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(54) ULTRASONIC PROBE AND ULTRASONIC IMAGING APPARATUS

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(57) **ABSTRACT**

There is provided an ultrasound probe including a capacitive transducer for reducing multiple reflections while maintaining a pulse characteristic with which a high-quality image can be obtained, and is also provided an ultrasound imaging apparatus using the ultrasound probe. The ultrasound probe including the capacitive transducer is configured so as to satisfy the condition $6.5/f_c<\alpha d$, where α [dB/mm/MHz] denotes the absorption coefficient of an acoustic lens, d [mm] denotes the maximum thickness of the acoustic lens, and f_c [MHz] denotes the center frequency of the capacitive transducer, and satisfy the condition $L<1/((3\pi f_c)^2\times C)$, where L [H] denotes an inductance value per channel of the capacitive transducer, C [pF] denotes a capacitance per channel of the capacitive transducer, and f_c [MHz] denotes the center frequency of the capacitive transducer.

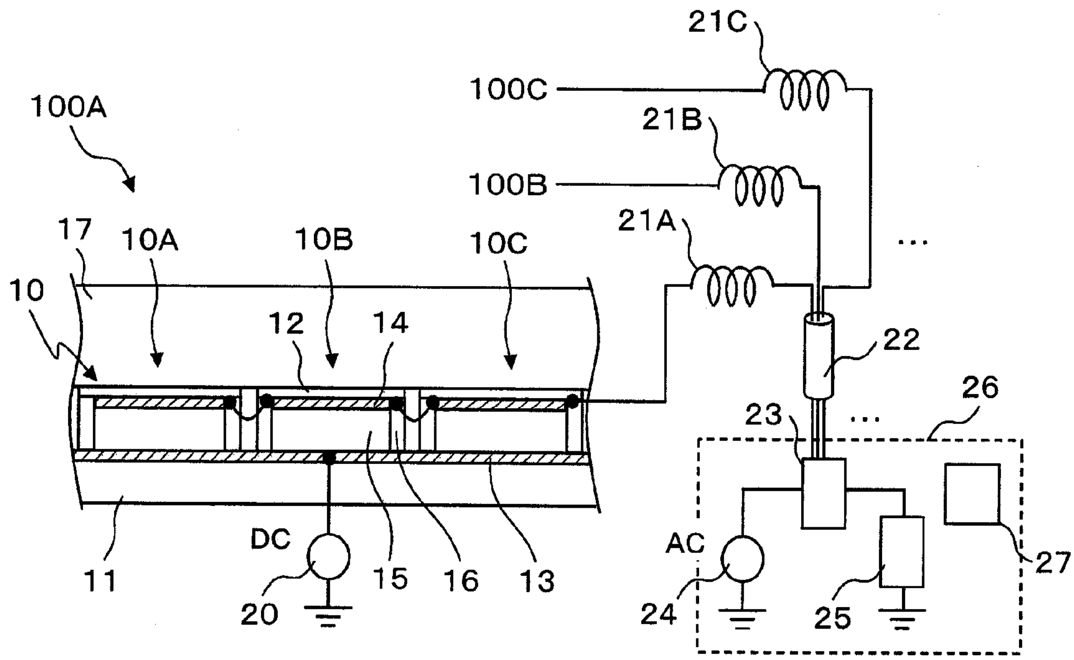


FIG. 1

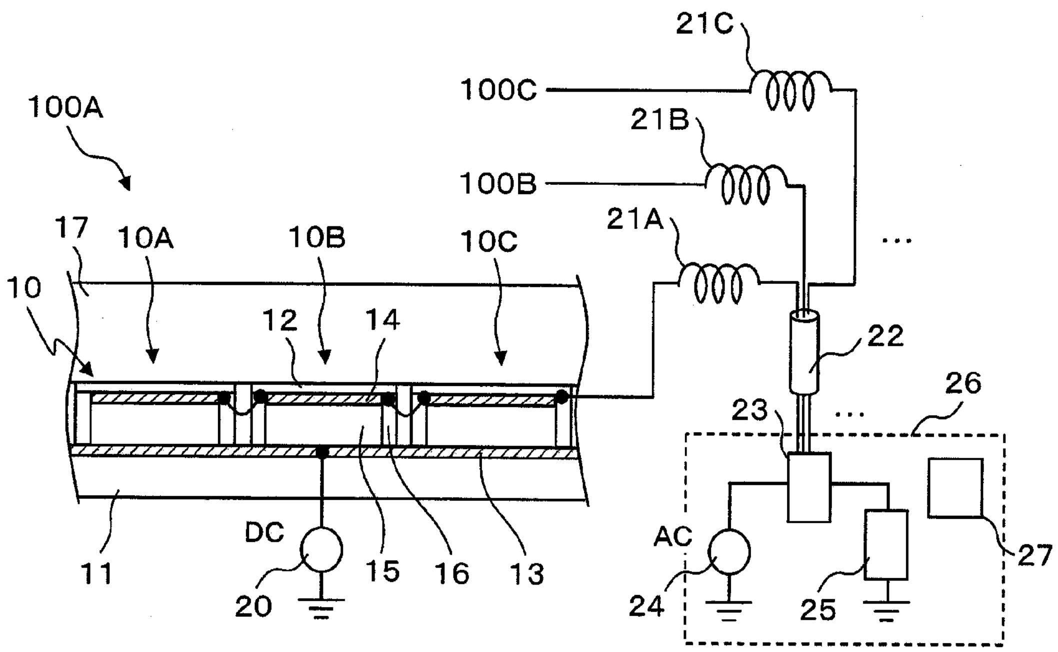

100A
17
10A
10B
10C
10
12
14
11
DC
20
15
16
13
100C
21C
100B
21B
21A
22
23
26
27
AC
24
25

FIG. 2

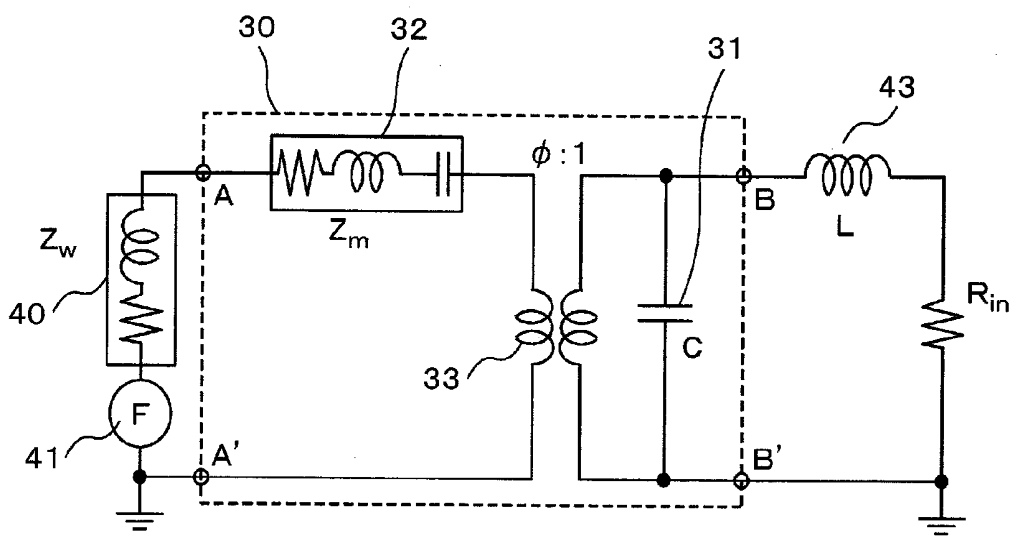

30
32
31
43
ϕ:1
A
B
L
Z_w
Z_m
40
R_{in}
33
C
41
F
A'
B'

