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(54) **Ultrasound transducer with improved vibrational modes.**

(57) The transducer of the present invention is diced into subelements which have a height-to-width ratio which determines the modality of their vibration. The subelements are then electrically connected to provide a transducer having the desired electrical configuration, i.e., an annular array transducer. Using the present invention, the electro-acoustic characteristics of the transducer are not determinitive of the vibrational characteristics of the individual subelements.

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ULTRASOUND TRANSDUCER WITH IMPROVED VIBRATIONAL MODES

The present invention relates to ultrasound transducers. In particular, it relates to ultrasound transducers of the type which generate and receive longitudinal waves for use in medical ultrasound imaging.

In ultrasound transducer technology, various modes of vibration of piezoelectric material are well known which are useful for generating longitudinal waves. These include the "plate" mode, in which a relatively flat plate of piezoelectric material vibrates in a manner such that ultrasound waves are transmitted in a direction normal to the surface of the plate when electrodes connected to the upper and lower plate surfaces are energized, and the "bar" mode, in which a long, thin bar of piezoelectric material having electrodes connected at either end of the bar vibrates to generate wave transmissions along the longitudinal axis of the bar. There is also a "beam" mode in which a long, thin bar of piezoelectric material having elongated electrodes on either side of the bar vibrates to generate wave transmissions which are perpendicular to the longitudinal axis of the bar, such as in a phased array or linear array transducer. Also, there are "mixed" modes of vibration, which may include "plate" mode, "bar" mode, or "beam" mode vibrations, together with lateral vibration modes. These lateral modes occur to an unacceptable level in piezoelectric material in which the ratio of the piezoelectric material's height to its width (H/W) is in a ratio of approximately 0.5 to 2 for transducers which utilize the half wavelength resonance mode or in a ratio of approximately 0.25 to 1 for transducers which utilize the quarter wavelength resonance mode. As will be understood by those skilled in the art, the lateral modes of vibration occur in any piezoelectric material to some extent, depending upon the geometry of each element which comprises the transducer and the properties of the particular piezoelectric material. It is only a severe problem in half wavelength transducers when H/W is between about 0.5 and 2 and in quarter wavelength transducers when H/W is between about 0.25 and 1.

The particular problem which the present invention is particularly adapted to solve is readily described by referring to piston type annular transducers of the type used in annular arrays. Heretofore, a variety of piston type annular array transducers have been used to provide electronically variable focusing capabilities. In such annular array transducers, the outer rings of the annular arrays are typically much narrower than the inner rings or the center piston. This results from the desire to keep the areas of the various transducer elements substantially equal in order to provide substantially uniform signals over the depth of penetration of the ultrasound. This phenomenon is well known in the art, and it is common in annular arrays to provide annular elements which have areas which are substantially equal to each other and to the area of the central piston.

The problem, which results from manufacturing annular arrays in the standard manner, is that the ratio of the height (of the piezoelectric material measured from its substrate) to the width of the individual elements (measured radially) gets close to 1 in the outer rings of the annular array. Unfortunately, as noted above, when the ratio of a transducer's height to its width is in the range of approximately 0.5 to about 2, the lateral modes of vibration occur at a level which is unacceptable in medical ultrasound piston transducers. Various attempts have been made heretofore to reduce the lateral vibration mode of the outer transducer rings. Such methods have included putting dampening material into the areas between and surrounding the outer rings. Overall, these methods have yielded little positive results.

Accordingly, a method for producing an annular array transducer which can be electronically focused over a large range without having to suffer the problems of lateral mode vibrations in the outer rings would be desirable. In general, it would be desirable to be able to select an arbitrary transducer type, e.g. an annular array, without thereby being forced to accept whatever spurious vibrational modes might occur, e.g. lateral modes in the outer rings. It would be desirable to have the same vibrational mode, e.g. plate or bar mode, in all elements of a transducer with any arbitrary geometry, e.g. the central piston and outer rings of an annular array.

