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(54) **INDUCTIVE TUNING SYSTEM FOR ULTRASOUND TRANSDUCER**

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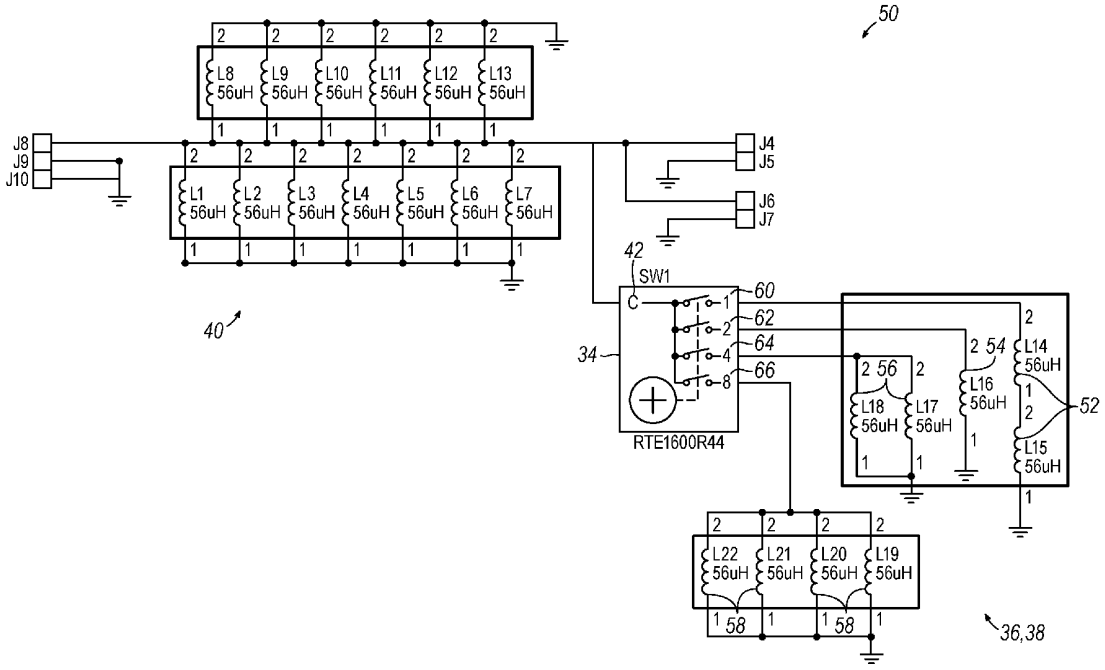
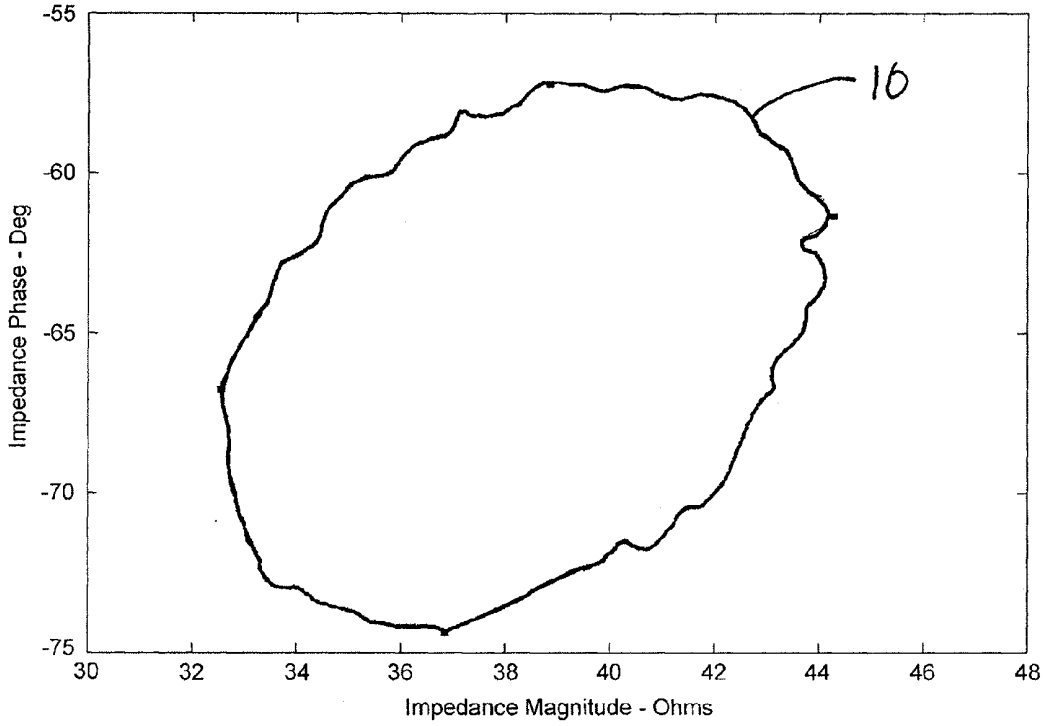
(57) **ABSTRACT**

Medical devices are disclosed that include a tunable ultrasonic transducer assembly, as well as related assemblies and methods. A medical device includes a transducer controller, a transducer having an input side connected with the ultrasound transducer controller via an input electrical conductor, and a tuning assembly that is electrically connected between the input electrical conductor and the ground potential. The tuning assembly is adjustable to provide a selected inductance from a number of different inductance values. The tuning assembly includes a multi-position switch and a plurality of tuning inductors. The switch is operable to select combinations of tuning inductors, thereby providing a selected inductance value between the input electrical connector and the ground potential so as inductively tune the medical device.




16
-55
-60
-65
-70
-75
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32
34
36
38
40
42
44
46
48
Impedance Phase - Deg
Impedance Magnitude - Ohms

