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(54) **INTEGRATED SYSTEM FOR ULTRASOUND IMAGING AND THERAPY**

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

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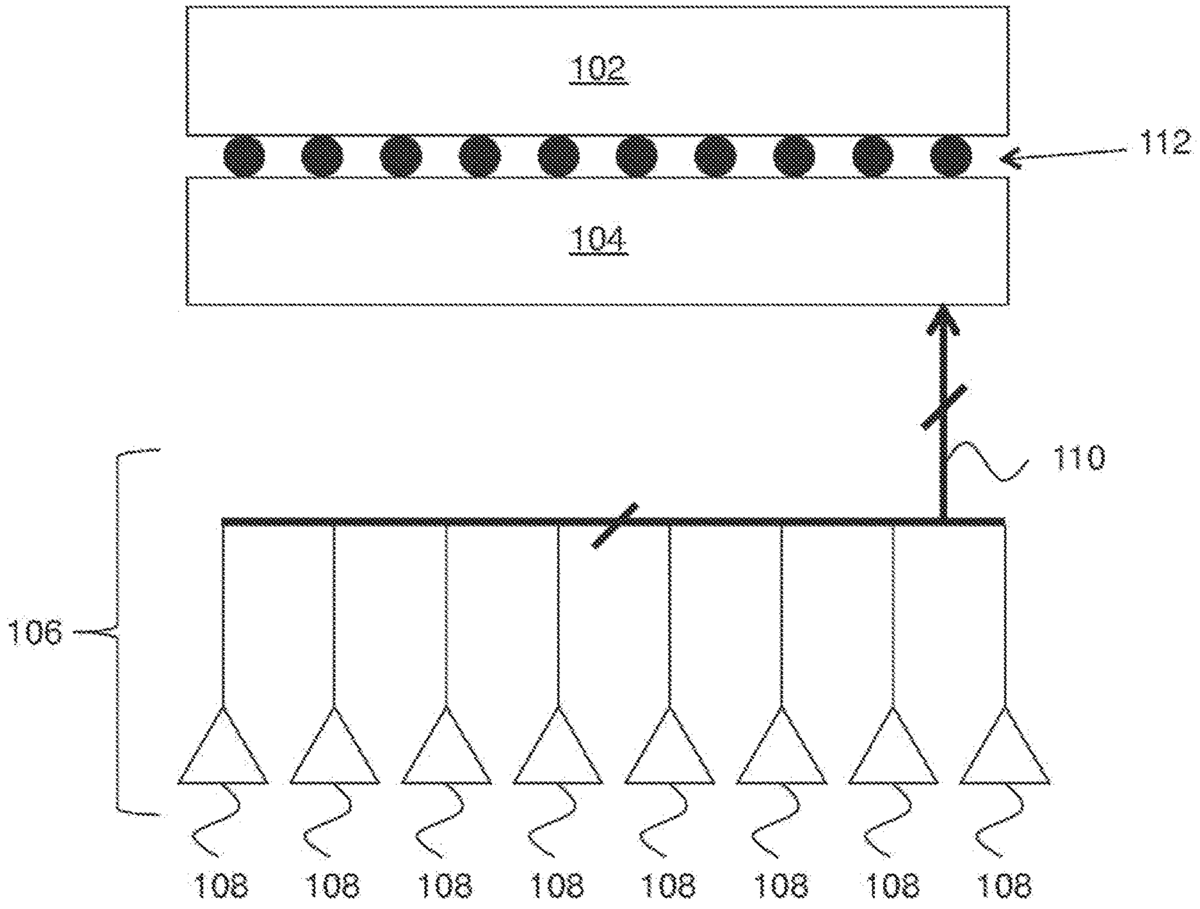
(57) **ABSTRACT**

Ultrasound imaging and therapy with the same array of capacitive micromachined ultrasonic transducers is provided. The electronics includes a per-pixel switch for each transducer element. The switches provide an imaging mode driven completely by on-chip electronics and a therapy mode where off-chip pulsers provide relatively high voltages to the transducer elements.



