(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
16 July 2009 (16.07.2009)

PCT

(10) International Publication Number
WO 2009/088307 A1

(51) International Patent Classification:
B06B 1/06 (2006.01) ***B06B 1/02*** (2006.01)

(21) International Application Number:
PCT/NO2009/000014

(22) International Filing Date: 9 January 2009 (09.01.2009)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:

61/010,545	9 January 2008 (09.01.2008)	US
61/011,006	14 January 2008 (14.01.2008)	US

(71) Applicant and
(72) Inventor: ANGELSEN, Bjørn A.J. [NO/NO]; Bugges vei 4B, NO-7051 Trondheim (NO).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **HANSEN, Rune** [NO/NO]; Wilhelm K. Størens veg 11, NO-7048 Trondheim (NO). **MÅSØY, Svein-Erik** [NO/NO]; Rosenborg gate 34 B, NO-7014 Trondheim (NO). **JOHANSEN, Tonni F.** [NO/NO]; Nordahl Griegs vei 13, NO-7024 Trondheim (NO). **NÄSHOLM, Sven Peter** [SE/SE]; Lektorsvägen 8a, S-35240 Växjö (SE).

(74) Agent: ABC-PATENT, SIVILING. ROLF CHR. B. LARSEN A.S; Postboks 6150, Etterstad, NO-0662 Oslo (NO).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM,

[Continued on next page]

(54) Title: MULTIPLE FREQUENCY BAND ACOUSTIC TRANSDUCER ARRAYS

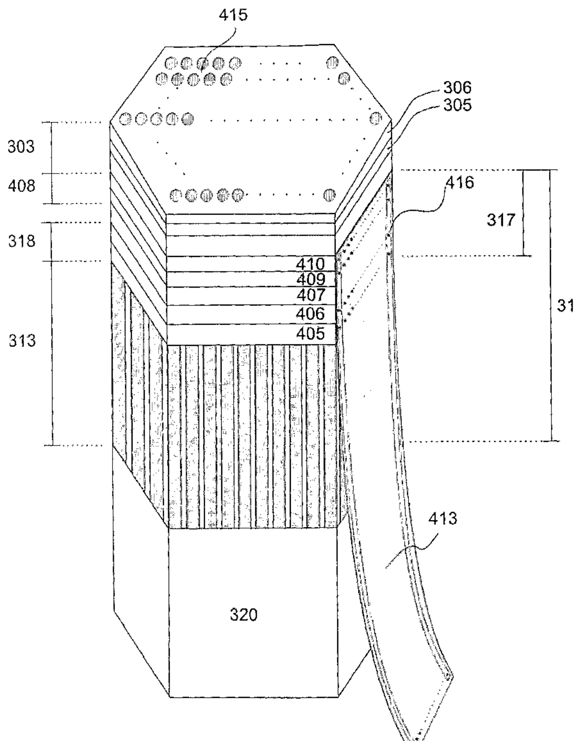

FIG. 4c

(57) Abstract: Acoustic probes that transmits/receives acoustic pulses with frequencies both in a high frequency (HF), a and a selectable amount of lower frequency (LF1, LF2,..., LFn,...) bands, where the radiation surfaces of at least two of the multiple frequency bands have a common region. Several solutions for transmission (and reception) of HF, LF1, LF2,.... pulses and signals through the common radiation surface are given. The arrays and elements can be of a general type, for example annular arrays, phased or switched arrays, linear arrays with division in both azimuth and elevation direction, like a 1.5D, a 1.75D and a full 2D array, curved arrays, etc. The element division, array type, and array aperture sizes for the different bands can also be different. Electronic substrate layers with integrated electronic that connects to array elements can be stacked within the probe.

ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

- *with international search report*
- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

MULTIPLE FREQUENCY BAND ACOUSTIC TRANSDUCER ARRAYS

1. Field of the invention

The present invention is directed to technology and designs of efficient acoustic (sonic and ultrasonic) bulk wave transducers for operation in at least two frequency bands. Applications of the transducers are for example, but not limited to, medical ultrasound imaging, nondestructive testing, industrial and biological inspections, geological applications, and SONAR applications.

2. Background of the invention

The utilization of the nonlinear elasticity of tissue and ultrasound contrast agent micro-bubbles in medical ultrasound imaging provides improved images with less noise. The widest use is in the so-called harmonic imaging, where the 2nd harmonic component of the transmitted frequency band is used for the imaging, extracted from the signal either through filtering or through the Pulse Inversion (PI) technique. A use of 3rd and 4th harmonic components of the transmitted pulse for imaging is also presented in US Pat 6,461,303.

US Pat applications 10/189,350 and 10/204,350 describe in depth different uses of dual band transmitted ultrasound and acoustic pulse complexes that provide images with reduced noise, images of nonlinear scattering, and quantitative object parameters that greatly enhance the use of ultrasound and acoustic imaging. The methods are applicable both with transmission and scatter imaging. For these applications one would transmit dual band pulse complexes as illustrated by the example in **FIG. 1**, where in **FIG. 1a** a high frequency (HF) pulse **101** rides on the peak pressure of a low frequency (LF) pulse **102**. **FIG. 1b** shows another situation where the HF pulse **103** rides on the maximal gradient of the LF pulse **102**. The ratios of the center frequencies of the LF and HF pulses can typically be in the range of 1:5 - 1:20, and at the same time the HF pulse must be found in defined intervals of the LF pulse throughout defined depth ranges of the images.

In other applications one wants from the same probe to transmit a low frequency (e.g. 0.5 - 2 MHz) wave for treatment of tissue (hyperthermia or cavitation destruction of tissue) or release of drug carried in nano or micro particles or bubbles, while being able to provide ultrasound imaging from the same probe surface at a higher frequency (e.g. 5 - 10 MHz). In yet another application one wants to have a probe for combined ultrasound treatment and imaging with 3 frequency bands, where for example a 2nd lower frequency (LF2) band ~ 400 kHz is used to generate pulses for cavitation in the tissue, for example to break nano-sized liposome particles containing drugs for drug delivery to tumors, a 1st low frequency (LF1) band ~ 3MHz is used for heating of the tissue for hyperthermia treatment of tumors, often referred to as HIFU - High Intensity Focused Ultrasound, or to increase blood flow in the tumor for improved oxygenation of the tumor or to improve the efficiency of the ~ 400 kHz breaking of drug carrying particle, and a high frequency (HF) band ~ 20 MHz is used for imaging, potentially also in combination with the ~ 3 MHz LF1 band for nonlinear manipulation of object elasticity for imaging, for example according to US Pat applications 10/189,350 and 10/204,350.

In yet other applications one simply wants to have a larger selection of frequency bands available for imaging from the same probe for a large variation of depth ranges. For example in portable ultrasound imaging systems for emergency medicine, one wants to use center frequencies of 2.5 MHz for deep object imaging, and use the same probe to image at 7 - 10 MHz center frequencies for objects closer to the body surface. The arrays can for example be arranged as phased linear arrays, switched linear arrays, and curvilinear arrays. The need for multiband transducers is also found in many other applications of acoustic imaging, for example as in non-destructive testing (NDT) of materials, observations of geological formations with elastic waves, and SONAR measurements and imaging of fish, for example close to the sea bottom, the sea bottom, and objects like mines both on the sea bottom and buried under the sea bottom or in the soil on land. This both relates to nonlinear measurements and imaging with multiband pulse complexes, and the ability to select different frequency band pulses for different needs, such as different measurement ranges.

Dual band transmitted pulses were used in M-mode and Doppler measurements in Br Heart J. 1984 Jan;51(1):61-9. Further examples are shown in US Pat 5,410,516 where sum and difference bands of the transmitted bands produced in the nonlinear scattering from contrast agent micro-bubbles where detected. A further development of this dual band transmission is done in US Pat 6,312,383 and US Pat application 10/864,992.

The current invention presents several solutions to these challenges of transducer array designs. We do in the description most often consider the situation where the elastic waves are in the ultrasound frequency range, but it should be clear to any-one skilled in the art that the solutions according to the invention can be applied to any frequency range of acoustic waves, and also to shear waves in solids.

3. Summary of the invention

This summary gives a brief overview of components of the invention and does not present any limitations as to the extent of the invention, where the invention is solely defined by the claims appended hereto.

The invention presents solutions to the general need for an acoustic, often ultrasound, array probe that transmits/receives acoustic pulses with frequencies in separated multiple frequency bands through an at least partially common radiation surface. The common radiation surface has many advantages, for example to minimize the size of a dual or multi band probe to be used from the same instrument. In other situations one needs a common radiation surface for simultaneous transmission of a high frequency (HF) and a low frequency (LF1) pulse with low or controllable phase sliding between the HF and LF1 pulses in an actual imaging range, so that the HF pulse is found in a defined region of the LF1 pressure oscillation.

The invention also presents a general procedure to design an array with a freely selectable number of operating frequency bands. In special one presents solutions to transducer arrays for transmission and reception of 3-band pulse complexes containing a high frequency (HF), a 1st lower frequency (LF1) and a 2nd lower frequency (LF2) band, or transmission and potential reception of separate pulses in 3 different frequency bands (HF, LF1, and LF2 bands). The invention provides solutions where the ratios of the center frequencies are in the range (HF:LF1) of ~ 3:1 - 20:1, with no defined upper or lower limit to the ratio. The ratio of the center frequencies of the LF1:LF2 bands can have similar values. With the lowest separation of the center frequencies one for example obtains a probe for multi-selection of image frequency bands, for example center frequencies as 2 MHz, 5.5 MHz, and 15 MHz. With a larger separation of the center frequencies one obtains a probe for imaging with the methods described in US Pat applications 10/189,350 and 10/204,350 that also can include frequency bands for HIFU and cavitation treatment of the tissue.

To achieve transmission of multi-band pulses where at least a part of the radiation surfaces are common, the invention presents solutions with a group of arrays that are resonant for each frequency band, and that has at least partially a common radiation surface. The arrays can have a general arrangement of the elements, for example linear phased or switched arrays, or annular arrays. The arrays can be flat or curved, both concave and convex, in one or two dimensions. Element divisions of the linear arrays in the elevation direction to for example a 1.5D, a 1.75D and even a full 2D array are also embodiments according to the invention. One can further have different sizes, forms, and divisions of the array elements for the different bands, for example, but not limited to, an annular array for low frequency treatment pulses with a linear switched or phased array for imaging. The invention also provides solutions for efficient packaging of electronics related to the array beam forming, such as transmit and receive amplifiers for the individual array elements, sub-aperture beam former electronics that allow connection of a group of elements to the instrument via a single wire, electronic switches for connecting selected groups of array elements in electric parallel to beam former channels via a single wire, both for transmit and receive, etc.

In order to minimize relative position sliding between the different frequency band pulses with depth, and defeat diffraction to obtain adequately collimated low frequency (LF1, LF2, ..., LFn,...) beams at deep ranges, the invention presents a solution where the arrays for the different bands have a large common radiation surface, and where parts of the radiation surfaces of the lower frequency arrays can be outside the radiation surfaces of higher frequency arrays. To minimize the overlap between the different frequency band pulses in the near field, the invention also presents solutions where central parts of the lower frequency apertures are inactive. To efficiently select between different sizes and overlaps of the radiation surfaces of the different bands, the invention devices the use of different arrays for the different bands, with special solutions of the array constructions to provide common radiation surfaces of the different bands.

In one embodiment according to the invention to obtain a common HF and LF1 array radiation surface, the HF and LF1 pulses are generated with separate piezoelectric layers stacked in front of each other with the HF piezo-layer in the front, and an isolation section for HF vibrations to the front of the LF1 piezo-layer. A load matching section of impedance matching layers is placed between the HF piezo-layer and the load material to the front. The isolation section is designed so that the reflection coefficient between the HF piezo-layer and the isolation section is high in the HF band so that the layers behind the HF piezo-layer has low influence on resonances in the electro-acoustic transduction of the HF piezo-layer in the HF band. The isolation section is also designed so that in the LF1 band it cooperates with the probe layers in front of the isolation section to provide acoustic matching of the LF1 piezo-layer to the load material.

Close to unit reflection coefficient between the HF piezo-layer and the isolation section is obtained when the impedance seen into the isolation section from the front is low or high compared to the characteristic impedance of the HF piezo-layer. When the impedance into the isolation section from the front is low in the HF band, the HF piezo-layer will have a thickness resonance when it is approximately half a wavelength thick around the center of the HF band. When the impedance into the isolation section from the front is high in the HF band, the HF piezo-layer will have a thickness resonance when it is approximately a quarter wavelength thick around the center of the HF band. The quarter wave resonance generally allows wider bandwidth of the HF layer resonance, but with poorer phase angle of the electrical impedance compared to for half wave length resonance of the HF piezo-layer.

The invention provides special designs of the isolation section that provides either adequately high or adequately low impedance into the front of the isolation section in the HF band, with low sensitivity to the impedance seen from the back of the isolation section. This is especially important when the LF1 piezo-layers are made as ceramic/polymer composites where one wants to minimize variations in the reflection coefficient from the HF layer towards the isolation section when the isolation section connects to polymer or ceramics in the composite. To achieve this reduced impedance sensitivity of the reflection coefficient, the invention provides solutions where the isolation section is composed of at least two acoustic layers.

In a 1st embodiment of the isolation section according to the invention, the isolation section contains an impedance regularizing layer at the back of the isolation section that is adequately thin and heavy so that it in the HF band approximately represents a mass, adequately large, in series with the impedance to the back. This mass is then in series with the loading of the isolation section to the back, and makes the impedance transformation of the whole isolation section less dependent on whether the isolation section ends into polymer or ceramic in the LF1 piezo-composite. The impedance regularizing layer is preferably a heavy material, for example Cu, Ag, Au, Pd, Pt, W, or alloys of such materials, or powders of such materials or their alloys sintered together or glued in a solvent such as a polymer. The thickness of the back layer can typically be of the order of $\lambda_{HF}/30$ or higher. Due to the large wave propagation velocity of Si (8.44 mm/μsec), a Si layer can also be used for an impedance regularizing layer with adequate mass, although the mass density of Si is only 2330 kg/m^3. The invention also presents a solution where the impedance regularizing layer of the isolation section is made of ceramics, where the ceramics layer can be part of the LF1 piezo-layer. This ceramics back layer may conveniently be combined with a thin layer (the order of $\lambda_{HF}/30$) of heavy material like Cu, Ag, Au, Pd, Pt, W, or alloys of such materials, or powders of such materials or their alloys sintered together or glued in a solvent such as a polymer.

A low impedance into the isolation section can then for example be obtained with a matching layer in front of said impedance regularizing layer of large mass, where said matching layer has low characteristic impedance and is quarter wavelength thick around the center of the HF band. Said matching layer can preferably be made of polymer or similar material. An approximate analysis on how to match the LF1 piezo-layer to the load in the LF1 band can be done by realizing that both said isolation section matching layer and the HF piezo-layer with load matching layers will be thin compared to the wavelength in the LF1 band. This allows a thin layer approximation where said low impedance matching layer behaves as an elastic spring in series with the mass of the HF piezo- and matching layers and the load impedance. The center frequency of the LF1 band is then selected at the resonance between this spring and mass where the phase of the impedance into said isolation section matching layer seen from the back is zero. This resonance frequency can be tuned by varying the stiffness of said isolation section matching layer and the mass of the HF piezo and load matching layers. This mass can for example be tuned by varying the ceramic volume fill in the HF piezo-composite.

The embodiment can be modified to obtain a high impedance into the isolation section by adding a 2nd $\lambda_{HF}/4$ matching layer with high characteristic impedance that connects to the HF piezo-layer in front of the 1st $\lambda_{HF}/4$ matching layer with low characteristic impedance. With this solution, the impedance seen from the front into the isolation section is less dependent on the thin impedance regularizing layer described above, where this layer in many situations can be removed when two $\lambda_{HF}/4$ matching layers are used. The selection of characteristic impedances of the 1st and 2nd matching layers can be done through standard considerations of impedance matching known to anyone skilled in the art. In the LF1 band the 1st, low impedance matching layer will then behave approximately as a spring in series with the combined mass of said 2nd, high impedance, matching layer and the HF piezo- and load matching layers, where the center frequency of the LF1 band is selected at the resonance frequency of said spring and load system, where the material parameters of the spring and mass system can be tuned for resonance in the LF1 band.

In a less efficient embodiment to provide high impedance into the isolation section in the HF band, one can use a single $\lambda_{HF}/4$ matching layer with high characteristic impedance to the front of said impedance regularizing layer of large mass. In the LF1 band this single matching layer will approximately behave as a mass in series with the mass of HF piezo- and load matching layers and provide a load impedance seen from the LF1 piezo-layer that has an inductive phase. This do not provide optimal impedance matching but a useful form of the LF1 electro-acoustic transfer function is obtained.

We have above given some examples of interesting structures of the isolation section, but it is clear to any-one skilled in the art that different designs of the isolation section can be found according to principles of impedance matching known to any-one skilled in the art, where the essence of the invention is to use an isolation section of at least two layers. The impedance regularizing mass layer is very useful when the LF1 piezo-layer is made as a ceramic polymer composite, but can be omitted when the LF1 piezo-layer is made as a whole ceramic. This can for example be the situation when the LF1 layer is used for high power therapy purposes without direction steering of the beam.

One can according to the invention add 2nd , 3rd , etc. lower frequency bands to the structure above by extending the piezo-layer structure backwards in front of the backing with sections containing an isolation section in front of a piezoelectric layer for each new low frequency band, where the resonance frequency for the piezo-layers has a monotone decrease with the position backwards in the structure. The isolation sections are designed according to the same principles as for the dual piezo-layer structure described above, where the reflection coefficient into the front of the isolation section is close to unity within the resonance band of the neighbor piezo-layer in front of said new section. Within the resonance frequency of said new piezo-layer, the new isolation section interacts with the layers in front of the isolation section to provide resonant impedance matching between the load and the new piezoelectric layer. The structure can hence be extended backwards with a new such combined isolation section and piezo-layer for each new lower frequency band, in principle ad infinitum, where most practical applications requires in total 2 or 3 lower frequency bands in addition to the HF band.

The structure typically ends with a backing material that has so high absorption that reflected waves in the backing material can be neglected. The last piezo-layer can attach directly to the backing material, or through back matching sections composed of impedance matching layers. The backing material can be used as acoustic power absorbant to reduce resonances in the electro-acoustic transfer functions. Resonances in any of the frequency bands can also be dampened with matching layers of absorbing materials, for example viscous damping polymer materials, and even adding particles to the polymer materials to increase absorption. Viscous damping polymer materials and particle filled polymer materials can also be used in the polymer fills of the ceramic/polymer composites of the piezoelectric layers. Solid/polymer composites can also be used for matching layers to tune the characteristic impedance, where viscous and/or particle filled polymers can be used for increased absorption in the matching layers.

Heavy layers or high-impedance layers of said isolation sections can conveniently be made of one or more electronic substrate layers (typically Si-layers) with electronic circuits, such as transmit and receive amplifiers for the array elements, channel number reducing circuits such as switches for electronically selectable connection of groups of array elements in electric parallel to beam former channels, sub-aperture beam forming for one or both of transmit and receive, so that groups of array elements can be connected to further processing, within the probe or in the instrument, via a reduced number of wires. The signals from groups of elements or groups of sub-apertures of elements may also be transmitted on a single wire by time-multiplexing samples of the signals from such groups, where the time-multiplexing circuits are integrated into said electronic substrate layers, to reduce the cable connections to the arrays.

The electronic substrate layers can conveniently be part of the heavy, impedance regularizing back layer of an isolation section, but also conveniently part of a high impedance front layer of an isolation section. In the latter situation, electronic circuits on the front of the substrate layer can connect directly to the array elements in front, for example HF array elements, through metal pads and known connection techniques such as anisotropic conducting polymer glue containing conducting particles, micro soldering, ultrasonic bonding, etc. Channel number reducing circuits are conveniently implemented in these front electronic substrate layers (e.g. switched element selection, sub-aperture electronics, etc.), to reduce the number of connections to further processing electronics that can comprise or be part of an impedance regularizing back layer of an isolation section. Such reduced number of connections through a matching layer with low electrical conduction can then be obtained via metal connectors through the layer that are so thin that they have minimal effect on the characteristic acoustic impedance of the matching layers. To extend the thickness of a back isolation section layer of Si substrates for increased processing and circuit complexity in these layers, the lower frequency array behind can conveniently be made as a ceramic/polymer composite with average characteristic acoustic impedance close to that of the electronic substrate (for Si substrate the characteristic impedance is approximately 19.7 MRayl) so that the electronic substrate layers participate in the definition of the resonance of said lower frequency array.

Substrate layers with electronics can also be placed in front of the HF array, behind the HF acoustic matching layers. With the front placement of the substrate layers, the HF array is conveniently made of piezo-ceramic/polymer composite with average characteristic impedance close to that of the electronic substrate layer, so that the substrate layers participate in the resonance definition of the HF array.

In another embodiment according to the invention to obtain common HF and lower frequency array radiation surfaces, the HF transduction is provided by vibrating membranes on a substrate activated by cmut/pmut technology, while the lower frequency pulses are generated with a piezo-layer to the back of said cmut/pmut structure. Behind the cmut/pmut substrate one can conveniently place several electronic substrate-layers with transmit and receive amplifiers, electronic switches, sub-aperture beam forming circuitry, etc. The high acoustic propagation velocity of Si (8.44 mm/μsec), means that the total thickness of such layers can be a fraction of the LF1 wave length in Si, and hence provide minimal modification of the lower frequency transmission through the Si layers. Such modification is further reduced by making the lower frequency piezo-layer closest to the substrates as a ceramic/polymer composite with characteristic impedance close to that of the electronic substrate layers. One can then according to the description above extend the structure backwards with more piezoelectric layers with resonances in lower frequency bands (LF2, LF3, …) including isolation sections for vibrations within the bands of the layers to the front, according to the principles of the invention described above.

In yet another embodiment according to the invention, to obtain common HF and LF1 array radiation surfaces, both the HF and the LF1 pulses are generated with separate cmut/pmut membranes on a common substrate, either side by side of each other or the HF membranes on top of the LF1 membranes. The HF LF1 membranes are then optimized for operation in their respective frequency bads. In yet another embodiment according to the invention, to obtain common array radiation surfaces for a HF band and more than one lower frequency bands, both the HF and more than one lower frequency bands are generated with different cmut/pmut membranes for the different frequency bands on a common substrate. The membranes for the different frequency bands can be either placed side by side of each other or some or all of the membranes are stacked on top of others with increasing frequency band from the lowest to the top, while the rest of the membranes are placed directly on the substrate by the side of the stacked membranes. Also in these embodiments one can conveniently place several electronic substrate-layers with transmit and receive amplifiers and beam forming circuitry behind the cmut/pmut substrate, and the structure can be extended backwards with added lower frequency piezo-layers with isolation section in front, as described above.

The arrays can be used for transmission and reception in each of the frequency bands. The methods cited in US Pat applications 10/189,350 and 10/204,350 would transmit dual band complexes and use only the received signal in the highest frequency band for processing to measurement or image signals. The frequency bands of the transmitted dual band complex can then be selected from any of the frequency bands in the probe.

The invention is also useful with sparse arrays, where the grating lobes from the HF aperture should be different from possible grating lobes of the lower frequency arrays, to suppress the effect of transmitted HF grating lobes for example with imaging methods and instruments according to US Pat applications 10/189,350 and 10/204,350.

The invention also prescribes instruments that uses acoustic multiple band array probes according to the invention for different purposes, for example the use of the different frequency bands of the probe for imaging at different depths, or acoustic tissue treatment at different frequencies, or imaging according to the methods described in US Pat applications 10/189,350 and 10/204,350, or combined acoustic treatment and imaging with any method. The frequency bands are selected by the instrument, either automatically from the operational settings of the instrument, or manually by the instrument operator through instrument controls. For example can with the imaging methods described in US Pat applications 10/189,350 and 10/204,350 the radiation surfaces of the lower frequency apertures be selectably varied to be one of equal to the HF transmit aperture, and larger than the HF aperture where the HF radiation area is part of the lower frequency radiation areas, and the LF1 and/or the HF apertures can be selected to have an inactive central region.