FIG. 3

CAPACITANCE	C	66pF
FORCE FACTOR	ϕ	1.31×10^{-2} N/V
MECHANICAL IMPEDANCE OF DIAPHRAGMS	z_m/ϕ^2	$102.3\Omega + j\omega(34.6\mu H) + 1/j\omega(11.6pF)$
ACOUSTIC LOAD IMPEDANCE	z_w/ϕ^2	$2190\Omega + j\omega(13.2\mu H)$

FIG. 4

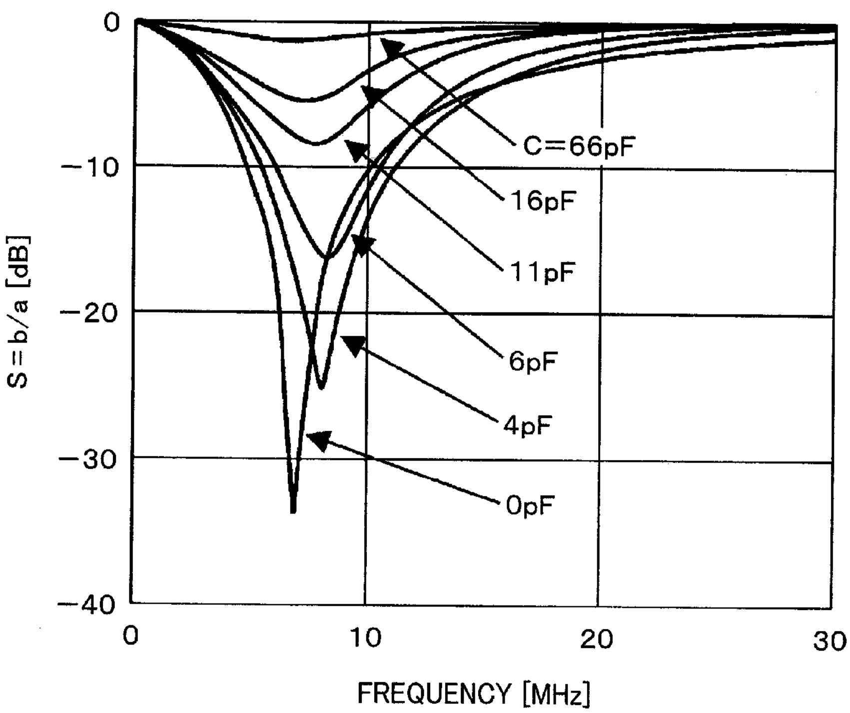
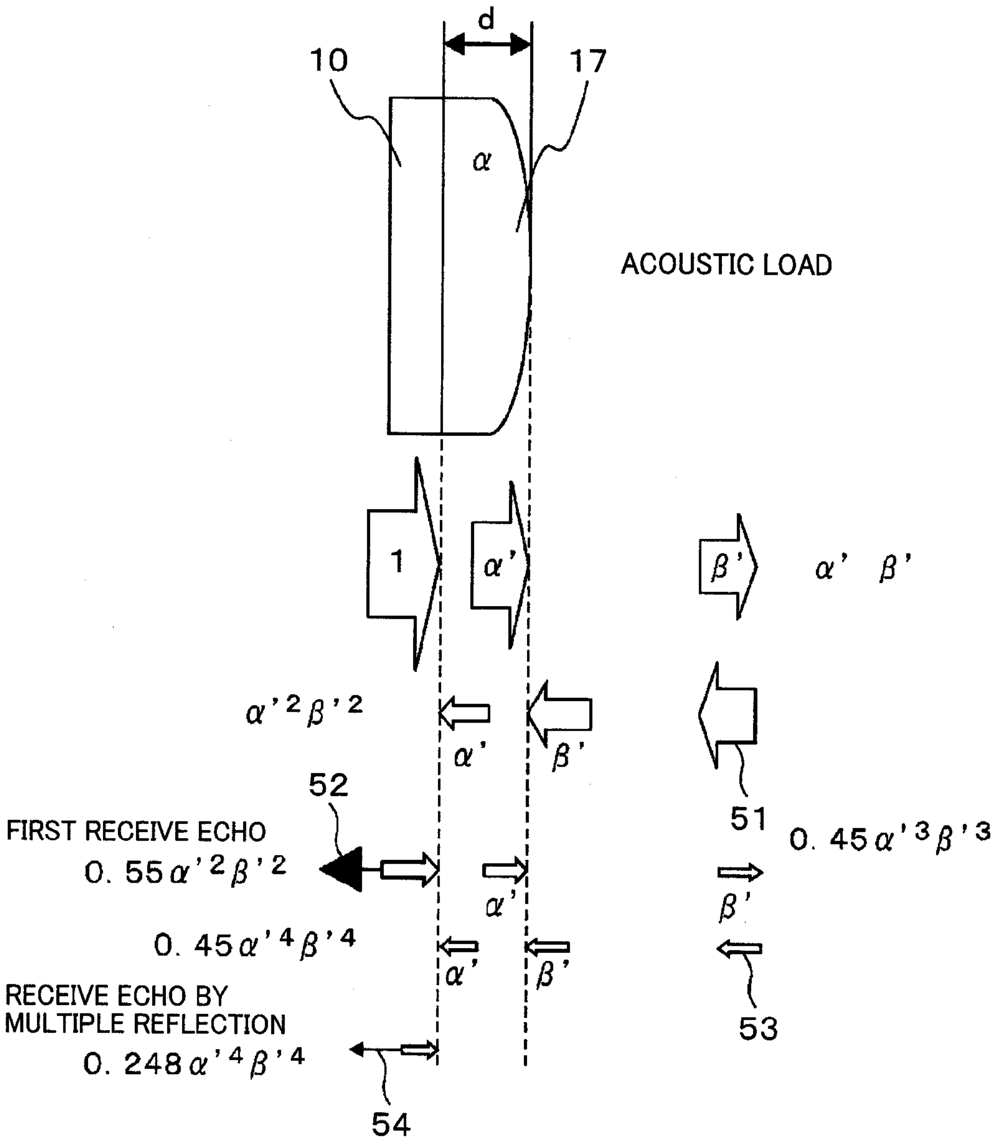


FIG. 5



$$\frac{\text{RECEIVE ECHO BY MULTIPLE REFLECTION}}{\text{FIRST RECEIVE ECHO}} = \frac{0.248\alpha'^4\beta'^4}{0.55\alpha'^2\beta'^2} = 0.45\alpha'^2\beta'^2$$