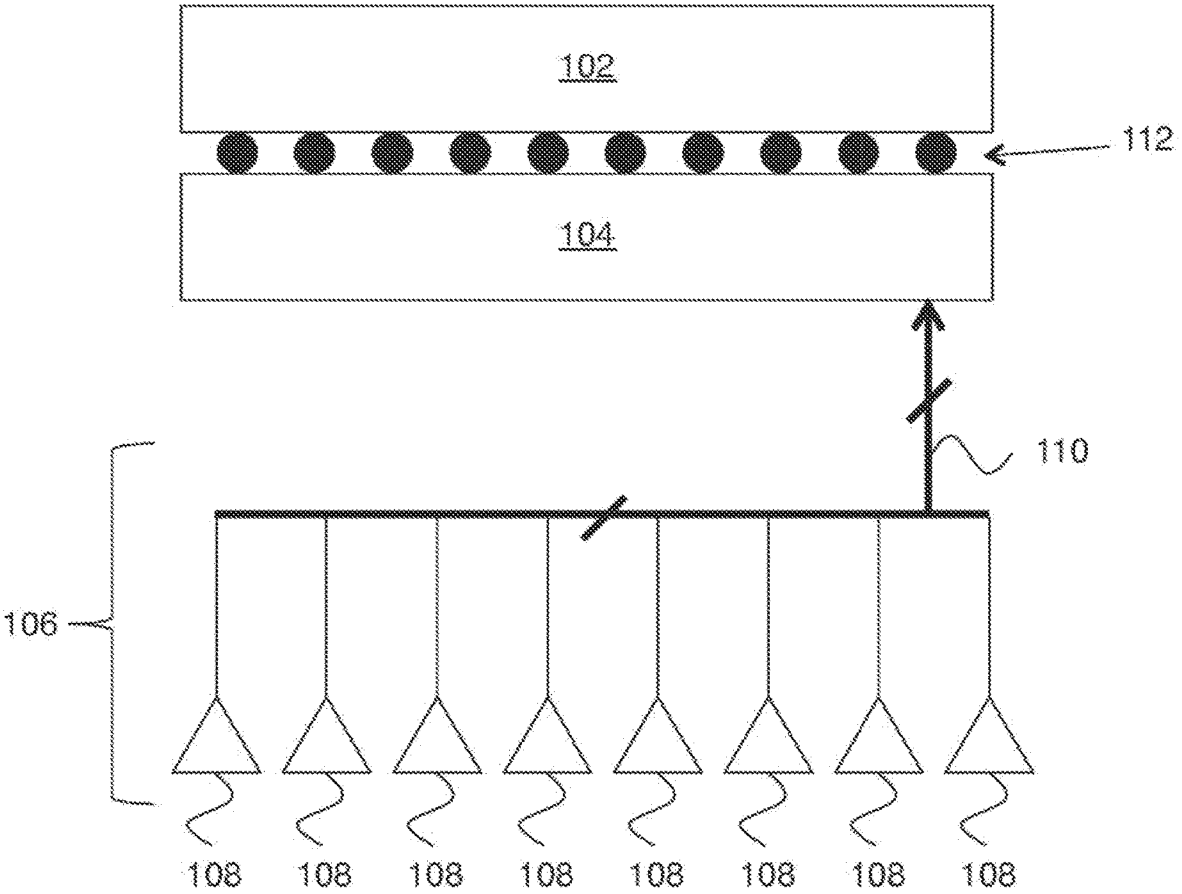


FIG. 1

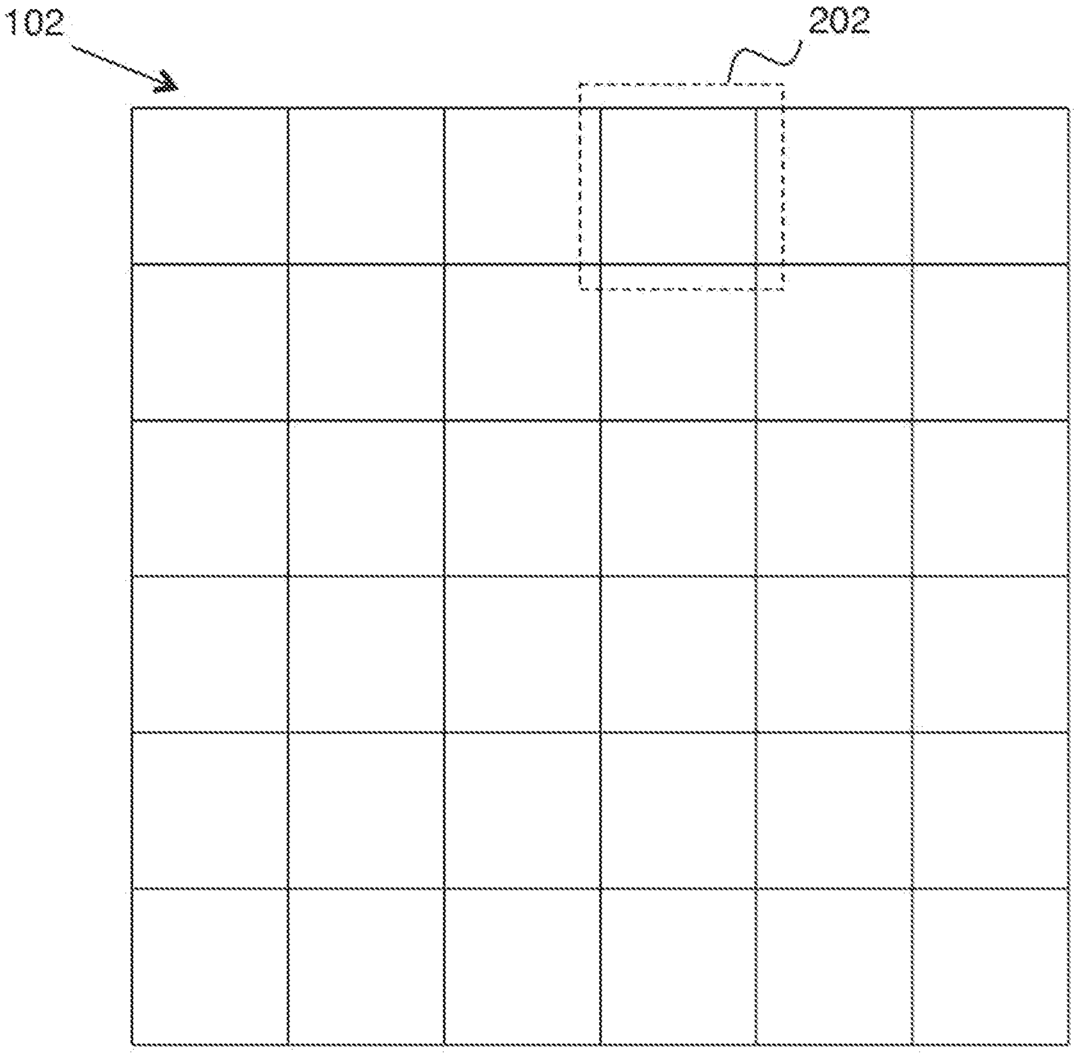


FIG. 2

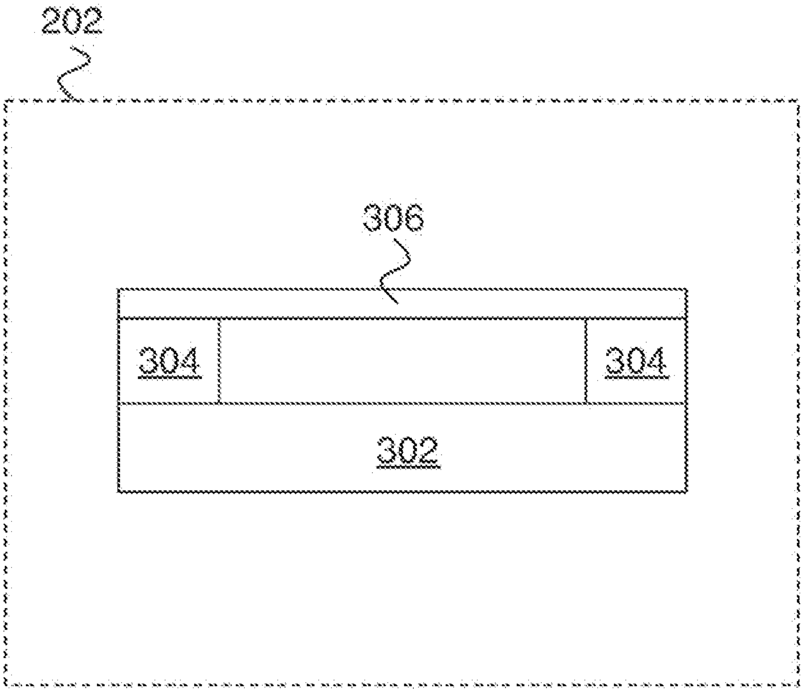


FIG. 3

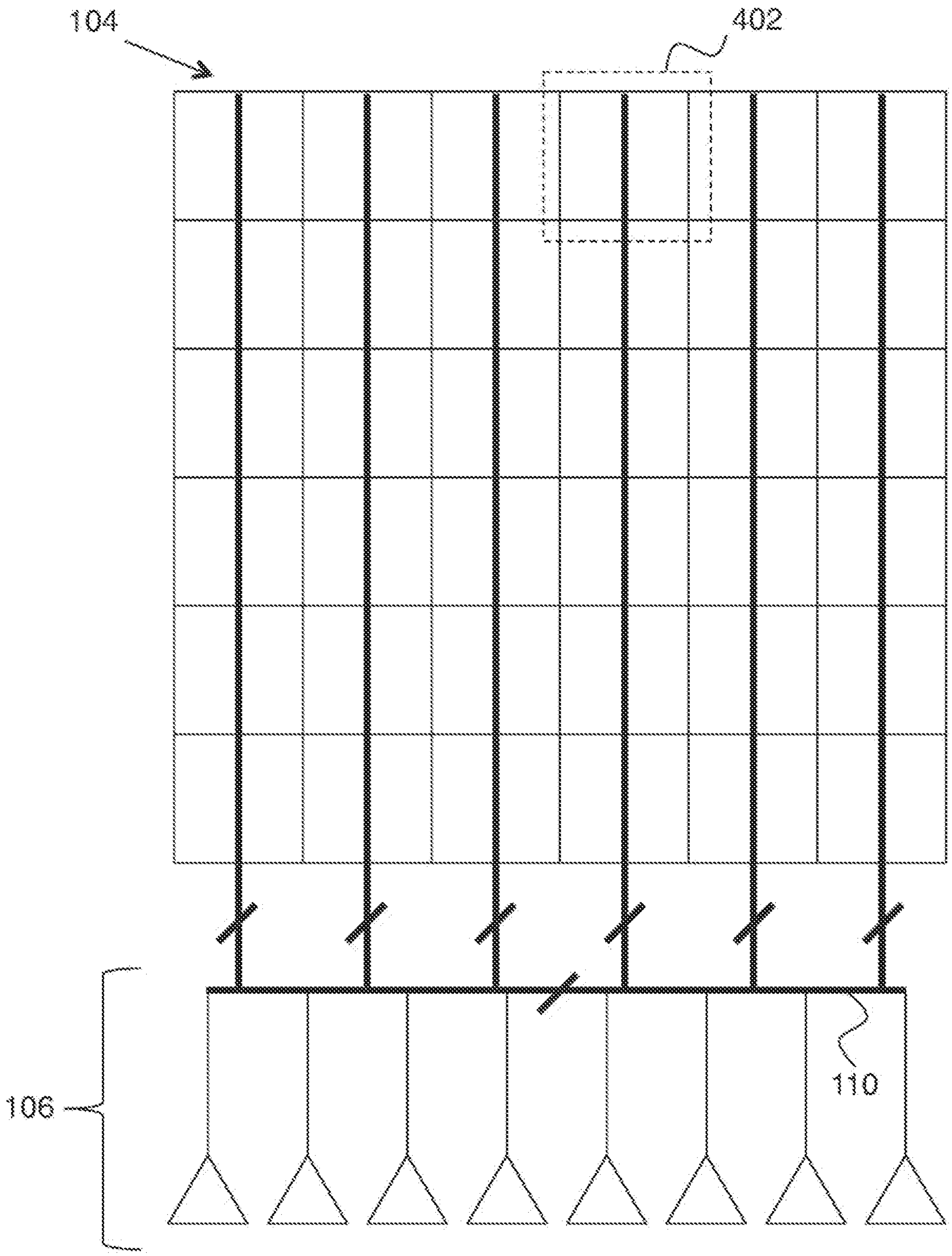


FIG. 4

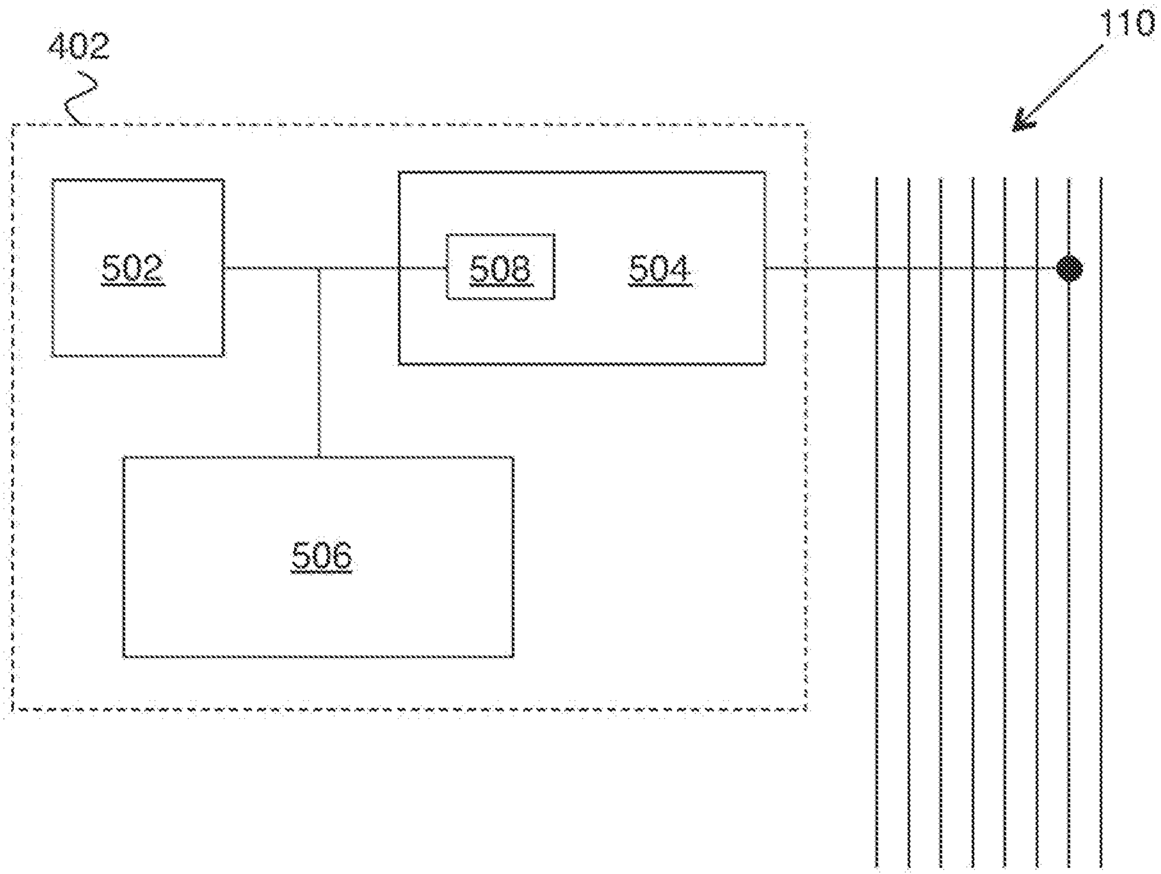


FIG. 5

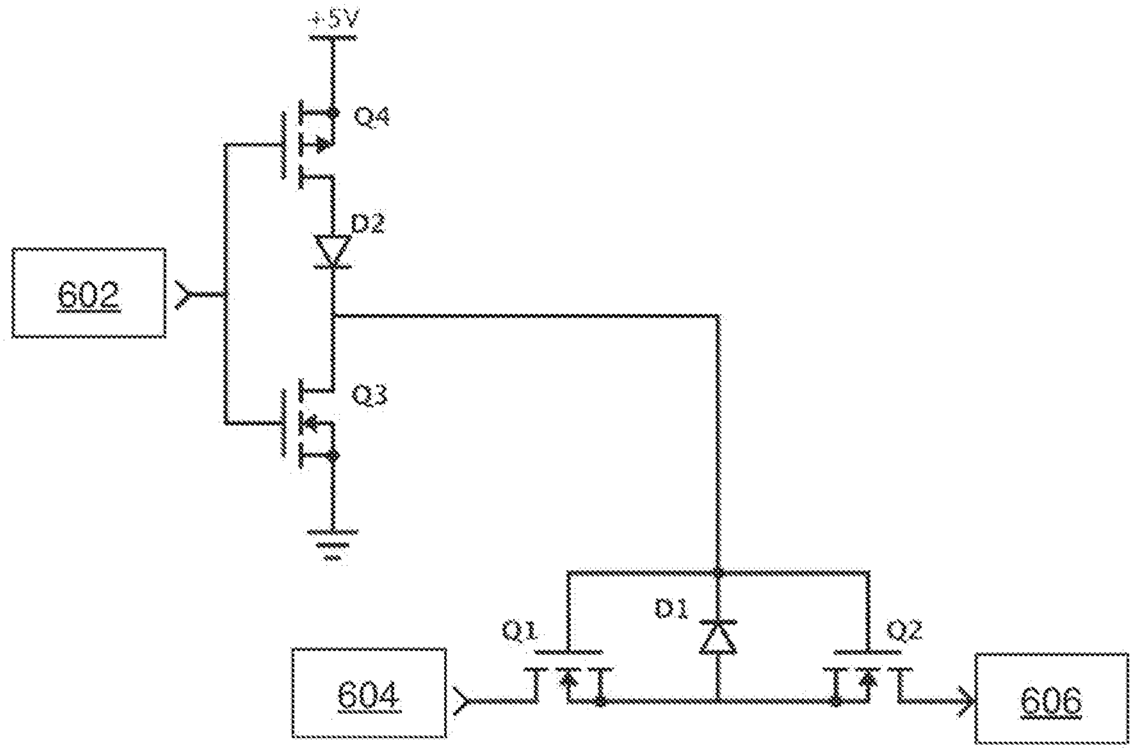


FIG. 6

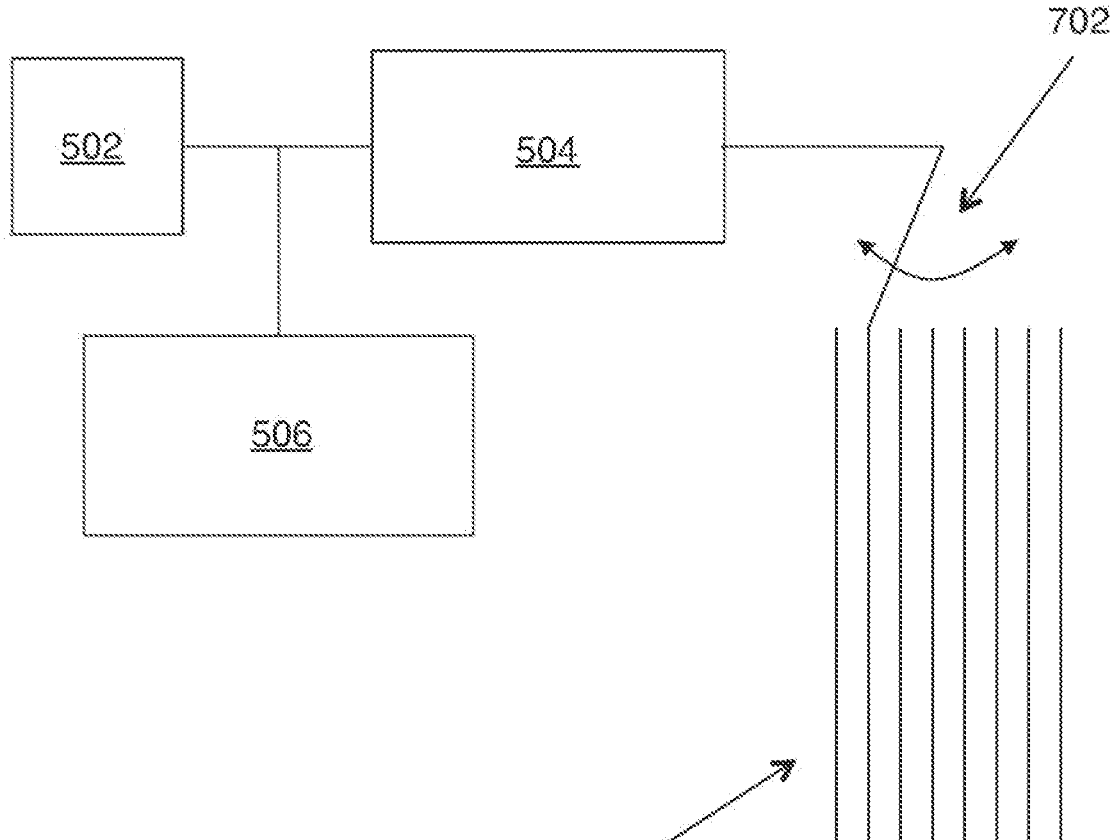


FIG. 7

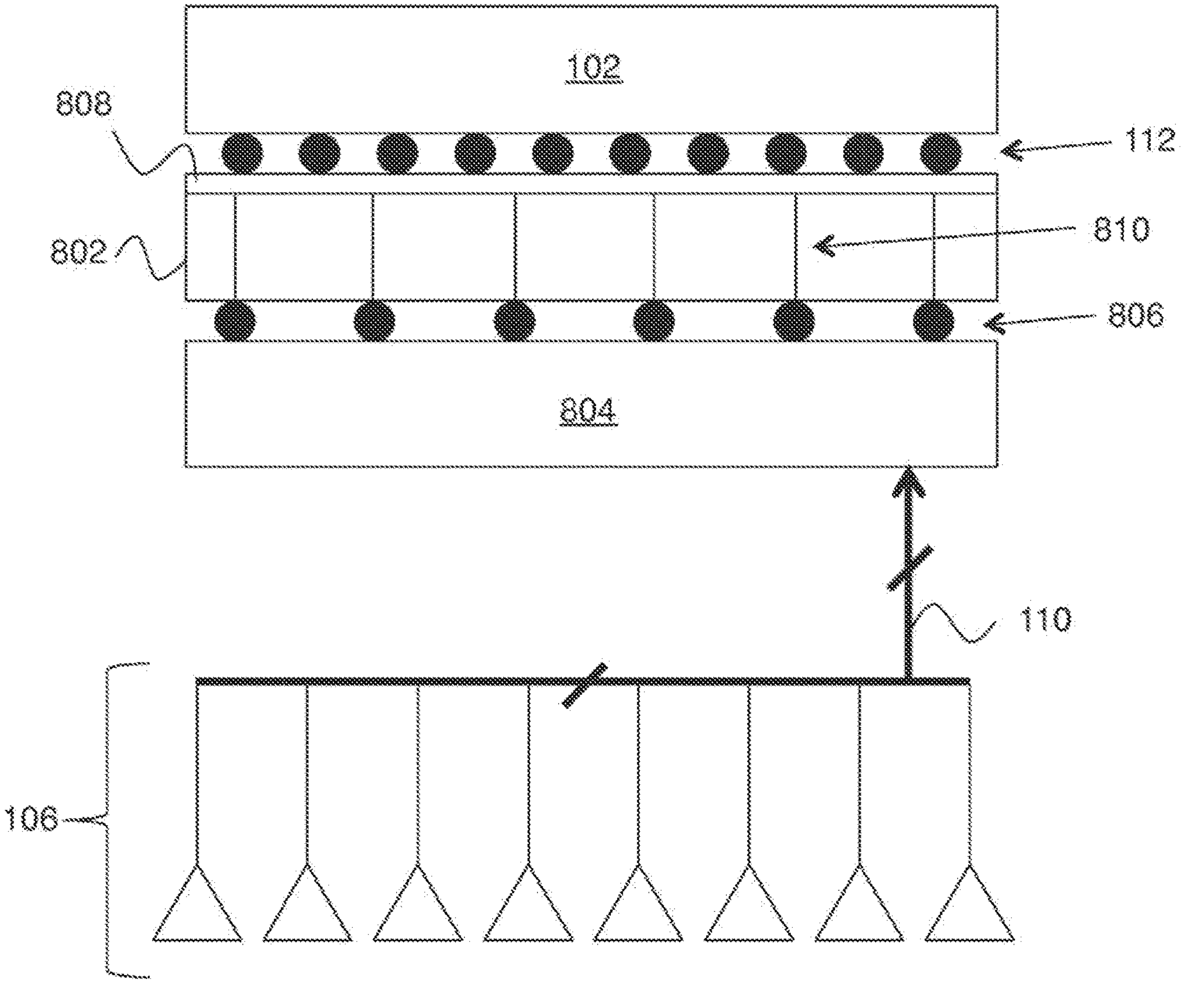


FIG. 8

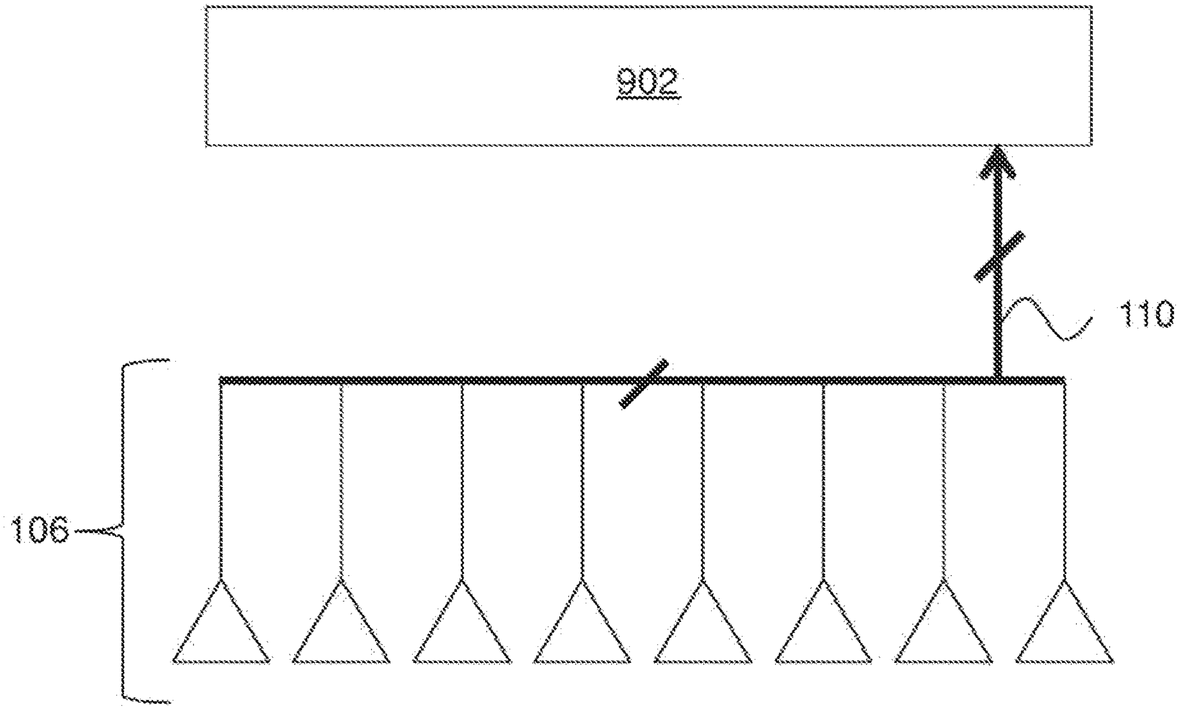


FIG. 9

INTEGRATED SYSTEM FOR ULTRASOUND IMAGING AND THERAPY

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. provisional patent application 62/021,341, filed on Jul. 7, 2014, and hereby incorporated by reference in its entirety.

GOVERNMENT SPONSORSHIP

[0002] This invention was made with Government support under contract number R01HL117740-01A1 awarded by the National Institutes of Health. The Government has certain rights in this invention.

FIELD OF THE INVENTION

[0003] This invention relates to combined ultrasound imaging and therapy.

BACKGROUND

[0004] Ultrasound is used in medicine for both imaging and therapy. However, conventional ultrasound imaging and therapy approaches tend to require different systems for imaging and therapy. This can