4. Summary of the drawings

FIG. **1**	shows examples of low frequency (LF1) and high frequency (HF) pulse complexes that one wants to transmit,
FIG. **2**	shows example HF and LF1 radiation surfaces according to the invention, and also for analysis of HF and LF1 pulse phase relationships,
FIG. **3**	shows a cross section of a dual and a tripple piezo-layer stack arrangement according to the invention that allows transmission and reception of a two and three frequency band pulses through a common front face,
FIG. **4**	shows examples of other layer structures that participate in the isolation of the piezo-

	electric sections in FIG. **3**, and also integrated circuit layers to be integrated in the acoustic stack,
FIG. **5**	shows a front view of a phased array probe according to the invention,
FIG. **6**	shows an example of a dual piezolayer arrangement to reduce the electric impedance of array elements,
FIG. **7**	shows a front view of a substrate with cmut/pmut micro-machined transduction cells,
FIG. **8**	shows a cross section of a transducer stack where the HF transduction is generated by cmut/pmut cells on a substrate in front of a piezolayer for LF1 transduction, and also inclusion of substrate layers with integrated electronics,
FIG. **9**	shows a cross section of a transducer stack where the LF1 transduction is generated by cmut/pmut cells on a substrate in front of a piezolayer for HF transduction,
FIG. **10**	shows a front and cross section view of a combined LF1 and HF section implemented by cmut/pmut transduction cells micro-machined on a substrate, where the HF cells are placed on top of the LF1 cells.
FIG. **11**	shows a front view of a LF1 and HF array arranged as a sparse array where the HF and LF1 elements are placed between each other,
FIG. **12**	shows a front view of a combined low and high frequency section implemented by cmut/pmut transduction cells micro-machined on a substrate, where the low and high frequency cells are placed side by side of each other.
FIG. **13**	shows how a 3rd electro-acoustic transduction band can be obtained with the cmut/pmut structures in FIG. 8 - 12.

5. Detailed description of the invention

Example embodiments of the invention will now be described in relation to the drawings. We start with describing solutions to dual frequency arrays, and describe how these designs can be extended with the same principle for operation in 3 or more frequency bands. Typical examples of dual frequency pulses that one wants to transmit are shown in **FIG.1** as described above. The challenges in the design of the arrays lie both in the design of the radiation surfaces so that the HF pulse is kept within desired location of the LF1 pulse for adequate image range while maintaining adequate amplitude of the LF1 pulse, and in design of a vibration structure that allows transmission of LF1 and HF pulses with such wide separation between the frequencies from the same surface.

In some of the applications it is important that the amplitude of the LF1 pulse at the location of the HF pulse is as high and close to constant as possible throughout an adequate imaging range. This can require large apertures of the LF1 radiation surface to avoid diffraction spread of the LF1 beam due to the long wavelength of the LF1 pulse compared to the HF pulse. The width of the HF transmission aperture can be limited by a requirement on the length of the HF transmit focal region. This gives situations where one would prefer a larger LF1 aperture than the HF aperture, which introduces a sliding between the position of the HF pulse relative to the LF1 pulse.

For further analysis of this sliding phenomenon we consider circular apertures because one have analytic expressions of the field on the axis of such apertures. **FIG. 2a** shows by way of example a circular HF transmit aperture **201** with diameter $D_{HO} = 2a_{HO}$ and a concentric LF1 transmit aperture **202** which for the example is shown as a ring with outer diameter $D_{LO} = 2a_{LO}$ and inner diameter $D_{LI} = 2a_{LI}$. A cross section diagram shows the HF and LF1 transmit apertures as **203**, where they by way of example are curved to the same focus F, **204**. The common focus for the HF and LF1 transmit apertures is chosen by way of example, and one can in other situations also have different foci of the two apertures, where the LF1 aperture also can be unfocused. The transmitted axial continuous wave field for the LF1 and the HF apertures at a frequency ω is as a function of the axial distance z given as

$$P_{LF}(z,\omega)=\frac{F}{z}\frac{e^{-ikR_{LI}(z)}-e^{-ikR_{LO}(z)}}{F/z-1}P_{L0}(\omega) \qquad \text{a)}$$
$$=i2e^{-ik(R_{LO}(z)+R_{LI}(z))/2}\frac{F}{z}\frac{\sin k(R_{LO}(z)-R_{LI}(z))/2}{F/z-1}P_{L0}(\omega)$$

$$(1)$$

$$P_{HF}(z,\omega)=\frac{F}{z}\frac{e^{-ikR_{HI}(z)}-e^{-ikR_{HO}(z)}}{F/z-1}P_{H0}(\omega) \qquad \text{b)}$$
$$=i2e^{-ik(R_{HO}(z)+R_{HI}(z))/2}\frac{F}{z}\frac{\sin k(R_{HO}(z)-R_{Hi}(z))/2}{F/z-1}P_{H0}(\omega)$$

where $k = \omega/c$ and ω is the angular frequency of the transmitted pulse and c is the acoustic propagation velocity. $R_{LO}(z)$ shown as **205** is the distance from the outer edge of the LF1 aperture to the point z (**208**) on the z-axis, $R_{LI}(z)$ shown as **206** is the distance from the inner edge of the LF1 aperture to **208** on the z-axis, and $R_{HO}(z)$ shown as **207** is the distance from the outer edge of the HF aperture to **208** on the z-axis, and $R_{HI}(z)$ is the distance from the inner edge of the HF aperture to **208** on the axis. As the HF aperture has no missing part in the center, we get $R_{HI}(z) = z$, but we shall also consider situations where a central part of the HF aperture with dimater $D_{HI} = 2a_{HI}$ is missing.

$P_{LO}(\omega)$ is the LF1 transmit pressure at the aperture while $P_{HO}(\omega)$ is the HF transmit pressure at the aperture. An absorbing medium can be modeled by a complex wave vector $k=k_r(\omega)-ik_d(\omega)=\omega/c_p(\omega)-i\alpha\omega$, where the imaginary part $-k_d$ represents power absorption and the real part k_r represents wave propagation with an in general frequency dependent phase velocity $c_p(\omega)$. The frequency variation of the phase velocity is produced by the absorption, and can for most situations in tissues and materials with similar absorption be neglected, i.e. $c_p(\omega) \approx c$. The absorption coefficient is often, due to multiple relaxation phenomena, proportional to the frequency, i.e. $k_d(\omega) \approx \alpha\omega$.

We note from the 1st lines of the expressions in Eqs.(1a,b) that the pressure do in the near field break up into two pulses with delays $R_{LI}(z)/c$ and $R_{LO}(z)/c$ for the LF1 pulse, and $R_{HI}(z)/c$ (from the center) and $R_{HO}(z)/c$ for the HF pulse. As z increases, the delay difference between these pulses reduces, so that the two pulses start to interfere, both for the LF1 and HF waves. We then get a longer pulse than given by $P_{L0}(\omega)$ and $P_{H0}(\omega)$ with complex central part due to interference between the edge pulses. The interference can introduce zeros in the middle of the LF1 and HF pulses with destructive interference, and maxima with constructive interference. For z < F, the propagation distance to z on the axis from the outer edge is longer than the propagation distance from the inner edge, and for an absorbing medium one hence do not get complete destructive interference with zeros of the central part of the LF1 and HF pulses. Apodization of the pressure drive amplitude across the array surface, so that the drive amplitude is reduced towards the edges, will also reduce in amplitude the pulses from the edges, i.e. with the delay $R_{LO}(z)/c$ for the LF1 pulse, and $R_{HO}(z)/c$ for the HF pulse.

In the focal region, Taylor expansion of the second lines of Eqs.(1a,b) shows that interference between the two pulses produces a pulse which approaches the time derivative of the transmitted pulses $P_{L0}(\omega)$ and $P_{H0}(\omega)$ in the focus, and with a delay given by the phase terms. This situation is also found in the far-field of an unfocused aperture, and generally relates to the region where the beam width is limited by diffraction. The phase terms in Eq.(1) represent the average propagation lag from the LF1 and HF apertures, respectively as

$$\tau_{LF}(z)=\frac{1}{2c}\left(R_{LO}(z)+R_{LI}(z)\right)$$
$$\tau_{HF}(z)=\frac{1}{2c}\left(R_{HO}(z)+R_{HI}(z)\right) \qquad (2)$$

The differentiation of the transmitted LF1 pulse $P_{L0}(\omega)$ towards the focus produces an added time advancement of $T_{LF}/4$ of the LF1 pulse oscillations, where T_{LF} is the temporal period of the LF1 pulse center frequency, with minor effect on the pulse envelope. We hence see that in the focal region, the LF1 and HF pulse lengths are given by the transmitted pulse lengths on the array surface, with a change in the oscillation phase of 90 deg due to the differentiation and propagation lags given by Eq.(2). Due the differentiation of the LF1 pulse, and in addition when $D_{LO} > D_{HO}$, HF and LF1 pulses will get z-dependent propagation delays that differ from each other, and the location of the HF pulse relative to the LF1 pulse will slide with depth as exemplified in **209** - **211** for depths z1, z2 and z3.

Albeit the above formulas are developed for circular apertures they illustrate a general principle for apertures of any shape, because the radiated beam originates as interference between spherical waves with origin at all points on the aperture (Huygen's principle). Hence, the waves originating from points on the LF1 aperture outside the HF aperture, will have longer propagation distance to the axis than points on the HF aperture. The difference between these propagation distances varies with depth z, which hence produces the position sliding between the HF and the LF1 pulse.

We see that when the LF1 and HF transmit apertures are equal, there is no sliding between the LF1 and HF pulses in the focal region, but we get a $T_{LF}/4$ advancement of the LF1 pulse oscillations from the near field to the focus, due to the temporal differentiation of the LF1 pulse in the diffraction limited region. An LF1 transmit aperture equal to the HF transmit aperture can in many situations be too small so that too high LF1 beam divergence due to diffraction is found. Therefore it is often desirable to have a wider LF1 transmit aperture than the HF transmit aperture. This produces some added sliding between the HF and LF1 pulses with depth, which can be established between tolerable limits through the dimensioning of the transmit apertures. This sliding can also be utilized for different purposes, for example to compensate for variations in the LF1 pulse amplitude so that the observed LF1 pressure at the location of the HF pulse has less variation with depth than the LF1 pulse amplitude.

To further analyze the situation when the LF1 and HF apertures are different we continue with the circular apertures. For a common focal depth F, we get the distances from outer and inner edges of the LF1 and HF apertures as

$$\begin{aligned} R_{gO}(z) &= \sqrt{z^2 + 2e_{gO}(F-z)} \qquad e_{gO} = F - \sqrt{F^2 - a_{gO}^2} \approx \frac{a_{gO}^2}{2F} \qquad g = L,H \\ R_{gI}(z) &= \sqrt{z^2 + 2e_{gI}(F-z)} \qquad e_{gI} = F - \sqrt{F^2 - a_{gI}^2} \approx \frac{a_{gI}^2}{2F} \qquad g = L,H \end{aligned} \tag{3}$$

where $D_{LO} = 2a_{LO}$, $D_{LI} = 2a_{LI}$, $D_{HO} = 2a_{HO}$, and $D_{HI} = 2\ a_{HI}$. When the last term under the root sign is relatively small, we can approximate

$$R_{gO}(z) \approx z + \frac{F-z}{2Fz}a_{gO}^2 \qquad R_{gI}(z) \approx z + \frac{F-z}{2Fz}a_{gI}^2 \qquad g = L,H \tag{4}$$

The z variation of the propagation lag difference between the LF1 and HF pulses is then found by inserting Eq.(4)

into Eq.(2) which gives

$$\Delta\tau(z)=\tau_{LF}(z)-\tau_{HF}(z)=\frac{1}{2c_0}\frac{F-z}{2Fz}\left(a_{LO}^2+a_{LI}^2-a_{HO}^2-a_{HI}^2\right) \tag{5}$$

Hence, by choosing

$$a_{HO}^2+a_{HI}^2=a_{LO}^2+a_{LI}^2 \tag{6}$$

we obtain, with accuracy within the approximation, zero sliding between the HF and LF1 pulses in the focal range of the LF1 pulse, even in the situation where the outer dimension of the LF1 transmit aperture is larger than the outer dimension of the HF aperture.

A disadvantage with the removed central part of the HF transmit aperture is that the side lobes in the HF transmit beam increase. However, these side lobes are further suppressed by a dynamically focused HF receive aperture. The approximation in Eq.(4) is best around the beam focus, and Eq.(6) do not fully remove phase sliding between the LF1 and HF pulses at low depths. For other than circular apertures (for example rectangular apertures) one does not have as simple formulas for the axial field as in Eq.(1) but the analysis above provides a guide for a selection of a HF transmit aperture with a removed center, for minimal phase sliding between the LF1 and the HF pulses with depth. With some two-dimensional arrays one can approximate the radiation apertures with circular apertures where Eq.(6) can be used as a guide to define radiation apertures with minimal phase sliding between the LF1 and HF pulses.

Different measurement situations put different requirements on tolerable variations of the LF1 amplitude and also position sliding between the HF and the LF1 pulses, and one therefore often wants at least the LF1 transmit aperture to be composed of elements so that the effective width of the LF1 transmit aperture can be selected together with the relative transmit timing of the HF and LF1 pulses so that in the desired range one gets best possible amplitudes and relative locations of the two pulses. The invention devices an instrument using such a probe, where the selection of the active LF1 transmit aperture surface can be done automatically by the instrument depending on the application (e.g. suppression of multiple scattering noise or detection of contrast agent micro bubbles) and image depth, or manually by the instrument operator. One also wants to vary the HF transmit aperture, and during reception of the scattered

HF signal one typically wants a receive aperture that increases dynamically with the focus to follow the scatterer depth. Hence, a preferred solution is a combined LF1 and HF array with common radiation surfaces, but where the actual LF1 and HF transmit apertures can be selected for the application, where the LF1 transmit aperture is typically larger than the HF transmit aperture, while the HF receive aperture can be selected wide or possibly wider than the LF1 transmit aperture at large depths, for example with dynamic receive aperture with depth.

In the above example, the LF1 and HF transmit amplitudes have common foci, which is an advantage in some situations, but differences in LF1 and HF transmit foci can also be utilized in the beam designs for different purposes. For example can one for practical purposes use a LF1 array that is flat outside the HF aperture, and has the same curvature or lens focus as the HF array within the HF aperture. For some applications one can prefer to use an unfocused LF1 aperture that is so wide that the actual imaging range is within the near-field region of the LF1 aperture, to avoid phase changes of the LF1 pulse due to the differentiation of the LF1 pulse as one moves into the diffraction limited region (far-field, focal region) of the LF1 beam. With a switched linear HF array where the HF beam directions are normal to the radiation surface (aperture), the LF1 aperture can for some applications be a single element array transducer with somewhat wider aperture than the linear HF array, so that the LF1 near field region covers the whole HF image ranger, for example as illustrated in **FIG. 2b**. In this Figure **220** illustrates the front view of a single element LF1 array, that produces a beam illustrated in side view as **221** up to the maximal image depth Z, which is within the near field of the LF aperture for this example. The front view of the radiating surface of a linear HF array is shown as **222**, indicating the linear array elements **223**, where a selected group of elements produces a selected HF transmit aperture **224** that produces the HF transmit beam **225**. For imaging the HF transmit and receive beams are scanned within the rectangular image field **226** while the LF1 beam covers the field **221** for all HF beams.

The example embodiment in **FIG. 2b** is useful to obtain low variation of the LF1 pressure along the HF pulse propagation, which is useful for imaging of nonlinear scattering of micro-bubbles and hard scatterers, as described in US Pat applications 10/189,350 and 10/204,350. However, for improved suppression of multiple scattering noise, for example as described in the same applications, it is useful to have a LF1 aperture that is inactive in a central region as indicated in **FIG. 2c**. This Figure shows a LF1 aperture **220** that is composed of two elements, a central element **227** with an outer element **228** around. In this example embodiment the central element is larger than the HF aperture **222**, but one can also see applications where the element **227** is narrower than the HF aperture in the elevation direction. For imaging of nonlinear scattering, the two LF1 elements **227** and **228** would typically be coupled electrically in parallel to give an active LF1 transmit aperture **220** as in **FIG. 2b**. For improved suppression of HF multiple scattering noise one could then use only the outer element **228** for transmission of the LF1 pulses, which would reduce the nonlinear interaction between the HF and LF1 pulses in the HF near field.

Hence, the invention provides solutions to different challenges for transmitting dual band pulse complexes, where one in general wants to select between a variety of radiation surfaces for the LF1 and HF pulses, as conceptually illustrated in **FIG. 2d**. The form of the apertures are chosen circular for conceptual demonstration of the variations, where one can choose any form of the apertures, for example rectangular, elliptical, curved, etc. according to what suits the application best. In **FIG. 2d 230** illustrates a concept where the HF aperture **(235)** is common to parts of the LF1 aperture (**236**) in a common aperture **238**, while the LF1 aperture also extends outside the HF aperture. **231** shows a modified concept where the central part **237** of the LF1 aperture is inactive as LF1 radiation surface, for example to reduce the nonlinear interaction between the LF1 and HF pulses in the HF near field. **232** illustrates a further modification to **231** where the inactive central part of the LF1 aperture is extended to be larger than the HF aperture, while **233** shows a modification where the LF1 and HF apertures are equal. In many situations one wants to have an array where one can select between two or more of these conceptual situations for different operations of the measurement or imaging. The selection of the apertures can for example be done automatically by the instrument depending on the application, or manually by the instrument operator to optimize the image quality in a given measurement situation.

Yet another example application of a dual or multiple frequency band array according to the invention, is to use the different frequency bands to image at different depth ranges with the same probe, for optimized selection of frequency for different image depths. One would then use the HF band to image at lower depths for improved resolution with focus in these depths, for example as a switched linear array operating at 10 MHz, and the LF1 band to image at deeper depths with correspondingly deeper focus for improved penetration, for example as a linear phased array operating at 2.5 MHz. Such a probe is for example desirable with portable scanners, especially for emergency use, as one reduces the amount of probes to be carried around. By dividing the apertures into array elements, one can electronically steer the focal depths of both the LF1 and HF apertures, and also the beam directions, according to known methods. Due to the larger wavelength of the LF1 band, the array elements for the LF1 band can have larger radiation surfaces with larger distance between neighboring element centers, than do the HF array elements within the common radiation surface, as for example discussed in relation to **FIG. 5** below. In **FIG. 2b** we even use a LF1 array composed of a single element, whereas the HF array has a large number of elements. In **FIG. 2c** we also see that the LF1 and HF elements have different shapes. The invention hence presents a general solution for a combined LF1 and HF array with a common radiation surface, also allowing the apertures, frequencies and foci to be electronically selectable for optimal measurements in different situations, either automatically by the instrument depending on the application, or manually by the instrument operator to optimize image quality.

The common radiation surfaces provide challenges in the structural design of electro/acoustic transduction due to the wide separation between the LF1 and HF frequency bands, where the current invention provides several solutions to this problem. A first example of a stack of piezoelectric and acoustic layers that allows operations of a LF1 and a HF pulse with widely separated frequencies from the same radiation surface, is shown in **FIG. 3a**. The Figure shows a cross section through a layered structure that radiates and receives both frequency bands through radiation surfaces that at least have a common region **302** in acoustic contact with the load material **301**. For typical applications, both the LF1 and the HF components might in addition be transmitted or received across separate surfaces outside the common surface. However, for equal LF1 and HF transfer functions across the whole aperture, it is advantageous to use the same thickness stack across the whole aperture, and define the LF1 and HF apertures by the areas of the active element electrodes as discussed below.

The HF pulse is received and/or generated by the transducer array assembly **303** which in this example is composed of a piezoelectric layer **304** that is resonant in the HF band, with two acoustic matching layers **305** and **306** in front that acoustically connect to the load material **301**. The acoustic contact can either be direct or through a fluid and a dome, all according to known methods. The piezoelectric layer **304** has a set of electrodes on the front and back faces that electrically define the array elements, where by example **FIG. 3a** shows the cross section of the electrodes **307** and **308** for one array element that generates the electric port **309** for that element. Driving the electric port **309** with a voltage signal V_0 in the HF band, will generate vibrations on the radiating surface **302** that generate a wave **310** propagating into the load material with frequencies in the high band. Similarly, an incoming wave **311** with frequencies in the high band will produce electrical voltage oscillations across the HF port **309**.

The LF1 pulse is in this example embodiment generated by the transducer array assembly **312**, which is composed of a piezoelectric layer **313** that is resonant in the LF1 band, covered on the front with a layered section **317** for acoustic isolation of HF vibrations in the HF structure from the LF1 structure.
The isolation section is designed so that the reflection coefficient between the HF assembly **303** towards the isolation section is close to unity in the HF band to avoid interference from the LF1 structure on vibrations of the HF structure in the HF band. The isolation section is also designed so that in the LF1 band it cooperates with the probe layers in front of the isolation section to provide acoustic matching of the LF1 piezo-layer **313** to the load material. When the LF1 piezo-layer is made as a ceramic/polymer composite it is advantageous that the isolation section **317** is made of at least two layers, where the back layer, or group of layers, **318** of this section preferably is a heavy, impedance regularizing structure for the reasons described below. The whole transducer assembly is mounted on a backing material **320** with so high absorption that reflected waves in the backing material can be neglected. In some embodiments one can have impedance matching layers between the LF1 layer **313** and the backing **320** to increase the acoustic coupling, according to known methods. The Figure also shows a cross section of the electrodes **314** and **315** for a particular LF1 array element, or parts of the LF1 array element as the LF1 array element often is wider than the HF array element. The electrodes constitute a LF1 electric port **316**, where driving this port with an electric voltage signal V_1 in the LF1 band produces LF1 vibrations on the array front face **302** that radiates a wave **310** into the

load material **301**.

Close to unit reflection coefficient between the HF piezo-layer and the isolation section is obtained when the impedance seen into the isolation section from the front is low or high compared to the characteristic impedance of the HF piezo-layer. When the impedance into the isolation section from the front is low in the HF band, the HF piezo-layer will have a thickness resonance when it is half a wavelength (or whole number of half wavelengths, where the half wave length is the most efficient) thick around the center of the HF band. When the impedance into the isolation section from the front is high in the HF band, the HF piezo-layer will have a thickness resonance when it is a quarter of a wavelength thick (or an odd number of quarter wavelengths) around the center of the HF band. The quarter wave resonance generally allows wider bandwidth of the HF layer resonance with poorer phase angle of the electrical impedance compared to for half wavelength resonance of the HF piezo-layer.

The thickness of the HF piezo-layer **304** is lower than the thickness of the LF1 piezo-layer **313** due to the separation of the HF and the LF1 frequencies. For this reason the cuts between elements or in the composite of the LF1 layer require a thicker saw blade than for the cuts in the HF layer. It can hence in the practical manufacturing situation be difficult to control whether the ceramic posts of the HF layer connect to ceramics or polymer fill in the LF1 piezo-layer. To make the HF isolation properties of the matching section **317** have enough low sensitivity to a connection into LF1 ceramic or polymer fill, the invention devices that the back layer or group of layers **318** of the section **317** close to the LF1 piezo-layer **313** to be made of heavy materials with high acoustic impedance, for example metals like Ag, Cu, Au, Pd, Pt, and W, or even a ceramic material or integrated electronic substrates as discussed below. Large shear stiffness of the layer(s) **318** will also help in reducing the sensitivity to connection of **317** into ceramic or polymer fill, but large shear stiffness of **318** would also introduce lateral vibration coupling between LF1 array elements, and hence the thickness of this layer should be limited, while still making the impedance seen from the front into the section **317** adequately insensitive to connection into ceramic or polymer fill on the back side. Thicknesses of layer(s) **318** less than $\lambda_{HF}/20$ are found useful, as discussed below. Of the listed metals, Ag, Au, Pd, and Pt have the lowest shear stiffness and still a high mass density which makes the materials most efficient for reducing the sensitivity to connection into ceramic or polymer fill with lowest lateral coupling between LF1 array elements.

