0022] FIG. **14** is a diagram illustrating a transmit aperture with a projection of a focal point and associated delay lines indicating transducer element delays in accordance with an embodiment of the present invention.

[0023] FIG. **15** is a schematic block diagram of a hardware implementation for the transmit sub-aperture configurations of FIGS. **13** and **14** formed in accordance with an embodiment of the present invention.

[0024] FIG. **16** is a diagram illustrating a transmit sub-aperture having a plurality of square receive sub-apertures in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0025] The foregoing summary, as well as the following detailed description of certain embodiments of the present invention, will be better understood when read in conjunction with the appended drawings. To the extent that the figures illustrate diagrams of the functional blocks of various embodiments, the functional blocks are not necessarily indicative of the division between hardware circuitry. Thus, for example, one or more of the functional blocks (e.g., processors or memories) may be implemented in a single piece of hardware (e.g., a general purpose signal processor or random access memory, hard disk, or the like). Similarly, the programs may be stand alone programs, may be incorporated as subroutines in an operating system, may be functions in an installed software package, and the like. It should be understood that the various embodiments are not limited to the arrangements and instrumentality shown in the drawings.

[0026] FIG. **1** illustrates a block diagram of an ultrasound system **100**. A probe **106** is connected to the system **100** via cable **142**. The probe **106** has a two-dimensional (2D) matrix array of transducer elements **104** and is capable of three-dimensional (3D) scanning. System channels (not shown) may be within the cable **142** and may convey transmit and receive signals to and from the probe **106**. Alternatively, separate transmit channels and receive channels may be used. At least one transmit (tx) sub-aperture processor (SAP) **124** and one receive (rx) SAP **126** is within the probe **106** for transmit and/or receive operations. In another embodiment, one tx/rx SAP may facilitate both of the receive and transmit functions. A SAP controller **128** communicates with system processor **116** and/or beamformer **110**. The SAP controller **128** also communicates with the SAP(s) **124** to configure transmit and receive sub-apertures by connecting particular transducer elements **104** with system channels (or transmit and receive channels) that are used to convey the ultrasonic signals to and from the probe **106**. The SAP controller **128** may be implemented in hardware or software, or a combination thereof, and may alternatively be located within the system **100**, such as within the processor **116**.

[0027] The ultrasound system **100** includes transmitters **102** that drive the transducer elements **104** within the probe **106** to emit pulsed ultrasonic signals into a body. The transmitters **102** are located outside of the probe **106**, such as within a housing (not shown) that encloses the internal components of the system **100**. Beamformer **110** supplies information to the transmitters **102** such as steering information, for example, provided as steering signals. The steering information may be different across the array of transducer elements **104**. The SAP controller **128** further communicates with the tx SAPs **124** and rx SAPs **126** to control the local steering direction of the individual sub-apertures (based upon the steering/focusing of the transmit and receive beams respectively).

[0028] The transmitted ultrasonic signals are back-scattered from structures in the body, like blood cells or muscular tissue, to produce echoes that return to the transducer elements **104**. The returning echoes are converted by the transducer elements **104** back to electrical energy that is received by a plurality of receivers **108**. The received signals are passed through the beamformer **110** that performs receive beamforming and outputs an RF signal. The RF signal then passes through an RF processor **112**. Alternatively, the RF processor **112** may include a complex demodulator (not shown) that demodulates the RF signal to form IQ data pairs representative of the echo signals. The RF or IQ signal data may then be routed directly to an RF/IQ buffer **114** for temporary storage.

[0029] A user input **120**, which may be configured as a user interface having a keyboard, mouse, trackball, control buttons, etc., may be used to control operation of the ultrasound system **100**, including, to control the input of patient data, scan parameters, to select or identify a focal point or region of interest, and the like, and may also include using voice commands provided via a microphone **144**. Other various embodiments may include a set of user controls that may be configured for controlling the ultrasound system **100** and may be provided, for example, as part of a touch screen or panel, and/or as manual inputs, such as user operable switches, buttons, and the like. The set of user controls may be manually operable or voice operated.

[0030] The ultrasound system **100** also includes the processor **116** (e.g., a processor module) to process the acquired ultrasound information (i.e., RF signal data or IQ data pairs) and prepare frames or volumes of ultrasound information for display on display **118**. The display **118** has a known resolution that may be defined in terms of pixels or other known parameter. The processor **116** is adapted to perform one or

more processing operations according to a plurality of selectable ultrasound modalities on the acquired ultrasound information. Acquired ultrasound information may be processed in real-time during a scanning session as the echo signals are received.

[0031] It should be understood that the functionality discussed with respect to the system **100** is not limited to any ultrasound system type. For example, the system **100** may be housed within a cart-based system or may be implemented in a smaller, portable system as discussed in FIG. **2**.