FIG. 6

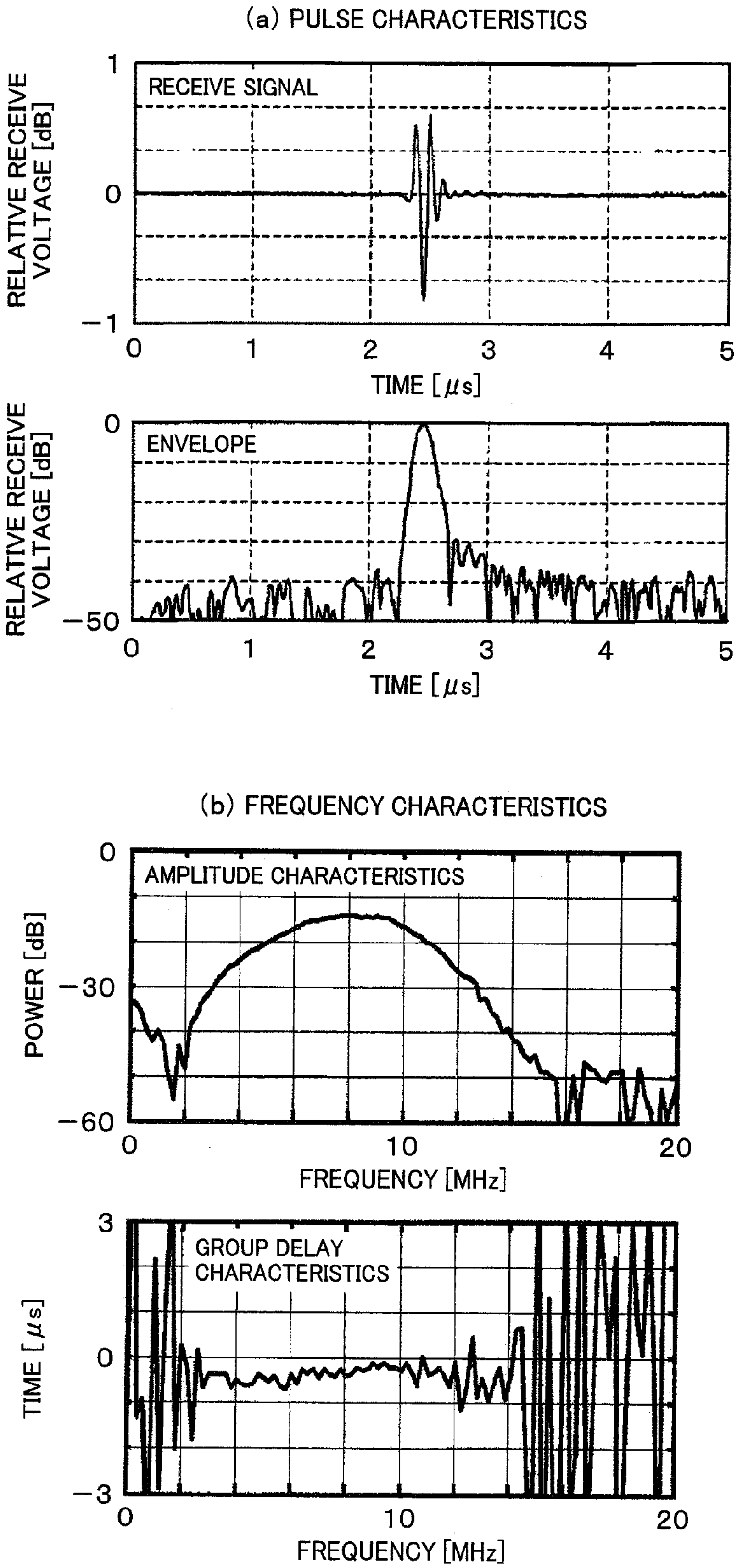
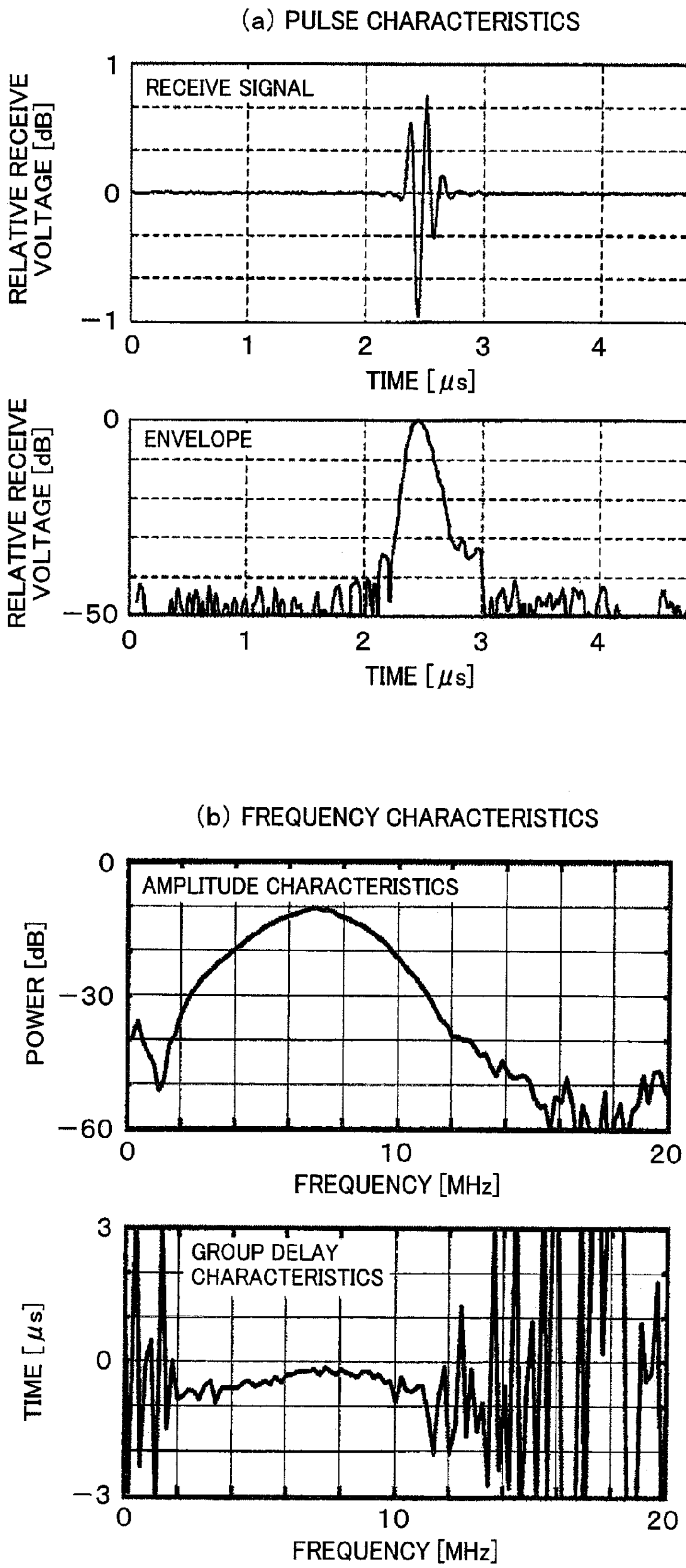

(a) PULSE CHARACTERISTICS
RECEIVE SIGNAL
RELATIVE RECEIVE VOLTAGE [dB]
1
0
−1
0
1
2
3
4
5
TIME [μs]
ENVELOPE
RELATIVE RECEIVE VOLTAGE [dB]
0
−50
TIME [μs]
(b) FREQUENCY CHARACTERISTICS
AMPLITUDE CHARACTERISTICS
POWER [dB]
0
−30
−60
10
20
FREQUENCY [MHz]
GROUP DELAY CHARACTERISTICS
TIME [μs]
3
−3
FREQUENCY [MHz]

FIG. 7


(a) PULSE CHARACTERISTICS
RECEIVE SIGNAL
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ENVELOPE
RELATIVE RECEIVE VOLTAGE [dB]
0
−50
TIME [μs]
(b) FREQUENCY CHARACTERISTICS
AMPLITUDE CHARACTERISTICS
POWER [dB]
0
−30
−60
10
20
FREQUENCY [MHz]
GROUP DELAY CHARACTERISTICS
TIME [μs]
3
0
−3
FREQUENCY [MHz]

FIG. 8

	MAXIMUM THICKNESS OF ACOUSTIC LENS	SERIES INDUCTANCE	TRANSMIT/ RECEIVE GAIN	MULTIPLE REFLECTION AMPLITUDE LEVEL
EXAMPLE UNRELATED TO THE PRESENT EMBODIMENT	0.65mm	0 μH	−58.1dB	−16.3dB
EXAMPLE OF THE PRESENT INVENTION	1.2mm	1.8 μH	−56.8dB	−21.4dB

ULTRASONIC PROBE AND ULTRASONIC IMAGING APPARATUS

TECHNICAL FIELD

[0001] The present invention relates to an ultrasound probe including a capacitive transducer so as to obtain a high-quality image, and an ultrasound imaging apparatus employing the capacitive transducer.