The other layers of the isolation section **317** are typically chosen with $\lambda_{HF}/4$ thickness at the high frequency. A low impedance into the isolation section **317** can for example be obtained with a matching layer in front of said impedance regularizing layer **318**, where said matching layer has low characteristic impedance and is quarter wavelength ($\lambda_{HF}/4$) thick at the center of the HF band. Said matching layer can preferably be made of polymer or similar material. A high impedance into the isolation section can for example be obtained with a 1st $\lambda_{HF}/4$ matching layer with low characteristic impedance to the front of said impedance regularizing layer **318** of large mass. This 1st matching layer connects into a 2nd $\lambda_{HF}/4$ matching layer with high characteristic impedance that connects to the HF piezo-layer. The selection of characteristic impedances of the 1st and 2nd matching layers can be done through standard considerations of impedance matching known to anyone skilled in the art. When the characteristic impedance of the 2nd $\lambda_{HF}/4$ matching layer is adequately high, it is also possible to omit the impedance regularizing structure **318** without large modification of the HF electro-acoustic transfer function.

An example of the effect of layers(s) **318** on the impedance seen into the section **317** from the front, is shown in **FIG. 3b-d**. In **FIG 3b** the isolation section **317** is composed of a single polymer layer that is $\lambda/4$ thick at 10 MHz. The curve **321** shows the acoustic impedance from the front into **317** as a function of frequency when the layer connects to the ceramic on the back. The impedance into the ceramics of layer **313** oscillates between a low value of the backing impedance Z_B when the LF1 ceramic is a whole number of $\lambda/2$ thick and a high value $(Z_{cer})^2/Z_B > Z_B$ when the LF1 ceramic is an odd number of $\lambda/4$ thick. Z_{cer} is the characteristic impedance of the ceramic. The $\lambda_{HF}/4$ polymer layer **317** then transforms this impedance into the curve **321** that oscillates with the frequency where close to 10 MHz we get a minimum value close to $(Z_{pol}/Z_{cer})^2 * Z_B$ and peak values close to Z_{pol}^2/Z_B, where Z_{pol} is the characteristic impedance of the $\lambda_{HF}/4$ polymer layer. The curve **322** shows the impedance from the front into **317** as a function of frequency when the section connects to the polymer fill between the LF1 ceramic posts. The impedance into the polymer fill in layer **313** oscillates between a high value of the backing impedance Z_B when the fill is a whole number of $\lambda/2$ thick, and a low value $(Z_{fill})^2/Z_B < Z_B$ when the fill is an odd number of $\lambda/4$ thick. Z_{fill} is the characteristic impedance of the polymer fill between the ceramic posts in the ceramic/polymer composite of layer **313**. The $\lambda/4$ polymer layer **317** then transforms this impedance into an oscillating variation **322** where close to 10 MHz the peak values are close to $(Z_{pol}/Z_{fill})^2 * Z_B$ and minimum values are close to Z_{pol}^2/Z_B.

FIG. 3c shows the impedance seen from the front into section **317** when a Cu layer **318** of 20 μm thickness (about $\lambda/25$ of Cu at 10 MHz) is introduced on the backside of the $\lambda_{HF}/4$ polymer layer described in **FIG. 3b**. The curve **323** shows the impedance seen from the front into the section **317** when the Cu layer is connected to the polymer fill between the LF1 ceramic posts. The Cu layer of this thickness gives an added inductive impedance of the mass load of the Cu seen into the fill, which increases the impedance seen from the $\lambda_{HF}/4$ layer towards the back, and the $\lambda_{HF}/4$ layer inverts this impedance into an impedance < 2 MRayl in the band 7 - 13 MHz which gives a very good isolation from the HF to the LF1 section in this band. The curve **324** shows the impedance seen into section **317** when the section is connected to the LF1 ceramic posts. We note that the effect of the Cu layer makes less modification from the curve **324** from **321** than of the curve **323** from **322** when connecting to the polymer fill. The reason is that because the ceramic has a high characteristic impedance, the Cu layer mainly changes the frequencies of the low and the high impedance seen from the back of the $\lambda_{HF}/4$ layer, and not so much the value of the low and the high impedance. However, by using a sufficiently high backing impedance, for example Z_B = 5 MRayl in this example, the maximal impedances seen into the isolation section **317** when connected to ceramic is still below 2 MRayl in the 7 - 13 MHz band, which gives a high isolation seen from the HF section in this band.

The effect of the Cu layer on the HF electro-acoustic transfer function is shown in **FIG. 3d**. The curve **325** shows the HF transfer function when isolation section **317** is composed of a single $\lambda_{HF}/4$ polymer layer as in **FIG. 3b** and connected to the polymer fill on the back. We note that this curve shows resonances due to internal HF reflections in the LF1 section **312** because the impedance curve **322** do not provide adequate reflection at the back of the HF piezo-layer **304**. Introducing a layer **318** of 20 μm Cu changes this transfer function to curve **326** where the resonances due to reflections in the LF1 section have disappeared. The curve **328** shows the transfer function without the layer(s) **318** and when the section **317** is directly connected to ceramics, where this curve moves to **327** when the Cu layer is introduced. We note that the Cu layer removes the resonances in curve **325** and makes the transfer function **326** for connection into polymer fill and **328** for connection into ceramic of the LF1 section close to equal. This Figure hence demonstrates that introducing the Cu layer makes the HF electro-acoustic transfer function insensitive to whether the isolation section connects to polymer fill or ceramics in the layer **313**. The dual band electro-acoustic transfer function can then typically take the form as in **FIG. 3d** where **331** shows the transfer function for the LF1 port and **332** shows the transfer function for the HF port.

We should note that the important effect of this thin Cu layer is its mass, i.e. ρL where ρ is the layer mass density and L is the layer thickness, that introduces an inductive impedance. The layer is therefore conveniently made of any heavy material, such as Cu, Ag, Au, Pd, Pt, W, and ceramics, or alloys of these materials powders of these materials or alloys cintered together or glued in a solvent. The heaviest materials allows the thinnest layers, and as stated above the materials Ag, Au, Pd, and Pt have the lowest shear stiffness for their mass density and therefore produces the least lateral coupling between the LF1 elements. The wave propagation velocity for Si is 8.44 mm/μsec and for Al it is 6.4 mm/μsec. This allows quite thick (L) layers while still $L \ll \lambda_{HF}$ so that the layer has the effect of a mass load. One hence can get adequate masses ρL for both Si and Al layers also, as described below.

The layer(s) **318** can also include part of the ceramics in layer **313** as illustrated in **FIG. 4a** where the labeling for the same layers follows that in **FIG 3a**. The polymer filled cuts **401** in the LF1 piezo-layer **313** are diced from the back of the layer but not diced completely through the LF1 ceramic layer **313** so that a complete ceramic layer **402** is left and included in the layer(s) **318** of the HF isolation section **317**. The LF1 front electrode **315** can also be made so thick that it has an acoustic effect in the HF band and also can be included as part of the layers **318**.

An approximate analysis on how to match the LF1 piezo-layer to the load in the LF1 band can be done by realizing that both said isolation section matching layers and the HF piezo-layer with load matching layers will be thin compared to the wavelength in the LF1 band. A thin low impedance layer between high impedance layers will then approximately behave as an elastic spring in series with the rest of the structure, while the thin high impedance layers will behave as a series mass. When the isolation section **317** is composed of a single $\lambda_{HF}/4$ low impedance matching layer in front of the impedance regularizing layer **318**, for low impedance into the isolation section in the HF band, the LF1 piezo-layer **313** will to the front observe the elastic spring of the low impedance $\lambda_{HF}/4$ layer in series with the mass of the HF section **303** that is dominated by the mass of the HF piezo-layer **304**. When the isolation section has a 2nd $\lambda_{HF}/4$ high impedance matching layer to obtain a high impedance into the isolation section as described above, this high impedance $\lambda_{HF}/4$ matching layer will give an added mass in series with the spring of the low impedance $\lambda_{HF}/4$ matching layer. The center frequency of the LF1 band may preferably then be selected around the resonance between this spring and mass system where the phase of the impedance into said isolation section matching layer seen from the back is zero. This resonance frequency can be tuned by varying the stiffness of said low impedance $\lambda_{HF}/4$ matching layer and the mass density of the HF piezo and load matching layers (and high impedance $\lambda_{HF}/4$ matching layer of **317**). This mass density can for example be tuned by varying the ceramic volume fill in the HF piezo-composite.

In a less efficient design to provide high impedance into the isolation section in the HF band, one can use a single $\lambda_{HF}/4$ matching layer with high characteristic impedance to the front of said impedance regularizing layer of large mass. In the LF1 band this single matching layer will approximately behave as a mass in series with the mass of HF piezo- and load matching layers and provide a load impedance seen from the LF1 piezo-layer that has an inductive phase. This matching system does not provide optimal LF1 impedance resonant matching, but a useful form of the LF1 electro-acoustic transfer function is obtained.

Using the method of an isolation section between piezoelectric layers, one can add piezoelectric layers at lower resonance frequencies backwards, in principle ad infinitum, for most applications with one or two layers, where **FIG. 3e** illustrates the general principle by adding one more lower frequency layer to the structure in **FIG. 3a**. In **FIG. 3e** a 2nd lower frequency section **340**, referred to as LF2 is added to the back of the 1st lower frequency section **312**, referred to as LF1. The layers of the LF1 and the HF section **303** are given the same labeling as in **FIG. 3a**. The LF2 section is composed of a piezo-layer **341** with an isolation section **342** to the front. The purpose of the isolation section is to isolate vibrations in the LF1 band in the section **312** in front to propagate backwards into the LF2 section **340**, to suppress the interference of section **340** with vibrations in the LF1 band in section **312**, in the same manner as discussed for the HF isolation section **317** above. The front and back of the piezo-layer **341** are then covered with electrodes **344** and **345** to form the electric port **346** of an element of the LF1 array, where the Figure illustrates single array elements or parts of a LF2 and a LF1 array elements when these are wider than the HF array elements.

The isolation is obtained when the impedance into the isolation section from the front is either much higher than or much lower than the characteristic impedance of the neighboring piezo-layer **313** in front as discussed for the HF isolation section **317**. For a high impedance into **342** from the front, the piezo-layer **313** would operate at $\lambda_{LF}/4$ resonance, while with a low impedance into **342** from the front, the piezo-layer **313** would operate at $\lambda_{LF}/2$ resonance. The $\lambda_{LF}/2$ can be preferred at high medical ultrasound frequencies (~ 10 MHz and upwards) as this gives thicker piezo-layers that simplifies machining, while for lower medical and SONAR frequencies the $\lambda_{LF}/4$ resonance can be preferred as this gives wider bandwidth and requires less piezoceramic material that is expensive. If the piezo-layer **341** is made as a composite, it can be advantageous that the isolation section **342** is composed of at least two layers, where the back layer **343** is a heavy, impedance regularizing layer thinner than the LF1 wave length, similar to **318**, to reduce the difference in impedance when the ceramic posts of the LF1 piezo-layer **313** connects to ceramic posts or polymer fill in the layer **341**.

In the LF2 band the layers in front of the LF2 section are so thin that they function approximately as a spring or mass in series. The low impedance layers of the isolation section **342** then generally functions as the spring in series with the mass of the layers in front, and the center of the LF2 band is selected at the resonance of this system as discussed for the LF1 band above. The backing material can be used as acoustic power absorbant to reduce peaking resonances in the electro-acoustic transfer functions. For improved acoustic coupling to the backing, one can also introduce acoustic matching layers between **340** and the backing **320** according to known methods. Resonances in any of the frequency bands can also be dampened with matching layers of absorbing materials, for example viscous polymer materials, and even adding particles to the polymer materials to increase absorption. Viscous polymer materials and particle filled polymer materials can also be used in the polymer fills of the ceramic/polymer composites of the piezoelectric layers. Solid/polymer composites can also be used for matching layers to tune the characteristic impedance, where viscous and/or particle filled polymers can be used for increased absorption in the matching layers.

It should now be clear that the procedure could be repeated by adding further lower frequency sections to the back, each section includes a piezo-layer for acousto-electric coupling and an isolation section for vibrations in the band of the neighbor section to the front. The procedure can hence be repeated in principle ad infinitum, where most applications would require only a single or a dual lower frequency band.

FIG. 3a, e, and **FIG. 4a** show thickness structures for example elements or parts of elements of the arrays according to the invention, where it is clear to anyone skilled in the art that the invention can be used to build acoustic arrays of any organization, for example annular arrays, linear phased, linear switched arrays, or linear arrays with divisions in the elevation direction of many scales from 1.5D via 1.75D up to 2D arrays for full 3D steering of the beams. The lateral width (radiation surface) of an array element is typically limited by a ratio to the wavelength in the object. As the LF1 wavelength is larger than the HF wavelength, one would often use wider LF1 array elements (larger element radiation surface) than HF array elements. The isolation section in **FIG. 3a** and **FIG. 4a** then allows independent selection of the LF1 and HF array elements, as the HF isolation is practically independent of whether the isolation section terminates into ceramics or polymer. This for example also allows that the arrays for the different bands are of different nature, for example, but not limited to, a 1.5D linear switched array for the HF band and a linear phased array for the LF1 band. When the LF2 array is used for therapy, one do not in some applications have to steer the beam direction, and the LF2 array can be made as a single element with fixed focus, or annular elements to steer the depth of the focus. With a single LF2 element composed of whole ceramic, the heavy back layer of the isolation section in front of the LF2 layer can then be left out, as the ceramic posts to the front would end in ceramics regardless of their lateral position.

When a multiple frequency probe according to the invention is used for imaging at multiple depth ranges at different frequencies, the front HF array can often be used as a switched linear (or curvilinear) array, while the LF1 array is used for phased array imaging. The required element pitch of the HF and the LF1 arrays can then be the same, for example 0.3 mm for a 7 MHz switched HF array, where the same pitch is $\lambda_{LF}/2$ for a phased array at 2.5 MHz. The structures of the isolation section given above is however still useful as one would like to have more dense cuts in the HF ceramic/polymer composite than the LF1 composite, and the isolation section **317** as described above also allows less accurate lateral positioning between the HF and lower frequency arrays. The larger LF1 wavelength also favors the use of larger LF1 than HF transmit apertures as discussed above. For large depths, the HF receive aperture can however be larger than the LF1 transmit aperture, where in general one would favor a design with the same thickness structure throughout the whole array, and the size of the transmit and receive apertures can be varied by electrically selecting the elements that participate in the apertures (radiation surfaces). Which of the arrays (HF, LF1, LF2, ...) that is connected to the instrument beam former can be selected through electronic switches, but also through electric filters that would guide the different frequency transmit pulses to the array for the frequency, and similarly to guide the receive signals from the actual frequency band array to the beam former, all according to known methods. The arrays of any frequency band would show some sensitivity in the lower frequency bands, which can be suppressed by electrical filtering at the electric port. Sensitivity to the higher frequency bands is suppressed by the acoustic isolation sections, so that one can omit the filter to the lowest frequency band.

For the large number of elements that are found with some linear arrays but specially with 1.5D, 1.75D and full 2D arrays, one can reduce the number of wires that connect the probe to the instrument by including in the probe electronic circuits, for example electronic switches that electronically selects and connects sub-groups of elements to the instrument beam former, or sub-aperture electronics that delay and combine the signal from several array elements into a single sub-aperture signal that connects to single channels in the instrument beam former, etc., all according to known principles. The signals from groups of elements or groups of sub-apertures of elements may also be transmitted on a single cable by time-multiplexing samples of the signals from such groups, where the time-multiplexing circuits are integrated into said electronic substrate layers, to reduce the cable connections to the arrays. The HF elements are generally more numerous than the LF1 elements, and more difficult to connect to electrically in the structure of **FIG. 3a** and **e**. Electrical connection with electronic switches and/or sub-aperture electronics and/or time multiplexing for large element number HF arrays can conveniently be done with electronics on substrate layers as shown in **FIG. 4b – d** below. For special high frequencies with less number of HF elements the structures are also useful for amplifiers only, preferably receive amplifiers but in special situations also transmit amplifiers.

To further illustrate this situation by way of example we analyze a 2D array concept probe according to the invention, illustrated in **FIG. 4c**, operating at a HF frequency of 3.5MHz and a LF1 frequency of 0.5MHz. With a $\lambda_{HF}/2$ pitch of 0.22mm, one gets a 20mm HF aperture with 90 HF elements in a diameter. With the hexagonal form of the aperture, this gives a total number of HF elements in the 2D array of approximately 90^2*3root(3)/8 = 5,261 elements. Using sub-apertures of 5*5 = 25 elements, the total HF aperture is supported with 210 sub-apertures, which is a convenient number for cable connection to an instrument for final beam forming. The $\lambda_{LF}/2$ pitch for a LF1 frequency of 0.5MHz is 1.54 mm, and one fills a 20mm LF1 aperture diameter with 13 elements. For the hexagonal aperture the total number of LF1 elements in the 2D array is then approximately 13^2*3root(3)/8 = 110 elements which is conveniently operated via a cable from an instrument with a LF1 transmit beam-former in the instrument. For abdominal applications one could increase the diameter to 40 mm and the frequency to 5 MHz with $\lambda_{HF}/2$ pitch of 0.154mm with a diameter of 256 elements and a total of 256^2*3root(3)/8 = 42,566 elements. With 7*7 = 49 elements per sub-aperture we get in total 868 sub-apertures, and using a time multiplex factor of 7 per electric cable, we can connect to the HF array with 128 coax cables with 7x multiplex per cable. The LF1 array will then get a similar increase in number of elements.

In **FIG. 4b** substrate layers with integrated electronics are included in the HF isolation section **317**, Si substrate layers are commonly used for integrated electronics and have a convenient characteristic impedance of 19.7 MRayl, which is a convenient value for a high impedance $\lambda_{HF}/4$ matching layer. Other substrate materials with high characteristic impedance, like GaAs, can also be used. In more detail, **FIG. 4b** shows the HF isolation section **317** composed of Si-substrate layers **405** and **406** included in the impedance regularizing section **318**, a 1st low impedance $\lambda_{HF}/4$ layer **407**, typically made of polymer, a 2nd high impedance $\lambda_{HF}/4$ layer **408** composed of two Si-substrate layers **409** and **410**. The LF1 front electrode **315** can also be made so thick that it gives acoustic contribution to the function of the layers **318**. The isolation function of the section **317** with this structure is described above. Taking the example of the 2D 3.5/0.5 MHz array above, we note that $\lambda_{Si}/4$ at 3.5 MHz is 0.6mm, which gives 0.3 mm thickness of the two Si-substrates **409** and **410**, which is a convenient thickness for integrated circuit electronics. One could even use lower thicknesses for more Si-layers or for higher frequencies. The thickness of each substrate could for example be reduced to 0.2 mm which would allow for 3 Si-substrate layers within the $\lambda_{HF}/4$ high impedance layer **408**. At 10 MHz the $\lambda_{HF}/4$ length in Si is 0.211mm that allows for a single Si substrate layer of this thickness in **408** at 10 MHz.

With 0.2 mm thickness of the Si-substrates **405** and **406** the layers **318** will approach $\lambda_{HF}/4$ in thickness, which reduces the impedance regularizing effect of **318**, but with the structure of a 1st low impedance $\lambda_{HF}/4$ layer **407** and a 2nd high impedance $\lambda_{HF}/4$ layer **408** one would still have a high impedance into the section **317** from the front. The thickness of the section **318** could be reduced by using only one or even zero Si-substrate layers, depending on how much processing electronics one want to put into the probe. The section **318** could even be made thicker with more Si-substrate layers to allow for more processing electronics in the probe, where one conveniently would match the characteristic impedance of the LF1 ceramic/polymer layer **313** to the impedance of the layer **318** so that they together define the resonance of the LF1 layer.

The front substrate layer **410** can by example contain receiver preamplifiers for the HF elements. The outputs of said pre-amplifiers can by example connect to the electronics in the 2nd substrate layer **409** that can for example contain sub-aperture beam forming electronics that delays and combines the signals from several HF elements into a single sub-aperture channel that considerably reduces the number of connections required to the instrument or further substrate layers of electronics. A reduced number of sub-aperture channels could then be transported to the instrument for final beam forming according to known methods. The final beam forming can typically also include corrections for wave front aberrations due to spatial variations in propagation velocity, according to known methods. The sub-aperture dimensions are then limited by the correlation length of the aberrations along the array surface.

The electronics in layers **410** or **409** could also contain switches that select subgroups of HF elements to the instrument beam former, for example as a switched array, or combining selected groups of 2D elements into linear elements of selectable direction as described in **FIG. 4d**. With the structure in **FIG. 4b** one obtains direct electrical connection between the HF array element electrodes and the front layer **410**, where element electrodes could connect to metal pads on the layer **410**. Micro-soldering, ultrasonic bonding, anisotropic conducting polymer glue with conducting particles are all known and useful methods for the connection. With conducting polymer glue the max thickness of the glue must be limited to minimize wave reflection between the substrate layers. A polymer glue between the Si layers can also be used to reduce the composite acoustic impedance of the substrate layers with glue. Electric connections between the stacked substrate layers can be obtained through via-holes in the substrates or with bonding at the edges of the layers, all according to known methods.

Electrical connections through an isolating layer, like the low impedance $\lambda_{HF}/4$ layer **407** can be obtained via metallic connectors **411** through the layer, where said metallic connectors are so thin that they have minor effect on the characteristic acoustic impedance of said low impedance layer **407**. In the example embodiment, the number of required connections through the isolating layer **407** can be greatly reduced by the circuits in layers **409** and **410**, which by the example array above is a reduction from 5261 to 210 connections through sub-aperture circuits. This shows the great advantage of channel reducing electronics in the high impedance section **408**.

The HF acousto-electric transfer function is shown as **412** in **FIG. 4b**. The relative - 3dB bandwidth is ~ 70 %, a high value that is partly achieved by the $\lambda_{HF}/4$ resonance of the HF piezo-layer **304** that is produced by the high impedance into the isolation section **317** in the HF band, produced by the high impedance $\lambda_{HF}/4$ matching layer **408**. At higher frequencies one might want a $\lambda_{HF}/2$ resonance of the HF piezo-layer to obtain a thicker layer that is easier to manufacture and handle. The resonance of the HF piezolayer can be considered to be a $\lambda_{HF}/2$ resonance of the composite HF piezo-layer **304** and the matching layer **408**. One can hence increase the thickness of HF piezo-layer **304** at the expense of reducing the thickness of layer **408**, for example by reducing the number of generating substrate layers, while maintaining the same center frequency of the

HF band. With higher frequencies one might not be using a full 2D HF array, rather a 1D, 1.25D, 1.5D or 1.75D switched array, which all have less total number of elements. One could then even find it practical to connect the HF elements directly through the isolating layer **407** to electronic layers in the structure **318** via thin connectors as **411**. This allows us to remove the high impedance layer **408** which produces full $\lambda_{HF}/2$ resonance of the HF piezo-layer.

A schematic 3D rendering of such a probe with a 2D array according to the invention, is illustrated in **FIG. 4c**, where the HF 2D elements are indicated as **415** on the front faces shining through the HF acoustic matching layers **305** and **306**. The layers are given the same labeling as in **FIG. 4b**. Connection between the electronic substrate layers (**405, 406, 409, 410**) and the instrument can for example be obtained through connecting pads **416** at the edges of one or more of the substrate layers. Flex print circuits **413** are then conveniently connected to these pads and brought along the side faces of the array structure and behind the backing where it can be connected to a flexible cable that connects to the instrument according to known methods. The connections can for example be obtained through micro-soldering, ultrasonic bonding, anisotropic conducting glue with conducting particles, etc., according to known methods. The flex prints conveniently follow the flat side surfaces of the probe that gives a minimal added thickness to the probe.

Amplifiers, both transmit and receive, and sub-aperture circuits for the LF1 array can be placed in the substrate layers in front of the LF1 piezo-layer, typically behind potential substrate layers with electronics for the HF array (e.g. layers **405**, **406**), and as part of the isolation group of layers **318**. Depending on the space available, electronics for the LF1 and HF arrays could be placed on same substrate layers. One would then typically locate the substrate with LF1 electronics closest to the LF1 array. Substrate layers with electronics for the LF1 array can also be placed at the back-side of the LF1 piezo-layer in front of the backing material **320**. With this last placements of the electronics, the connection to the cable can be done with wires through the backing material, where said wires are so thin that they do not propagate acoustic waves through the backing. The connection from the circuits to the cable is also conveniently done with for example flex print circuits on the side of the structure, as for the HF electronics described above. When placing the electronic substrates to the back of the array, the characteristic impedance of the piezo-layer is preferably close to that of the substrate to minimize reflections between the substrate and the piezo-layer so that the substrate layers participate in the definition of the LF1 resonance together with the LF1 piezo-layer, as discussed for the front placement above. The net acoustic impedance of the substrate layers can also be reduced by thin intermediate layers of lower characteristic impedance, for example an anisotropic polymer glue as described above.