[0032] FIG. **2** illustrates a 3D-capable miniaturized ultrasound system **130** having a probe **132** configured to acquire 3D ultrasonic data. Although not shown, the probe **132** has a 2D array of transducer elements **104** as well as the tx SAPs **124** and rx SAPs **126** as discussed previously with respect to the probe **106** of FIG. **1**. A user interface **134** (that may also include an integrated display **136**) is provided to receive commands from an operator. As used herein, "miniaturized" means that the ultrasound system **130** is a handheld or hand-carried device or is configured to be carried in a person's hand, pocket, briefcase-sized case, or backpack. For example, the ultrasound system **130** may be a hand-carried device having a size of a typical laptop computer, for instance, having dimensions of approximately 2.5 inches in depth, approximately 14 inches in width, and approximately 12 inches in height. The ultrasound system **130** may weigh about ten pounds, and thus is easily portable by the operator. The integrated display **136** (e.g., an internal display) is also provided and is configured to display a medical image.

[0033] The ultrasonic data may be sent to an external device **138** via a wired or wireless network **140** (or direct connection, for example, via a serial or parallel cable or USB port). In some embodiments, external device **138** may be a computer or a workstation having a display. Alternatively, external device **138** may be a separate external display or a printer capable of receiving image data from the hand carried ultrasound system **130** and of displaying or printing images that may have greater resolution than the integrated display **136**.

[0034] As another example, the ultrasound system **130** may be a 3D capable pocket-sized ultrasound system. By way of example, the pocket-sized ultrasound system may be approximately 2 inches wide, approximately 4 inches in length, and approximately 0.5 inches in depth and weigh less than 3 ounces. The pocket-sized ultrasound system may include a display, a user interface (i.e., keyboard) and an input/output (I/O) port for connection to the probe (all not shown). It should be noted that the various embodiments may be implemented in connection with a miniaturized ultrasound system having different dimensions, weights, and power consumption.

[0035] FIG. **3** illustrates an aperture **170** extending across the face of an ultrasonic probe, such as the probe **106** of FIG. **1** that comprises a large number of transducer elements **104** arranged as a 2D array. The aperture **170** is divided into a plurality of receive sub-apertures **172** that are illustrated as triangular in this embodiment. In this example, there are 176 different receive sub-apertures **172**. Each of the receive sub-apertures **172** comprise 15 transducer elements **104** (FIG. **1**). Each of the receive sub-apertures **172** is connected to one channel of the beamformer **110** through a rx SAP, such as rx SAP **126**. During ultrasound reception the signals received by the transducer elements **104** are passed through independent delays (or phase shifters) within the rx SAP **26** and summed together to a single output that is connected to the associated system channel.

[0036] FIG. **4** illustrates a transmit sub-aperture **180** and a portion **202** of the transmit sub-aperture organization in a 2D array. The portion **202** illustrates a plurality of the transmit sub-apertures **180** organized in non-overlapping rectangular sub-arrays. Each transmit sub-aperture **180** comprises eight triangular receive sub-apertures **172**, each of which has 15 transducer elements **104** as discussed previously. Therefore, the transmit sub-aperture **180** has a total of 120 transducer elements **104** arranged such that ten adjacent transducer elements **104** extend along a horizontal (azimuthal) axis **181** and twelve adjacent transducer elements **104** extend along a vertical (elevational) axis **197**. Other configurations of the receive sub-apertures **172** may be used. The transmit sub-aperture **180** is repeated with a plurality of transmit sub-apertures throughout the portion **202**. Each of the transmit sub-apertures is connected to a fixed group of the transducer elements **104**, and each of the transmit sub-apertures within the portion **202** is connected to a different fixed group of transducer elements **104**. For example, the transmit sub-aperture **180** is connected to the fixed group of the 120 transducer elements **104** formed by first and second element groups **198** and **200**.

[0037] During transmission of an ultrasound pulse, eight channels associated with eight receive sub-apertures **182-194** drive the transducer elements **104** within the transmit sub-aperture **180**. As discussed below, each of the transducer elements **104** may be connected to any of the eight channels and is not limited by the configuration of the receive sub-apertures **182-194**.

[0038] In one embodiment, signals received from four adjacent receive sub-apertures **172** along the horizontal axis **181**, such as first, second, third and fourth receive sub-apertures **182**, **184**, **186** and **188** are processed within a first integrated circuit containing four rx SAPs (not shown) and fifth, sixth, seventh, and eighth receive sub-apertures **190**, **192**, **194**, and **196** are processed within a second integrated circuit (not shown) that may be identical to the first integrated circuit. The first through fourth receive sub-apertures **182-188** form a first element group **198** and the fifth through eighth receive sub-apertures **190-196** form a second element group **200**. The first and second element groups **198** and **200** are also referred to as element groups k_1 and k_1+1, respectively, within the portion **202**. A second transmit sub-aperture **204** within the portion **202** has first and second groups **206** and **208** having element groups k_1+2 and k_1+3, respectively.