BACKGROUND ART

[0002] A capacitive transducer has been proposed as a transducer array that is more highly efficient and more broadband than a conventional piezoelectric transducer.

[0003] The capacitive transducer is, as described in, for example, non-patent document 1, structured to have numerous diaphragms formed on a silicon substrate. The capacitive transducer is used with a DC bias voltage applied to electrodes formed on each of the diaphragms and silicon substrate. With the voltage applied, an AC voltage is further applied in order to transmit sound waves. Arriving sound waves are received with the DC bias voltage applied.

[0004] When the DC bias voltage is stepped up, the diaphragms are brought into contact with the silicon substrate due to Coulomb force. The DC bias voltage at this time is called a collapse voltage. The DC bias voltage that is equal to or lower than the collapse voltage is normally applied for use.

[0005] In the capacitive transducer, as described in, for example, non-patent document 2, the conversion efficiency between electric energy and mechanical energy (electromechanical coupling factor) is known to depend on the DC bias voltage.

[0006] Non-patent document 1: "A Surface Micromechined Electrostatic Ultrasonic Air Transducer" (Proceedings of 1994 IEEE Ultrasonics Symposium, pp. 1241-1244)

[0007] Non-patent document 2: "A Single Distributed Model for cMUT" (Proceedings of 2004 IEEE Ultrasonics Symposium, pp. 248-251)

DISCLOSURE OF THE INVENTION

Problems to be Solved by the Invention

[0008] The electrostatic transducer is a capacitive transducer, and a large parasitic capacitance is present in the electrostatic transducer. The DC bias voltage equal to or lower than the collapse voltage causes the electromechanical coupling factor to be so small as to hinder matching between an acoustic load and a receiver circuit. Part of received echoes is reflected from the transducer. The reflected waves are further reflected from a target in the acoustic load, and become receiving echoes. In case of imaging, there is a fear that image quality may be degraded by an artifact due to multiple echoes.

[0009] Even when an acoustic matching layer is formed in order to match an acoustic load with a transducer, since the matching is attained at a specific frequency determined with the material (density and speed of sound) of the acoustic matching layer and the thickness thereof, a receiving signal is a narrow-band one. In addition, a pulse exhibits a ringing because phase linearity is disturbed. Therefore, there is a fear that a pulse characteristic for providing a high resolution may be deteriorated.

[0010] In the capacitive transducer, how to cope with degradation in image quality or deterioration in a pulse characteristic is left as an unsolved problem. As mentioned above, an ultrasound probe including the capacitive transducer and an ultrasound imaging apparatus employing the ultrasound probe are confronted with an issue that an artifact caused by multiple echoes cannot be reduced while a pulse characteristic for providing a high resolution is sustained.

Means of Solving the Problems

[0011] An example of an ultrasound probe in accordance with the present invention includes a capacitive transducer having at least one channel formed on a substrate, an acoustic lens disposed on one surface of the capacitive transducer, and a series inductor connected in series with each channel of the capacitive transducer. The acoustic lens is formed with the absorption coefficient of the acoustic lens and the maximum thickness of the acoustic lens based on the resonant frequency of the capacitive transducer. As for the inductance value of the series inductor, the inductance value per channel of the capacitive transducer is specified based on the electrostatic capacity per channel of the capacitive transducer and the center frequency of the capacitive transducer.

[0012] An example of an ultrasound imaging apparatus in accordance with the present invention includes: an ultrasound probe that includes a capacitive transducer having plural channels formed on a substrate, an acoustic lens disposed on one surface of the capacitive transducer, and an inductor connected to the capacitive transducer; a DC electrical source that applies a DC bias to the ultrasound probe; an AC electrical source that applies an AC voltage; and a receiver circuit that processes a receiving signal of the ultrasound probe.

EFFECTS OF THE INVENTION

[0013] According to the invention, an ultrasound probe including a capacitive transducer capable of reducing an artifact due to multiple echoes while sustaining a pulse characteristic for providing a high resolution, and an ultrasound imaging apparatus employing the ultrasound probe can be provided.

BEST MODE FOR CARRYING OUT THE INVENTION

[0014] Referring to the drawings, an embodiment of an ultrasound probe in accordance with the present invention will be described below.

[0015] FIG. **1** is a configuration diagram showing an embodiment of an ultrasound probe in accordance with the present invention. The ultrasound probe of the present embodiment includes plural capacitive transducer array channels **100** (**100**A, **100**B, **100**C, etc.). One inductor **21**A, **21**B, **21**C, or the like is connected in series with each array channel.

[0016] The mechanical component of each channel, for example, the channel **100**A includes plural diaphragm structures **10**A, **10**B, **100**, etc. formed on a silicon substrate **11** through a silicon process, and an acoustic lens **17** disposed on one surface of the capacitive transducer **10**.

[0017] One diaphragm structure **10**A (or **10**B or **10**C) included in the capacitive transducer **10** has a diaphragm **12** formed by way of ribs **16**. A layer of cavity **15** is formed between the diaphragm **12** and silicon substrate **11**.

[0018] An upper electrode **14** is contained in the diaphragm **12**, and a lower electrode **13** is contained in the silicon substrate **11**. A DC bias voltage is applied to the lower electrode **13** by a DC electrical source **20**. For use, the diaphragm **12** is deformed toward the silicon substrate due to Coulomb force. The DC bias voltage is normally set to a voltage value that ranges from about 80% to 90% of a voltage (the collapse voltage) bringing the diaphragm **12** into contact with the silicon substrate **11**.

[0019] In general, transducers included in an ultrasound probe for acquiring a two-dimensional ultrasound image have a one-dimensional array structure composed of plural channels arranged like strips. The ultrasound probe of the present embodiment has the array structure of plural channels. One channel has plural diaphragm structures **10**A, **10**B, **10**C, etc. concatenated in parallel. Specifically, the upper electrodes **14** included in the diaphragms **12** of the respective diaphragm structures **10**A, **10**B, **10**C, etc. are connected in parallel with one another within the channel. One inductor **21** is connected in series with one channel. In the present embodiment, since a DC voltage is applied to the lower electrode, the inductor **21** is connected to the upper electrodes **14**. The terminal of the series inductor **21** opposite to the terminal thereof on the side of the capacitive transducer is connected to transmitter/receiver circuits (T/R circuits) **23** of a control circuit **26**, each of which is included in an ultrasound imaging apparatus, over a probe cable **22** having a length of about 2 m. If the ultrasound probe is for medical use, it usually includes plural channels, for example, includes an array of one hundred channels, and one hundred inductors. Therefore, the probe cable in FIG. **1** has plural lines bundled therein, and the transmitter/receiver circuits **23** includes the same number of transmitter receivers as the number of array channels. For brevity's sake, the transmitter/receiver circuit is shown as one transmitter/receiver circuit. For transmitting ultrasound waves, the transmitter/receiver circuit **23** operates so that an AC electrical source **24** for transmission can be connected to the series inductors **21**. For receiving ultrasound waves, the transmitter/receiver circuit **23** operates so that a receiver circuit **25** can be connected to the series inductors **21**. For the operations, a diode switch or the like may be included, or a multiplexer may be used to allow a controller **27** to control a connected state.