undesirably lead to increased time in diagnosis and treatment of the patient. Also, a physician may need to use a "best guess" strategy for therapy/stimulation of a particular region because of lack of real-time spatial and anatomical information of the region of interest. Therefore, methods of providing both imaging and therapy with the same system have been considered.

[0005] One example is considered in US 2009/0240148. In this work, the system includes both an imaging array and a therapy array integrated to form a composite array. Thus some parts of the array are dedicated to imaging and other parts of the array are dedicated to therapy.

[0006] Another example is considered in US 2014/0288428. In this work, the system includes a single transducer array used for both imaging and therapy, and all corresponding electronics is monolithically integrated with the transducer array.

SUMMARY

[0007] We have found that known approaches for providing both imaging and therapy in a single ultrasound system have undesirable drawbacks. In cases where a composite imaging array is used, extra complexity may be incurred by having some parts of the array dedicated to imaging and other parts of the array dedicated to therapy. In cases where full monolithic integration is employed, the on-chip power dissipation caused by the relatively high-voltage pulsers used for ultrasound therapy can be excessive.

[0008] This work alleviates the above-described drawbacks by providing a transducer configuration where the electronics includes a per-pixel switch for each transducer element. The switches provide an imaging mode driven completely by on-chip electronics and a therapy mode where off-chip pulsers provide relatively high voltages to the transducer elements.

[0009] Furthermore, it is important that the transducer elements be capacitive micromachined ultrasonic transducer (CMUTs), as opposed to piezoelectric transducers. One reason for this is that CMUTs dissipate far less heat in the therapy mode than piezoelectric transducer do. Another important factor is the surprising ability of a single CMUT design to work well for both imaging and therapy.

[0010] Some design considerations relating to CMUT design for both imaging and therapy follow. Ultrasound imaging has typically used transducers that operate in frequency ranges from 5-15 MHz. Two-dimensional CMUT arrays operating at 5 MHz have been developed to achieve volumetric imaging. The wide bandwidth nature of the transducer (low Q) provides superior imaging qualities due to better image resolution, when compared to conventional piezoelectric transducers.