[0039] FIG. **5** illustrates a schematic block diagram that conceptually indicates the use of a cross-point switch to connect the transducer elements **104** to the system channels during the transmit operation. It should be understood that the receive circuitry is omitted. First, second, third and fourth cross-point switches **210**, **212**, **214** and **216** are illustrated and each have a plurality of switches (not shown) therein for interconnecting the transducer elements **104** and the system channels. Each of the first through fourth cross-point switches **210-216** is configuration and has a first side **226** interconnecting with the transducer elements **104** and a second side **228** interconnecting with the system channels. It should be noted that although not all of the cross-point switches are discussed, the descriptions apply to the other cross-point switches. The first cross-point switch **210** is connected to the first element group **198** (element group k_1) and the second cross-point

switch **212** is connected to the second element group **200** (element group k_1+1). Eight channels are connected to each of the cross-point switches and convey signals from and to the system transmitters **102** and receivers **108**, respectively, of FIG. **1**. The channels are illustrated as groups of four channels wherein first and second channel groups **218** and **220** are connected to the first and second cross-point switches **210** and **212** and third and fourth channel groups **222** and **224** are connected to the third and fourth cross-point switches **214** and **216**. By way of example, the combination of the first and second cross-point switches **210** and **212** may be referred to as a tx SAP **124** and the combination of the third and fourth cross-point switches **214** and **216** may be referred to as a tx SAP **124** wherein each of the tx SAPs **124** connect to eight system transmit channels to drive **120** transducer elements **104**.

[0040] Each of the transducer elements **104** may be connected to one, more than one, or any of the associated channels using the cross-point switch. For a given transducer element **104** and a given transmit vector, at most one switch within the cross-point switch may be closed. In this example, there are 60 transducer elements **104** within the first element group **198** and the first and second channel groups **218** and **220** provide eight channels capable of both transmit and receive operations. Therefore, there may be up to eight switches inside the cross-point switch **210** for each of the transducer elements **104** (for a total of 480 switches) to provide the ability to connect each of the transducer elements **104** to each of the channels within the first and second channel groups **218** and **220**. For a given transmit vector, the cross-point switch is programmed to select which of the 480 switches in the cross-point switch to close. The selection may be based on delays associated with the particular transducer element **104** as discussed below. At most, 60 switches (one for each transducer element **104**) will be closed at a time.

[0041] Alternatively, a cross-point switch may be provided that has a lesser number of total internal switches. Therefore, one or more transducer elements **104** may be attached to one or more channels, but to less than eight channels. For example, two or four switches rather than eight switches may be available for each of the transducer elements **104** to connect to two or four channels, respectively. In another example, a subset of the transducer elements **104** may be provided with a single switch such that the transducer element **104** is always connected to the same channel when being used for transmission. In this case, other transducer elements **104** may be provided with multiple switches. Reducing the number of switches by "sparsing" the cross-point switch reduces the amount of silicon area needed to make an integrated circuit.

[0042] FIG. **6** illustrates an example of a transmit configuration. An aperture **420** is illustrated having a 2D array of transducer elements **104**. In this example, the 2D array comprises 60×48 transducer elements **104**. The 2D array is divided into 24 transmit sub-apertures, such as first, second and third transmit sub-apertures **422**, **424** and **426**, each having a 2D array of 10×12 transducer elements **104**. Not all of the transmit sub-apertures are identified by item numbers.

[0043] The transducer elements **104** within each of the transmit sub-apertures are connected to a system channel to form a transmit configuration based on a beam steering direction. The beam steering direction may be based on one or more focal point, which in this example, is straight down from the probe face or straight with respect to the field of view of the probe. The transducer elements **104** of the second transmit sub-aperture **424** are illustrated in more detail. Different sets of the transducer elements **104** within the second transmit sub-aperture **424** are mapped to different channels within the eight system channels. For example, first set **428**, second set **430**, third set **432**, fourth set **434**, fifth set **436**, sixth set **438**, seventh set **440** and eighth set **442** of the transducer elements **104** may be mapped to the first, second, third, fourth, fifth, sixth, seventh, and eighth system channel (not shown), respectively.

[0044] FIG. **7** illustrates an aperture **450** that has a transmit configuration mapped to steer the focus to one side. Again, the aperture **450** is separated into 24 transmit sub-apertures and transmit sub-aperture **452** is indicated. The beam steering direction is towards one side of the field of view of the probe **106**. The transducer elements **104** of the transmit sub-aperture **452** are mapped to the system channels (not shown) in the transmit configuration as shown. First set **454**, second set **456**, third set **458**, fourth set **460**, fifth set **462**, sixth set **464**, seventh set **466** and eighth set **468** of the transducer elements **104** may be mapped to the first, second, third, fourth, fifth, sixth, seventh and eighth system channels.