By connecting to the lowest frequency elements with wires through the backing **320**, one can place potential amplifiers, switching circuits, and sub-aperture circuits for the lowest frequency elements behind of the backing, potentially located in stacked substrate layers with electronics, or with other arrangements according to known methods. One do generally have adequate space available in the probe handle, so that this solution can be simpler than circuit layers stacked together with the LF1 array. The LF1 elements are however larger and fewer with lower frequency than the HF array, and the pay-off is therefore less for using amplifiers and sub-aperture electronics in the probe itself, where one for many embodiments according to the invention will not use such circuits for the LF1 array in the probe.

Instead of using the sub-aperture method to form beams within a volume sector in front of the probe, it is also interesting with a 2D array structure to use electronic switches in the electronic layers (**409, 410**) that connect groups of HF 2D elements into linear elements. An example embodiment is shown in **FIG. 4d**, where the HF 2D array **420** is composed of triangular elements **421** that can be connected to sets of linear elements **422**, **423**, **424** that with phased array steering can be used to produce 2D scan planes in different directions illustrated as **425**, **426**, **427**. With the 3.5/0.5 MHz example array above, it would then be sufficient with 96 - 128 channels in the HF phased array beam former. Selectable linear arrays with different directions of the linear elements could also be implemented with a dual piezoelectric layer structure as described in US Pat appl 10/387,775.

Combination of 2D LF1 elements into linear LF1 elements could also for example be done in the electronic layers **405** and **406**, or in electronics of other arrangements, or via a dual layer structure as described in US Pat appl 10/387,775. For the LF1 linear array beam former in the example array above it would then be sufficient with 13 channels. However, the number of total LF1 array elements in the example array described above is only 110, so that one could also connect all LF1 elements to the instrument and do the LF1 element combination in the instrument. This would provide full flexibility in the use of the LF1 array as a 2D volume scanning array or as a linear array with selectable 2D scan directions. It would then be convenient that the electronics in layers **405 - 410** would also include both sub-aperture connection to the 2D HF array for full volume sector scanning of the HF beam together with such scanning of the LF1 beam, and connection of 2D elements into linear elements for 2D sector scanning of the HF beam together with the LF1 beam.

LF1 transmit beam former electronics in the probe is especially interesting when the LF1 array is used for transmit only, as described with the methods in US Pat applications 10/189,350 and 10/204,350, where only a transmit sub-aperture beam former is needed. For transmit amplifiers that switches the element signals to positive and negative power voltages, the power losses can be made so low that the whole transmit beam former with amplifiers can be integrated into the probe. Such a probe would have a simplified connection to existing scanners, for direct field upgrade to existing scanners with the methods described in the cited US Pat applications.

Making the piezo-composite **304** with close to the same characteristic impedance as the Si-substrates, one could also place Si-substrate layers to the front of the HF piezo-layer **304** as illustrated in **FIG. 4e** where the Si-substrate layers are labeled as **430**, **431**, **432**. The HF resonance is then defined by the combined thickness of the piezo-layer **304** and the Si-substrate layers, i.e. the structure **433**. A simulated electro-acoustic HF transfer function for this structure is shown as **434**.
The example placements of electronic substrates within the acoustic structure in **FIG. 4b-e** can also be combined and modified in various forms for simplified connection between the HF and LF1 array elements, the substrate electronics, and the instrument beam former. The probe could typically also contain electronic circuits in the handle, behind the backing material.

By example we show in **FIG. 5** another linear phased array according to the invention, seen from the front face, where **501** indicates the elements of the phased array HF aperture, where λ_1 is the HF wave length with a pitch of the HF elements of $\lambda_1/2$. With proper steering of the signal on each element according to known methods, such an array allows steering of the beam direction within a sector in the azimuth direction. Steering in the elevation direction requires division of the elements also in the elevation direction into a two-dimensional (2D) array, and we will at this point emphasize that the basic methods of the invention is also applicable to 2D arrays.

The center of the HF band of this linear array is by example f_1 = 3.5 MHz which suggests a high frequency element pitch of $\lambda_1/2$ ~ 0.22 mm. 84 high frequency elements then produces a total aperture of 18.48mm. With a center of the low frequency band of f_0 = 0.5 MHz we get $\lambda_0/2$ ~ 1.54 mm, which suggests 12 of the low frequency elements **502** that also produces a total aperture of 18.48mm. For better collimation of the LF1 beam one could add extra LF1 elements to each side of the HF elements, where the Figure shows by way of example two elements **503** increasing the LF1 azimuth aperture to 14 elements ~ 21.56 mm. To increase the LF1 elevation aperture one could similarly expand the LF1 aperture by the elements in the elevation direction, where the Figure shows by way of example the elements **504**. As follows from the analysis in relation to **FIG. 2a-d**, one would in some situations like to use the same transmit aperture of the LF1 and HF radiation surfaces when it is critical that the phase between the HF and LF1 pulses has minimal sliding with depth, while for higher LF1 amplitude at large depths it can be desirable that the LF1 transmit aperture is larger than the HF transmit aperture to reduce diffraction broadening of the LF1 beam with depth. To reduce the nonlinear manipulation by the LF1 pulse in the propagation and scattering of the HF pulse close to the array, one could like to remove the central radiation surface of the array. This can be obtained by further dividing the LF1 elements into the sub elements **505**. The LF1 array in **FIG. 5** then allows selection of the size of the LF1 aperture, for example as one of 1) to be equal to the HF aperture, 2) to be larger than the HF aperture either in the azimuth and elevation directions separately or in both the azimuth and elevation direction, and 3) a LF1 aperture with an inactive area in the center of the HF aperture. We also point out that such variation of the LF1 aperture relative to the HF aperture is obtained with other array configurations, for example 2D arrays, annular arrays, etc. where anyone skilled in the art can apply the essentials of this invention to all array configurations. For many applications one would like to use 2) only, which is achieved by combining the elements **502/504/505** into a single LF1 element with elevation dimension equal to or larger than the HF aperture, and add extra LF1 elements in the azimuth direction (**503/504**) to obtain a LF1 aperture that is larger than the HF aperture in the azimuth direction.

To get the same vibration conditions for the LF1 elements over their whole area, one could typically use a stack like in **FIG. 3** and **4** for the whole array area, and define the LF1 and HF elements by the element electrodes and cuts in the piezoelectric layers as described above. It would also be advantageous to use ceramic/polymer composites for both HF and LF1 piezoelectric layers, where the element dimensions could be defined by the electrodes. The HF radiation area could then for example be defined by a common ground electrode on the front side which would define the elevation width of the elements both through electrical coupling but also by defining the areas of the ferroelectric ceramic that is polarized to show piezoelectric properties. The azimuth width of the HF elements are then defined by the back side hot electrodes which can conveniently be extended to the edge of the assembly for electrical connection to the cable as the electro-acoustic coupling outside the ground electrode is low, both due to reduced electric field and reduced electric polarization of the ferroelectric ceramic material.

The isolation section **317** in **FIG. 3** and **4** then makes accurate position matching between cuts in the HF and LF1 piezo-layers less critical, as the impedance seen into the section **317** from the front has little variation with termination into polymer or ceramic, as for example discussed in relation to **FIG.3b-d**. This reduced sensitivity allows dicing of the LF1 layer with thicker saw than the HF layer, and also reduces requirements for accurate lateral positioning between the HF and LF1 layers.

The HF array in **FIG. 5** could also be used as a switched linear array where the HF beams would be normal to the HF aperture. It is then in some applications useful to make the LF1 array as a single element, that provides an unfocused LF1 aperture. The LF1 aperture would then be chosen so large, that the whole HF imaging depth would be within the near field of the LF1 aperture, as described above. For suppression of multiple scattering noise, for example as described in US Pat Appl 11/189,350, one could then also remove from the LF1 transmit aperture composed of the elements **502** and **505**. For flexibility, the LF1 aperture could then be composed of two elements: i) A central element composed of the elements **502** and **505** in parallel, and ii) an outer element composed of the elements **504** and **503** in parallel. For nonlinear imaging one would use both the central and outer LF1 elements in parallel for the LF1 transmit aperture, while for suppression of multiple scattering noise one could take the central element from the LF1 transmit aperture.

It is also known that the piezo-layers **304**, **313** and **341** can be made of multiple layers, both piezoelectric and non-piezoelectric to alter and increase the bandwidth of the electro/acoustic transfer functions and reduce the electric impedance of the electric ports. Adding the stacks of substrate layer exemplified in **FIG. 4b** and **4e** can be viewed as a way to add a non-piezoelectric layer that interferes with the resonance definition, for example as described in US Pat 6,645,150. To obtain lower electric impedance of the array elements for example, especially the lower frequency elements to be able to transmit high pressures with manageable drive voltage amplitudes, one could conveniently make one or more of the piezo-sections **304**, **313** and **341** as stacked piezoelectric layers covered with electrodes.

FIG. 6 shows an example embodiment of two layers **601** and **602**. The layers are covered with the electrodes **603**, **604**, and **605**, where typically one would galvanically connect electrodes **603** and **605** to ground where the electrode **604** would be used as the hot electrode. The two piezoelectric layers would then have opposite polarization directions **606** and **607**, so that the electrode coupling would provide an electrical parallel coupling of the layers **601** and **602** to provide a lower electric impedance port **608**, which allows driving the low frequency array with lower voltages for the high pressures. For improved bandwidth of the layers, one can introduce a high impedance layer in front of the active piezolayers, as presented in US Pat 6,645,150. Parallel coupling of more layers can be done for even lower electric port impedance, also for the high frequency layer **304**, according to known methods. In US Pat appl 10/387,775 it is also described how one with dual layers can obtain linear arrays with selectable direction of the electrodes, for electronic rotation of the 2D scan plane. This solution is interesting both for the higher and lower frequency arrays within the structure of this invention.

It is also possible to base the electro-acoustic transduction on micro-machined transduction cells on the surface of a substrate, for example a Si (silicon) substrate, or other substrate of other materials such as Cu and Al. With these techniques, increased vibration of the surface is obtained by vibrating membranes on the substrate surface, with gas or vacuum behind the membrane, where the membrane connects to the acoustic load material either directly or through acoustic layers. The electromechanical coupling can either be obtained by capacitive coupling from the membrane to a reference electrode, referred to as cmuts (capacitive micro-machined ultrasound transducers), or through piezoelectric films on the membranes, referred to as pmuts (piezolayer micromachined ultrasound transducers). Examples of such membranes are illustrated as **701** shown from the front radiation face in **FIG. 7**, mounted on the front surface of the substrate **700**. The dimensions and thicknesses of the membranes determine the resonant band where the transduction is most efficient, and several of the cmut/pmut cells are usually coupled together electrically to form one array element. In the current invention we are concerned with inventive implementations of the cmut/pmut techniques to transmit dual or triple band pulses from essentially the same radiating surfaces, where the Figures show inventive steps to achieve the dual or triple band function, and where details of the membranes, electrodes, and electrical connections are left out as many solutions for this are presented in the literature. We shall in the following refer to this technology as cmut/pmut transducers, cmut/pmut cells, and cmut/pmut membranes.

The characteristic impedance of Si is 19.7 MRayl and Al is 17.4 MRayl, which gives an interesting possibility of transmitting the LF1 wave through a HF substrate. By example **FIG. 8a** shows a cross section of a structure with a cmut/pmut HF section **806** mounted in front of a LF1 section made by a piezo-layer **801** with electrodes **803** and **804** generating the LF1 element electric port **805**. Details of the cmut/pmut drums with electrodes and electrical coupling are not shown as several examples exist in the literature per the discussion above. The total structure is in this example mounted on a backing material **802** (which can be low impedance or air) and a protection structure **808** is placed in front of the cmut/pmut drums **807**. The protection structure can contain one or more layers designed for acoustic impedance matching between the load **301** and the cmut/pmut array, and absorption layers to reduce lateral coupling between array elements along the substrate, and it can also contain an acoustic lens that focuses the acoustic beams, etc..

The Figure also shows an optional absorbing layer **812** to reduce lateral acoustic coupling in the Si or Al substrate between the HF array elements and also between the substrate and the LF1 section in the HF frequency band. The drums **807** reduces the effective acoustic impedance of the layer **806** below that of Si/Al, and by making the piezolayer **801** as a ceramic/polymer composite, the acoustic impedances of layer **801** and **806/808** can be matched so that the reflection coefficient between the piezoelectric layer **801** and the cmut layer **806** is low for improved bandwidth of the LF1 port.

The acoustic velocity of Si is 8.4 mm/μsec and for Al it is 6.4 mm/μsec. One can therefore add further substrate layers of electronics (typically Si-substrate layers) between the cmut/pmut substrate and the piezo-layer **801** and the thickness of the total Section **806** can still be a fraction of the LF1 wavelength in the layers. This is illustrated in **FIG. 8b** where the Section **806** is by example composed of the cmut/pmut layer **820** mounted on 3 Si layers with integrated electronics, where by example **821** can be a receiver amplifier layer that is mounted on a sub-aperture beam forming layer **822** and a transmitter amplifier layer **823**, similar to the substrate layers in **FIG. 4b-e**. Electrical connection between the different layers can be obtained with via-holes and connecting pads according to known methods in integrated circuit technology, or one can use known bonding techniques for example between connections at the edges of the substrates, as discussed in relation to **FIG. 4b - e**. With a layer thickness of 0.2 mm the total thickness of the Section **806** is 0.8mm, less than $\lambda_{Si}/8$ for LF1 frequencies less than 1.319 MHz.

The structure is for example useful for a 2D array probe similar to the one shown in **FIG. 4c**. One would typically use the similar apertures, number of elements, and number of sub-apertures, where one also would like to connect 2D array elements into linear array elements as described in relation to **FIG. 4d**. A perspective view of a 2D array concept probe with integrated electronics as part of the acoustic design, is illustrated in **FIG. 8c**. The cmut and integrated circuit layers are shown as **806** mounted on the LF1 piezo-array **801** and the backing **802** with the front radiating surface **810**. Connection between the instrument cable and the electronic circuits can for example be done with flex print circuitry from the back of the assembly to the edges of the circuit substrates as indicated in **FIG. 4c**.

The electronic layers closest to the LF1 piezo layer, starting with **823**, can be electrically connected to the LF1 array elements **801**, where one can integrate LF1 switches, amplifier and sub-aperture electronics. The LF1 array can also be connected to amplifier and sub-aperture electronics for example at the front of the LF1 array, at the back of the LF1 array, or inside the probe behind the backing, as discussed in relation to **FIG. 4c**. This can be especially interesting when the LF1 array is used for transmit only, as described with the methods in US Pat applications 10/189,350 and 10/204,350, where only a transmit sub-aperture beam former is needed. For transmit amplifiers that switches the element signals to positive and negative power voltages, the power losses are so low that the whole transmit beam former with amplifiers can be integrated into the probe.

For cardiac applications, the aperture dimension is limited by the distance between the ribs, but for abdominal applications one could double the HF aperture diameter, which would increase the number of HF and LF1 elements by a factor of 4. This increases the number of HF sub-apertures to 840, and the LF1 number of elements to 440, which also can be handled with cable connections to an instrument for beam forming. One could also use time multiplex of samples of the signals from several sub-apertures along a single wire, as discussed above, to reduce the number of wires required to connect to the instrument, where 8x time multiplex would require 105 wires to connect the HF array to the instrument.

Per the discussion above, one would often use a LF1 radiation aperture that is wider than the HF radiation aperture. For parallel receive beam-forming one would typically use less than the whole HF aperture for transmit of the HF pulses to obtain a wide enough HF transmit beam. To further increase both the HF and LF1 apertures without increasing the number of instrument channels too much, one could use sparse arrays as discussed in relation to **FIG. 11**, where not all element sites are connected electrically. This introduces grating lobes, but designing the sparse arrays so that potential grating lobes from the LF1 and HF apertures do not overlap, one can with the imaging methods described in US Pat applications 10/189,350 and 10/204,350 highly suppress the effect of grating lobes in the images.

Another example in **FIG. 9** shows a cmut/pmut LF1 section **906** in front of the HF piezolayer **901** made of ceramic/polymer composite mounted on a backing material **902**. The element electrodes **903** and **904** constitute the HF element electric port **905**. The LF1 transduction is provided by the cmut/pmut drums **907** on the substrate layer **906**. Details of the cmut/pmut drums with electrodes and electrical coupling are not shown as several examples exist in the literature per the discussion above. By making the piezolayer **901** as a ceramic/polymer composite one can match the acoustic impedance of this layer to the effective acoustic impedance of the Si layer **906** with drums **907** to define the HF acoustic resonance. In front of this structure there are placed acoustic impedance matching layers (typically one or two) **908** that connect the HF and LF1 sections acoustically to the load material **301** for transmission (**310**) and reception (**311**) of dual band pulse waves in the load material. These layers can also be used to reduce lateral coupling between the LF1 array elements through absorption. The acoustic matching section is together with the cmut/pmut layer **906** used to increase the bandwidth of the HF electro/acoustic transfer function, and will at the low frequency function as an acoustically thin protection cover layer for the LF1 array **906**, where the stiffness of the cmut/pmut membranes is tuned to the acoustic layer/load transfer. Due to the high longitudinal wave velocity of Si (8.44 mm/µsec), the thickness of the Si substrate can be made adequately thin for acceptable effect on the HF electro/acoustic transfer function. To further limit lateral coupling inside the Si substrate one can also use an optional absorbing isolation layer **912** at the back of the substrate, the isolation being made adequately thin at the high frequencies to have limited effect on the HF transfer function.

The layered structure in **FIG. 9** has interesting advantages for 2D arrays for three-dimensional (3D) beam steering and imaging, where one have electrical access to the large number (~ 3000) of HF elements from the back of the array structure for simplest connection to cable or sub-aperture beam forming electronics. The LF1 2D array will have much fewer elements (1/50 - 1/100 of the HF number) simplifying the connection to the LF1 elements, for example with thin wires through the backing material **902**, where also simplified connection techniques are available with the cmut/pmut manufacturing technology.

The invention further presents a solution to the LF/HF transduction with common radiation surface where high frequency cmut/pmut cells are mounted on top of low frequency cells, for example as illustrated in **FIG. 10**. **FIG. 10a** shows the substrate front **1000** with one low frequency cell **1001**, and several high frequency cells **1002** on top of the low frequency cell. As the low frequency allows large dimensions of the low frequency cell, this cell might be micro-machined from the back side of the substrate as indicated in **FIG. 10b** which shows a cross section through the substrate **1003** where etching from the substrate back side provides the thin low frequency membrane **1004** in capacitive interaction with an electrode **1005** that is mounted on or part of a 2nd substrate **1006** that is attached to the substrate **1003** through gluing or other bonding techniques. On the front of the low frequency membrane **1004** is micro-machined several high frequency cells **1002** from the front side of the substrate. With more complex manufacturing techniques, both the low and the high frequency cells can be manufactured from the front side. As for the other cmut/pmut solutions we have not shown details of the electrode arrangements and possible placement of piezoceramic elements, as several examples of such are given in the literature, and we stress in this description essential features of the design to be able to transmit both the LF1 and HF pulses from the same radiation surface. However, when Si is used as a substrate, the Figure indicates LF1 electrode solutions where a front layer **1007** of the Si-substrate is highly n-doped (n++) to provide a common ground electrode for the LF1 and HF cells. The hot LF1 electrode could similarly be obtained by high n-doping of a region **1005** of the 2nd Si-substrate **1006**.

Dual frequency band operation with widely separated frequency bands can also conveniently be implemented as sparse arrays, where the low and the high frequency elements are placed at different locations on the array surface, but sufficiently close so that at outside a certain distance from the array, the two frequency beams appear to originate from at least partially the same radiating surface. 2D sparse arrays are especially useful for 3D acoustic imaging where the sparse arrays allow two-dimensional direction steering of the acoustic beam with a reduced number of elements (~ 1000). 2D sparse arrays are also useful for corrections for wave front aberrations and pulse reverberations, both with 2D and 3D beam scanning. An example illustration is shown in **FIG. 11** which shows a part of the array surface **1100** with four LF1 array elements **1101** with open space **1102** in between for placement of HF array elements in a sparse array pattern. Sparse arrays produce grating lobes in off-set directions from the beam main lobe, where the transmit and receive apertures must be designed for non-overlapping directions of the grating lobes. For imaging methods that are based on the nonlinear interaction between the dual frequency beams, for example as described in US Pat applications 10/189,350 and 10/204,350, one gets improved suppression of the grating lobes in the image when the grating lobes for the LF1 and HF beams are non-overlapping. In fact, because of the large wavelength of the low band ($\lambda \sim$ 3mm @ 500 kHz), it is possible to design an array with small low frequency array elements that do not have low frequency grating lobes but still with so large distance between the elements (~ 2 mm) that one can place many high frequency elements between the low frequency elements.

With resonant bulk piezo-ceramic elements for the electro-acoustic transduction similar to **FIG. 3**, one can with the sparse arrays for example manufacture a high frequency array with division of all its elements, and then select a subgroup of these element locations for the LF1 elements which are produced by attaching a piezo-ceramic slab at the back of said selected HF elements and do electrical connection between the front electrode of the high frequency element, which is commonly the ground electrode, and a back electrode of said attached piezo-ceramic slab. With less electro-acoustic transduction efficiency, one can reduce the resonance frequency for the LF1 elements by attaching a mass of a heavy and stiff material, for example metals like Cu, Ag, Au, Pd, Pt, or W at the back of the selected HF elements, and use the surface electrodes of the high frequency piezo-ceramic element for transduction.

Micro machined transduction elements on the front of a Si-substrate are also well suited for sparse array implementation of the dual frequency array, as the large low frequency cells and the smaller high frequency cells are machined at different locations on the array surface, as for example shown in **FIG. 12**, where **1201** shows cmut/pmut cells for the low frequency band on the substrate **1200**, encircled by cmut/pmut cells **1202** for the high frequency band. High frequency band cells are electrically connected to form high frequency elements, while the low frequency band cells are connected to form larger low frequency elements, for example as illustrated for the phased array in **FIG. 5**. Typically several cells are electrically connected for each array element.

Acousto-electric transduction in a 2nd LF2 band can also be obtained with the cmut/pmut solutions in **FIG. 8 - 12** for a HF and a 1st LF1 band, and adding structures **1301** for the LF2 band as illustrated in **FIG. 13a.** The structure to represent the HF and LF1 transduction according to one of **FIG. 8 - 12** is indicated by **1321**, with acoustic coupling to the load material **301**, and with the HF electric port **1309** and LF1 electric port **1316**. The LF2 electro acoustic transduction is in this embodiment according to the invention obtained with the piezo-layer **1302** mounted on the backing material **1320** with an isolation section **1303** to the front with the same functionality as in relation to **FIG. 3e**, producing the LF2 electric port **1307** which couples acoustically to the load through the HF/LF1 structure **1321**.

An acoustic transducer array probe with 3 band operation can also be obtained with the structure in **FIG. 13a** with a triple membrane cmut/pmut solution similar to **FIG. 10** and **12**, where the LF1 band is operated with the piezo-layer at the location of **1302** and the LF2 band is operated by the large membranes **1001** in **FIG. 10** or **1201** in **FIG. 12**. Yet another embodiment is a structure as in **FIG. 10** and **12** where one of the membranes **1001/1002** in **FIG. 10** or **1201/1292** in **FIG. 12** has dual resonance frequencies, so that three resonance frequencies are obtained with two membranes. Typically could the large membranes **1001** or **1201** operate both the LF1 and LF2 bands, while the smaller membranes **1002** or **1202** operate at the HF band, or the smaller membranes **1002** or **1202** operate the HF and LF1 bands, while the large membranes **1001** or **1201** operates the LF2 band.

Yet another embodiment is to use three separate types of membranes for the LF2, the LF1, and the HF bands, for example as shown in **FIG. 13b**, where **1343** shows the HF membranes mounted on top of the LF1 membranes **1342** which again are mounted on top of the LF2 membranes **1341** on the common substrate **1340**. Alternatively one could mount all the membranes by the side of each other similar to that in **FIG. 12**, or one membrane type mounted on the top of one of the other types, while the third membrane type is mounted by the side of the others.