[0011] However, using the same transducer for therapy has its trade-off—one being inferior penetration performance (typical transducers used for therapeutic application operate at 1 MHz) and the other being the fact that these transducers have a low mechanical Q (high Q devices are desirable for therapeutic application). One way to compensate for the low Q is to use series inductors and tune them to achieve as high a Q possible. The benefit of doing this is the reduced voltage drive requirements of the pulsers. The drive voltage seen by the transducer is Q times amplified allowing for reduced power dissipation by the driving circuit. Such a scheme can make dual-modality of the CMUT system more practical, where, in one mode, we use the wide bandwidth nature of CMUTs to achieve high resolution imaging, and in the other mode, we use the inductors to tune the front end transducers to achieve high Q, allowing for a better therapeutic system.

[0012] This approach has widespread applications. Any ultrasound application that requires simultaneous imaging and HIFU(high intensity focused ultrasound)/therapy capabilities can benefit. For example, applications include ultrasound imaging and neural stimulation.

[0013] Significant advantages are provided. At present, ultrasound imaging and therapy/stimulation usually needs to be done using different devices leading to increased time in diagnosis and treatment of the patient. Also, physicians may need to use a "best guess" strategy to determine the treatment location since it does not have real-time spatial and anatomical information of the region of interest. Use of the present approach will allow one to remove such uncertainties in the actual region of interest and improve the speed of diagnosis/treatment.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] FIG. **1** shows an embodiment of the invention.

[0015] FIG. **2** shows a 2-D array of transducer elements.

[0016] FIG. **3** shows one of the transducer elements of the array of FIG. **2**.

[0017] FIG. **4** shows circuitry to perform ultrasonic therapy with the 2-D array of transducer elements.

[0018] FIG. **5** is a more detailed view of per-pixel circuitry.

[0019] FIG. **6** shows a preferred circuit for mode switching.