[0045] FIG. **8** illustrates a method for determining a mapping of the transducer elements **104** to the channels during transmission. The method may be performed for each transmit sub-aperture **180** and is performed repeatedly over the course of an ultrasonic exam to dynamically focus the ultrasound beams. At **270**, the processor **116** (as shown in FIG. **1**) calculates a delay for each transducer element **104**. The delays may be calculated using known techniques and may be based on directional (or beam steering) set-up information specific to the transmit sub-aperture, such as based on a focal point, local steering angle or direction, and/or location within the aperture **170** (FIG. **3**) of the probe **106**. Alternatively, the delays may be calculated by the beamformer **110** and/or sub-aperture controller **128**. At **272**, the processor **116** compares the delays to determine the maximum and minimum delay. At **274**, the processor **116** assigns the maximum delay and the minimum delay to two separate channels and at **276** the processor **116** assigns intermediate delay values to the remaining channels.

[0046] For example, the processor **116** may determine the delays for each of the transducer elements **104** within the first element group **198** of FIG. **5**. By way of example only, the minimum delay may be zero and may be assigned to a first channel within the first channel group **218**. The maximum delay may be 500 nanoseconds and may be assigned to a fourth channel within the second channel group **220**. The intermediate delay values are based on the maximum and minimum delays and may be determined, for example, by using uniform quantization. The intermediate delay values are then assigned to the remaining six channels. It should be understood that any of the delays may be assigned to any channel and are not limited to the sequential example discussed herein.

[0047] In another embodiment, the transducer element **104** to channel assignment as well as the channel delay distribution (as determined at **274** and **276**) may be set according to a minimized optimization criterion. Such criteria may be an average mean-square delay error or minimization of the maximum side lobe level of the transmitted beam profile.

[0048] At **278**, the processor **116** compares the delay of each of the transducer elements **104** to each of the eight delays assigned to the eight channels to determine the smallest magnitude of the delay error for each transducer element **104**. At

280, the processor **116** may determine whether load balancing should be accomplished to minimize variation between channels. Some of the eight channels within the first and second channel groups **218** and **220** may have many more transducer elements **104** assigned compared to other channels and thus, for a given transmit vector, the electrical load on the different transmit channels will not be the same. The system transmitters **102** have a finite output impedance and having a different load on each channel may result in some additional amplitude and/or delay variations. The series resistance of the probe cable **142** may also cause similar errors unless load balancing is done. Therefore, the method may return to **274** and/or **276** to modify the delay values assigned to one or more of the channels and determine the smallest magnitude of delay error for each transducer element **104** based on the adjusted delay values.

[0049] At **282**, the sub-aperture controller **128** programs or controls the cross-point switch **210** to connect or map the transducer elements **104** to the associated channel that gives the smallest absolute delay error based on information from the processor **116**. This forms a transmit configuration for the transmit sub-aperture. Each transmit sub-aperture may have a different transmit configuration, and the transmit configuration may change from beam to beam and may change over time for a transmit sub-aperture based on operator input, such as a different focal point. Continuing the example above, the cross-point switch **210** is programmed to connect each of the transducer elements **104** in the first element group **198** to one of the channels within the first and second channel groups **218** and **220** during the transmit operation. Optionally, the cross-point switch **210** may not connect all of the transducer elements **104** during each transmit operation. The transmit configuration information is communicated to the beamformer **110** and/or transmitters **102**, including communicating the delays assigned to each of the system channels to the transmitters **102**.

[0050] Typically, small delay errors result for transmit vectors having small steering angles. The magnitude of the delay error may increase as the amount of steering increases. To improve the beam profile for transmit beams that have larger steering angles, the maximum delay value may be constrained to, for example, two periods of the center frequency being transmitted. Transducer elements **104** that have larger delays may be "wrapped" into this domain by adding or subtracting a time corresponding to one period of the center frequency to preserve the desired phased relationship of the waveform. Alternatively, the transducer elements **104** that have delays that relatively are very large may be turned off during transmit by not assigning the transducer element **104** to any channel. This would, however, result in some degree of sparsing during transmission. Sparsing may be minimal, but may occur for some of the transmit sub-apertures **180** over the array surface or aperture **170** of the probe **106** for certain directions in space.

[0051] In addition, each switching element within the cross-point switch **210** may have a finite on-resistance. The resistance may be chosen to be significantly less than an expected electrical load (the electrical impedance of transducer elements plus interconnect capacitance). This may minimize heat generation and improve manufacturing consistency. In addition, in-probe power losses may be reduced if the transmit signal consists of a sine-line burst at the center frequency f0 with a relatively low amount of harmonics at 2*f0, 3*f0, 4*f0, and so on.