FIG. 13a and **b** show example structures that allow electro-acoustic transduction in 3 frequency bands. One typically wants to divide the radiation surfaces into arrays of elements, for steering of the focus and/or the direction of the beams at all three frequency bands. Typical arrays could be annular, linear, 1.5D, 1.57D, and 2D arrays. The lateral width of the elements (element radiation surface) is then related to the acoustic wavelength in the object **301** for the different frequency bands. The HF array would then require the lowest element width, with intermediate width elements for the LF1 array, and largest width for the LF2 array, and so on. One would then typically use a layer structure as in **FIG. 13a, b** across the whole array width, and define array elements for each frequency band with electrodes and cuts in ceramic layers. With the two layer isolation structures **317** (HF) and **1303** one is less sensitive to location of cuts between the HF, LF1, and LF2 ceramic layers (See discussion in relation to **FIG. 3b-e**). Typically one would make each of the piezo-layers as piezo-ceramic/polymer composites, and the elements of these layers would then be defined by the division between the electrodes on the composite surfaces at the cuts through the ceramic layers. This would allow different dimensions and even different shapes of the elements for the different frequency bands, as described above.

Thus, while there have shown and described and pointed out fundamental novel features of the invention as applied to preferred embodiments thereof, it will be understood that various omissions and substitutions and changes in the form and details of the devices illustrated, and in their operation, may be made by those skilled in the art without departing from the spirit of the invention.

It is also expressly intended that all combinations of those elements and/or method steps which perform substantially the same function in substantially the same way to achieve the same results are within the scope of the invention. Moreover, it should be recognized that structures and/or elements and/or method steps shown and/or described in connection with any disclosed form or embodiment of the invention may be incorporated in any other disclosed or described or suggested form or embodiment as a general matter of design choice. It is the intention, therefore, to be limited only as indicated by the scope of the claims appended hereto.

6. Claims

1. An acoustic transducer array probe for transmission from a front face of said probe of acoustic waves in separate high frequency (HF) and at least a 1st lower frequency (LF1) bands, and reception of acoustic waves at least in the HF band, characterized by

- different arrays of transducer elements configured for respective HF and the LF1 electro-acoustic transduction, the array for the HF electro-acoustic transduction having HF array elements and the array for the LF1 electro-acoustic transduction having LF1 array elements, and

- radiation surfaces for the HF band and the LF1 band, wherein at least a portion of said radiation surfaces for the HF and LF1 bands is common in a common radiation surface, wherein the LF1 array elements within the common radiation surface have larger radiation surfaces with larger distance between neighboring element centers, than do the HF array elements within the common radiation surface, and

- at least one electronic substrate layer with integrated electronics connecting to array elements where said at least one electronic substrate layer is one or both of i) stacked within said acoustic vibration structure of the probe, and ii) mounted in the probe behind said acoustic vibration structure.

2. An acoustic transducer array probe according to claim **1**, where the LF1 transmit surface has a central region without active LF transmit.

3. An acoustic transducer array probe according to claim **1** or **2**, where the thickness structure for the LF1 and HF transduction is the same throughout the whole array surface, and the size of HF and LF1 transmit and receive apertures can selectably be varied by selectable electric connection to array elements

4. An acoustic transducer array probe according to claim **3**, where one can select the HF receive surface to be wider than the LF1 transmit surface.

5. An acoustic transducer array probe according to claim **1**, where in addition acoustic pulses in one or more lower frequency bands (LF2, LF3, ...) can be transmitted and received through at least said common radiation surface, where the electro-acoustic transduction for said one or more lower frequency bands are obtained with electro-acoustic transduction structures for each of said one or more lower frequency bands, where at least parts of the radiation surface of said one or more lower frequency bands are common with the radiation surface of the higher frequency bands.

6. An acoustic transducer array probe according to claim **5**, where the electro-acoustic transduction arrays for each of said further lower frequency bands are obtained with a piezo-layer placed behind the transduction structures for higher frequency bands.

7. An acoustic transducer array probe according to claim **6**, where an acoustic isolation section is placed to the front of each said piezo-layer, where said isolation section provides backwards acoustic attenuation for vibrations in the resonant band of the transduction structure to the front of said each piezo-layer.

8. An acoustic transducer array probe according to claim **1**, where the LF1 transmit surface is selectable between at least two of
a) at least in a region there is a LF1 transmit surface outside the HF transmit surface, and
b) the LF1 transmit surface is equal to the HF transmit surface, and
c) the LF1 transmit surface has a central region with no LF1 transmit, and
d) a combination of a) and c).

9. An acoustic transducer array probe according to claim **1**, where the HF and LF1 arrays are independently arranged as one of
- a single element array, and
- an annular array of transducer elements, and
- a linear array of transducer elements, and
- a two dimensional array of transducer elements, and
- a composition of transducer elements of any other form.

10. An acoustic transducer array probe according to claim **1**, where
- at least one of said LF1 and HF transmit and/or receive surfaces is made as a sparse array of elements, and where
- said sparse arrays are designed so that potential grating lobes of said sparse HF transmit array are directed relative to the LF beam so that the LF pulse pressure at the HF pulse in said HF grating lobes is so

low that the nonlinear manipulation of the object elasticity by the LF pulse at the HF pulse is negligible along said HF grating lobes compared to along the HF main lobe.

11. An acoustic transducer array probe according to claim **1**, where the LF and HF arrays are stacked behind at least said common transmit surface.

12. An acoustic transducer array probe according to claim **7**, where the thickness structure of the array is the same throughout the whole array surface, and the size of LF1 and HF transmit and receive apertures are defined by the electrical connection to array element electrodes.

13. An acoustic transducer array probe according to claim **1**, where

- the LF1 and HF electro acoustic transduction is obtained with separate piezoelectric layers where said HF piezolayer is stacked in front of said LF1 piezolayer in a multilayered structure, and where

- an acoustic isolation section composed of at least two acoustic layers is placed between said HF and LF1 piezolayers, and where

- an acoustic matching section for the HF band is placed in front of said HF piezolayer.

14. An acoustic transducer array probe according to claim **13**, where said isolation section is composed of a back layer with characteristic acoustic impedance greater than 17 MRayl and at least one layer with characteristic impedance less than 5 MRayl.

15. An acoustic transducer array probe according to claim **13**, where said isolation section is made of one of the materials Cu, Ag, Au, Pd, Pt, W, and alloys of these materials, and powders of one of these materials or their alloys sintered or glued together.

16. An acoustic transducer array probe according to claim **13**, where said isolation section is composed of a ceramic layer to the back.

17. An acoustic transducer array probe according to claim **16**, where
said LF1 piezoelectric layer is made as a ceramic/polymer composite where the ceramic is diced from the back not fully through said LF piezoelectric

layer, so that a front portion of said LF ceramic piezoelectric layer forms a ceramic layer that forms said back layer of said isolation section.

18. An acoustic transducer array probe according to claim **17**, where
a 2nd layer from the back of said isolation section is made of one of the materials Cu, Ag, Au, Pd, Pt, W, and alloys of these materials, and powders of one of these materials or their alloys sintered or glued together.

19. An acoustic transducer array probe according to claim **13**, where one or both of the LF1 and HF piezoelectric layers are composed of at least two piezoelectric sub-layers on top of each other with electrodes on the surfaces of said sub-layers, and where the electrodes from different sub-layers are coupled together in relation to the electric polarization of said sub-layers so that said sub-layers are electrically coupled in parallel, while the thickness vibration of said sub-layers are in series, to reduce the electric impedance of the array elements.

20. An acoustic transducer array probe according to claim **13**, where at least one electronic substrate layer with integrated electronics connecting to array elements is stacked in the layer structure as at least one of
- part of said acoustic isolation section, and
- to the back of said HF piezo-layer, and
- to the front of said HF piezo-layer, and
- to the front of said LF1 piezo-layer, and
- to the back of said LF1 piezo-layer, and
- to the back of a backing material.

21. An acoustic transducer array probe according to claim **13**, where acoustic waves in further lower frequency bands (LF2, LF3, …) can be transmitted and received through at least said common radiation surface, where
- the electro-acoustic transduction for each of said further lower frequency bands are obtained with an added electro-acoustic transduction structure composed of a piezo-layer with an acoustic isolation section to the front, and where
- said isolation section is placed in acoustic contact with the back-side of the transduction section for the next higher frequency band, and where
- said isolation section provides backwards isolation of vibrations in the next higher frequency band of the neighbor transduction section to the front.

22. An acoustic transducer array probe according to claim **1**, where

- one of the LF1 and HF electro acoustic transduction is obtained by a piezoelectric layer, and

- the other of said HF and LF1 electro acoustic transduction is obtained by a substrate layer with cmut/pmut based transduction membranes on the front face,

- said layer based on cmut/pmut transduction membranes is placed to the front of said piezolayer.

23. An acoustic transducer array probe according to claim **22**, where said LF1 electro acoustic transduction is obtained by said piezolayer.

24. An acoustic transducer array probe according to claim **22**, where said HF electro acoustic transduction is obtained by said piezolayer.

25. An acoustic transducer array probe according to claim **22**, where at least one electronic substrate layer with integrated electronics connecting to array elements are stacked in the layer structure as at least one of
- electronic substrate layers are mounted to the back of said substrate layer with cmut/pmut membranes, and
- electronic substrate layers are mounted to the back of said LF piezo-layer, and
- electronic substrate layers are mounted to the back of a backing material.

26. An acoustic transducer array probe according to claim **22**, where acoustic waves in further lower frequency bands (LF2, LF3, …) can be transmitted and received through at least said common radiation surface, where
- the electro-acoustic transduction for each of said further lower frequency bands are obtained with an added electro-acoustic transduction structure composed of a piezo-layer with an acoustic isolation section to the front, and where
- said isolation section is placed in acoustic contact with the back-side of the transduction section for the next higher frequency band, and where
- said isolation section provides backwards isolation of vibrations in the next higher frequency band of the neighbor transduction section to the front.

27. An acoustic transducer array probe according to claim **22**, where the thickness structure for the LF and HF transduction is the same across the whole probe maximal transmit/receive surface, and the active LF1 and HF apertures for radiation and reception can selectably be varied by selectable electric connection to array element electrodes.

28. An acoustic transducer array probe according to claim **1**, where both the LF1 and HF electro/acoustic transduction are obtained by cmut/pmut based membrane transducer technology on the same substrate where separate membranes are used for the LF1 and HF transduction that are separately optimized for vibrations within the LF1 and HF bands.

29. An acoustic transducer array probe according to claim **28**, wherein at least one electronic substrate layer with integrated electronics connecting to array elements is placed to the back of said substrate layer with cmut/pmut membranes.

30. An acoustic transducer array probe according to claim **28**, where
the HF transduction membranes are placed on top of the LF1 transduction membranes.

31. An acoustic transducer array probe according to claim **28**, where
the HF transduction membranes are placed side by side of the LF1 transduction membranes, so close to each other that after a certain depth from the probe surface the LF1 and HF beams appear to originate from radiation surfaces that at least have a common region.

32. An acoustic instrument utilizing an acoustic probe according to claim **28**, where in addition acoustic pulses in a 2nd lower frequency (LF2) band can be transmitted and received through the common radiation surface, where the LF1 cmut/pmut membranes also have resonances in the LF2 band.

33. An acoustic instrument utilizing an acoustic probe according to claim **28**, where in addition acoustic pulses in a 2nd lower frequency (LF2) band can be transmitted and received through the common radiation surface, where the electro-acoustic transduction for said LF2 band is obtained with cmut/pmut membranes on the same substrate, where one of
- the HF and LF1 membranes are placed on the top of the LF2 membranes, and
- the LF2 membranes are placed by the side of the HF and

LF1 membranes.

34. An acoustic instrument utilizing an acoustic probe according to claim **28**, where in addition acoustic pulses in a 2nd lower frequency (LF2) band can be transmitted and received through the common radiation surface, where the electro-acoustic transduction for said LF2 band is obtained with a LF2 piezo-layer placed behind said HF/LF1 common substrate, so that the LF2 radiation surface at least has a part common to the common radiation surface of said HF and LF2 array.

35. An acoustic instrument utilizing an acoustic probe according to claim **34**, where acoustic waves in further lower frequency bands (LF3, LF4, …) can be transmitted and received through at least said common radiation surface, where
- the electro-acoustic transduction for each of said further lower frequency bands are obtained with an added electro-acoustic transduction structure composed of a piezo-layer with an acoustic isolation section to the front, and where
- said isolation section is placed in acoustic contact with the back-side of the transduction section for the next higher frequency band, and where
- said isolation section provides backwards isolation of vibrations in the next higher frequency band of the neighbor transduction section to the front.

36. An acoustic transducer array probe according to claim **13** or **22** or **28**, where
said LF1 and HF radiation surfaces are equal.

37. An acoustic transducer array probe according to claim **22** or **28**, where
the LF1 and HF transmit and receive apertures can selectably be varied by selectable electric connection to array element electrodes.

38. An instrument utilizing an acoustic probe according to claim **1**, where
the active LF1 transmit aperture is selected through one of
a) automatic selection by the instrument depending on the image range and the ultrasound imaging modality and application, and
b) directly by the instrument operator through instrument controls.

39. An acoustic transducer array probe according to claim **1**, where said at least one electronic substrate layer with

electronic circuits include one or more of
a) receiver pre-amplifiers connected to array elements, and
b) transmitter amplifiers connected to array elements, and
c) electronic switches that connect selectable groups of array elements to a single wire that further connects to an instrument, and
d) sub-aperture circuits connecting to a group of elements and adding delays to the individual sub-aperture signals before summing to sub-aperture signals that each connect to a single wire that further connects to an instrument, and
e) time multiplex circuits that time multiplex samples of signals from groups of elements or groups of sub-apertures of elements on single wires that further connect to an instrument.

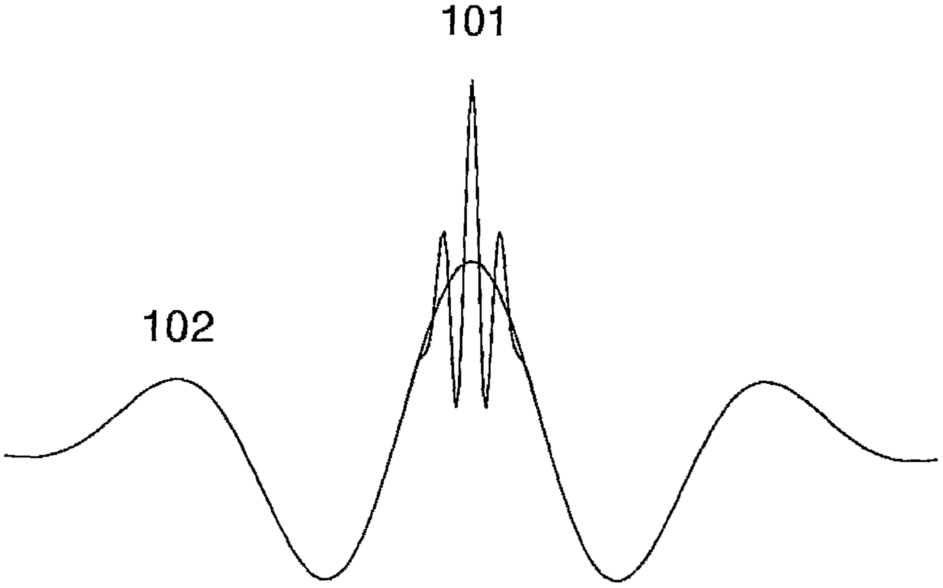

FIG 1a

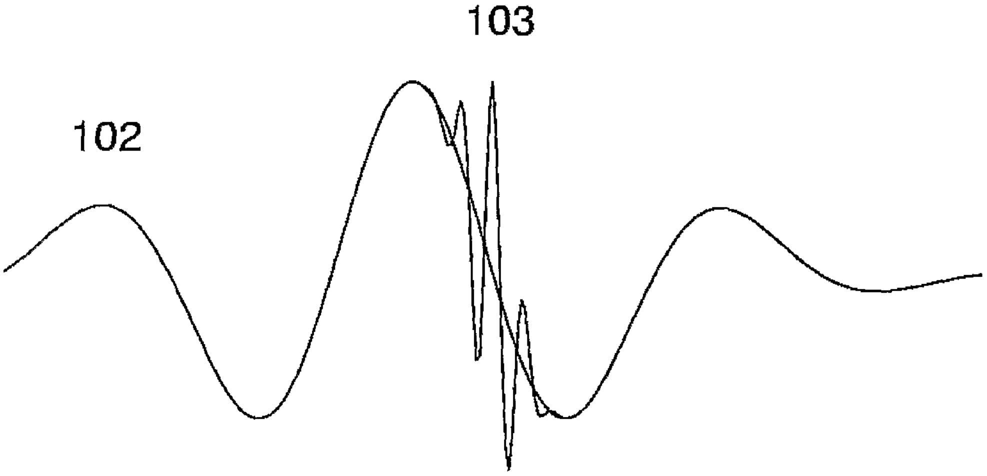

FIG 1b

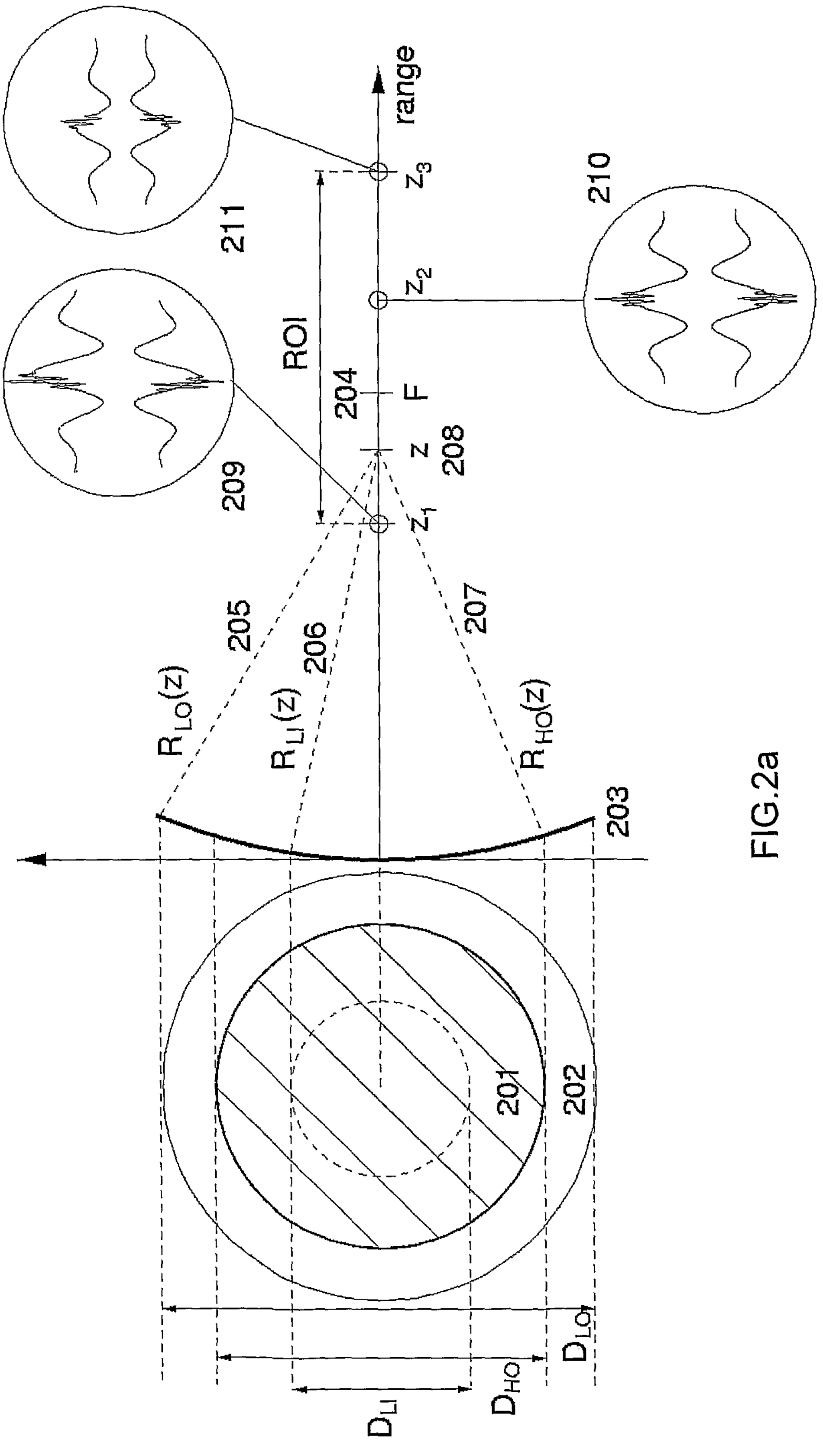
range
z_3
211
210
z_2
ROI
209
204
F
z
208
z_1
205
206
207
$R_{LO}(z)$
$R_{LI}(z)$
$R_{HO}(z)$
203
201
202
D_{LO}
D_{HO}
D_{LI}

FIG.2a

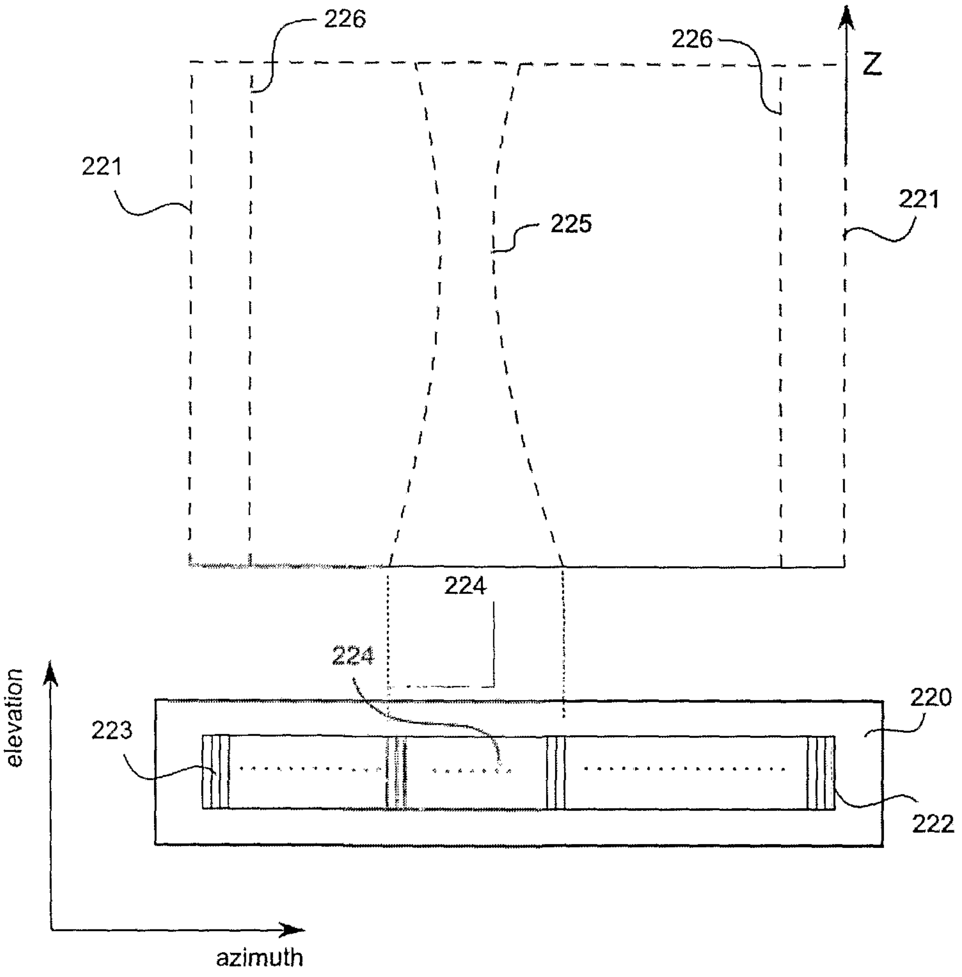
226
226
Z
221
221
225
224
224
elevation
223
220
222
azimuth