[0020] FIG. **7** shows a pixel switch configured to connect or disconnect its corresponding transducer element to a selectable one of the off-chip pulsers.

[0021] FIG. **8** shows another embodiment of the invention.

[0022] FIG. **9** shows a further embodiment of the invention.

DETAILED DESCRIPTION

[0023] This work provides a novel method for integrating ultrasound imaging and therapy (or ultrasound neuromodulation) using the same ultrasound transducer array integrated with electronics. Having the same device for both purposes can be very beneficial. However, there are challenges in incorporating imaging and continuous-wave (CW) or quasi-CW ultrasound application capabilities in a single integrated chip (such as power dissipation, and area requirements). This work provides a solution to these challenges using switches in the integrated circuit that can switch between an imaging mode (Mode I) and a CW/quasi-CW mode (Mode II). The switches enable the use of external off-chip pulsers for Mode II allowing it to outsource the power dissipation to the back-end system.

[0024] A 2D CMUT array can be integrated with an IC (integrated circuit) that includes transceivers for using the integrated chip for imaging. The transceivers include transmit beam-formers that are capable of providing a high voltage (HV) pulse and receivers that signal condition the receive signals from the CMUT array. For Mode I, a single (or very short) HV pulse is used (duty cycle of the pulse is miniscule). However, for Mode II, multiple cycles of HV pulsing is desirable, to increase the time-averaged intensity of the focal spot. This leads to large power dissipation of the IC chip, if on-chip pulsers are used, since there are multiple elements pulsing. Therefore, using on-chip pulsers for Mode II applications is impractical.

[0025] This problem is alleviated by using HV switch(s) in each element, that can route the connection of the ultrasound transducer array element directly to an off-chip HV pulser. Though the overall power dissipation still remains high, the dissipation occurs at the back-end which is not near the patient. Utilizing these switches allow us to switch a single sensor array between Mode I and Mode II. Different elements can be pulsed at different phases to provide focusing in Mode II. In one implementation, we use 8 off-chip pulsers with equally spaced phases and distribute the elements amongst these 8 pulsers to enable focusing at a given spot. With such a configuration, we can use the same integrated array for Mode I as well as for Mode II, as and when desired by the physician when performing a medical procedure.

[0026] FIG. **1** shows an exemplary embodiment of the invention. In this example, a 2-D CMUT array **102** is flip chip bonded (**112**) to chip **104** that includes imaging electronics and the per-pixel switches. Off-chip pulsers **108** provide a high-voltage assembly **106** that is connected to chip **104** via bus **110**. Bus **110** has one line for each pulser **108**.

[0027] FIG. **2** is a plan view of the 2-D array of transducer elements **102**. One of the transducer elements is referenced as **202**. FIG. **2** shows a 6×6 array of transducers, but any other 2D array dimensions can also be used. The low on-chip power dissipation of the present approach can enable large array sizes (e.g., 32×32 or larger). FIG. **3** shows transducer element **202** in more detail. As indicated above, the transducer elements are CMUTs. The general configuration for a CMUT is shown here, with **306** being an elastic membrane suspended above a substrate **302** by one or more support members **304**.

[0028] FIG. **4** shown circuitry to perform ultrasonic therapy with the 2-D array of transducer elements. Here chip **104** is regarded as having cells that correspond to the elements of transducer array **102**. Bus **110** is shown being available at all cells, and one of these cells is referenced as **402**. FIG. **5** is a more detailed view of cell **402**. Here **502** is a flip chip pad that is connected to the corresponding transducer element of transducer array **102**, **504** is the per-pixel switch, **506** is on-chip imaging circuitry, and **508** is an optional inductance in series with the CMUT capacitance that is present in preferred embodiments to provide electrical resonance in the therapy mode.

[0029] Thus an exemplary embodiment of the invention is apparatus for ultrasonic imaging and therapy, where the apparatus includes:

[0030] 1) a 2-D array of transducer elements monolithically integrated on a transducer chip (**102**), wherein each of the transducer elements is a capacitive micromachined ultrasonic transducer (FIG. **3**);

[0031] 2) first electronic circuitry (**506**) configured to perform ultrasonic imaging with the 2-D array of transducer elements, wherein the first electronic circuitry is integrated with the transducer chip (e.g., hybrid integration as on FIGS. **1** and **8**, or monolithic integration as on FIG. **9**);

[0032] 3) second electronic circuitry (**106**) configured to perform ultrasonic therapy with the 2-D array of transducer elements, wherein the second electronic circuitry comprises one or more off-chip pulsers (**108**) disposed remotely from the transducer chip; and

[0033] 4) mode switching circuitry (**504**) configured to switch operation of each of the transducer elements between an ultrasonic imaging mode and an ultrasonic therapy mode.

[0034] As indicated above, it is preferred that the second electronic circuitry include an inductor corresponding to each transducer element configured such that the combination of inductor and transducer element is electrically resonant at the ultrasound therapy frequency. This electrical resonance helps to compensate for the relatively low mechanical Q of the CMUT transducer elements. There are several options for the location of the series inductors. The inductors can be located inside block **504**, e.g., **508** on FIG. **5**. Another option is to have another die with just inductor arrays.

[0035] FIG. **6** shows a preferred circuit **504** for mode switching, without the optional inductor **508**. Here **602** is the control input to the switch, **604** is an input from the corresponding off-chip pulser, and **606** is a connection to the corresponding CMUT transducer element. In the circuit of FIG. **6**, devices D**2**, Q**3**, Q**1** and Q**2** need to be high voltage devices (i.e., capable of handling the voltages provided at input **604** by the pulser), while devices D**1** and Q**4** can be low voltage devices. The net effect of this circuit configuration is to allow a drive voltage to be applied to transistors Q**1** and Q**2** that is greater than the gate-source voltage of any single transistor in the circuit. This configuration can be regarded as a first pair of series-connected transistors and a diode having an output that drives a second pair of series-connected transistors and a reverse-biased diode.