[0052] The delay errors are of concern both for the different transmit channels within one transmit vector and between different transmit vectors. For example, if the transmit vector is orthogonal to the face of the probe **106** with focus at infinite range, all of the transducer elements **104** should have the same delay, such as zero delay. In this case, it is desirable to assign a substantially identical signal to all eight transmit channels within the first and second channel groups **218** and **220** and connect fifteen transducer elements to each of the eight channels, rather then connecting 120 transducer elements **104** to one channel and leaving the remaining seven channels unused. In this example, load balancing (**280** of FIG. **8**) may be accomplished by redistributing the transducer elements **104** between the channels. In other embodiments, different intermediate delays may be selected to accomplish the redistribution.

[0053] The larger size of the transmit sub-aperture **180** with respect to the receive sub-apertures, such as the first through eighth receive sub-apertures **182-196** of FIG. **4**, may help to reduce delay errors associated with the transducer elements **104** during transmission. Typical receive sub-aperture sizes are in the range of 15-25 transducer elements **104**, while the transmit sub-aperture **180**, in one embodiment, has 120 transducer elements **104**. In one embodiment, the entire array may be spanned with one cross-point switch connecting all of the transducer elements **104** to all of the channels.

[0054] In some embodiments, it may be desirable to partition the transmit electronics in the same way as the receiver electronics. This is possible even if one transmit sub-aperture spans two receive ASICs. For example, returning to FIG. **4**, as discussed previously the first through fourth receive sub-apertures **182-188** are processed by a first receive ASIC and the fifth through eighth receive sub-apertures **190-196** are processed by a second receive ASIC. FIG. **5** illustrates how pairs of transmit ASICs, each containing one cross-point switch of size 8×15, may be interconnected to give the topology of FIG. **4**.

[0055] FIG. **9** illustrates a transmit/receive architecture **300** for a tx SAP using a cross-point switch matrix **310** that comprises first, second, third and fourth cross-point switches **360**, **362**, **364** and **366**. First, second, third and fourth rx SAPs **302**, **304**, **306** and **308** are illustrated. The architecture **300** includes only one-half of a transmit SAP. First, second, third and fourth input transmit/receive (t/r) switches **312**, **314**, **316** and **318** are connected with receive input lines **328**, **330**, **332** and **334** to inputs of the first through fourth rx SAPs **302-308**, respectively. First, second, third and fourth output t/r switches **320**, **322**, **324** and **326** are connected with receive output lines **336**, **338**, **340** and **342** to outputs of the first through fourth rx SAPs **302-308**, respectively. During transmission, first, second, third and fourth input t/r switches **312-318** and the first through fourth output t/r switches **320-326** disconnect the inputs and outputs, respectively, of the first through fourth rx SAPs **302-308** to protect the first through fourth rx SAPs **302-308** from the high-voltage transmit pulses. During the reception period, the input and output t/r switches **312-326** are closed. All switches inside the cross-point switch matrix **310** are opened during reception so that the rx SAP output is not shorted.

[0056] The cross-point switches **360-366** as well as the internal beamformer settings, illustrated in FIG. **9** as the cfg**0**, cfg**1**, cfg**2** and cfg**3** inputs to the rx SAPs **302**, **304**, **306** and **308**, respectively, may be controlled using, for example, a chain of shift registers, although other system architecture

may be used. Each of the switches inside the cross-point switches **360-366** in one ASIC may be assigned one bit in the shift register and the value of that bit determines if the switch is open or closed.

[0057] FIG. **10** illustrates how the functionality of the architecture **300** of FIG. **9** may be separated into two portions, namely, a tx SAP **350** and a rx SAP **352**. In one embodiment, the tx and rx SAPs **350** and **352** are formed on two separate silicon dies. The tx SAP **350** is typically formed using a silicon process with high-voltage capability, as typical transmit pulses are +/−50-100 Volts, while the rx SAP **352** may be formed in standard low-voltage silicon process. The two dies may then be stacked on top of each other. Alternatively, a single die configuration may be possible based on a silicon process that can handle high voltages and low-noise analog design, as well as digital control. Optionally, digital control electronics may be added as a third die in the stack.

[0058] FIG. **11** illustrates stacking of tx and rx SAP dies **354** and **356**. The stacked configuration is compact and reduces the number of off-chip connections required. For example, the fifteen receive input lines **328-334** (as shown in FIG. **9**) and the receive output lines **336-342** are connected only between the tx and rx SAP dies **354** and **356** and thus an outer connection or connections to other integrated circuits (ICs) can be avoided.

[0059] Returning to FIG. **9**, in one embodiment, the first through fourth input t/r switches **312-318**, the first through fourth rx SAPs **302-308** and the first through fourth output t/r switches **320-326** may be removed. In this example, the first through fourth cross-point switches **360-366** would be used as bi-directional switches, connecting the selected group of transducer elements **104** to the system transmitters **102** and receivers **108**, during both of the transmit and receive operations. This embodiment thus requires less electronics.