[0020] For some usages including a usage for non-destructive testing, a one-channel ultrasound probe may be used to perform a mechanical scan. In this case, one series inductor **21** is connected to one capacitive transducer array channel **100** included in the ultrasound probe.

[0021] Next, an electrical equivalent circuit of the capacitive transducer shown in FIG. **1** is used to describe a reverberation occurring during reception. FIG. **2** is a diagram of an electrical equivalent circuit for reception equivalent to one channel of the capacitive transducer **10** shown in FIG. **1**. The capacitive transducer **10** is excited by driving force **41** (F) by arriving sound as receiving echoes, with an acoustic load impedance **40** (z_w) of a living body or the like as a resistance.

[0022] An electrical equivalent circuit **30** of the capacitive transducer **10** has a mechanical impedance **32** (z_m) of the diaphragms **12** and a capacitance C of a capacitor **31** electromechanically converted with a force factor φ. The force factor φ is a factor whose dimension is [N/V] and related to an electromechanical coupling factor. The larger the force factor value is, the higher the conversion efficiency between electric energy and mechanical energy is. The electromechanical coupling factor is electrically written as a transformer **33** of a winding ratio φ:1. Therefore, the acoustic load impedance **40** and the mechanical impedance **32** of the diaphragms **12** are written as electrical impedances z_w/ϕ^2 and z_m/ϕ^2 respectively. A receive impedance **42** is connected to a terminal on the side of the capacitor **31**, and received as an electric signal. A series inductor **43** (inductance value L) that is a feature of the present invention is inserted to a terminal B in FIG. **2**, that is, between the capacitor **31** and the receive impedance **42**. Normally, when the electric impedance of the probe observed at a BB' end (on the left side of the BB' end in FIG. **2**) is squared with the receive impedance **42**, the energy transmission efficiency is maximized. In the present invention, the series inductor **43** is used to perform tuning so that the energy transmission efficiency can be upgraded without impairment of a feature that the phase linearity of the capacitive transducer is excellent over a broad frequency band.

[0023] In FIG. **2**, an issue of a conventional ultrasound probe that does not have a series inductor connected (electrical matching is not attained) will be described below. The acoustic load impedance **40** per one channel is expressed approximately as $z_w=r_w+j\omega I_w$ in relation to a forward resistance and an inductance. Herein, ω denotes a frequency, and j denotes an imaginary unit. An inductance component I_w is derived from the fact that since the width of one channel of the capacitive transducer **10** included in the array is about ½ of a wavelength at an employed frequency, a load of a plane wave is not identified. In contrast, the nature of the diaphragms **12** as a mechanical vibrating membrane for one channel can be represented by the mechanical impedance **32** (z_m) or represented by a series circuit of a forward resistance r_m representing a mechanical loss, an inductance I_m representing a mass effect of the diaphragms **12**, and a capacitor c_m representing a compliance of the diaphragms **12**, and expressed as an equation (1).

$$Z_m=r_m+j(\omega I_m-1/\omega c_m) \tag{1}$$

[0024] ω under $\omega I_m-1/\omega c_m=0$ denotes a mechanical resonant angular frequency of the diaphragms **12**.

[0025] Next, a scattering parameter (S-parameter) S will be described below in order to discuss to what extent energy induced by the driving force **41** by arriving sound is reflected from the capacitive transducer. In the electrical equivalent circuit diagram of FIG. **2**, reflection from an AA' end of the part of electrical equivalent circuit **30** should merely be discussed. Assuming that a wave incident on the electrical equivalent circuit **30** of the capacitive transducer from the side of the acoustic load impedance **40** is "a" and a reflected wave is "b", the scattering parameter S is expressed as an equation (2) by regarding an impedance of the entire electrical equivalent circuit **30** of the capacitive transducer, which is observed at the AA' end, as Z_{in}.

$$S=b/a=(Z_{in}-Z_w^*)/(Z_{in}+Z_w) \tag{2}$$

[0026] Herein, under $Z_w=z_w/\phi^2$, the acoustic load impedance zw is expressed as an electric impedance. In addition, * denotes a conjugate complex number.

[0027] A capacitive transducer in which the mechanical resonant frequency of the diaphragms **12** is approximately 8 MHz is reviewed through calculation based on a finite element method. For a conventional type of ultrasound probe in which a series inductor is not connected, constants of the equivalent circuit shown in FIG. **2** are calculated. As a result, the electrical equivalent circuit constants shown in FIG. **3** are obtained. FIG. **4** is a characteristic diagram showing the scattering parameter S in relation to a frequency on the basis of the values in FIG. **3**. FIG. **4** is based on the assumption that the receive impedance R_{in} is equal to a real number of the acoustic load impedance Z_w.

[0028] As apparent from FIG. **4**, when the capacitance C equals 66 pF, the value of the scattering parameter S is very large. A reflected wave of about 90% (when the incident wave is 0 dB, the reflected wave is approximately −1 dB) is present even at a frequency near the resonant frequency. This is because the impedance of the capacitance C of the capacitor **31** is large for the acoustic load impedance. In FIG. **4**, results obtained when the capacitance C gets smaller than 66 pF are shown on a simulated basis. Unless the capacitance C is considerably small, no effect is exerted. Even when the capacitance C is 0, a reactance component of the mechanical impedance z_m of the diaphragms **12** cannot be canceled. An effect is seen to be confined to a narrow band.

[0029] In contrast, in order to attain acoustic matching between an acoustic load impedance and a transducer, an acoustic matching layer is generally employed in a probe using a PZT. However, although an effect is exerted at a specific frequency determined with the material and thickness of the matching layer, the employment of the matching layer becomes a cause of disturbing the phase linearity at a frequency near the specific frequency in a wide frequency band, and deteriorates the pulse characteristic. Namely, the pulse characteristic is degraded to the one that a ringing is present, and often causes a blur in an image.

[0030] As mentioned above, in the ultrasound probe including the capacitive transducer, intense multiple echoes occur due to the low electroacoustic conversion efficiency. It is hard to reduce the multiple echoes while sustaining the pulse characteristic that a ringing is absent in a wide frequency band and that is specific to the capacitive transducer.

[0031] In consideration of the foregoing problems, an ultrasound probe of an embodiment of the present invention has reduction of multiple echoes by an acoustic lens and improvement of sensitivity through insertion of a series inductor combined under a specific condition for the purpose of minimizing multiple echoes while sustaining the pulse characteristic of a little ringing that is a feature of the capacitive transducer.

[0032] FIG. **5** is a schematic diagram showing reduction of multiple echoes by an acoustic lens to which a series inductor is not connected. Sound waves radiated from the capacitive transducer **10** are passed through the acoustic lens **17** and propagated to an acoustic load such as a living body that is not shown. A first reflection echo **51** reflected from a certain target in the acoustic load is passed through the acoustic lens **17**, and received by the capacitive transducer **10**. As described in conjunction with FIG. **4**, a portion of the first reflection echo to be converted into electric energy as a first receive echo **52** by the capacitive transducer is about 10% in spite of the center frequency thereof. More particularly, since an amplitude ratio of pulses has a significant meaning, the amplitude ratio of the first receive echo **52** to the first reflection echo **51** is calculated on the assumption that the first reflection echo **51** whose center frequency is 8 MHz, which numbers two waves, and which is Hanning-weighted has arrived at the capacitive transducer **10** exhibiting the electrical equivalent circuit constants shown in FIG. **3**. This results in:

(Amplitude of the first receive echo **52**)/(Amplitude of the first reflection echo **51**)=0.55

[0033] Assuming that the amplitude of the first reflection echo is 0 dB, a pulse component having an amplitude of −7 dB is reflected, passed through the acoustic lens **17**, and radiated again to the acoustic load that is not shown. The re-radiated pulse is reflected from a certain target in the acoustic load. The multiple reflection echo **53** is passed through the acoustic lens **17**, and received as a receive echo **54** by multiple reflection, which has an amplitude that is about 0.55 times larger than the amplitude of the multiple reflection echo **53**, by the capacitive transducer.