FIG. 2b

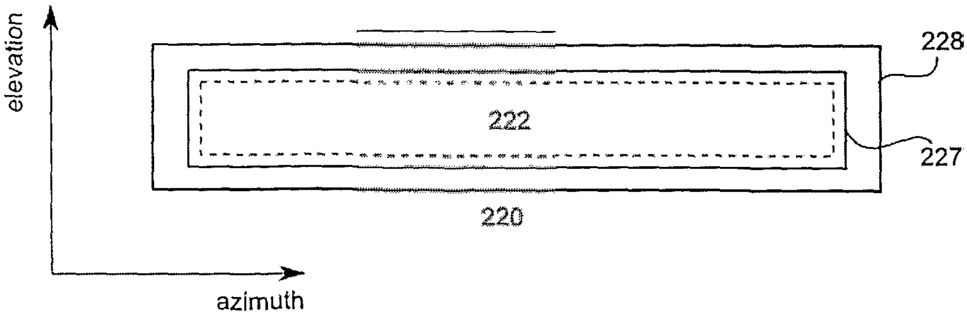
elevation
228
222
227
220
azimuth

FIG. 2c

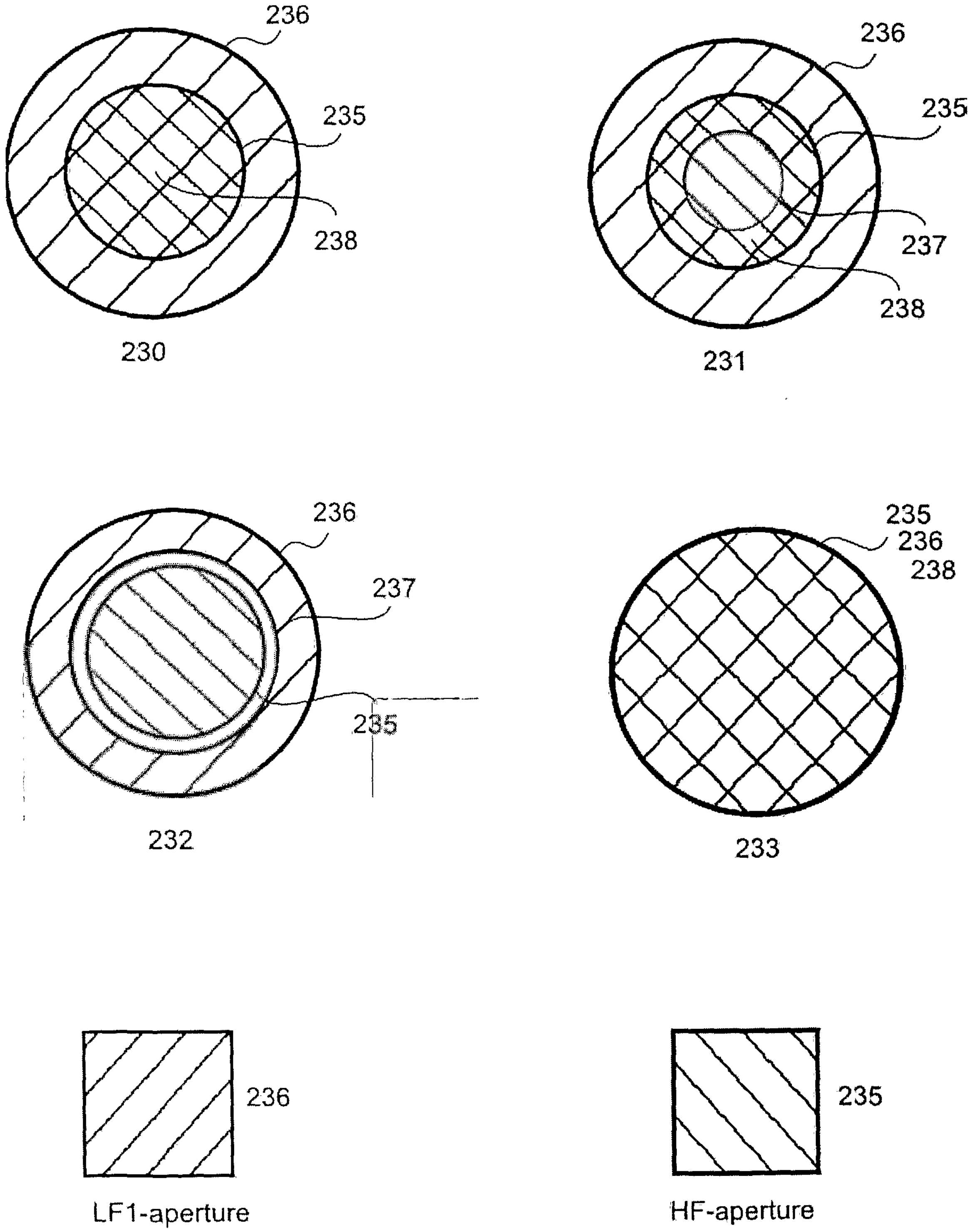
236
235
238
230
236
235
237
238
231
236
237
235
232
235
236
238
233
236
LF1-aperture
235
HF-aperture

FIG. 2d

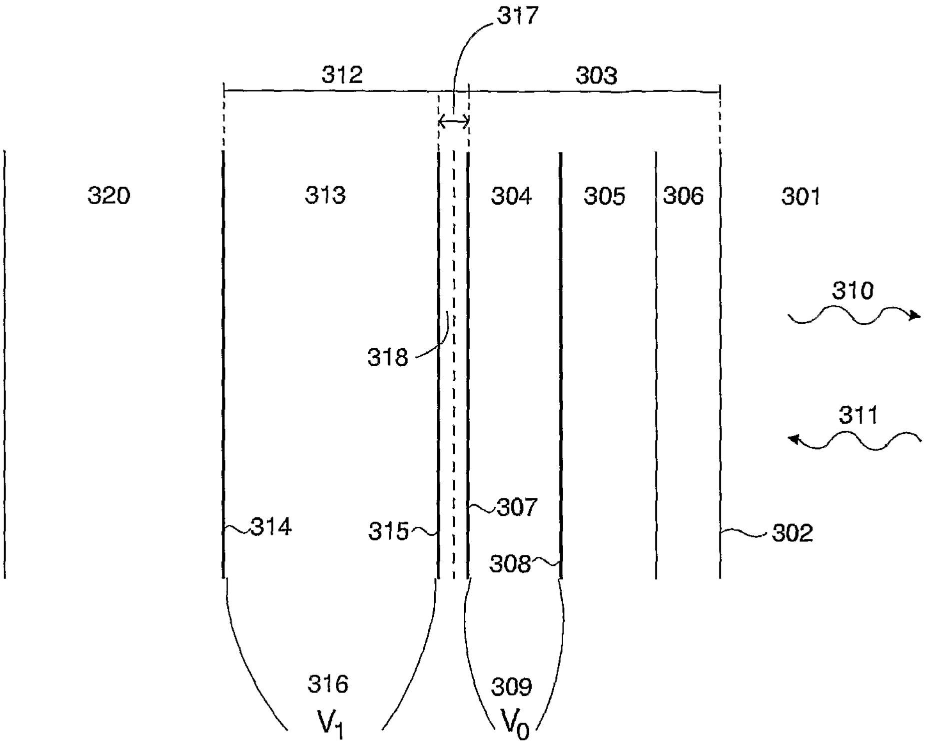
317
312
303
320
313
304
305
306
301
310
318
311
314
315
307
302
308
316
V1
309
V0

FIG. 3a

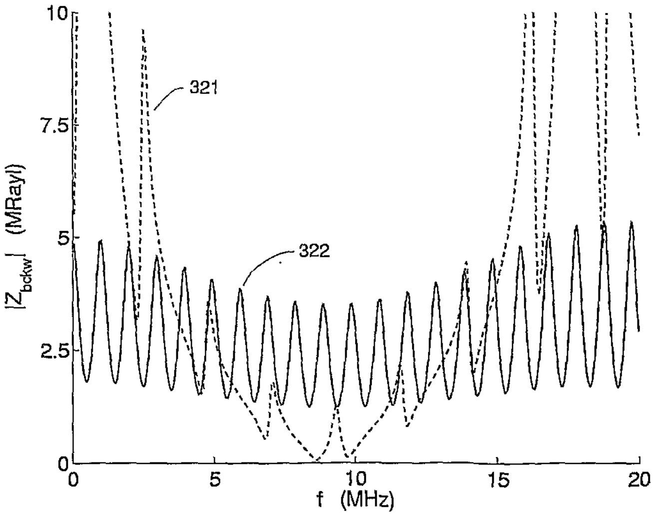
10
7.5
5
2.5
0
|Z_bckw| (MRayl)
321
322
0
5
10
15
20
f (MHz)

FIG. 3b

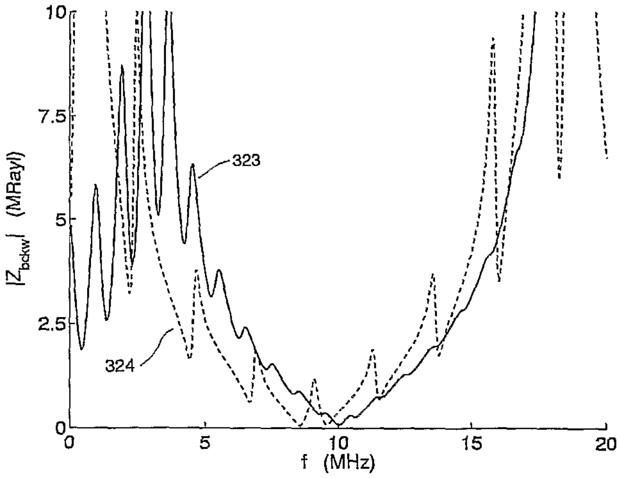
10
7.5
5
2.5
0
$|Z_{bckw}|$ (MRayl)
323
324
0
5
10
15
20
f (MHz)

FIG. 3c

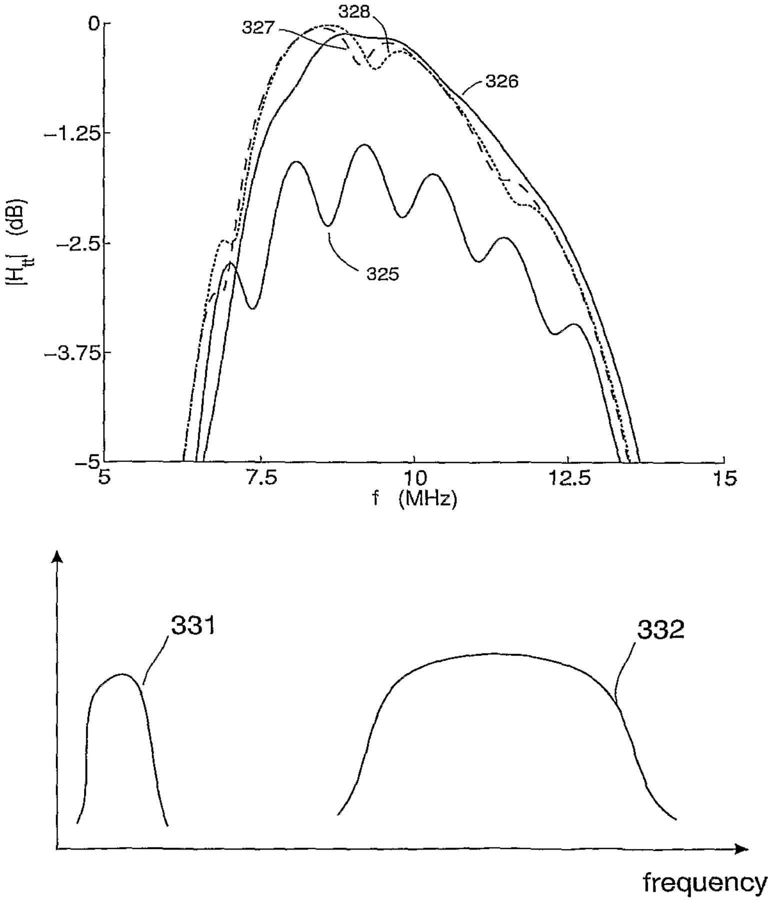
0
-1.25
-2.5
-3.75
-5
$|H_{tt}|$ (dB)
327
328
326
325
5
7.5
10
12.5
15
f (MHz)
331
332
frequency

FIG. 3d

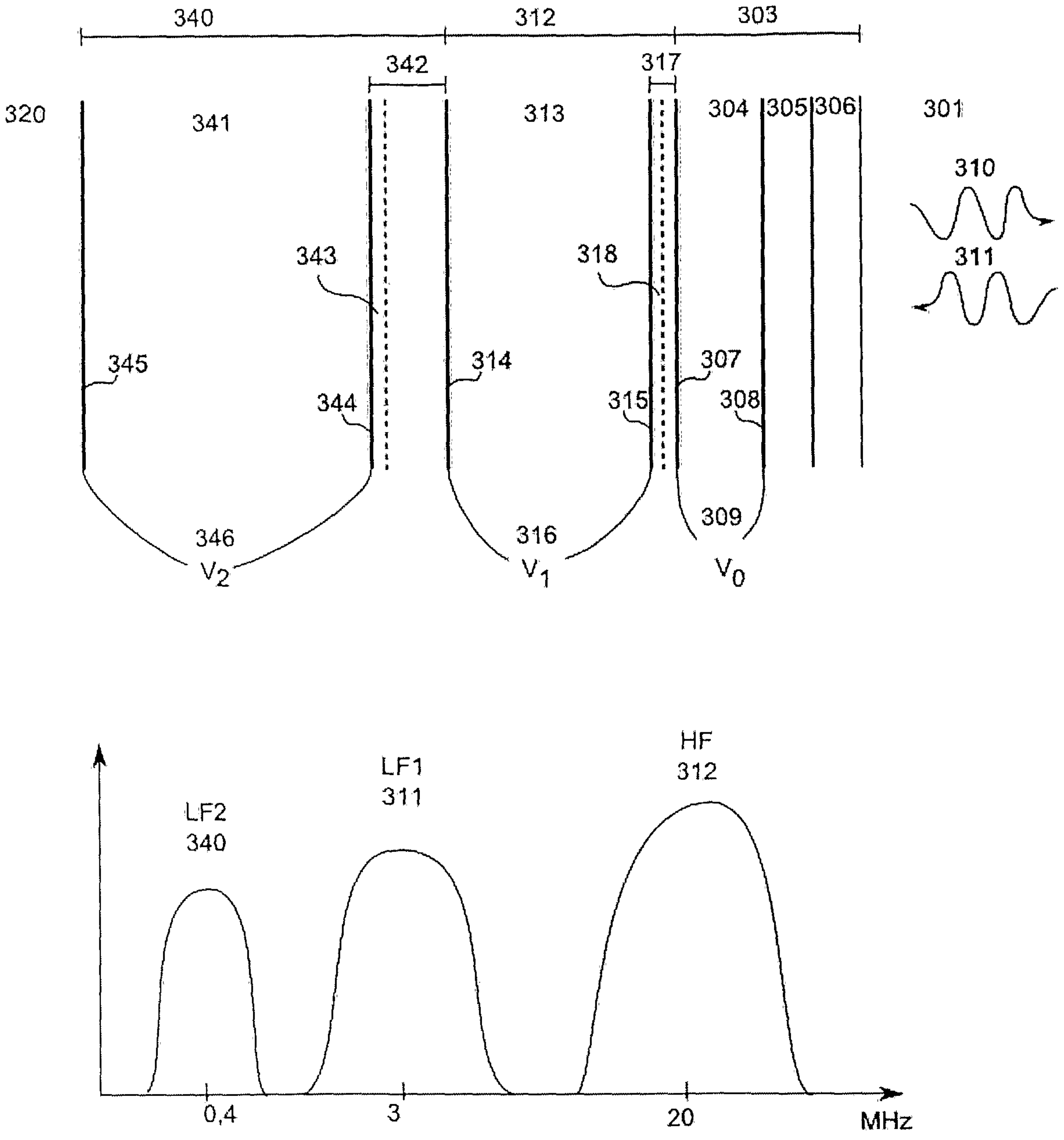
340
312
303
342
317
320
341
313
304
305
306
301
310
311
343
318
345
314
307
344
315
308
346
316
309
V2
V1
V0
LF2
340
LF1
311
HF
312
0,4
3
20
MHz

FIG.3e

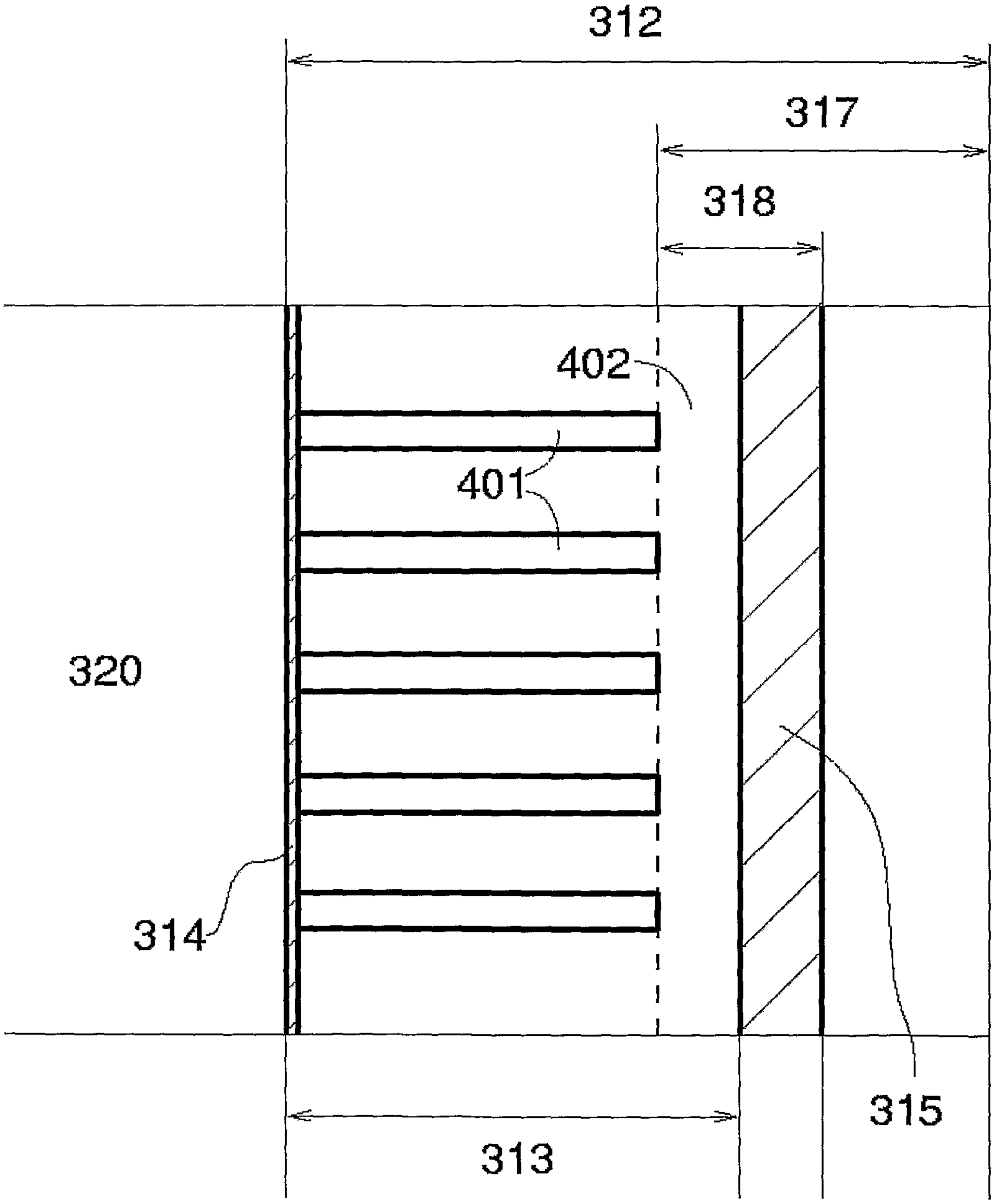

Fig. 4a

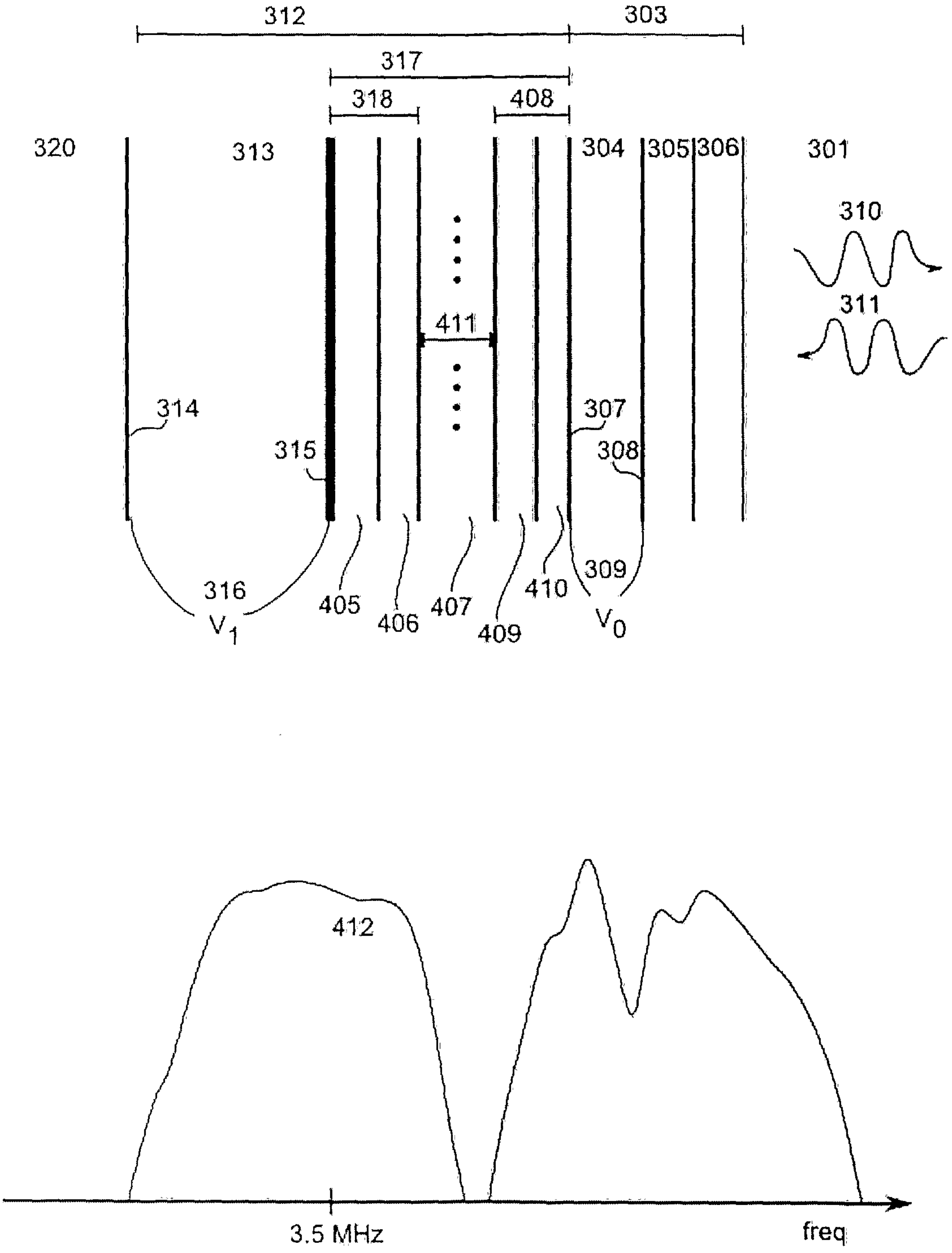
312
303
317
318
408
320
313
304
305
306
301
310
311
411
314
307
315
308
309
316
405
406
407
409
410
V_1
V_0
412
3.5 MHz
freq