[0036] The off-chip pulsers **108** can be configured to provide inputs having distinct electrical phase. This can provide beam control for ultrasonic therapy. In some cases each pixel switch is configured to connect or disconnect its corresponding transducer element to a predetermined one of the off-chip pulsers. FIG. **5** shows an example of this configuration. The resulting beam forming for therapy is fixed (e.g., focusing in the center of the imaging field of view). In other cases each pixel switch is configured to connect or disconnect its corresponding transducer element to a selectable one of the off-chip pulsers. FIG. **7** shows an example of this configuration, where line switch **702** selects the line of bus **110** that is connected to block **504**. The resulting beam forming for therapy is adjustable. For example, the therapy beam can be brought to a focus at any selected location within the imaging field of view. As another example, the therapy beam could be configured to scan within the imaging field of view along any desired path.

[0037] Practice of the invention does not depend critically on details of how integration is performed, provided that the pulsers for the therapy mode are not integrated with the transducer chip. FIG. **1** shows a two-chip hybrid bonded configuration. In the specific example given above, both the first electronic circuitry (for imaging) and the mode control circuitry (for switching) were included in chip **104**. Other two-chip configurations can be obtained by moving the imaging or switching circuitry to be monolithically integrated with transducer chip **102**. In these cases, chip **104** will have only the switching circuitry or only the imaging circuitry, respectively.

[0038] Three-chip configurations are also possible. FIG. **8** shows an example, where a switch chip **802** and an imaging chip **804** are integrated with transducer array **102**. Here it is assumed that mode switching circuitry **80***e* is on the top side of switch chip **802**, and that through-chip vias **810** are used to connect mode switching circuitry **808** to imaging chip **804**. Imaging chip **804** is flip chip bonded (**806**) to switch chip **802**.

[0039] A final possibility is full monolithic integration of everything except the off-chip pulsers. FIG. **9** shows a example of this approach. Here the first electronic circuitry (for imaging), the second electronic circuitry (except for pulsers **108**) and the mode switching circuitry are all monolithically integrated on transducer chip **902**.

1.-**10**. (canceled)

11. A apparatus for ultrasound imaging and therapy, the apparatus comprising:

an array of ultrasound transducer elements;

means for switching an ultrasound transducer element of the array between an imaging mode and a therapy mode;

imaging circuitry configured to perform ultrasound imaging when the ultrasound transducer element is in the imaging mode; and

a pulser configured to drive the ultrasound transducer element in the therapy mode, wherein the apparatus is arranged such that power associated with the pulser is dissipated remotely from the imaging circuitry.

12. The apparatus of claim **11**, wherein the imaging circuitry is on a chip, and wherein the pulser is located off-chip.

13. The apparatus of claim **11**, wherein the array of ultrasound transducer elements is on a transducer chip, wherein the imaging circuitry is integrated with the transducer chip, and wherein the pulser is external to the transducer chip.

14. The apparatus of claim **13**, wherein the means for switching is on the transducer chip.

15. The apparatus of claim **11**, wherein the means for switching is on a chip, and wherein the pulser is located off-chip.

16. The apparatus of claim **11**, wherein the array of transducer elements is on a first chip, the means for switching and the imaging circuitry is on a second chip, and the first chip is flip chip bonded to the second chip.

17. The apparatus of claim **11**, wherein the array of transducer elements, the means for switching, and the imaging circuitry are monolithically integrated on a chip, and wherein the pulser is external to the chip.

18. The apparatus of claim **11**, further comprising a line switch configured to selectively electrically connect the pulser to the means for switching.

19. The apparatus of claim **11**, wherein the means for switching comprise transistors arranged to pass a voltage from the pulser that is greater than a gate-to-source voltage of any one of the transistors.

20. The apparatus of claim **11**, wherein the ultrasound transducer elements comprise capacitive micromachined ultrasonic transducers (CMUTs).

21. The apparatus of claim **11**, further comprising an inductor connected in series between the means for switching and the ultrasound transducer element, wherein a combination of the inductor and the ultrasound transducer element is electrically resonant at an ultrasound frequency of the therapy mode.

22. The apparatus of claim **11**, further comprising additional means for switching ultrasound transducer elements of the array between the imaging mode and the therapy mode, wherein each of the ultrasound transducer elements of the array is connected to the means for switching or the additional means for switching.

23. The apparatus of claim **11**, wherein the array of ultrasound transducers elements generates continuous wave ultrasound or quasi-continuous wave ultrasound in the therapy mode.

24. The apparatus of claim **11**, further comprising additional pulsers, wherein the pulser and the additional pulsers have electrical phases spaced with each other to focus a therapy beam generated by the array of ultrasound transducer elements for the therapy mode.

25. A method of operating an array of ultrasound transducers in an imaging mode and a therapy mode, the method comprising:

performing ultrasound imaging with the array of ultrasound transducers in the imaging mode;

connecting a pulser to an ultrasound transducer of the array of ultrasound transducers in the therapy mode, wherein the ultrasound transducer produces a continuous wave of ultrasound or a quasi-continuous wave of ultrasound in the therapy mode; and

dissipating power from the pulser external to a chip that includes the array of ultrasound transducers, wherein the pulser in external to the chip.

26. The method of claim **25**, further comprising adjusting a therapy beam transmitted from the array of ultrasonic transducers during the therapy mode.

27. The method of claim **26**, wherein the therapy beam is focused at a selected location.

28. The method of claim **25**, further comprising connecting the ultrasound transducer of the array of ultrasonic transducers to another pulser using a switch and a line switch, wherein the switch is configured to connect the line switch and the ultrasound transducer, and wherein the line switch is configured to connect the switch to a selected one of a plurality of pulsers, and wherein the plurality of pulsers comprises the pulser and the other pulser.

29. The method of claim **25**, wherein the ultrasound transducers are capacitive micromachined ultrasonic transducers (CMUTs).

30. An apparatus comprising:

an array of capacitive ultrasonic transducer elements;

imaging circuitry on a chip, the imaging circuitry configured to perform ultrasound imaging with the capacitive ultrasonic transducer elements in an ultrasound imaging mode of the capacitive ultrasonic transducer elements;

a plurality of pulsers external to the chip, the plurality of pulsers configured to provide voltages with electrical phases spaced with each other in an ultrasonic therapy mode of the capacitive ultrasonic transducer elements; and

switches configured to the mode switching circuitry configured to switch operation of the capacitive ultrasonic transducer elements between the ultrasonic imaging mode and the ultrasonic therapy mode by switching connections between the capacitive ultrasonic transducer elements and the plurality of pulsers.

* * * * *