FIG. 1

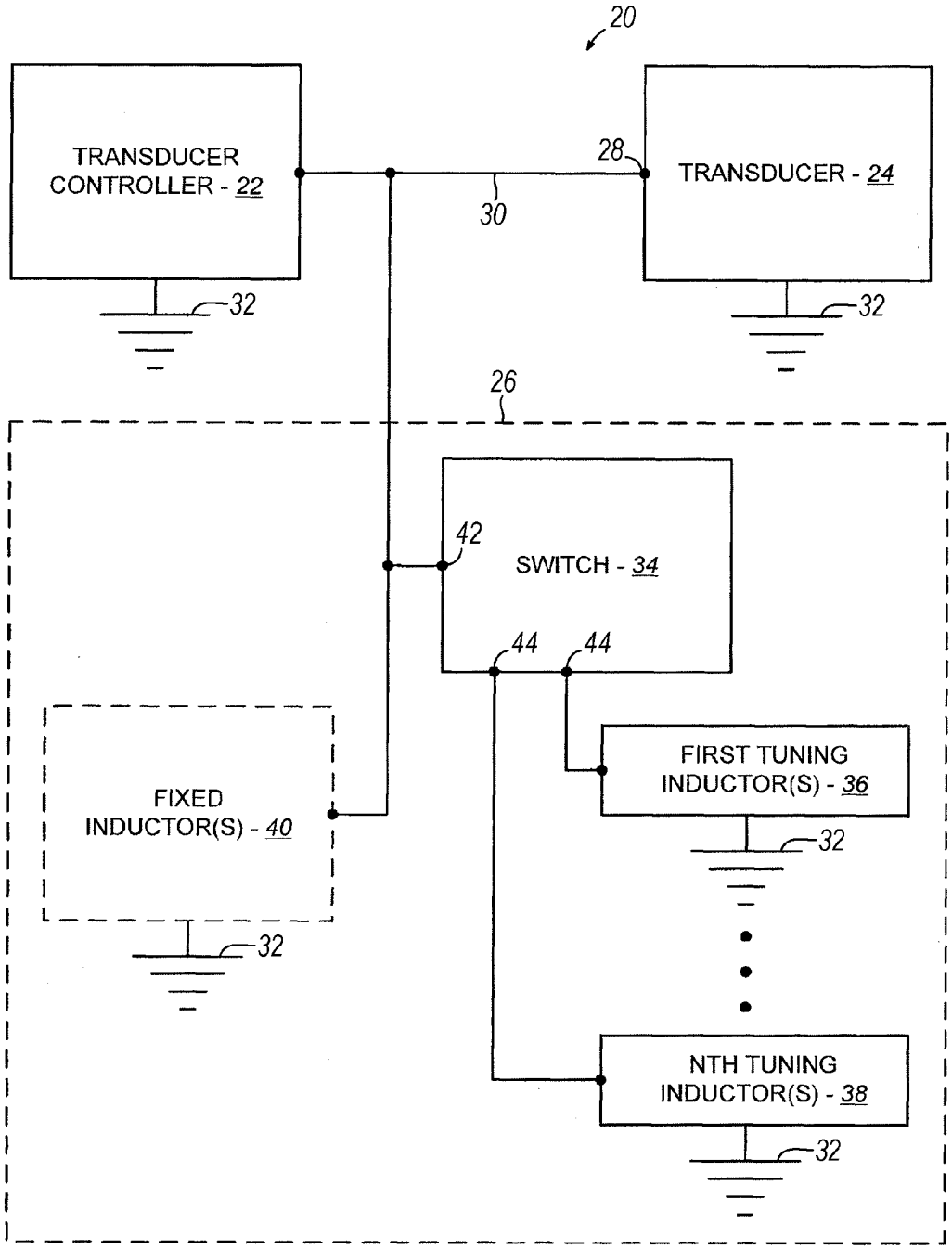
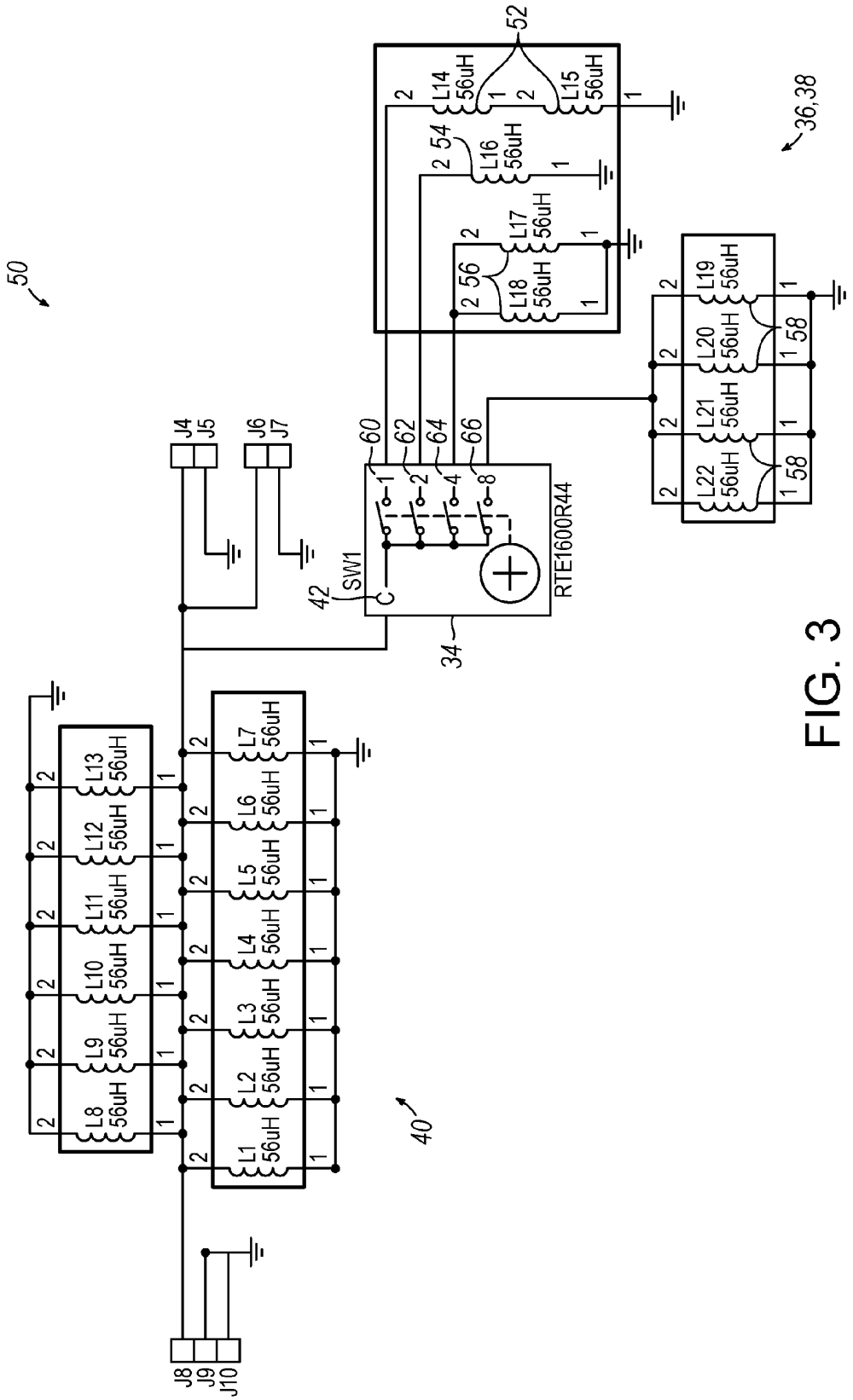

20
TRANSDUCER CONTROLLER - 22
28
TRANSDUCER - 24
30
32
32
26
42
SWITCH - 34
44
44
FIXED INDUCTOR(S) - 40
32
FIRST TUNING INDUCTOR(S) - 36
32
NTH TUNING INDUCTOR(S) - 38
32

FIG. 2


50
52
36,38
L14 56uH
L15 56uH
L16 56uH
L17 56uH
L18 56uH
54
56
L19 56uH
L20 56uH
L21 56uH
L22 56uH
58
J4
J5
J6
J7
60
62
64
66
SW1
42
RTE1600R44
34
L13 56uH
L12 56uH
L11 56uH
L10 56uH
L9 56uH
L8 56uH
L7 56uH
L6 56uH
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40
J8
J9
J10