FIG.4b

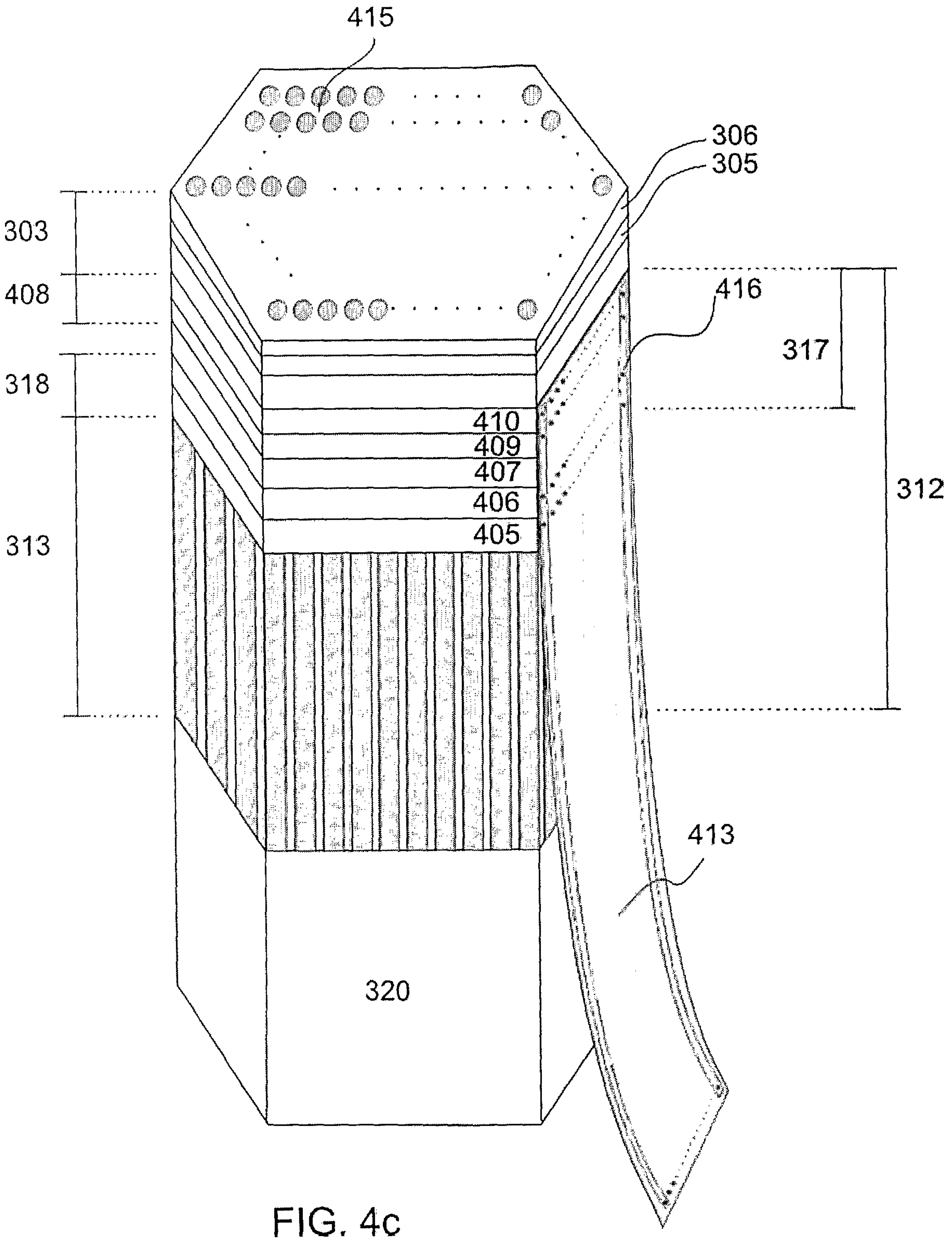
415
306
305
303
408
416
317
318
410
409
407
406
405
312
313
413
320

FIG. 4c

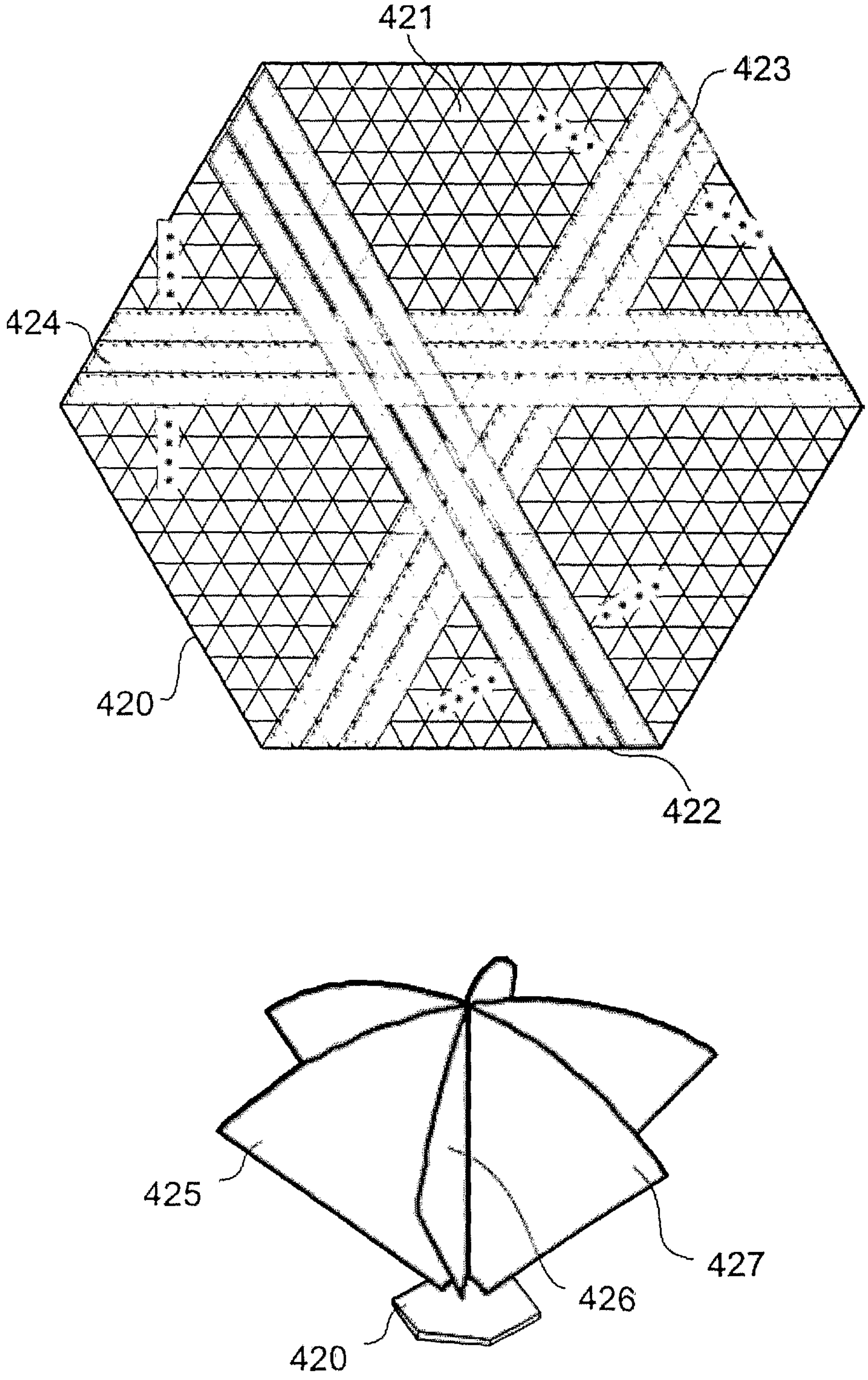

FIG. 4d

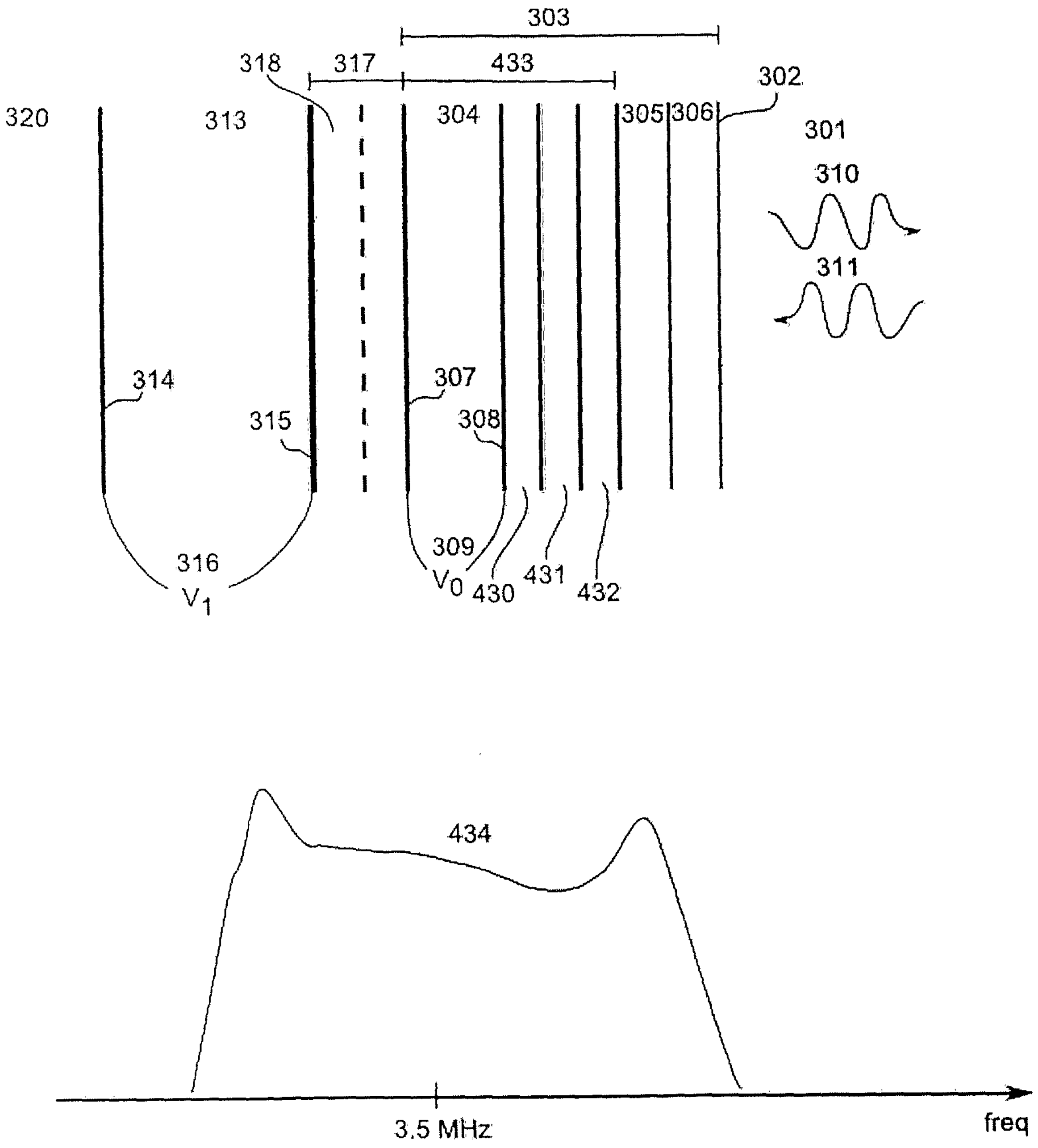
303
318
317
433
302
320
313
304
305
306
301
310
311
314
307
315
308
309
316
V1
V0
430
431
432
434
3.5 MHz
freq

FIG.4e

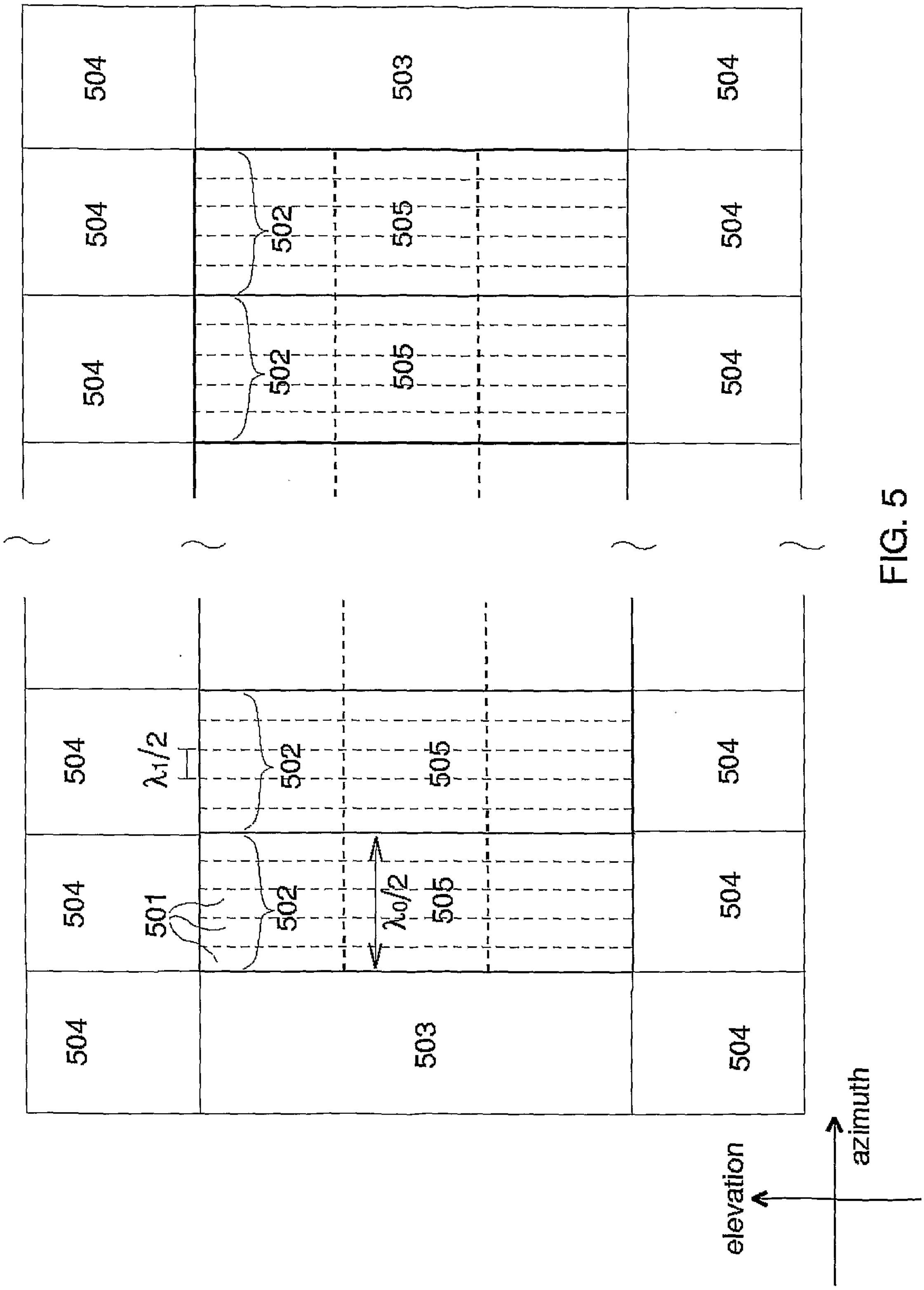
504
503
504
504
502
505
504
504
502
505
504
504
$\lambda_1/2$
502
505
504
504
501
502
$\lambda_0/2$
505
504
504
503
504
elevation
azimuth

FIG. 5

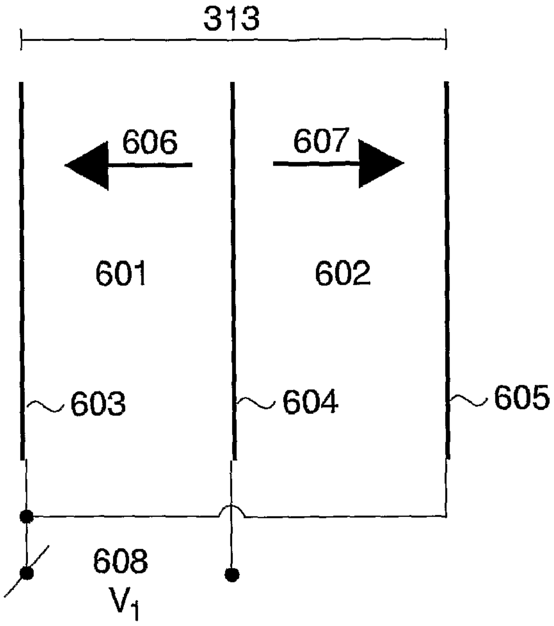

FIG. 6

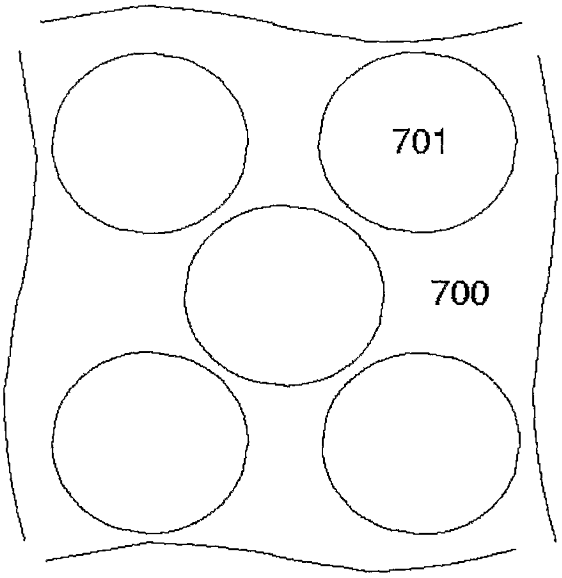

FIG. 7

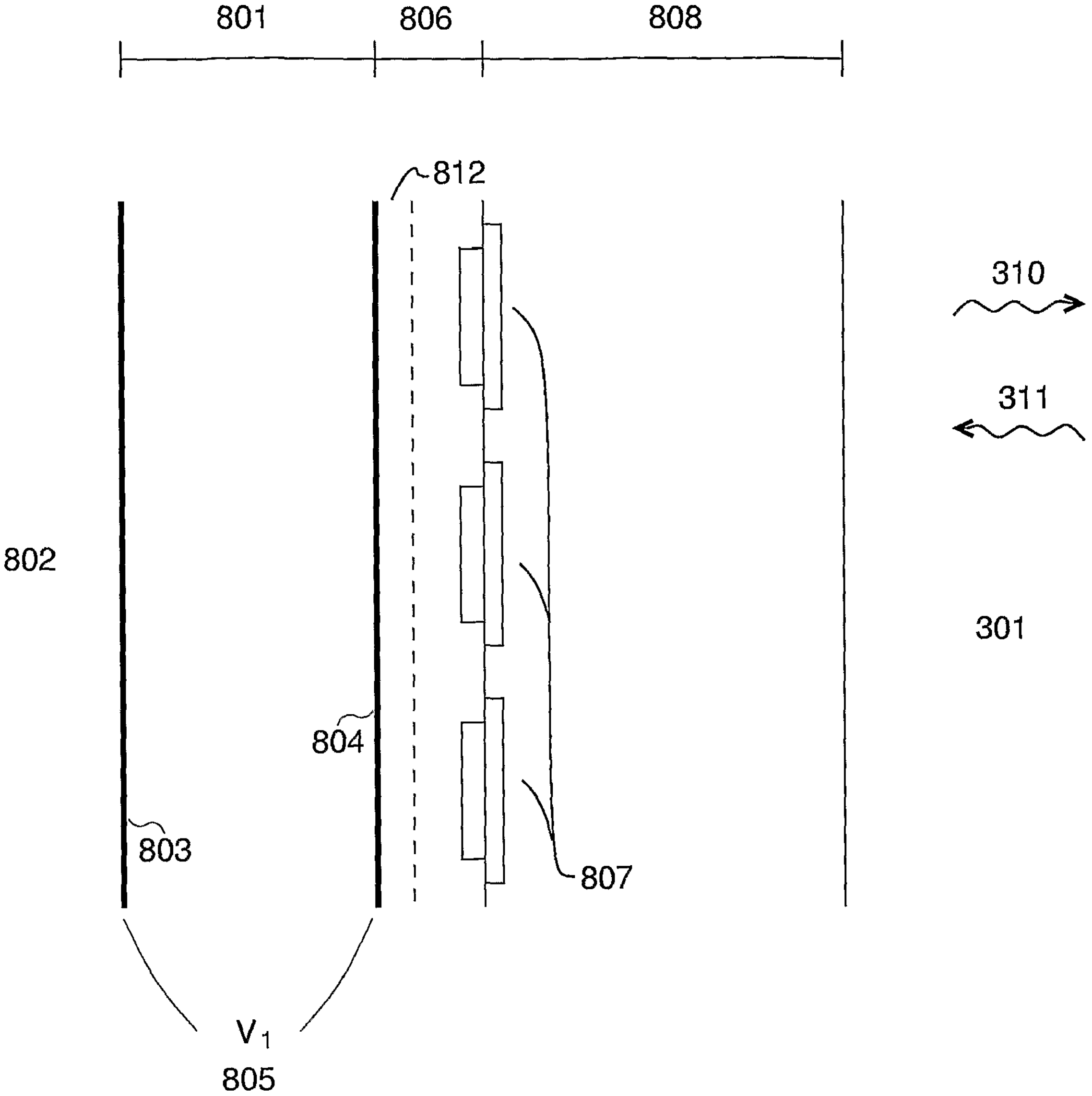

FIG. 8a

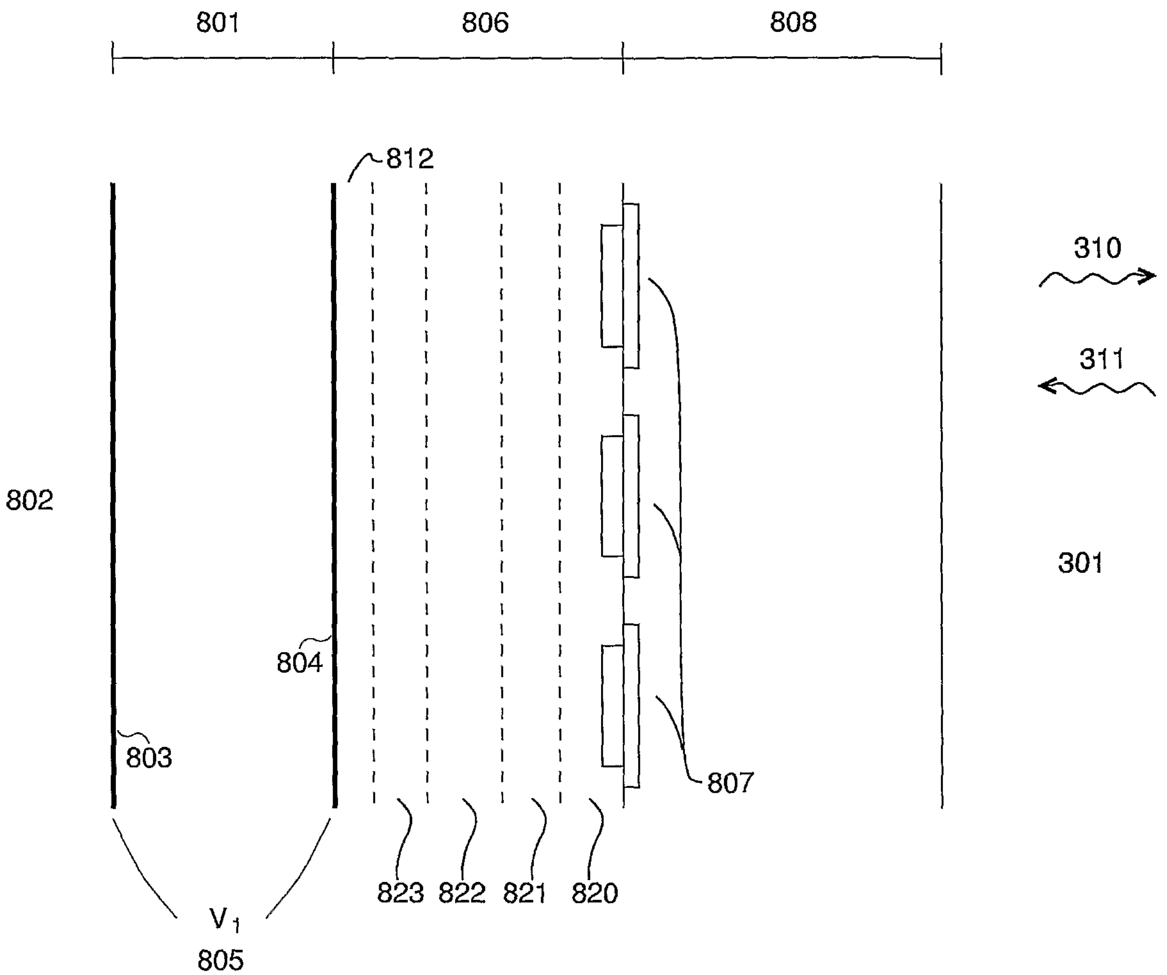
801
806
808
812
310
311
802
301
804
803
807
823
822
821
820
V1
805