[0034] Mathematically, assuming that the one-way attenuation factors at the acoustic lens **17** and the acoustic load that is not shown are α' and β' respectively, the ratio of the amplitude of the receive echo **54** by multiple reflection to that of the first receive echo **52** is expressed as an equation (3).

(Amplitude of the receive echo **54** by multiple reflection)/(Amplitude of the first receive echo **52**)=0.45$\alpha'^2\beta'^2$ (3)

[0035] In general, the absorption coefficient of a living body ranges from 0.7 to 1 dB/cm/MHz. In a frequency band usually employed in ultrasound imaging (from about 1 to 15 MHz), when a perfect reflecting body lies at a distance of 1 cm, up to about 30 dB is attenuated. If a ringing of a pulse is larger by about −20 dB than the size of a main pulse, a blur in an image often becomes outstanding. Therefore, if attenuation of about −20 dB is attained only through attenuation by the acoustic lens **17**, an artifact due to multiple echoes is thought to be suppressed to such an extent that it will not affect image quality. Namely, an inequality (4) should be established.

$$20\,\mathrm{Log}_{10}(0.45\alpha'^2)<-20 \quad (4)$$

[0036] Therefore, when the absorption coefficient of the acoustic lens **17** is α [dB/mm/MHz] and the maximum lens thickness is d [mm], assuming that the center frequency of the capacitive transducer is f_c [MHz], a converted value in dB of the on-way attenuation factor α' at the acoustic lens **17**, 20 $\mathrm{Log}_{10}(\alpha')$, is squared with $-\alpha d f_c$. Herein, the conditional inequality (4) for suppressing an artifact due to multiple echoes is deformed into an inequality (5) below.

$$20\,\mathrm{Log}_{10}(0.45)+2\times 20\,\mathrm{Log}_{10}(\alpha')<-20 \quad (5)$$

Then, 20 $\mathrm{Log}_{10}(\alpha')=-\alpha d f_c$ is assigned to the inequality (5), whereby an inequality (6) is obtained.

$$20\,\mathrm{Log}_{10}(0.45)-2\alpha d f_c<-20 \quad (6)$$

The inequality is straightened in order to obtain an inequality (7) below.

$$6.5/f_c<\alpha d \quad (7)$$

[0037] Therefore, when the inequality (7) is satisfied, multiple echoes can be suppressed by the acoustic lens **17**.

[0038] The foregoing reduction of multiple echoes depending on the thickness of the acoustic lens is attributable to the fact that the number of times by which the acoustic lens is passed through along a sound-wave propagation path is different between the receive echo **54** by multiple reflection and first receive echo **52**. By thickening the acoustic lens **17**, the first receiving echo necessary to perform imaging is affected by attenuation. This poses an issue of a decrease in sensitivity.

[0039] In the ultrasound probe of the present embodiment, as shown in the equivalent circuit in FIG. **2**, the series inductor **43** (inductance value L) is inserted in order to cancel the capacitance C of the capacitor **31** so as to improve sensitivity. However, as described in conjunction with FIG. **4**, even if the capacitance C is fully canceled, a broadband signal is not obtained. In the ultrasound probe of the present embodiment, matching with the fractional bandwidth of the capacitive transducer is attained at a frequency near an upper-limit frequency of a high frequency by means of the series inductor **21**.

[0040] Herein, the impedance Z of a series circuit including a resistor R, an inductor L, and a capacitor C is written as an equation (8).

$$Z=R+j\omega L+(1/j\omega C)=R+j(\omega L-(1/\omega C)) \tag{8}$$

where ω (=2πf) denotes an angular frequency.

[0041] According to the circuit constants employed in FIG. **3**, the impedance is very high for a sensor, and it is hard to attain electrical matching with a receiver circuit. In order to improve sensitivity, the absolute value of Z is thought to be decreased. In order to minimize the absolute value of Z, the imaginary number should be made null. The condition is expressed as $\omega=1/\sqrt{(LC)}$, that is, a condition for series resonance. Thus, by inserting the series inductor **43**, the capacitance of the capacitor C can be canceled. In this case, C denotes the capacitance of the impedance on the side of the probe observed at the BB' end. In practice, the influence of the capacitor **31** is significant. When the capacitance of the capacitor **31** is large, the impedance of the capacitor **31** diminishes. A current largely flows into the capacitor, and the receiver circuit does not exhibit receiving sensitivity. In this case, even cancelation of the capacitor **31** is effective. A decrease in the impedance Z attained by inserting the series inductor **43** is maximized under the condition for series resonance. A remedial effect is markedly manifested at a series resonant frequency, but is hardly exerted at the other frequencies. Therefore, if the series resonant frequency falls within the frequency band for the sensor, the frequency band is narrowed. Therefore, in the present invention, as described below, the angular frequency ω is varied (shifted from the resonant frequency) in order to exert the remedial effect for receiving sensitivity over a wide frequency band.

[0042] The frequency band of the capacitive transducer is wide, and a capacitive transducer exhibiting a fractional bandwidth of about 100% can be manufactured. The broadband frequency characteristic is accompanied by the advantages that not only an amplitude characteristic but also phase linearity are excellent, that is, a group delay characteristic is flat. In FIG. **1**, assuming that the center frequency of the capacitive transducer **10** is f_c, when the fractional bandwidth is 100%, the upper-limit frequency of the bandwidth is $1.5f_c$. Assuming that the inductance value of the series inductor **21** is L, a condition for canceling the capacitance C using the series inductor **21** at the frequency is expressed as an equation (9) providing the condition for series resonance of LC. The equation (9) is deformed in order to obtain an equation (10) below.

$$1.5f_c=1/(2\pi(LC)^{0.5}) \tag{9}$$

$$L=1/((3\pi f_c)^2\times C) \tag{10}$$

[0043] Under the condition under which LC resonance occurs at a frequency equal to or lower than $1.5f_c$, the LC resonance occurs within the frequency band of the capacitive transducer. There is a fear that the flat group delay characteristic may be disturbed. The LC resonant frequency should therefore be higher than $1.5f_c$. Namely, the inductance value L of the series inductor **21** should satisfy a condition expressed by an inequality (11) below.

$$L<1/((3\pi f_c)^2\times C) \tag{11}$$

In the above inequality, the dimensions of the center frequency f_c and capacitance C are megahertz and picofarads respectively.

[0044] As mentioned above, when the capacitance C is canceled using the series inductor **21**, the phase linearity is degraded at a frequency near the frequency of $1.5f_c$. As for the amplitude characteristic, peaking is arisen to cause the pulse characteristic to indicate occurrence of a ringing. However, due to attenuation by the acoustic lens **17**, a high-frequency component undergoes a high attenuation effect. Therefore, although the fractional bandwidth is a bit narrowed, while the pulse characteristic that the group delay characteristic is flat is sustained, sensitivity can be improved.

[0045] In an ultrasound probe employing a piezoelectric ceramic such as PZT, a multilayer matching layer is used to take measures for expanding a bandwidth. There is difficulty in manufacturing an ultrasound probe whose group delay characteristic is flat and whose fractional bandwidth is 100% or more.