FIG. 3

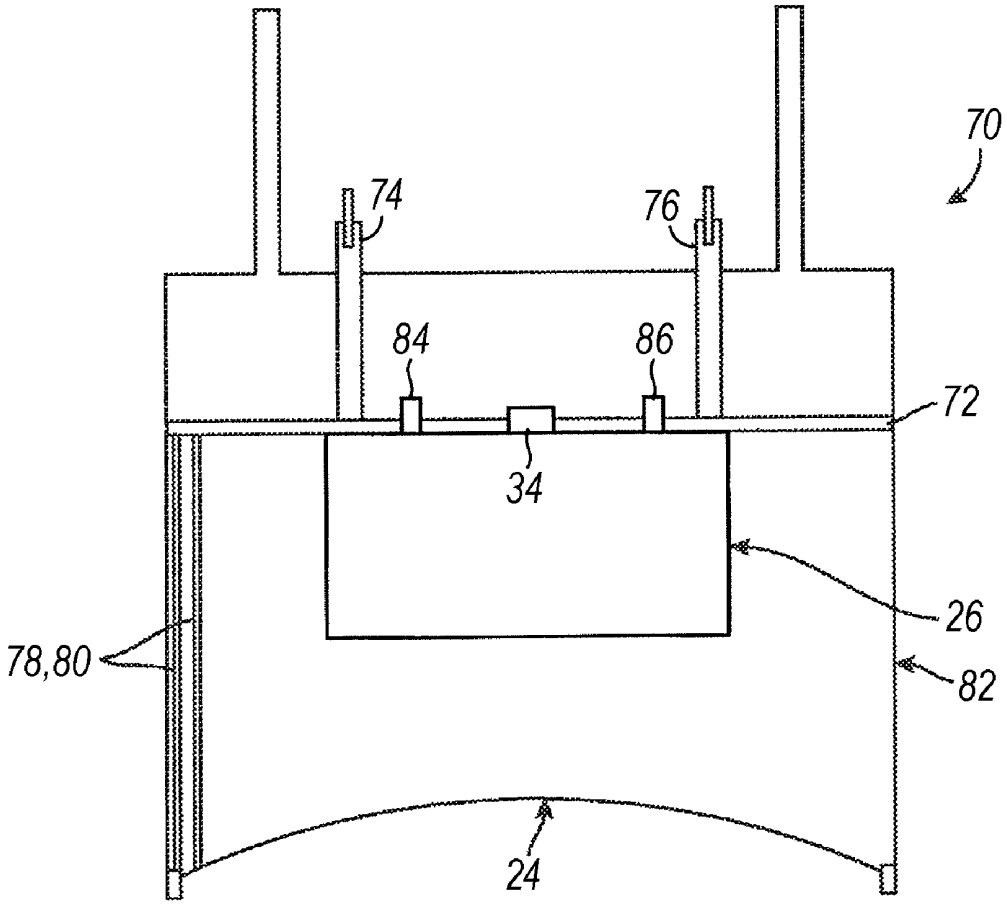

FIG. 4

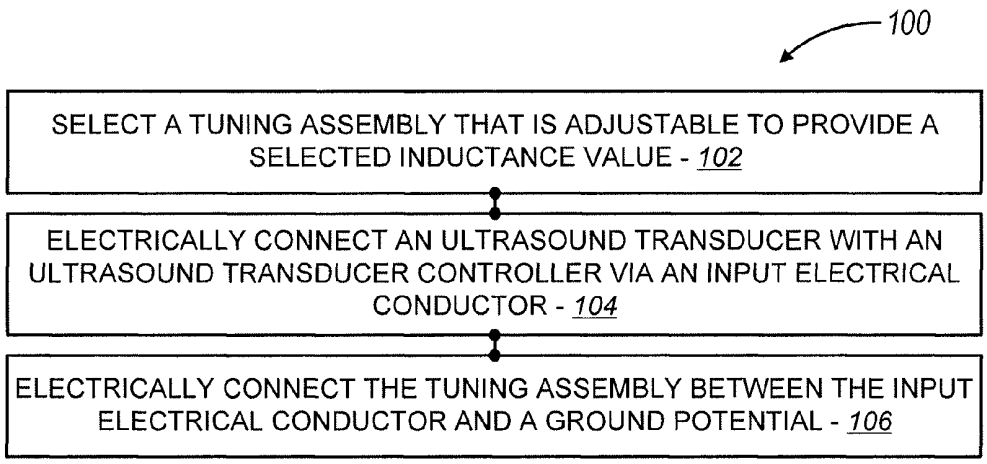
100
SELECT A TUNING ASSEMBLY THAT IS ADJUSTABLE TO PROVIDE A SELECTED INDUCTANCE VALUE - 102
ELECTRICALLY CONNECT AN ULTRASOUND TRANSDUCER WITH AN ULTRASOUND TRANSDUCER CONTROLLER VIA AN INPUT ELECTRICAL CONDUCTOR - 104
ELECTRICALLY CONNECT THE TUNING ASSEMBLY BETWEEN THE INPUT ELECTRICAL CONDUCTOR AND A GROUND POTENTIAL - 106

FIG. 5

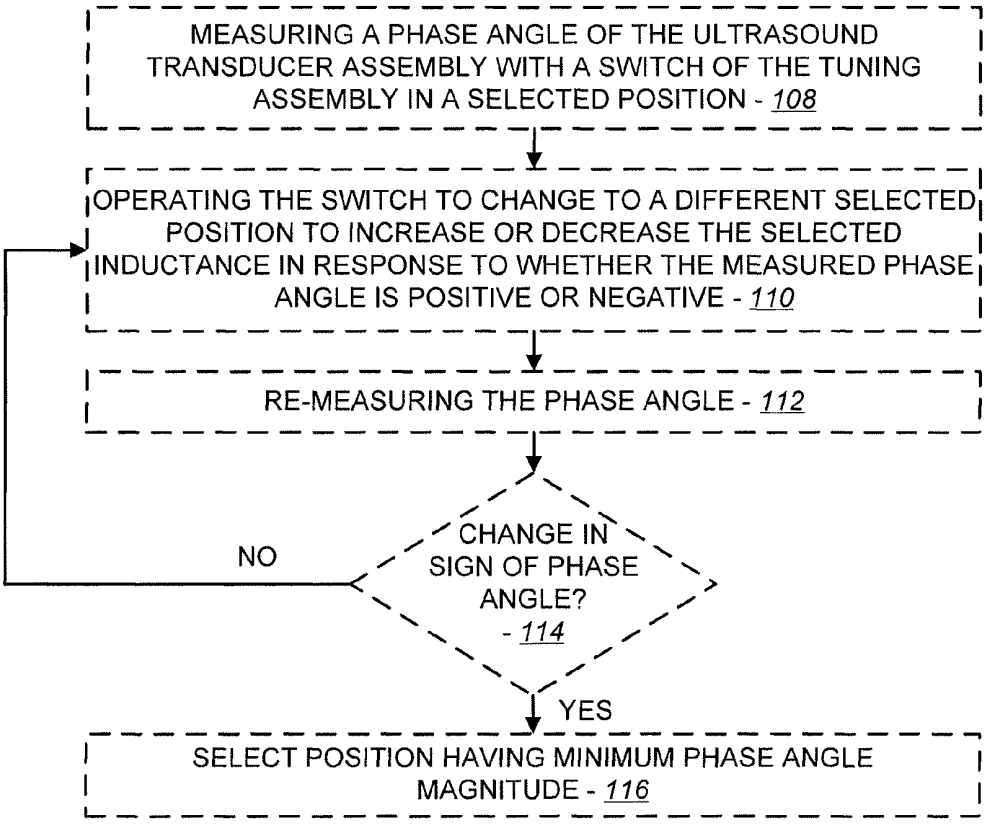
MEASURING A PHASE ANGLE OF THE ULTRASOUND TRANSDUCER ASSEMBLY WITH A SWITCH OF THE TUNING ASSEMBLY IN A SELECTED POSITION - 108
OPERATING THE SWITCH TO CHANGE TO A DIFFERENT SELECTED POSITION TO INCREASE OR DECREASE THE SELECTED INDUCTANCE IN RESPONSE TO WHETHER THE MEASURED PHASE ANGLE IS POSITIVE OR NEGATIVE - 110
RE-MEASURING THE PHASE ANGLE - 112
CHANGE IN SIGN OF PHASE ANGLE? - 114
NO
YES
SELECT POSITION HAVING MINIMUM PHASE ANGLE MAGNITUDE - 116

FIG. 6

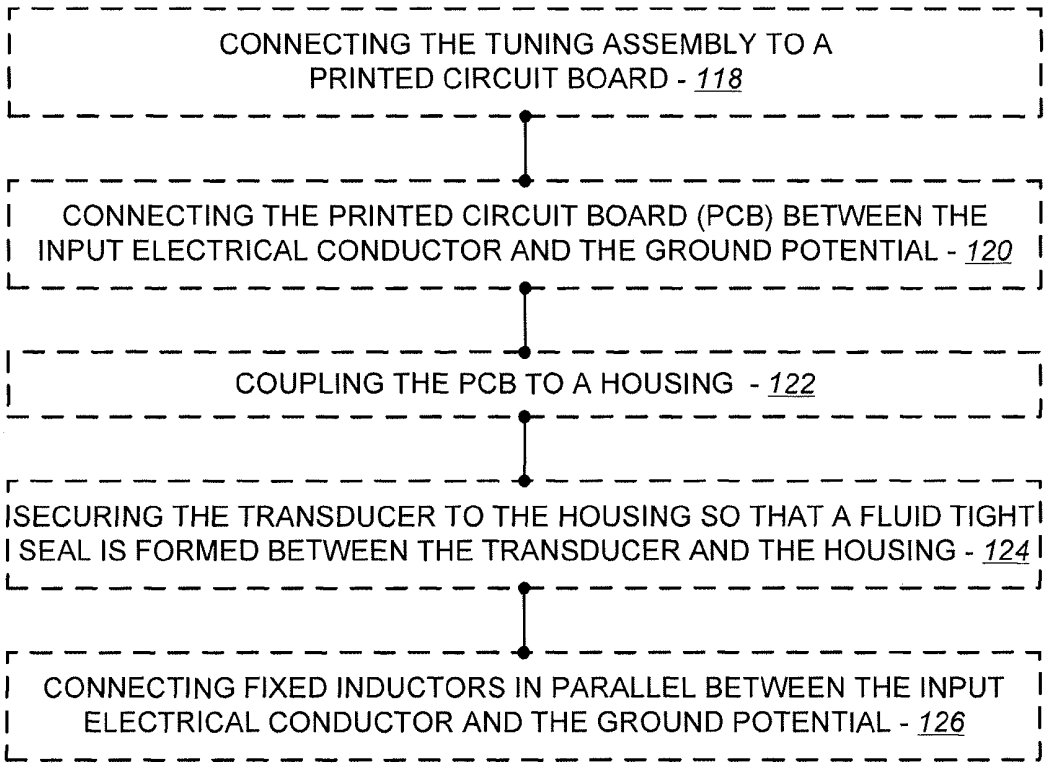
CONNECTING THE TUNING ASSEMBLY TO A PRINTED CIRCUIT BOARD - 118
CONNECTING THE PRINTED CIRCUIT BOARD (PCB) BETWEEN THE INPUT ELECTRICAL CONDUCTOR AND THE GROUND POTENTIAL - 120
COUPLING THE PCB TO A HOUSING - 122
SECURING THE TRANSDUCER TO THE HOUSING SO THAT A FLUID TIGHT SEAL IS FORMED BETWEEN THE TRANSDUCER AND THE HOUSING - 124
CONNECTING FIXED INDUCTORS IN PARALLEL BETWEEN THE INPUT ELECTRICAL CONDUCTOR AND THE GROUND POTENTIAL - 126