FIG. 8b

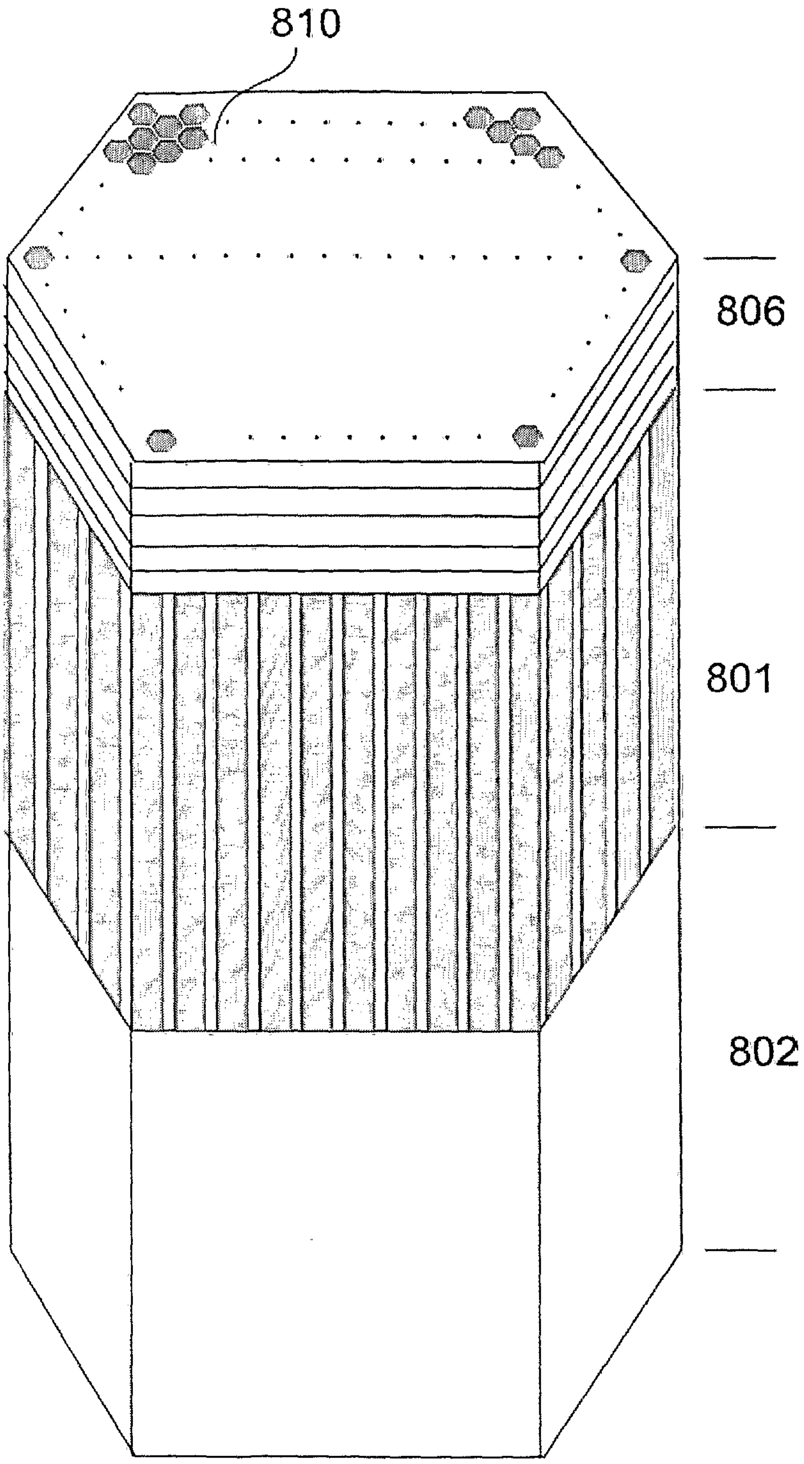

FIG. 8c

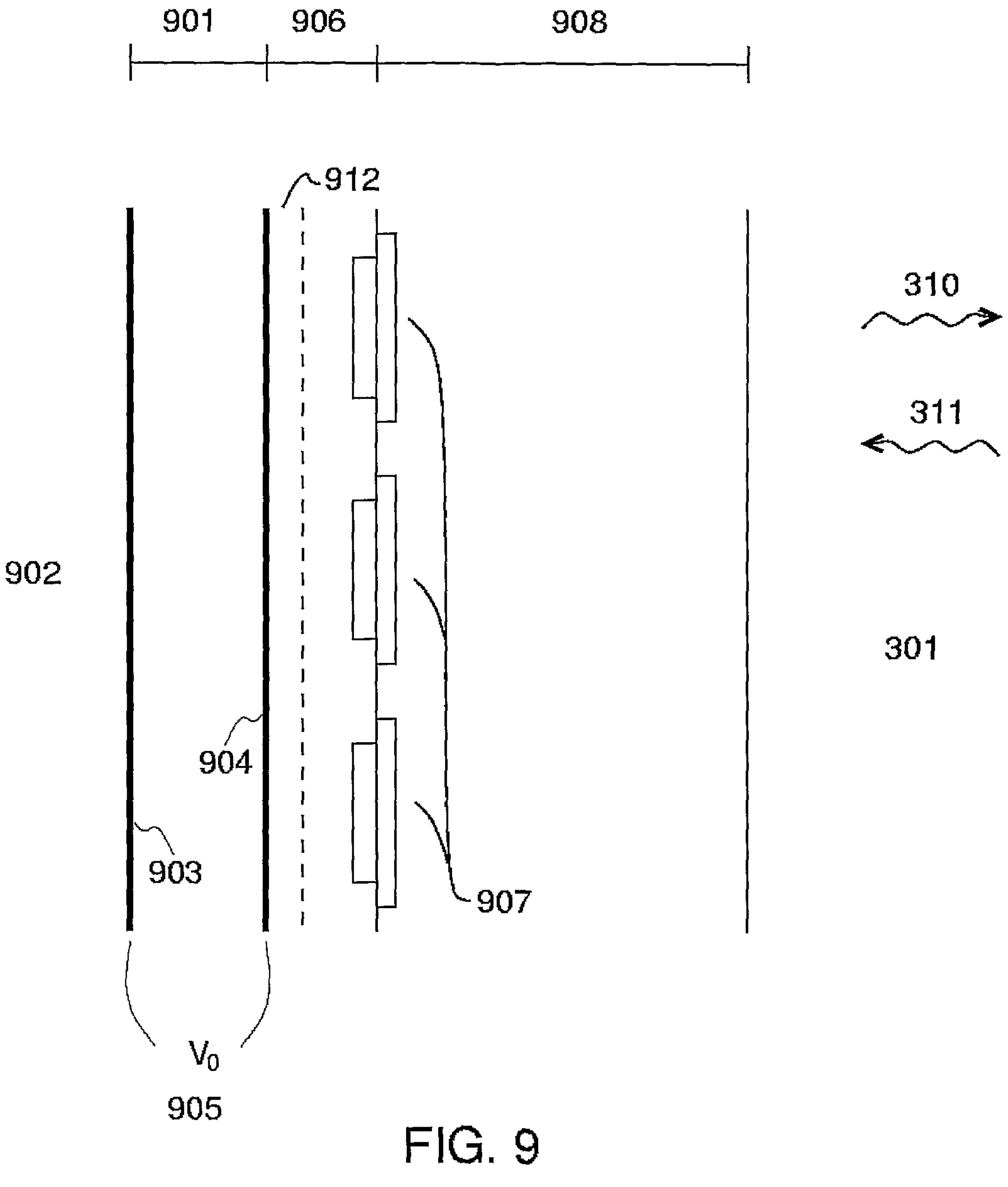

FIG. 9

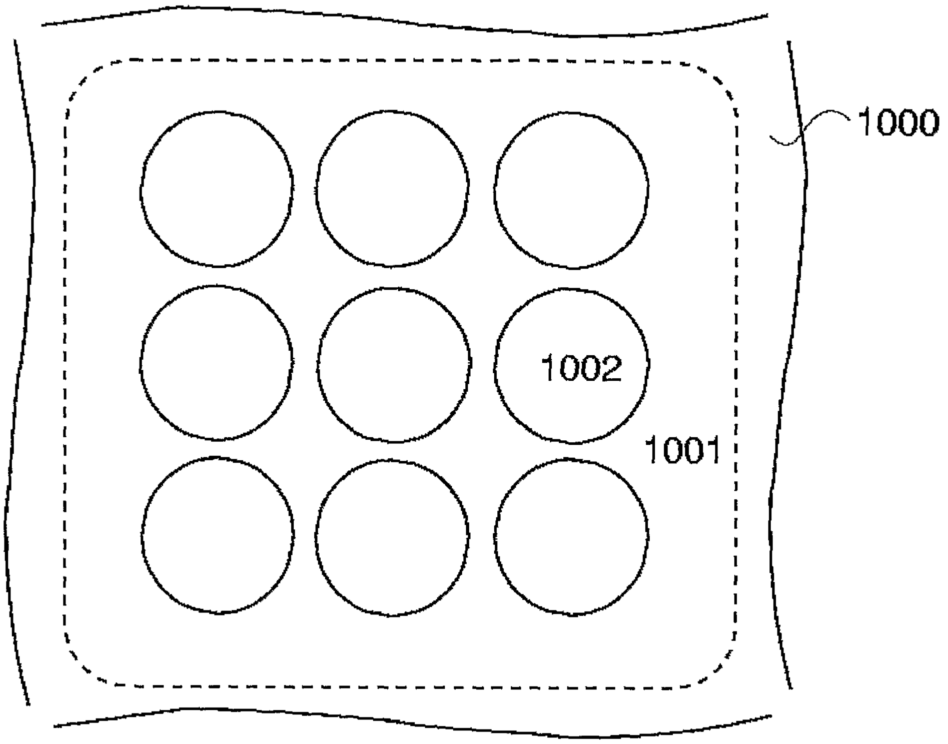

FIG.10a

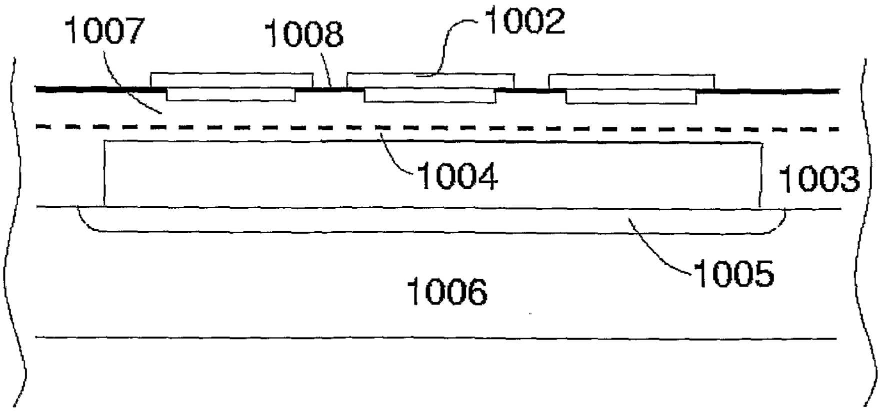

FIG.10b

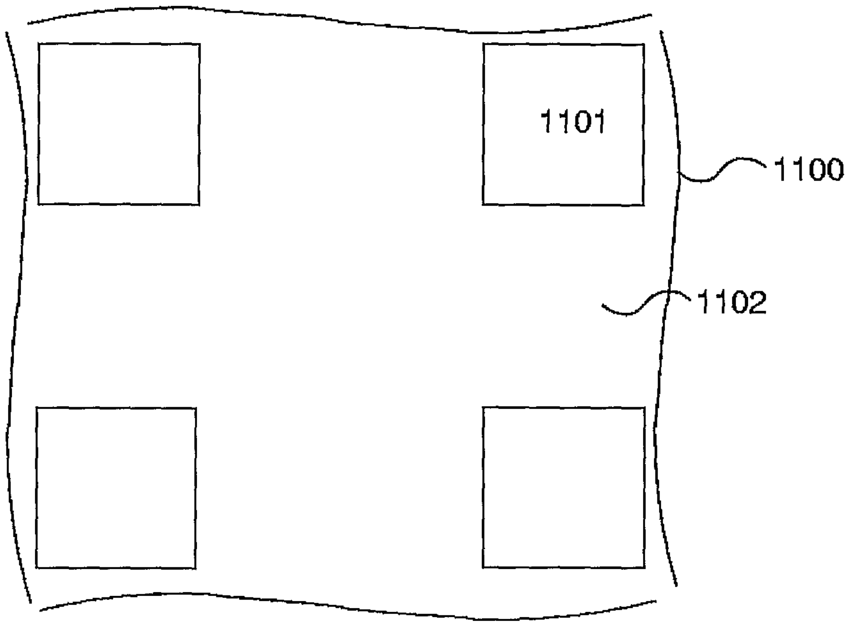

FIG.11

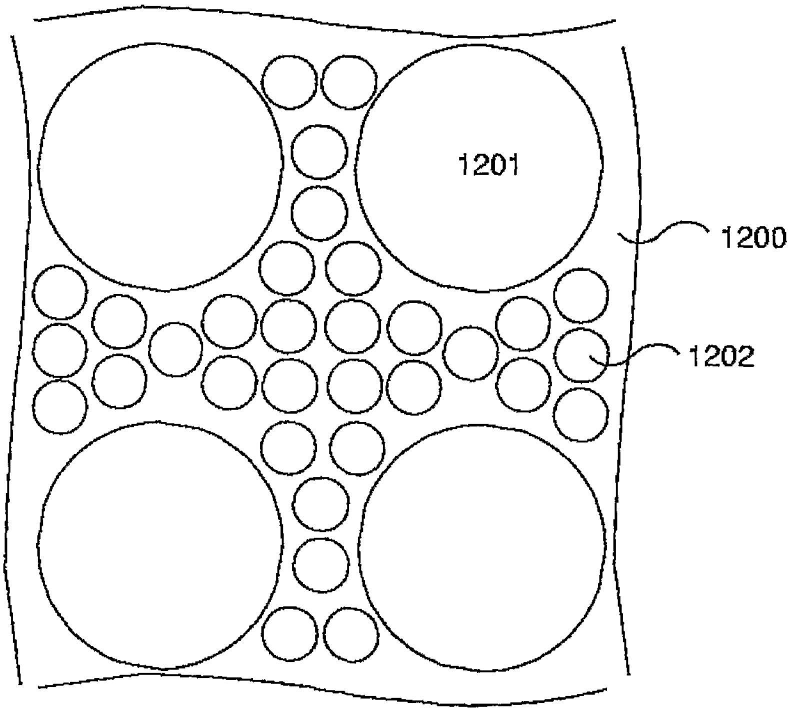

FIG. 12

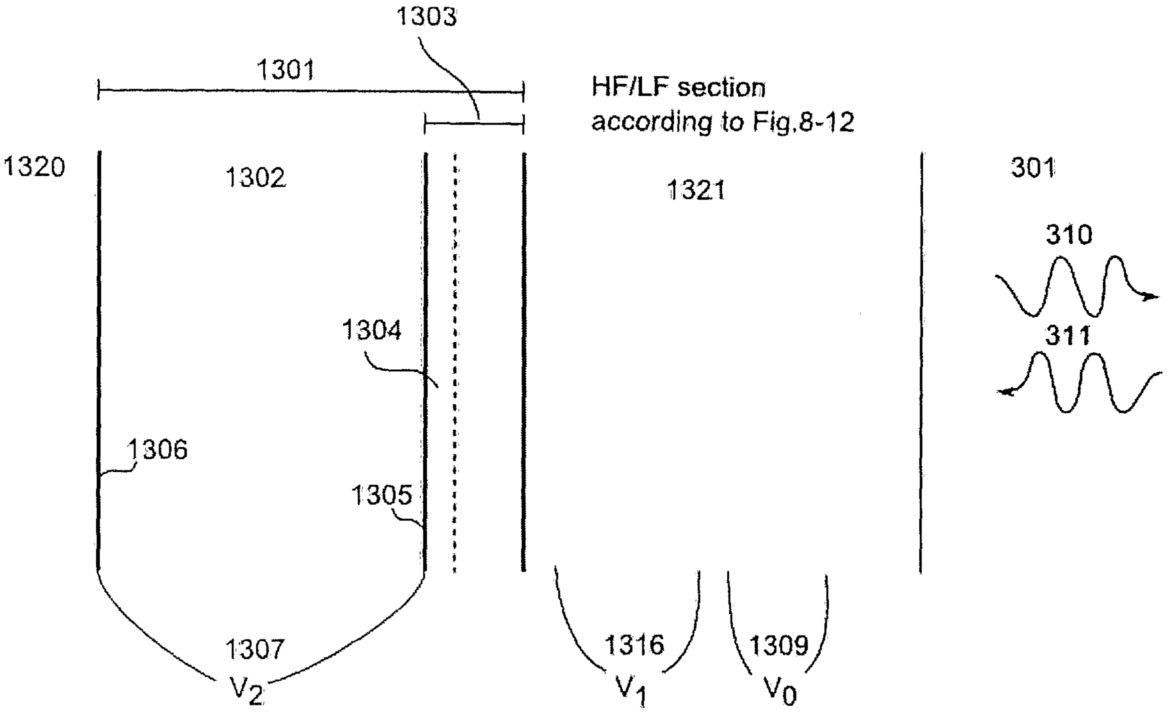
1303
1301
HF/LF section
according to Fig.8-12
1320
1302
1321
301
310
311
1304
1306
1305
1307
V2
1316
V1
1309
V0

FIG. 13a

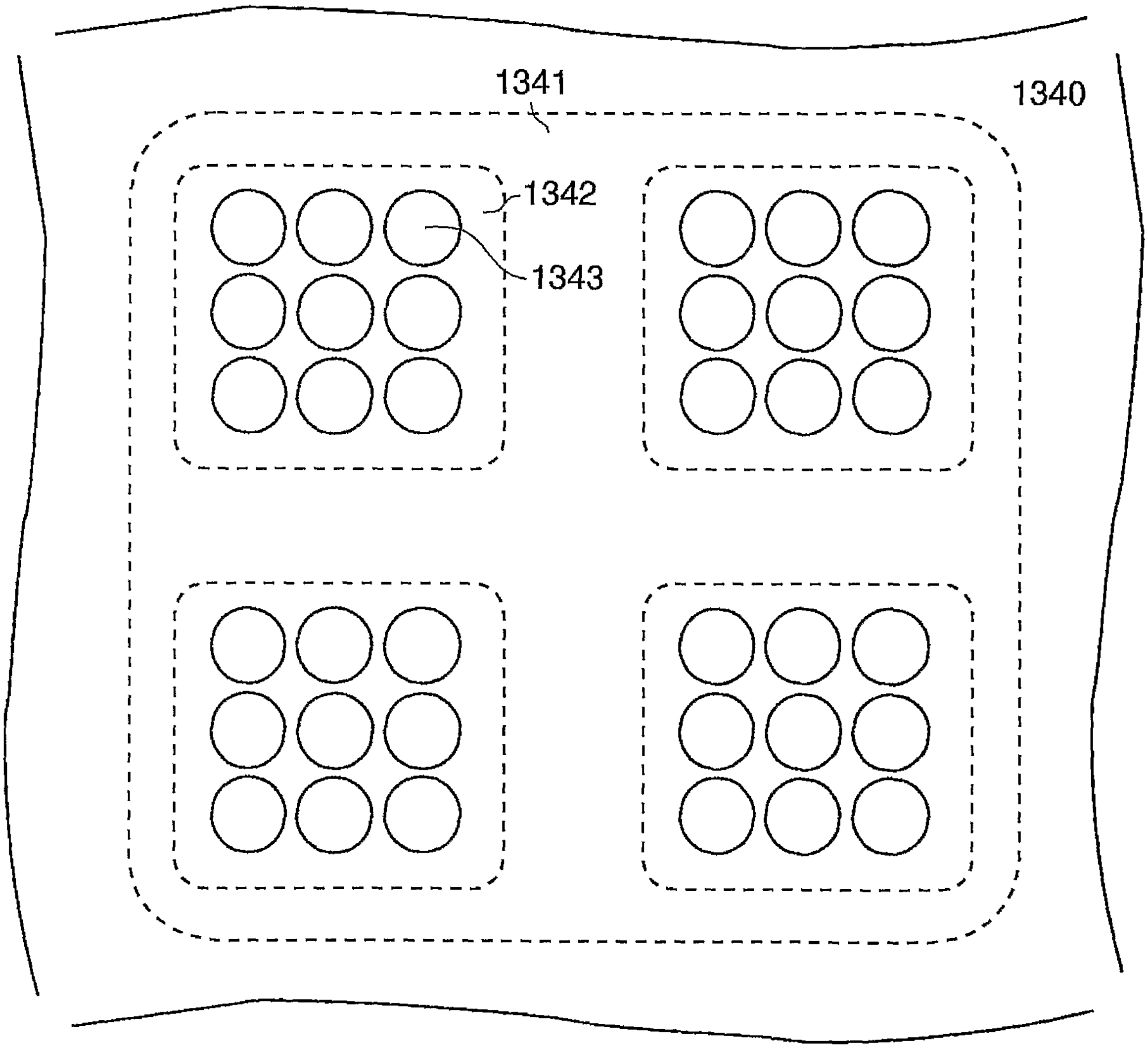

FIG.13b

INTERNATIONAL SEARCH REPORT

International application No
PCT/NO2009/000014

A. CLASSIFICATION OF SUBJECT MATTER
INV. B06B1/06 B06B1/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B06B H04R H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2007/013814 A (ANGELSEN BJOERN A J [NO]; JOHANSEN TONNI F [NO]; HANSEN RUNE [NO]; MAA) 1 February 2007 (2007-02-01) page 7, line 25 - page 11, line 34; figures 2,3a page 16, line 35 - page 22, line 23; figure 5.8.9 -----	1-39
Y	US 2002/156379 A1 (ANGELSEN BJORN A J [NO] ET AL) 24 October 2002 (2002-10-24) paragraphs [0024], [0097] paragraphs [0123], [0124]; figure 8a -----	1-39
Y	JP 2005 103193 A (HITACHI MEDICAL CORP; JIKEI UNIV SCHOOL OF MEDICINE) 21 April 2005 (2005-04-21) abstract; figure 1 ----- -/--	1-39

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search
9 June 2009

Date of mailing of the international search report
16/06/2009

Name and mailing address of the ISA/
European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer
Häusser, Thomas

INTERNATIONAL SEARCH REPORT

International application No
PCT/NO2009/000014

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	DE 29 14 031 B1 (SIEMENS AG) 14 May 1980 (1980-05-14) column 4, line 24 - line 36; figure 2 -----	1-39

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/NO2009/000014

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2007013814 A	01-02-2007	CN 101262960 A	10-09-2008
		EP 1912749 A2	23-04-2008
		JP 2009503990 T	29-01-2009
		US 2007035204 A1	15-02-2007
US 2002156379 A1	24-10-2002	NONE	
JP 2005103193 A	21-04-2005	NONE	
DE 2914031 B1	14-05-1980	AU 5715680 A	09-10-1980
		CA 1154861 A1	04-10-1983
		EP 0017216 A2	15-10-1980
		JP 1225107 C	31-08-1984
		JP 55140392 A	01-11-1980
		JP 58056320 B	14-12-1983
		US 4354132 A	12-10-1982