[0060] FIG. **12** illustrates an example of using cross-point switches to connect the system channels to the transmit and receive sub-apertures for the transmit and receive operations, respectively. Optionally, a preamplifier **370** may be placed between cross-point switches **372** and **374** and channel group **376**. Transmit/receive switches **378** and **380** may be placed on either side of the optional preamplifier **370** and may be opened during the transmit operation and closed during the receive operation. When receiving signals, the cross-point switch **372** may be programmed to connect the transducer elements **104** within receive sub-apertures comprising the element group k_1 to one of the first through fourth channels such as first channel **382**, and the cross-point switch **374** may be programmed to connect the transducer elements **104** within receive sub-apertures comprising the element group k_1+1 to, for example, second channel **384**. The cross-point switches **372** and **374** may use a set receive configuration for assigning the transducer elements **104** to a specific channel during the receive operation that is different than the transmit configuration.

[0061] FIG. **13** illustrates embodiments of four different configurations of the transmit sub-apertures that may be used to steer ultrasound beams during transmission. First, second, third and fourth transmit configurations **230**, **232**, **234** and **236** are shown. A transmit configuration may be selected based on at least the local steering direction for each transmit sub-aperture to steer the beams in the desired direction. In one embodiment, each group of four triangular receive sub-apertures may be connected to four system channels.

[0062] Referring again to FIG. **4**, the transmit sub-aperture **180** is divided into the first and second element groups **198** and **200** that are arranged in a horizontal and stacked configuration with respect to each other. The configuration of FIG. **4** is illustrated as the first transmit configuration **230** wherein first element group **238** and second element group **240** are horizontal and stacked with respect to each other. The second transmit configuration **232** divides the transmit sub-apertures into first and second element groups **242** and **244** that are side-by-side with respect to each other. The third transmit configuration **234** divides the transmit sub-apertures diagonally into first and second element groups **246** and **248**, and the fourth transmit configuration **236** divides the transmit sub-apertures diagonally into first and second element groups **250** and **252**. By way of example only, the first transmit configuration **230** may steer the beam upward and downward with respect to the plane of the figure, the second transmit configuration **232** may steer the beam left and right, the third transmit configuration **234** may steer the beam towards upper left and lower right corners and the fourth transmit configuration **236** may steer the beam towards the upper right and lower left corners.

[0063] FIG. **14** illustrates a transmit aperture **254** with a focal point **256** located outward away from the plane of the illustrated transmit aperture **254** and towards an upper right corner of the transmit aperture **254**. In other words, the illustrated focal point **256** is the projection of the actual focal point location. The transmit aperture **254** is divided into a plurality of transmit sub-apertures, each having first and second transducer element groups. A plurality of delay lines **258** indicate areas through the transmit aperture **254** that have the same delay and the direction of the delay lines depends on the selected steering direction and focal point for the transmit beam. In this example, each of the transmit sub-apertures is individually configured to accomplish the desired steering with respect to the focal point **256**. For example, the first sub-aperture **260** is configured in the fourth transmit configuration **236** and the second sub-aperture **262** is configured in the second transmit configuration **232**.

[0064] FIG. **15** illustrates a hardware implementation for the embodiment of FIGS. **13** and **14**. A smaller cross-point switch matrix **390** may be used and is preceded by a multiplexer matrix **392** that is programmed according to the desired group configuration (first transmit configuration **230**, second transmit configuration **232**, etc.). The transmit current that flows through the multiplexer matrix **392** is much higher than the current that flows through the cross-point switch matrix **390**. Therefore, the on-resistance of the multiplexer matrix **392** may be less than the on-resistance of the cross-point switches within the cross-point switch matrix **390** by, for example, at least a factor of 4. The transducer element **104** to channel delay assignments and switch programming may be determined as previously described in connection with FIG. **8**.

[0065] FIG. **16** illustrates an embodiment wherein a transmit sub-aperture **400** comprises a plurality of square receive sub-apertures **402**. In this example, each transmit sub-aperture **400** has four receive sub-apertures **402**. The transmit sub-aperture **400** may be divided into first and second element groups **404** and **406** as previously discussed in FIG. **4**. The first and second element groups **404** and **406** are illustrated in the first transmit configuration **230** (as shown in FIG. **13**) and may also be configured in the second transmit configuration **232**.

[0066] A technical effect of at least one embodiment is partitioning the transducer elements of a probe into non-overlapping rectangular transmit sub-apertures during the transmit operation to steer the transmit beam in a desired direction. Each of the transmit sub-apertures may include more than one receive sub-aperture. The transmit sub-apertures may be individually configured into different transmit configurations. To reduce delay errors, the transducer elements within each transmit sub-aperture are mapped to a system channel based on the delay of the particular transducer element.