FIG. 7

INDUCTIVE TUNING SYSTEM FOR ULTRASOUND TRANSDUCER

BACKGROUND

[0001] Ultrasonic medical systems, such as ultrasonic diagnostic imaging systems and ultrasonic therapeutic systems, are in widespread use. Ultrasonic diagnostic imaging systems are used to perform ultrasonic imaging and measurements. For example, cardiologists, radiologists, and obstetricians use ultrasonic imaging systems to examine the heart, various abdominal organs, or a developing fetus, respectively. Diagnostic images are obtained from these systems by placing a scan head against the skin of a patient, and actuating an ultrasonic transducer located within the scan head to transmit ultrasonic energy through the skin and into the body of the patient. In response, ultrasonic echoes are reflected from the interior structure of the body, and the returning acoustic echoes are converted into electrical signals by the transducer in the scan head. Ultrasonic therapeutic systems apply ultrasonic emissions to a patient to produce a therapeutic effect, such as a cosmetic therapeutic effect involving the destruction an adipose tissue as described in U.S. Pat. No. 7,993,289, entitled "Systems and Methods for the Destruction of Adipose Tissue," the entire disclosure of which is hereby incorporated by reference herein.

[0002] For an ultrasound system, the ideal impedance of a source (system based pulser and receiver) used to drive an ultrasound transducer depends on the impedance characteristics of the ultrasound transducer, with a resulting phase angle of zero degrees being ideal. The impedance values of ultrasound transducers, however, vary from unit to unit to some degree. Existing approaches for tuning a source to a transducer can be inconvenient (e.g., labor intensive). Additionally, high intensity ultrasound systems, such as used in some ultrasonic therapeutic systems, use power levels which may, over time, damage existing tuning networks.

[0003] Accordingly, improved approaches for inductively tuning an ultrasonic system are desirable. For example, improved approaches for tuning ultrasonic systems to account for the impedance characteristics of the particular ultrasound transducer employed are desirable. And improved tuning assemblies that can withstand prolonged exposure to the high power levels used in high intensity ultrasound systems are desirable.

BRIEF SUMMARY

[0004] The following presents a simplified summary of some embodiments of the invention in order to provide a basic understanding of the invention. This summary is not an extensive overview of the invention. It is not intended to identify key/critical elements of the invention or to delineate the scope of the invention. Its sole purpose is to present some embodiments of the invention in a simplified form as a prelude to the more detailed description that is presented later.

[0005] Tuning assemblies and related methods are disclosed for inductively tuning ultrasonic systems. The disclosed tuning assemblies and related methods can be used to in conjunction with ultrasound transducer configurations that exhibit unit to unit variation in impedance characteristics so as to adjust the impedance of the ultrasonic system appropriate to the impedance characteristics of the ultrasound transducer used in a particular ultrasonic system. The disclosed tuning assemblies and related methods provide for fast and convenient tuning of ultrasonic systems. And the disclosed tuning systems and methods may better tolerate the high power levels used to drive high intensity ultrasound transducers as compared to existing tuning networks.

[0006] Thus, in one aspect, an adjustable tuning network for a high intensity ultrasonic transducer is provided. The tuning network includes inductors and a multi-position (e.g., 16) rotary switch. The tuning network provides impedance matching for the transducer. The switch is used to vary the amount of inductance placed in parallel with the transducer to minimize phase angle. Tuning is accomplished by coupling the transducer to water and working through the rotary switch positions until the phase angle is closest to zero. The network primarily tunes phase angle.

[0007] In another aspect, a method is provided for forming a tuned ultrasound transducer assembly and assembling the tuned ultrasound transducer assembly into a medical device. The method includes selecting a tuning assembly that is adjustable to provide a selected inductance value from at least three different inductance values, electrically connecting an ultrasound transducer controller of the medical device with an input side of a transducer via an input electrical conductor, and electrically connecting the tuning assembly between the input electrical conductor and a ground potential so as to provide the selected inductance between the input electrical conductor and the ground potential. The ultrasound transducer controller and the transducer are electrically coupled with the ground potential. At least one of the at least three different inductance values is appropriate to the operation of the transducer. The transducer is operable to produce a cyclic sound pressure output with a frequency of at least 20 kilohertz. The tuning assembly includes a switch and a plurality of tuning inductors. The switch includes a first connection and a plurality of second connections. The switch has at least three positions, each position being operable to selectively connect the first connection with any one of at least three different combinations of the second connections including a combination connecting the first connection with at least two of the second connections. Each of the second connections is connected to at least one of the tuning inductors so that the switch is operable to select which subset of the tuning inductors is connected to the first connection so as to provide the selected inductance value. The switch can include a position selection feature that is rotated to select one of the positions.

[0008] In many embodiments, the tuning assembly is adjustable to provide the selected inductance value from at least six different inductance values, at least one of the six different inductance values being appropriate to the operation of the transducer. And the switch can include at least three of the second connections and have at least six positions, each of the six positions being operable to selectively connect the first connection with any one of at least six different combinations of the second connections.

[0009] In many embodiments, the tuning assembly is adjustable to provide the selected inductance value from at least ten different inductance values, at least one of the ten different inductance values being appropriate to the operation of the transducer. And the switch can have four to six of the second connections and have at least ten positions, each of the ten positions being operable to selectively connect the first connection with any one of at least ten different combinations of the second connections.

[0010] In many embodiments, the tuning assembly is adjustable to provide the selected inductance value from at least twelve different inductance values, at least one of the twelve different inductance values being appropriate to the operation of the transducer. And the switch can have four or five of the second connections and have at least twelve positions, each of the twelve positions being operable to selectively connect the first connection with any one of at least twelve different combinations of the second connections.

[0011] In many embodiments, the tuning assembly is adjustable to provide the selected inductance value from at least sixteen different inductance values, at least one of the sixteen different inductance values being appropriate to the operation of the transducer. And the switch can include at least four of the second connections and have at least sixteen positions, each of the sixteen positions being operable to selectively connect the first connection with any one of at least sixteen different combinations of the second connections.

[0012] The method can further include additional acts relating to the selection of a position for the tuning assembly switch. For example, the method can include: (a) measuring a phase angle of the ultrasound transducer assembly with the switch in a selected position; (b) operating the switch to change the switch to a different selected position to increase or decrease the selected inductance in response to whether the measured phase angle is positive or negative; (c) subsequent to act (b), re-measuring the phase angle of the ultrasound transducer assembly; and (d) repeating acts (b) and (c) until a change in sign of the measured phase angles occurs. And the method can include selecting a position for the switch that minimizes an absolute magnitude of the corresponding measured phase angle.