[0046] As a material of the acoustic lens **17**, for an acoustic load such as a living body, the intrinsic acoustic impedance of the acoustic lens **17** is preferably squared with that of the acoustic load such as the living body for fear reflection may occur on the border between the acoustic lens **17** and acoustic load. For example, the sound speed of silicon rubber ranges from about 900 to 1000 m/s, and is about ⅔ of the sound speed of the living body. Further, the density of silicon rubber is about 1.3 to 1.4 times larger than that of the living body. The intrinsic acoustic impedance of silicon rubber is nearly equal to that of the living body. Silicon rubber is therefore an appropriate material.

[0047] The results of experiment on the ultrasound probe of the present embodiment will be described below, and the advantages of the present invention will be described below.

[0048] FIG. **6** includes pulse characteristic diagrams and frequency characteristic diagrams concerning an ultrasound probe unrelated to the embodiment of the present invention. FIG. **7** includes pulse characteristic diagrams and frequency characteristic diagrams concerning an ultrasound probe to which the embodiment of the present invention is applied. Herein, the pulse characteristic diagram expresses absolute values obtained by performing Hilbert transformation on an obtained receiving signal, or shows an envelope of pulses.

[0049] Each of (a) and (b) in FIGS. **6** and **7** show the same characteristic in different ways of expression. The pulse characteristic in each (a) of FIGS. **6** and **7** is expressed with an impulse response of a probe, and the frequency characteristic in each (b) of FIGS. **6** and **7** has the pulse characteristic of each (a) of FIGS. **6** and **7** expressed in a frequency domain. A resonant frequency is a frequency at which the mechanical impedance **32** shown in FIG. **2** takes on a value under series resonance.

[0050] To the ultrasound probe which is shown in FIG. **6** and is unrelated to the present embodiment, an acoustic lens that is made of silicon rubber and designed to be focused on width the elevational axis direction of 7.9 mm at a distance on a sound axis of 35 mm is attached. The maximum thickness d is 0.65 mm. The absorption coefficient α of silicon rubber ranges from about 0.7 to 1 dB/mm/MHz, and the resonant frequency and center frequency f_c of a sole capacitive transducer is about 9 MHz. Therefore, $6.5/f_c>\alpha d$ is established. Apparently, the ultrasound probe is constituted to fall outside the range defined as the inequality (7) in the present embodiment. As apparent from FIG. **6**, when the silicon rubber acoustic lens of 0.65 mm thick is attached, the center frequency is approximately 8 MHz. Namely, when the acoustic lens **17** is attached, sound waves to be actually transmitted or received are attenuated while being passed through the lens. The higher the frequency is, the larger the attenuation is. In terms of a power spectrum of the frequency characteristic, the higher frequencies are more markedly affected. Even when the center frequency of the sole capacitive transducer is 9 MHz, the center frequency of the probe including the acoustic lens is slightly lowered. In the example of FIG. **6**, the center frequency is approximately 8 MHz. If the thickness of the acoustic lens **17** is further increased, the center frequency of the probe is lowered. If the thickness thereof is decreased, the center frequency of the probe approaches the center frequency of the sole transducer. In the example of FIG. **7**, since the thickness of the acoustic lens is larger than that in the example of FIG. **6**, the center frequency is about 7 MHz.

[0051] FIG. **8** lists the results of measurement performed in water on a transmit/receive gain and a multiple-echo level with an aluminum block disposed at an elevational focal point. As seen from FIG. **8**, in the ultrasound probe (example of FIG. **6**) unrelated to the present embodiment, the amplitude level of a multiple-echo signal with respect to the amplitude of the first receiving echo is −16.3 dB. There is a high possibility that the amplitude level may cause an artifact in case of imaging.

[0052] In contrast, when the constitution of the present embodiment is applied, the absorption coefficient of silicon rubber that is a material of an acoustic lens ranges from about 0.7 to 1 dB/mm/MHz, and the center frequency of a sole capacitive transducer is about 9 MHz. Therefore, under the condition of $6.5/f_c<\alpha d$, the maximum thickness of the acoustic lens is equal to or larger than at least about 0.73 mm, or preferably, equal to or larger than about 1.1 mm. Herein, the word "about" shall imply the extent of a manufacture error.

[0053] By increasing the thickness of an acoustic lens, a decrease in a transmit/receive gain accompanying attenuation by the acoustic lens poses a problem. When an inductance value of a series inductor to be connected in series with a capacitive transducer is obtained according to the present embodiment, the inductance value is expressed as an inequality (12) below.

$$L<1/((3\pi f_c)^2\times C)=2.1\ \mu H \tag{12}$$

In the above inequality, the dimension of the center frequency f_c is megahertz, the dimension of the capacitance C is picofarads, and f_c=9 MHz and C=66 pF are adopted.

[0054] Based on the above results, the material of the acoustic lens is set to silicon rubber, the thickness thereof is set to 1.2 mm (however, the elevational focus position is 25 mm). Generally, locally procurable inductors are available in the lineup of 1.0 μH, 1.2 μH, 1.5 μH, 1.8 μH, and 2.2 μH. Therefore, assuming that the inductance value of a series inductor connected to a capacitive transducer is smaller than 2.1 μH and is 1.8 μH at maximum, the pulse characteristic and frequency characteristic are measured according to the same method as the aforesaid one.

[0055] FIG. **7** shows the results of measurement. FIG. **8** shows the measured values of a transmit/receive gain and a multiple-echo level along with the results of measurement on the ultrasound probe (example of FIG. **6**) unrelated to the present embodiment.

[0056] As seen from FIG. **8**, the ultrasound probe in accordance with the present embodiment has the multiple-echo level suppressed to −20 dB or less without a decrease in the transmit/receive gain.

[0057] As seen from FIG. **7**, although the fractional bandwidth is slightly narrowed, degrading in phase linearity caused by insertion of an inductance is prevented, and a flat group delay characteristic is sustained. Therefore, it is seen that an excellent pulse characteristic of a little ringing is obtained. Specifically, as apparent from the comparison of FIG. **7** with FIG. **6**, since the frequency band of high frequencies can be diminished by increasing the thickness of an acoustic lens, the bandwidth is slightly narrowed. When the bandwidth is narrowed, a pulse duration is generally widened and an axial resolution is degraded. When the inductance **21** is inserted, electrical matching is attained at one frequency. Therefore, a gain increases at the frequency at which matching is attained (series resonance is attained). As a result, a narrow band ensues, and the phase linearity is lost. When the phase linearity is lost, the shape of a pulse is varied. As a result, even when an incident pulse is an impulse, a ringing occurs in a received wave. This causes the axial resolution to be degraded or causes an artifact to be generated. However, according to the present embodiment, degradation in the phase linearity caused by insertion of an inductance can be prevented, and the flat group delay characteristic can be sustained. Therefore, image quality is hardly affected.

[0058] As presented as the embodiment above, the ultrasound probe of the present invention can acquire a high-quality image with a little blur or a little artifact due to multiple echoes.

[0059] For the main receiving echo intensity to be originally used as image data, the receiving echo intensity due to multiple reflections is suppressed through attenuation by an acoustic lens. Therefore, a high-quality ultrasound image having an artifact due to multiple echoes suppressed can be obtained.

[0060] A series inductance is inserted so that matching can be attained at a frequency near an upper-limit frequency of a frequency band for a capacitive transducer included in an ultrasound probe. While a pulse characteristic of a little ringing is sustained in order to obtain image quality of a high resolution, the sensitivity for a main receiving echo can be improved through attenuation by an acoustic lens.

[0061] The condition for an inductance may be expanded from the center frequency to a bandwidth.