According to the invention, we provide an improved ultrasonic transducer comprising a piece of piezoelectric material which has been subdivided into subelements smaller than the electrodes attached to said subelements, whereby the vibrational mode of the subelements is determined by their physical shape and dimensions, rather than by the shape or dimensions of the electrode geometry.

As hereinafter described with reference to the drawing, the bar vibrational mode can be combined with any transducer design, because the piezoelectric material is sawed into a large number of subelements which each vibrate in the bar mode due to their physical shape and dimensions. These subelements are then electrically connected to have any desired element geometry. Accordingly, it is possible to design transducers of arbitrary configuration which have the same vibrational mode in all elements.

In the Drawing:

FIG. 1 is a top plan view of one embodiment of a transducer utilizing the present invention; and

FIG. 2 is a side view of a transducer utilizing the present invention;

FIG. 3 is a bottom plan view of the transducer of FIG. 1 illustrating the electrode pattern of the annular array; and

FIG. 4 is a side view of a transducer utilizing a second embodiment of the present invention.

As mentioned above, it is desired to substantially eliminate the lateral mode of vibration in the outer rings of an annular array. In order to accomplish that result, a circular piece of piezoelectric material 10, shown in FIG. 1, is sawed, by a semiconductor dicing saw, for example, into a number of subelements 12. In the preferred embodiment of the invention, the subelements 12 are substantially square, having an edge length, W, which is substantially smaller than the height, H, of the piezoelectric material 10. By way of example, if the PZT4 composition of PZT (lead-zirconate-titanate) piezoelectric material is used, H may be approximately 20 mils (0.5 mm), and W may be approximately 8 mils (0.2 mm) for a 3 MHz medical ultrasound transducer. As shown in FIG. 2, the saw kerfs 14 extend from a top surface 16 of the piezoelectric material 10 substantially down to the bottom surface 18. However, in the preferred embodiment of the invention, the saw kerfs 14 do not extend completely through to the bottom surface 18 of the piezoelectric material 10, thereby maintaining the structural integrity of the piezoelectric material 10 and the electrode pattern. However, as will be explained hereinafter, it is possible to have the saw kerfs 14 extend through the bottom surface 18 with appropriate changes to the preferred process described below.

After the saw kerfs 14 are formed through the top surface 16, the subelements 12 of the top surface 16 must be reconnected electrically. While there are a number of ways in which this can be done, in the preferred method the saw kerfs 14 are filled with a low viscosity, non-conductive epoxy. Then, in the preferred embodiment, a tri-metal system is sputtered onto the surface of the epoxy to form the upper electrode 20 which also functions as an RF shield if electrically connected to ground. As is well known in the art, a tri-metal system provides a first metal which adheres well to the underlying material, a second metal which provides coupling between the first metal and a third metal, and a third metal which is relatively impervious to oxidation and which can be soldered to easily. In the preferred embodiment of the invention, the first metal is chrome, the second metal is nickel, and the third metal is copper. One or more quarter wave acoustic matching layers 22 of, for example, non-conductive, filled epoxy is then applied over the surface of the top electrode 20 in a manner and for reasons which are well known in the art.

Electrodes 24 are formed on the bottom surface 18 in any desired configuration. In the preferred embodiment of the invention, the electrodes 24 are in the form of an annular array pattern, as shown in FIG. 3. In the preferred embodiment of the invention, a layer of conductive material, such as copper, is applied to the bottom of the piezoelectric material 10. Then, a layer of resist material is printed in the form of the pattern of the bottom electrodes on the conductive layer, and the exposed portions of the conductive layer are etched to remove the undesired portions down to the piezoelectric material 10. An acoustic backing layer 26 is applied to the bottom electrode pattern 24, the purpose of which is well known in the art. As should be obvious, the minimum interelectrode spacing between the annular rings of the electrode pattern is selected to insure that no two electrodes can energize the same subelement 12. This can be accomplished by using an interelectrode spacing which is greater than W times the square root of 2 (for square subelements 12 having an edge length W).