[0013] The method can include electrically connecting the tuning assembly to a printed circuit board (PCB) and electrically connecting the PCB between the input electrical conductor and the ground potential. The PCB can have a first lead and a second lead so that the PCB first lead and the tuning assembly switch first connection are electrically connected and the PCB second lead is electrically connected with the tuning inductors, each of the tuning inductors being electrically connected between the PCB second lead and a corresponding connection of the switch second connections. The PCB first lead and the input electrical conductor can be electrically connected and the PCB second lead and the ground potential can be electrically connected. Alternatively, the PCB first lead and the ground potential can be electrically connected and the PCB second lead and the input electrical conductor can be electrically connected. The PCB can be coupled to a housing. And the transducer can be secured to the housing so that a fluid tight seal is formed between the transducer and the housing.

[0014] In many embodiments, the transducer includes a high intensity focused ultrasound (HIFU) transducer operable to produce ultrasound output having a power level of at least 1 Watt average and typically higher than 10 Watts average to achieve a therapeutic effect in a timely manner. Peak power levels can range from the average power to many multiples of the average power to, for example, take advantage of non-linear effects such as associated heating. And the tuning assembly can include an inductor having an open core construction, which may better tolerate the power levels used to operate the HIFU transducer.

[0015] In many embodiments, the method further includes electrically connecting a plurality of fixed inductors in parallel between the input electrical conductor and the ground potential to provide a fixed inductance value between the input electrical conductor and the ground potential. The fixed inductance value and the selectable inductance values can have suitable values. For example, in many embodiments the fixed inductance value can be between 2.0 uH and 7.0 uH and the range of selectable inductance values can be within a range suitable for a particular transducer configuration, for example, between 0.15 uH and 150 uH.

[0016] In another aspect, a medical device having a tunable ultrasound transducer assembly is provided. The medical device includes an ultrasound transducer controller electrically connected with a ground potential, a transducer having an input side connected with the ultrasound transducer controller via an input electrical conductor, and a tuning assembly that is electrically connected between the input electrical conductor and the ground potential. The transducer is operable to produce a cyclic sound pressure output with a frequency of at least 20 kilohertz. The transducer is electrically connected with the ground potential. The tuning assembly is adjustable to provide a selected inductance from at least three different inductance values, at least one of the at least three different inductance values being appropriate to the operation of the transducer. The tuning assembly includes a switch and a plurality of tuning inductors. The switch includes a first connection and a plurality of second connections. The switch has at least three positions, each position being operable to selectively connect the first connection with any one of at least three different combinations of the second connections including a combination connecting the first connection with at least two of the second connections. Each of the second connections is connected to at least one of the tuning inductors so that the switch is operable to select which subset of the tuning inductors is connected to the first connection so as to provide the selected inductance value. The switch can include a position selection feature that is rotated to select one of the positions.

[0017] In many embodiments, the medical device tuning assembly is adjustable to provide the selected inductance value from at least six different inductance values, at least one of the six different inductance values being appropriate to the operation of the transducer. And the switch can include at least three of the second connections and have at least six positions, each of the six positions being operable to selectively connect the first connection with any one of at least six different combinations of the second connections.

[0018] In many embodiments, the medical device tuning assembly is adjustable to provide the selected inductance value from at least ten different inductance values, at least one of the ten different inductance values being appropriate to the operation of the transducer. And the switch can have four to six of the second connections and have at least ten positions, each of the ten positions being operable to selectively connect the first connection with any one of at least ten different combinations of the second connections.

[0019] In many embodiments, the medical device tuning assembly is adjustable to provide the selected inductance value from at least twelve different inductance values, at least one of the twelve different inductance values being appropriate to the operation of the transducer. And the switch can have four or five of the second connections and have at least twelve positions, each of the twelve positions being operable to

selectively connect the first connection with any one of at least twelve different combinations of the second connections.

[0020] In many embodiments, the medical device tuning assembly is adjustable to provide the selected inductance value from at least sixteen different inductance values, at least one of the sixteen different inductance values being appropriate to the operation of the transducer. And the switch can include at least four of the second connections and have at least sixteen positions, each of the sixteen positions being operable to selectively connect the first connection with any one of at least sixteen different combinations of the second connections.

[0021] The medical device can include a housing and a printed circuit board (PCB) coupled with the housing. In many embodiments, the transducer is secured to the housing so that a fluid tight seal is formed between the transducer and the housing. The PCB can have a first lead and a second lead so that the PCB first lead and the tuning assembly switch first connection are electrically connected and the PCB second lead is electrically connected with the tuning inductors, each of the tuning inductors being electrically connected between the PCB second lead and a corresponding connection of the switch second connections. The PCB first lead and the input electrical conductor can be electrically connected and the PCB second lead and the ground potential can be electrically connected. Alternatively, the PCB first lead and the ground potential can be electrically connected and the PCB second lead and the input electrical conductor can be electrically connected.

[0022] In many embodiments, the medical device transducer includes a high intensity focused ultrasound (HIFU) transducer operable to produce ultrasound output having a power level of at least 1 Watt average and typically higher than 10 Watts average to achieve a therapeutic effect in a timely manner. Peak power levels can range from the average power to many multiples of the average power to, for example, take advantage of non-linear effects such as associated heating. And the medical device tuning assembly can include an inductor having an open core construction, which may better tolerate the power levels used to operate the HIFU transducer.

[0023] In many embodiments, the medical device includes a plurality of fixed inductors connected in parallel between the input electrical conductor and the ground potential to provide a fixed inductance value between the input electrical conductor and the ground potential. The fixed inductance value and the selected inductance value can have suitable values. For example, in many embodiments the fixed inductance value can be between 2.0 uH and 7.0 uH and the range of selectable inductance values can be within a range suitable for a particular transducer configuration, for example, between 0.15 uH and 150 uH.

[0024] For a fuller understanding of the nature and advantages of the present invention, reference should be made to the ensuing detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] FIG. **1** illustrates how the impedance characteristics of an exemplary ultrasound transducer configuration can vary from unit to unit.

[0026] FIG. **2** schematically illustrates a tunable ultrasound transducer assembly, in accordance with many embodiments.

[0027] FIG. **3** schematically illustrates a tuning assembly for inductively tuning an ultrasonic system, in accordance with many embodiments.

[0028] FIG. **4** shows a sectional view illustrating a tunable ultrasound transducer assembly, in accordance with many embodiments.

[0029] FIG. **5** shows acts of a method for forming a tuned ultrasound transducer assembly, in accordance with many embodiments.

[0030] FIG. **6** shows optional acts that can be used in conjunction with the method of FIG. **5** to tune the ultrasound transducer assembly, in accordance with many embodiments.

[0031] FIG. **7** shows additional optional acts that can be used in conjunction with the method of FIG. **5**, in accordance with many embodiments.

DETAILED DESCRIPTION

[0032] In the following description, various embodiments of the present invention will be described. For purposes of explanation, specific configurations and details are set forth in order to provide a thorough understanding of the embodiments. However, it will also be apparent to one skilled in the art that the present invention can be practiced without the specific details. Furthermore, well-known features may be omitted or simplified in order not to obscure the embodiment being described.

[0033] Referring now to the drawings, in which like reference numerals represent like parts throughout the several views, FIG. **1** shows the results of a tolerance analysis of the un-tuned impedance of a high intensity focused ultrasound (HIFU) transducer configuration in the form of a contour **10** in P2 impedance space enclosing a region with 99% probability of occurrence. As illustrated, the unit to unit un-tuned impedance within this 99% probability population can vary significantly, for example, from impedance magnitudes from about 32.5 Ohms to about 44 Ohms and from impedance phase angles of about −57 degrees to about −74 degrees. The HIFU transducer configuration has a center frequency of 2.15 MHz+/−3.2%.

[0034] FIG. **2** schematically illustrates a tunable ultrasound transducer assembly **20**, in accordance with many embodiments, that includes a transducer controller **22**, a transducer **24**, and a tuning assembly **26** that can be used to compensate for unit to unit variation in impedance characteristics of the transducer **24**, for example, the unit to unit impedance characteristic variations as shown in FIG. **1**. An input side of the transducer **28** is electrically coupled with the transducer controller **22** via an input electrical conductor **30**. Each of the transducer controller **22** and the transducer **24** are electrically coupled with a ground potential **32**, thereby completing a circuit by which the transducer controller **22** drives the transducer **24**.