[0067] It is to be understood that the above description is intended to be illustrative, and not restrictive. For example, the above-described embodiments (and/or aspects thereof) may be used in combination with each other. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from its scope. While the dimensions and types of materials described herein are intended to define the parameters of the invention, they are by no means limiting and are exemplary embodiments. Many other embodiments will be apparent to those of skill in the art upon reviewing the above description. The scope of the invention should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled. In the appended claims, the terms "including" and "in which" are used as the plain-English equivalents of the respective terms "comprising" and "wherein." Moreover, in the following claims, the terms "first," "second," and "third," etc. are used merely as labels, and are not intended to impose numerical requirements on their objects. Further, the limitations of the following claims are not written in means-plus-function format and are not intended to be interpreted based on 35 U.S.C. §112, sixth paragraph, unless and until such claim limitations expressly use the phrase "means for" followed by a statement of function void of further structure.

What is claimed is:

1. An ultrasound system comprising:

a probe including a two-dimensional (2D) array of transducer elements that form an aperture having a plurality of receive elements that are configured to receive ultrasound signals, the transducer elements forming at least one transmit sub-aperture that is configured to be interconnected with a fixed group of the transducer elements within the aperture;

transmitters for generating electrical transmit signals; and

at least one transmit sub-aperture processor (tx SAP) for mapping the transducer elements within the fixed group of the transducer elements to the transmitters in a transmit configuration based on a beam steering direction.

2. The ultrasound system of claim **1**, further comprising:

the at least one tx SAP comprising a cross-point switch;

system channels interconnected with the transmitters and the cross-point switch for conveying the transmit signals there-between; and

a SAP controller configured to control the cross-point switch to select the transducer elements within the fixed group of the transducer elements to be driven by one of the system channels based on the transmit configuration.

3. The ultrasound system of claim **1**, further comprising:

system channels interconnected with the transmitters for conveying the transmit signals; and

a processor configured to determine delays associated with each of the transducer elements within the fixed group of the transducer elements, the delays being based at least on the beam steering direction, the at least one tx SAP being configured to assign at least one of the transducer elements within the fixed group of transducer elements to one channel of the system channels based on the delays.

4. The ultrasound system of claim **1**, wherein the plurality of receive elements are configured to form receive sub-apertures, the at least one transmit sub-aperture comprising at least two adjacent receive sub-apertures.

5. The ultrasound system of claim **1**, the system further comprising a SAP controller configured to divide the receive elements of the at least one transmit sub-aperture into two element groups that are oriented with respect to each other by one of horizontally, vertically and diagonally, the two element groups forming different transmit configurations for steering the transmit signals in different directions.

6. The ultrasound system of claim **1**, wherein the at least one tx SAP comprises at least one cross-point switch for interconnecting the fixed group of the transducer elements and the transmitters, the at least one cross-point switch having at least one switch for each of the transducer elements within the fixed group of the transducer elements.

7. The ultrasound system of claim **1**, further comprising:

system channels for conveying the transmit signals between the transmitters and the at least one tx SAP; and

a processor being configured to determine a maximum delay and a minimum delay based at least on the beam steering direction and delays associated with the transducer elements within the fixed group of transducer elements, the processor further configured to determine intermediate delays based on at least the maximum and minimum delays, the processor assigning one of the maximum delay, the minimum delay and the intermediate delays to each of the system channels.

8. The ultrasound system of claim **1**, further comprising:

receivers for receiving electrical receive signals;

system channels for conveying the transmit signals between the transmitters and the at least one tx SAP;

the tx SAP comprising at least one cross-point switch for interconnecting a group of the system channels with the fixed group of transducer elements; and

preamplifiers for receiving the receive signals from the cross-point switch, the system channels further configured to convey the receive signals between the preamplifiers and the receivers.

9. A method for transmitting ultrasound signals using a 2D array of transducer elements, comprising:

forming at least one transmit sub-aperture comprising a fixed group of transducer elements for transmitting ultrasonic transmit signals and at least two receive sub-apertures for receiving ultrasonic receive signals, the at least one transmit sub-aperture and the at least two receive sub-apertures being associated with a predetermined group of system channels;

calculating a delay for each of the transducer elements within the fixed group of transducer elements, wherein the delay is based at least on a steering angle associated with the transducer element and a transmit operation; and

connecting at least a portion of the transducer elements within the fixed group of transducer elements to the predetermined group of system channels based at least on the delays associated with the transducer elements.

10. The method of claim **9**, wherein the transmit and receive sub-apertures comprise the same transducer elements.

11. The method of claim **9**, further comprising:

determining a maximum delay and a minimum delay based on the delays for each of the transducer elements within the fixed group of transducer elements;

determining intermediate delays based on the maximum and minimum delays, the intermediate delays being further based on a total number of system channels within the predetermined group of system channels; and

assigning channel delays to each of the system channels based on the maximum delay, the minimum delay and the intermediate delays, the connecting further comprising connecting each of the transducer elements within the fixed group of transducer elements to one of the system channels based on a smallest magnitude difference between the delay of the transducer element and the channel delay assigned to the system channel.