[0062] Assuming that the absorption coefficient of the acoustic lens is α [dB/mm/MHz], the maximum thickness of the acoustic lens is d [mm], the center frequency of the capacitive transducer is f_c [MHz], and reflection from an interface of the capacitive transducer is R, the acoustic lens is formed with a material and a thickness that satisfy $10\,\mathrm{Log}_{10}(R+1)/f_c<\alpha d$. As mentioned above, the FBW of the sole capacitive transducer is nearly 100%. The upper-limit frequency of a bandwidth is set to 1.5fc with the fractional bandwidth regarded as 100%. Under FBW=100% and δ=0.5, $L<1/((3\pi f_c)^2\times C)$ of the inequality (12) can be rewritten into an equation (13) below.

[0063] Specifically, assuming that an inductance value per channel of a capacitive transducer is L [H], an electrostatic capacity per channel of the capacitive transducer is C [pF], the center frequency of the capacitive transducer is f_c [MHz], FBW denotes a fractional bandwidth, and δ denotes a coefficient determining an LC resonant frequency ω_{LC} concerning a stray capacitance C' and the series inductor **21**, the series inductor is constructed to exhibit an inductance value satisfying the equation (13) below.

$$L=1/((2\pi(1+\delta FBW)f_c)^2\times C') \quad (13)$$

[0064] The stray capacitance C' is a capacitance including a capacitance C of a device effective as a sensor for the capacitor **31** and a parasitic capacitance due to wiring.

[0065] δ takes on a value ranging from 0.3 to 1.0. Especially, under $\delta \geqq 0.5$, a pulse-characteristic remedial effect is great. Under $\delta<0.5$, the resonant frequency falls within a sensitivity band, the phase linearity is lost, and the pulse characteristic is gradually deteriorated. In contrast, when δ is too large, a resonant condition is met at a frequency far away from the sensitivity band. Therefore, the sensitivity remedial effect due to an inductance is gradually lost.

BRIEF DESCRIPTION OF THE DRAWINGS

[0066] FIG. **1** It is a configuration diagram showing an embodiment of an ultrasound probe in accordance with the present invention.

[0067] FIG. **2** It is a diagram of an electrical equivalent circuit for reception equivalent to one channel of a capacitive transducer.

[0068] FIG. **3** It is a table listing constants for the electrical equivalent circuit of the capacitive transducer.

[0069] FIG. **4** It is a characteristic diagram showing a scattering parameter S in relation to a frequency.

[0070] FIG. **5** It is an outline diagram concerning reduction of multiple echoes by an acoustic lens.

[0071] FIG. **6** It includes pulse characteristic diagrams and frequency characteristic diagrams concerning an ultrasound probe unrelated to the present invention.

[0072] FIG. **7** It includes pulse characteristic diagrams and frequency characteristic diagrams concerning an ultrasound probe in accordance with the present invention.

[0073] FIG. **8** It is a comparison table for a transmit/receive gain and a multiple-echo level.

EXPLANATION OF REFERENCE NUMERALS

[0074] **10** . . . capacitive transducer

[0075] **10**A, **10**B, **10**C . . . diaphragm structure

[0076] **11** . . . silicon substrate

[0077] **12** . . . diaphragm

[0078] **13** . . . lower electrode

[0079] **14** . . . upper electrode

[0080] **15** . . . layer of cavity

[0081] **16** . . . rib

[0082] **17** . . . acoustic lens

[0083] **20** . . . DC electrical source

[0084] **21** . . . series inductor

[0085] **22** . . . probe cable

[0086] **23** . . . transmitter/receiver circuit

[0087] **24** . . . AC electrical source

[0088] **25** . . . receiver circuit

[0089] **30** . . . part of electrical equivalent circuit of capacitive transducer

[0090] **31** . . . capacitor

[0091] **32** . . . mechanical impedance of diaphragms

[0092] **40** . . . acoustic load impedance

[0093] **41** . . . driving force by arriving sound

[0094] **42** . . . receive impedance

[0095] **51** . . . first reflection echo

[0096] **52** . . . first receive echo

[0097] **53** . . . multiple reflection echo

[0098] **54** . . . receive echo by multiple reflection

1. An ultrasound probe comprising:

a capacitive transducer including at least one channel formed on a substrate;

an acoustic lens disposed on one surface of the capacitive transducer; and

a series inductor connected in series with each channel of the capacitive transducer,

wherein the acoustic lens is formed with the absorption coefficient of the acoustic lens and the maximum thickness of the acoustic lens based on the resonant frequency of the capacitive transducer; and

wherein, as for the inductance value of the series inductor, the inductance value per channel of the capacitive transducer is specified based on the electrostatic capacity per channel of the capacitive transducer and the center frequency of the capacitive transducer.

2. The ultrasound probe according to claim **1**,

wherein, assuming that the absorption coefficient of the acoustic lens is α [dB/mm/MHz], the maximum thickness of the acoustic lens is d [mm], and the resonant frequency of the capacitive transducer is f_c [MHz], the acoustic lens satisfies the relationship of $6.5/f_c<\alpha d$.

3. The ultrasound probe according to claim **1**,

wherein, assuming that the inductance value per channel of the capacitive transducer is L [H], the electrostatic capacity per channel of the capacitive transducer is C [pF], and the center frequency of the capacitive transducer is f_c [MHz], the inductance value of the series inductor satisfies the relationship of $L<1/((3\pi f_c)^2\times C)$.

4. The ultrasound probe according to claim **1**, comprising a plurality of capacitive transducer array channels formed on the substrate,

wherein each series inductor is connected in series with the respective capacitive transducer array channel.

5. The ultrasound probe according to claim **1**, further comprising a cable over which an ultrasound signal is drawn out,

wherein the series inductor has one terminal thereof connected to the channel of the capacitive transducer, and has the other terminal thereof connected onto the cable.

6. The ultrasound probe according to claim **1**, wherein the material of the acoustic lens is silicon rubber.

7. The ultrasound probe according to claim **1**, wherein the absorption coefficient of the acoustic lens is equal to or larger than 0.7 dB/mm/MHz and equal to or smaller than about 1 dB/mm/MHz.

8. The ultrasound probe according to claim **1**, wherein the maximum thickness of the acoustic lens is equal to or larger than 0.73 mm.

9. An ultrasound imaging apparatus comprising:

a capacitive transducer including a plurality of channels formed on a substrate;

an ultrasound probe including an acoustic lens disposed on one surface of the capacitive transducer and an inductor connected to the capacitive transducer;

an AC electrical source that applies an AC voltage to the ultrasound probe; and a receiver circuit that processes a receiving signal of the ultrasound probe,

wherein the ultrasound probe is the ultrasound probe set forth in claim **1**.

10. The ultrasound imaging apparatus according to claim **9**, further comprising a transmitter/receiver circuit and a controller,

wherein, for transmitting ultrasound waves, the controller connects the transmitter/receiver circuit to the AC electrical source and inductor; and

wherein, for receiving ultrasound waves, the controller connects the transmitter/receiver circuit to the receiver circuit and conductor.

* * * * *

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摘要(译)

提供了一种超声探头，其包括用于减少多次反射同时保持可以获得高质量图像的脉冲特性的电容换能器，并且还提供了使用超声探头的超声成像设备。包括电容换能器的超声探头被配置为满足条件6.5 / fc <αd，其中α[dB / mm / MHz]表示声透镜的吸收系数，d [mm]表示声学的最大厚度。透镜，fc [MHz]表示电容传感器的中心频率，满足条件L <1 /（（3πfc）2×C），其中L [H]表示电容传感器每通道的电感值，C [pF]表示电容换能器的每个通道的电容，并且fc [MHz]表示电容换能器的中心频率。