[0035] The tuning assembly **26** is adjustable to provide a selected inductance value between the input electrical conductor **30** and the ground potential **32** so that a phase angle of a signal used to drive the transducer **24** can be adjusted to be close to zero degrees. The tuning assembly **26** includes a switch **34** (e.g., a rotary Dual In-Line Package (DIP) switch), a plurality of tuning inductors (one or more first tuning inductors **36** through one or more n^{th} tuning inductors **38**), and optionally one or more fixed inductors **40**. Each of the one or more first tuning inductors **36** through the one or more n^{th} tuning inductors **38** can include, for example, a single inductor, two or more inductors connected in series, two or more inductors connected in parallel, and any suitable combination of single, series, and/or parallel connected inductors.

[0036] The switch **34** includes a first connection **42** and a plurality of second connections **44**. The second connections **44** are connected to the one or more first tuning inductor(s) **36** through the one or more n^{th} tuning inductor(s) **38**. In many embodiments, the switch **34** has multiple positions including positions that connect the first connection **42** to only one of the second connections **44** and one or more positions that connect the first connection **42** to two or more of the second connections **44**, thereby increasing the number of possible inductance values that can be connected to and between the input electrical conductor **30** and the ground potential **32**.

[0037] Accordingly, the switch **34** is operable to connect a selected combination of the one or more first tuning inductors **36** through the one or more n^{th} tuning inductors **38** to and between the input electrical conductor **30** and the ground potential **32**. For example, in many embodiments, the switch **34** has a configuration (i.e., a position) that connects only the first tuning inductor(s) **36** to and between the input electrical conductor **30** and the ground potential **32**, additional positions that each connect one of the second through the n^{th} tuning inductors to and between the input electrical conductor **30** and the ground potential **32**, and yet one or more additional positions that each connects a different combination of the first through the n^{th} tuning inductors to and between the input electrical conductor **30** and the ground potential **32**. In many embodiments, the one or more first tuning inductor(s) **36** through the one or more n^{th} tuning inductor(s) **38** are selected so that each of the one or more first tuning inductor(s) **36** through the one or more n^{th} tuning inductor(s) **32** provides a different inductance value between the switch **34** and the ground potential **32**.

[0038] In many embodiments, the tuning assembly **26** includes the one or more fixed inductor(s) **40**. The combination of the fixed inductance provided by the one or more fixed inductor(s) **40** and the range of selectable inductances provided by the switch **34** and the tuning inductors covers a desired range of total inductances suitable for the expected range of un-tuned transducer impedances for a population of transducers.

[0039] The tuning assembly **26** can be configured for use with a transducer operating at a relatively high power level (e.g., greater than 1 Watt average and typically greater than 10 Watts average), such as with a high intensity focused ultrasound (HIFU) transducer used in a therapeutic ultrasound system. For example, in many embodiments, the fixed inductors **40** include two or more inductors connected in parallel so as to reduce the current that any one of the fixed inductors is exposed to, thereby increasing the resulting life of the fixed inductors by reducing the power (and the resulting heat) generated by the fixed inductors. Likewise, the tuning inductors can also be to connected in series or parallel to a suitable extent so as to reduce the voltage or current that any one of the tuning inductors is exposed to, thereby increasing the resulting life of the tuning inductors by reducing the power (and resulting heat) generated by the tuning inductors. And the tuning assembly **26** can use inductors (for the fixed and/or the tuning inductors) having an open-core configuration, which are typically used for large rating power converters and may better tolerate the current levels associated with the operation of a high intensity ultrasound transducer as compared to inductors having a non-open-core configuration.

[0040] FIG. **3** schematically illustrates a tuning assembly **50** for inductively tuning an ultrasonic system, in accordance with many embodiments. The tuning assembly **50** is constructed in conformance with the above-described tuning assembly **26** of FIG. **2**, but includes a specific configuration that provides an example of how the fixed inductor(s) **40**, the switch **34**, and the tuning inductors **36**, **38** can be configured to provide the tuning assembly **50** with excellent adjustability (e.g., 16 different selectable inductances) as well as the capability for use with a high intensity ultrasound transducer system due to the use of open-core inductors connected in parallel.

[0041] The fixed inductors **40** include thirteen 56 uH open-core inductors (e.g., Coilcraft part number ME3220-563KLB) connected in parallel. Accordingly, the thirteen fixed inductors provide an equivalent inductance of 4.31 uH. In many embodiments, surface mount inductors are used because they are suitable for automated assembly and are state of the art.

[0042] The tuning inductors **36**, **38** include nine 56 uH open-core inductors connected in the illustrated ways, including two first tuning inductors **52** connected in series, a single second tuning inductor **54**, two third tuning inductors **56** connected in parallel, and four fourth tuning inductors **58** connected in parallel. The two first tuning inductors **52** provide a combined inductance of 112 uH. The two third tuning inductors **56** provide an equivalent inductance of 28 uH. And the four fourth tuning inductors **58** provide an equivalent inductance of 14 uH.

[0043] The switch **34** is an RTE1600R44 low profile rotary dual in-line package (DIP) switch having 16 positions with a hexadecimal code switch function. The switch **34** includes a first connection **42** and four second connections **60**, **62**, **64**, **66**. Table 1 below illustrates the connections between the first connection **42** and the four second connections **60**, **62**, **64**, **66**, as well as the resulting tuning inductance and total inductance, for each of the 16 positions.

TABLE 1

Tuning Inductance and Total Inductance by Switch Position

Switch Position	First Tuning Inductors - 52	Second Tuning Inductor - 54	Third Tuning Inductors - 56	Fourth Tuning Inductors - 58	Tuning Inductance	Total Inductance
0	open	open	open	open	open	4.31 uH
1	114 uH	open	open	open	114 uH	4.15 uH
2	open	56 uH	open	open	56.00 uH	4.00 uH
3	114 uH	56 uH	open	open	37.55 uH	3.86 uH
4	open	open	28 uH	open	28.00 uH	3.73 uH
5	114 uH	open	28 uH	open	22.48 uH	3.61 uH
6	open	56 uH	28 uH	open	18.67 uH	3.50 uH
7	114 uH	56 uH	28 uH	open	16.04 uH	3.40 uH

TABLE 1-continued

Tuning Inductance and Total Inductance by Switch Position

Switch Position	First Tuning Inductors - 52	Second Tuning Inductor - 54	Third Tuning Inductors - 56	Fourth Tuning Inductors - 58	Tuning Inductance	Total Inductance
8	open	open	open	14 uH	14.00 uH	3.29 uH
9	114 uH	open	open	14 uH	12.47 uH	3.20 uH
10	open	56 uH	open	14 uH	11.20 uH	3.11 uH
11	114 uH	56 uH	open	14 uH	10.20 uH	3.03 uH
12	open	open	28 uH	14 uH	9.33 uH	2.95 uH
13	114 uH	open	28 uH	14 uH	8.63 uH	2.87 uH
14	open	56 uH	28 uH	14 uH	8.00 uH	2.80 uH
15	114 uH	56 uH	28 uH	14 uH	7.48 uH	2.73 uH

Note:
open = no inductor connected.

[0044] As shown in the resulting total inductances listed in Table 1, the tuning assembly **50** is operable to provide any one selected inductance between the input electrical conductor **30** and the ground potential **32** ranging from a low of 2.73 uH with the switch **34** in position 15 to a high of 4.31 uH with the switch **34** in position 0. The tuning assembly **50** is configured to provide a range of tuning suitable for the unit to unit transducer impedance variation exhibited in FIG. **1**. For example, the tuned impedance is:

$$Z_{tuned}=1/((1/Z_{transducer})+(1/Z_{tuneinductor}))$$

where: $Z_{tuneinductor}=j*2*pi*f*L_{tuneinductor}$

[0045] $L_{tuneinductor}$=inductance of the tuning inductor

[0046] f=operating frequency

Setting the phase angle of $Z_{tuned}=0$ for ideal tuning and solving for $L_{tuneinductor}$ yields:

$$L_{tuneinductor}=\text{Magnitude}(Z_{transducer})/(2*pi*f*\sin(-\text{Phase}(Z_{transducer})))$$

[0047] Table 2 below includes the values of transducer impedance, from FIG. **1**, at the corners (min/max magnitude and min/max phase angle) along with the ideal tuning inductor value. All values are at f=2 Mhz. As can be seen, the tuning range of Table 1 covers the tuning values of Table 2.