12. The method of claim **9**, wherein the connecting further comprises distributing the transducer elements within the fixed group of transducer elements between the system channels of the predetermined group of system channels based on one of load balancing and uniform quantization.

13. The method of claim **9**, further comprising:

identifying a center frequency associated with the ultrasonic transmit signal; and

identifying the delays that are greater than a predetermined number of periods of the transmitted center frequency, wherein the transducer elements within the fixed group of transducer elements that are associated with the identified delays are one of modified by subtracting at least one period of the center frequency and not connected to the system channels.

14. The method of claim **9**, further comprising minimizing an optimization criterion based on at least one of an average mean-square delay error and a maximum side lobe level of a transmitted beam profile, the connecting at least a portion of the transducer elements within the fixed group of transducer elements to the predetermined group of system channels being further based on the minimizing.

15. An ultrasound system comprising:

a probe including a 2D array of transducer elements that form an aperture having a plurality of receive elements that are configured to receive ultrasound signals;

at least one configurable cross-point switch having first and second sides, the at least one configurable cross-point switch being interconnected with a fixed group of the transducer elements on a first side, the fixed group of the transducer elements forming a transmit sub-aperture configured to transmit ultrasound signals;

system channels being configured to convey at least the transmit ultrasound signals, the system channels interconnecting with the at least one configurable cross-point switch on the second side, the at least one configurable cross-point switch comprising at least one switch associated with each of the transducer elements within the fixed group of the transducer elements, the at least one configurable cross-point switch connecting at least one of the transducer elements with one of the system channels; and

a sub-aperture processor (SAP) controller configured to control the at least one configurable cross-point switch to map each of the transducer elements within the fixed group of transducer elements to the system channels in a transmit configuration based on delays associated with ultrasound transmit signals.

16. The ultrasound system of claim **15**, wherein the transmit sub-aperture is divided into at least first and second receive sub-apertures, wherein the first and second receive sub-apertures comprise first and second predetermined subsets of transducer elements from within the fixed group of transducer elements for receiving the ultrasound signals.

17. The ultrasound system of claim **15**, wherein the transmit sub-aperture is divided into at least first and second receive sub-apertures, wherein the first and second receive sub-apertures comprise first and second predetermined subsets of transducer elements from within the fixed group of transducer elements, wherein the at least one configurable cross-point switch is further configured to map the first and second predetermined subsets of transducer elements to a first system channel and a second system channel, respectively, from within the system channels for receiving the ultrasound signals.

18. The ultrasound system of claim **15**, wherein the SAP controller is further configured to determine a maximum delay and a minimum delay based at least on a delay associated with each of the transducer elements, the SAP controller further configured to determine intermediate delays based on at least the maximum and minimum delays, the SAP controller further configured to assign one of the maximum delay, the minimum delay and the intermediate delays to each of the system channels.

19. The ultrasound system of claim **15**, further comprising:

at least one receive SAP for processing the received ultrasound signals detected by the plurality of receive elements;

a receive SAP die including the at least one receive SAP; and

a transmit SAP die including the at least one configurable cross-point switch and further comprising input and output switches, the input switches inputting the receive ultrasound signals to the at least one receive SAP and the output switches receiving output signals from the at least one receive SAP.

20. The ultrasound system of claim **15**, wherein the at least one configurable cross-point switch comprises at least one switch for each of the transducer elements within the group.

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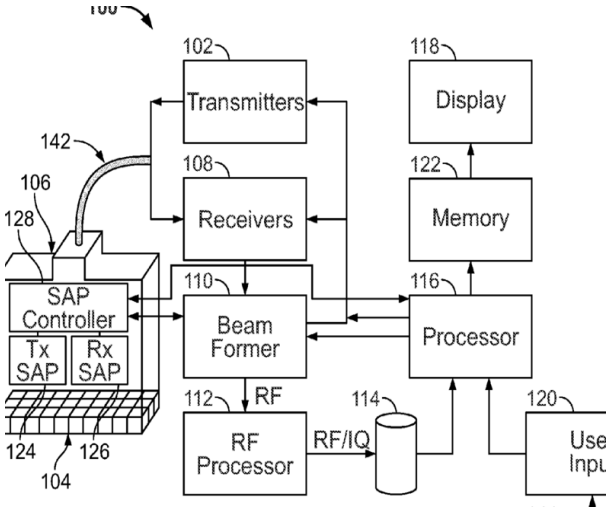
超声系统包括探头，该探头包括二维（2D）换能器元件阵列，其形成具有多个接收元件的孔，所述多个接收元件被配置为接收超声信号。换能器元件形成至少一个发射子孔径，该发射子孔径被配置成与孔径内的固定组换能器元件互连。发射器产生电发射信号，并且至少一个发射子孔径处理器（tx SAP）基于波束控制方向将换能器元件的固定组内的换能器元件映射到发射器配置中的发射器。