TABLE 2

Example Ideal Tuning Inductor Values

$Z_{transducer}$ (Ohms)	$L_{tuneinductor}$ (uH)
32.5714 at −66.7460 degrees	2.82
38.8751 at −57.2222 degrees	3.68
44.2857 at −61.3492 degrees	4.02
36.8571 at −74.3651 degrees	3.05

[0048] FIG. **4** shows a cross-section of a tunable ultrasound transducer assembly **70**, in accordance with many embodiments. Components of the tunable ultrasound transducer assembly **70** common to the above-described tunable ultrasound transducer assembly **20** of FIG. **2** share the same reference numerals. The tunable ultrasound transducer assembly **70** includes the tuning assembly **26**, a printed circuit board (PCB) **72**, the transducer **24**, a system connection first electrical path **74**, a system connection second electrical path **76**, a transducer connection first electrical path **78**, a transducer connection second electrical path **80**, and a housing **82**.

[0049] As in the tunable ultrasound transducer assembly **20** of FIG. **2**, the tuning assembly **26** provides a selectable impedance between the ground potential **32** and an electrical path used to transfer a driving signal from the transducer controller **22** to the transducer **24**. The system connection first electrical path **74** is configured to be electrically connected with the transducer controller **22** to receive the driving signal. The system connection second electrical path **76** is configured to be electrically connected with the ground potential **32**. The system connection first and second electrical paths **74**, **76** are shown as a pair of spring loaded connection pins on "top" of the PCB **72** and are configured to engage corresponding electrical traces in a receptacle that is electrically coupled with the transducer controller **22** and the ground potential **32**. The PCB **72** includes a first electrical trace (not shown) that electrically couples the system connection first electrical path **74** to the transducer connection first electrical path **78**. And the PCB includes a second electrical trace (not shown) that electrically couples the system connection second electrical path **76** to the transducer connection second electrical path **80**. The tuning assembly **26** includes a first connection **84** that is electrically coupled with the PCB first electrical trace and a second connection **86** that is electrically coupled with the PCB second electrical trace, thereby electrically coupling the tuning assembly **26** between the driving signal in the PCB first electrical trace and the ground potential **32** that is electrically coupled with the PCB second electrical trace. The tuning assembly **26** includes the switch **34**, which is selectively operated as described herein to select the impedance provided by the tuning assembly **26**.

[0050] Tuned Ultrasound Transducer Assembly Methods

[0051] FIG. **5** shows acts of a method **100** for forming a tuned ultrasound transducer assembly and assembling the tuned ultrasound transducer assembly into a medical device, in accordance with many embodiments. The assemblies and components described herein can be used to practice the method **100**. In act **102**, a tuning assembly (e.g., tuning assembly **26**, **50**) is selected that is adjustable to provide a selected inductance value. In many embodiments, the tuning assembly is adjustable to provide the selected inductance value from a number of different inductance values as described herein. In act **104**, an ultrasound transducer (e.g., the ultrasound transducer **24**) is electrically connected with an ultrasound transducer controller (e.g., the ultrasound controller **22**) via an input electrical conductor (e.g., the input

electrical conductor **30**). And in act **106**, the tuning assembly is electrically connected between the input electrical conductor and a ground potential.

[0052] FIG. **6** shows optional acts that can be used in conjunction with the method **100** to tune the ultrasound transducer assembly, in accordance with many embodiments. In act **108**, with the switch of the tuning assembly in a selected position, a phase angle of the ultrasound transducer assembly is measured. In act **110**, the switch is operated to change to a different selected position to increase or decrease the selected inductance in response to whether the measured phase angle is positive or negative. For example, if the phase angle measurement is a positive 15 degrees, the switch can be operated in a direction so that the newly selected inductance will result in a reduction of the measured phase angle corresponding to the newly selected inductance. In act **112**, the phase angle of the ultrasound transducer assembly is re-measured, thereby providing a phase angle measurement corresponding to the newly selected inductance. In act **114**, sequential phase angle measurements are inspected to see if a change in sign of the phase angle measurements has occurred. If no change in sign of the phase angle measurements has occurred, act **110** through act **114** are repeated until a change in sign of the phase angle measurements has occurred. Once a change in sign in the phase angle measurements has occurred, the switch position providing the minimum phase angle magnitude can be selected in act **116**.

[0053] FIG. **7** shows additional optional acts that can be used in conjunction with the method **100**, in accordance with many embodiments. In act **118**, the tuning assembly is connected to a printed circuit board (PCB) (e.g., the PCB **72**). In many embodiments, the tuning assembly is both physically attached to the PCB and electrically connected to the PCB as in the tunable ultrasound transducer assembly **70** of FIG. **4**. In act **120**, the PCB is electrically connected between the input electrical conductor and the ground potential. In act **122**, the PCB is coupled to a housing (e.g., the housing **82**). In act **124**, the transducer is secured to the housing so that a fluid tight seal is formed between the transducer and the housing. And in act **126**, fixed inductors (e.g., the fixed inductor(s) **140**) are connected in parallel between the input electrical conductor and the ground potential.

[0054] Other variations are within the spirit of the present invention. Thus, while the invention is susceptible to various modifications and alternative constructions, certain illustrated embodiments thereof are shown in the drawings and have been described above in detail. It should be understood, however, that there is no intention to limit the invention to the specific form or forms disclosed, but on the contrary, the intention is to cover all modifications, alternative constructions, and equivalents falling within the spirit and scope of the invention, as defined in the appended claims.

[0055] The use of the terms "a" and "an" and "the" and similar referents in the context of describing the invention (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms "comprising," "having," "including," and "containing" are to be construed as open-ended terms (i.e., meaning "including, but not limited to,") unless otherwise noted. The term "connected" is to be construed as partly or wholly contained within, attached to, or joined together, even if there is something intervening. Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided herein, is intended merely to better illuminate embodiments of the invention and does not pose a limitation on the scope of the invention unless otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the invention.

[0056] Preferred embodiments of this invention are described herein, including the best mode known to the inventors for carrying out the invention. Variations of those preferred embodiments may become apparent to those of ordinary skill in the art upon reading the foregoing description. The inventors expect skilled artisans to employ such variations as appropriate, and the inventors intend for the invention to be practiced otherwise than as specifically described herein. Accordingly, this invention includes all modifications and equivalents of the subject matter recited in the claims appended hereto as permitted by applicable law. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the invention unless otherwise indicated herein or otherwise clearly contradicted by context.

[0057] All references, including publications, patent applications, and patents, cited herein are hereby incorporated by reference to the same extent as if each reference were individually and specifically indicated to be incorporated by reference and were set forth in its entirety herein.

What is claimed is:

1. A method for forming a tuned ultrasound transducer assembly and assembling the tuned ultrasound transducer assembly into a medical device, the medical device having an ultrasound transducer controller, the method comprising:

selecting a tuning assembly that is adjustable to provide a selected inductance value from at least three different inductance values, at least one of the at least three different inductance values being appropriate to the operation of a transducer, the transducer having an input side, the transducer being operable to produce a cyclic sound pressure output with a frequency of at least 20 kilohertz, the tuning assembly including a switch and a plurality of tuning inductors, the switch including a first connection and a plurality of second connections, the switch having at least three positions, each position being operable to selectively connect the first connection with any one of at least three different combinations of the second connections including a combination connecting the first connection to at least two of the second connections, each of the second connections being connected to at least one of the tuning inductors so that the switch is operable to select which subset of the tuning inductors is connected to the first connection so as to provide the selected inductance value;

electrically connecting the ultrasound transducer controller with the transducer input side via an input electrical conductor; and

electrically connecting the tuning assembly between the input electrical conductor and a ground potential so as to provide the selected inductance between the input electrical conductor and the ground potential, the ultrasound transducer controller and the transducer being electrically coupled with the ground potential.

2. The method of claim 1, wherein:
the tuning assembly is adjustable to provide the selected inductance value from at least six different inductance values, at least one of the at least six different inductance values being appropriate to the operation of the transducer;
the switch includes at least three of the second connections; and
the switch has at least six positions, each position being operable to selectively connect the first connection with any one of at least six different combinations of the second connections.

3. The method of claim 2, wherein:
the tuning assembly is adjustable to provide the selected inductance value from at least ten different inductance values, at least one of the at least ten different inductance values being appropriate to the operation of the transducer;
the switch has four to six of the second connections; and
the switch has at least ten positions, each position being operable to selectively connect the first connection with any one of at least ten different combinations of the second connections.

4. The method of claim 3, wherein:
the tuning assembly is adjustable to provide the selected inductance value from at least twelve different inductance values, at least one of the at least twelve different inductance values being appropriate to the operation of the transducer;
the switch has four or five of the second connections; and
the switch has at least twelve positions, each position being operable to selectively connect the first connection with any one of at least twelve different combinations of the second connections.

5. The method of claim 2, wherein:
the tuning assembly is adjustable to provide the selected inductance value from at least sixteen different inductance values, at least one of the at least sixteen different inductance values being appropriate to the operation of the transducer;
the switch includes at least four of the second connections; and
the switch has at least sixteen positions, each position being operable to selectively connect the first connection with any one of at least sixteen different combinations of the second connections.

6. The method of claim 5, wherein the switch includes a position selection feature that is rotated to select one of the at least sixteen positions.

7. The method of claim 4, wherein the switch includes a position selection feature that is rotated to select one of the at least twelve positions.

8. The method of claim 3, wherein the switch includes a position selection feature that is rotated to select one of the at least ten positions.

9. The method of claim 2, wherein the switch includes a position selection feature that is rotated to select one of the at least six positions.

10. The method of claim 9, further comprising:
(a) measuring a phase angle of the ultrasound transducer assembly with the switch in a selected position of the at least six positions;
(b) operating the switch to change the switch to a different selected position to increase or decrease the selected inductance in response to whether the measured phase angle is positive or negative;
(c) subsequent to act (b), re-measuring the phase angle of the ultrasound transducer assembly; and
(d) repeating acts (b) and (c) until a change in sign of the measured phase angles occurs.

11. The method of claim 10, further comprising selecting a position for the switch from the at least six positions that minimizes an absolute magnitude of the corresponding measured phase angle.

12. The method of claim 1, wherein the switch includes a position selection feature that is rotated to select one of the at least three positions.

13. The method of claim 1, further comprising:
electrically connecting the tuning assembly to a printed circuit board (PCB) having a first lead and a second lead so that the PCB first lead and the tuning assembly switch first connection are electrically connected and the PCB second lead is electrically connected with the tuning inductors, each of the tuning inductors being electrically connected between the PCB second lead and corresponding connections of the switch second connections; and
electrically connecting the PCB between the input electrical conductor and the ground potential so that (1) the PCB first lead and the input electrical conductor are electrically connected and the PCB second lead and the ground potential are electrically connected, or (2) the PCB first lead and the ground potential are electrically connected and the PCB second lead and the input electrical conductor are electrically connected.

14. The method of claim 13, further comprising:
coupling the PCB to a housing; and
securing the transducer to the housing so that a fluid tight seal is formed between the transducer and the housing.

15. The method of claim 1, wherein the transducer comprises a high intensity focused ultrasound (HIFU) transducer operable to produce an ultrasound output having an average power of at least 1 Watt.

16. The method of claim 15, wherein the ultrasound output has an average power of at least 10 Watts.

17. The method of claim 15, wherein the tuning assembly inductors comprise an inductor having an open core construction.

18. The method of claim 1, further comprising electrically connecting a plurality of fixed inductors in parallel between the input electrical conductor and the ground potential to provide a fixed inductance value between the input electrical conductor and the ground potential.

19. The method of claim 18, wherein the fixed inductance value is between 2.0 uH and 7.0 uH and the selected inductance value is adjustable within a range that lies between 0.15 uH and 150 uH.

20. A medical device having a tunable ultrasound transducer assembly, the medical device comprising:
an ultrasound transducer controller electrically connected with a ground potential;
a transducer having an input side connected with the ultrasound transducer controller via an input electrical conductor, the transducer being operable to produce a cyclic sound pressure output with a frequency of at least 20 kilohertz, the transducer being electrically connected with the ground potential; and

a tuning assembly that is electrically connected between the input electrical conductor and the ground potential, the tuning assembly being adjustable to provide a selected inductance value from at least three different inductance values, at least one of the at least three different inductance values being appropriate to the operation of the transducer, the tuning assembly including a switch and a plurality of tuning inductors, the switch including a first connection and a plurality of second connections, the switch having at least three positions, each position being operable to selectively connect the first connection with any one of at least three different combinations of the second connections including a combination connecting the first connection to at least two of the second connections, each of the second connections being connected to at least one of the tuning inductors so that the switch is operable to select which subset of the tuning inductors is connected to the first connection so as to provide the selected inductance value.

21. The device of claim **20**, wherein:

the tuning assembly is adjustable to provide the selected inductance value from at least six different inductance values, at least one of the at least six different inductance values being appropriate to the operation of the transducer;

the switch includes at least three of the second connections; and

the switch has at least six positions, each position being operable to selectively connect the first connection with any one of at least six different combinations of the second connections.

22. The device of claim **21**, wherein:

the tuning assembly is adjustable to provide the selected inductance value from at least ten different inductance values, at least one of the at least ten different inductance values being appropriate to the operation of the transducer;

the switch has four to six of the second connections; and

the switch has at least ten positions, each position being operable to selectively connect the first connection with any one of at least ten different combinations of the second connections.

23. The device of claim **22**, wherein:

the tuning assembly is adjustable to provide the selected inductance value from at least twelve different inductance values, at least one of the at least twelve different inductance values being appropriate to the operation of the transducer;

the switch has four or five of the second connections; and

the switch has at least twelve positions, each position being operable to selectively connect the first connection with any one of at least twelve different combinations of the second connections.

24. The device of claim **21**, wherein:

the tuning assembly is adjustable to provide the selected inductance value from at least sixteen different inductance values, at least one of the at least sixteen different inductance values being appropriate to the operation of the transducer;

the switch includes at least four of the second connections; and

the switch has at least sixteen positions, each position being operable to selectively connect the first connection with any one of at least sixteen different combinations of the second connections.

25. The device of claim **24**, wherein the switch includes a position selection feature that is rotated to select one of the at least sixteen positions.

26. The device of claim **23**, wherein the switch includes a position selection feature that is rotated to select one of the at least twelve positions.

27. The device of claim **22**, wherein the switch includes a position selection feature that is rotated to select one of the at least ten positions.

28. The device of claim **21**, wherein the switch includes a position selection feature that is rotated to select one of the at least six positions.

29. The device of claim **20**, wherein the switch includes a position selection feature that is rotated to select one of the at least three positions.

30. The device of claim **20**, further comprising:

a housing, the transducer being secured to the housing so that a fluid tight seal is formed between the transducer and the housing; and

a printed circuit board (PCB) coupled with the housing, the PCB having a first lead and a second lead so that the PCB first lead and the tuning assembly switch first connection are electrically connected and the PCB second lead is electrically connected with the tuning inductors, each of the tuning inductors being electrically connected between the PCB second lead and corresponding connections of the switch second connections, the PCB being electrically connected between the input electrical conductor and the ground potential so that (1) the PCB first lead and the input electrical conductor are electrically connected and the PCB second lead and the ground potential are electrically connected, or (2) the PCB first lead and the ground potential are electrically connected and the PCB second lead and the input electrical conductor are electrically connected.

31. The device of claim **20**, wherein the transducer comprises a high intensity focused ultrasound (HIFU) transducer operable to produce an ultrasound output having an average power of at least 1 Watt.

32. The device of claim **31**, wherein the ultrasound output has an average power of at least 10 Watts.

33. The device of claim **31**, wherein the tuning inductors comprise an inductor having an open core construction.

34. The device of claim **20**, further comprising a plurality of fixed inductors connected in parallel between the input electrical conductor and the ground potential to provide a fixed inductance value between the input electrical conductor and the ground potential.

35. The device of claim **34**, wherein the fixed inductance value is between 2.0 uH and 7.0 uH and the selected inductance value is adjustable within a range that lies between 0.15 uH and 150 uH.

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摘要(译)

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