Referring now to FIG. 4, an alternative embodiment 28 of the present invention is shown in cross-section. In this particular embodiment, the piezoelectric material 30 is diced into subelements 32, with the saw kerfs 34 going completely through to a quarter wavelength mismatching layer 36. The piezoelectric material 30 is itself approximately a quarter wavelength thick rather than one-half wavelength thick. Again, one or more quarter wavelength thick matching layers 38 are applied to an electrode 39 on the face 40 of the piezoelectric material 30. The particular material used for the mismatching layer 36 is selected to have an acoustic impedance of Z_L with a backing layer 37 (on the mismatching layer 36) having an acoustic impedance of Z_B, resulting in an input impedance into the mismatching layer 36, as seen from the piezoelectric material 30, which is $(Z_L)^2/Z_B$ near the frequency for which the layer 36 is approximately one-quarter wavelength thick. If the subelements 32 are diced completely through the piezoelectric material 30 to the mismatching layer 36, the mismatching layer 36 is preferably conductive so that the rear electrode pattern 41 may be formed in the mismatching layer 36. In certain instances, as will be understood by those skilled in the art, optimization of a particular transducer design may require the mismatching layer 36 to be other than one-quarter wavelength thick.

When Z_L is chosen to be relatively large with respect to Z_B, the impedance into the mismatching layer 36 becomes relatively large. Accordingly, substantially all of the acoustic energy is transmitted through the face 40 of the piezoelectric material 30, rather than into the mismatching layer 36 and the piezoelectric material vibrates in a quarter wavelength resonance mode due to the sign change of the reflection coefficient at the rear boundary 43, as will be obvious to those skilled in the art. An advantage of manufacturing a transducer 10 in accordance with this embodiment is that the individual subelements 32 are less fragile since the piezoelectric material 30 is thinner for a given frequency.

As this particular embodiment involves a piece of piezoelectric material 30 having a thickness of about a quarter wavelength rather than a piece of piezoelectric material 30 having a thickness of about one-half wavelength, the height-to-width ratio (H/W) required to substantially eliminate undesired mixed vibrational modes is governed by different rules than for a half wavelength thick piece of piezoelectric material 30. Accordingly, the mixed mode of operation will not be experienced in this particular embodiment unless the height-to-width ratio is substantially in the range of about 0.25 to 1. Accordingly, the individual subelements 32 can have a height-to-width ratio of approximately 1.25 which makes them structurally stronger than in the embodiment described with respect to FIG. 2.

With particular reference to FIG. 2, the height-to-width ratio H/W, is selected to be substantially greater than 2. In particular, a ratio of 2.5 has been found to be acceptable.

While the present invention is particularly adapted for use in annular array type devices, it could also be used in linear or phased array type devices, in which case the electrode pattern which is applied at this step would be different. For purposes of describing the present invention, an annular array electrode pattern is used. Those skilled in the art will recognize that in appropriate situations the present invention can be utilized in order to provide a linear array in which the elements operate in a "bar mode" rather than in the conventional beam mode. Particular advantage can be taken in that bar mode devices experience greater coupling between electrical energy and acoustic energy which can provide advantages in linear arrays or phased arrays.

As hereinbefore described, an annular array ultrasound transducer having individual annular elements which are well matched to provide substantially equal intensity signals at various depths and which have excellent frequency match between elements is constructed. The problems heretofore experienced with annular array transducers have been substantially eliminated. In addition, using the present invention, medical ultrasound transducers can be manufactured in any desirable transducer geometry, such as the annular array described herein, with a uniform vibration mode for all the elements of the transducer.

CLAIMS

1. An improved ultrasonic transducer comprising a piece of piezoelectric material which has been subdivided into subelements smaller than the electrodes attached to said subelements, whereby the vibrational mode of the subelements is determined by their physical shape and dimensions, rather than by the shape or dimensions of the electrode geometry.

2. The improved ultrasonic transducer of Claim 1 wherein the transducer is an annular array transducer and said subelements are separated by saw kerfs which extend substantially, but not completely, through said piezoelectric material.

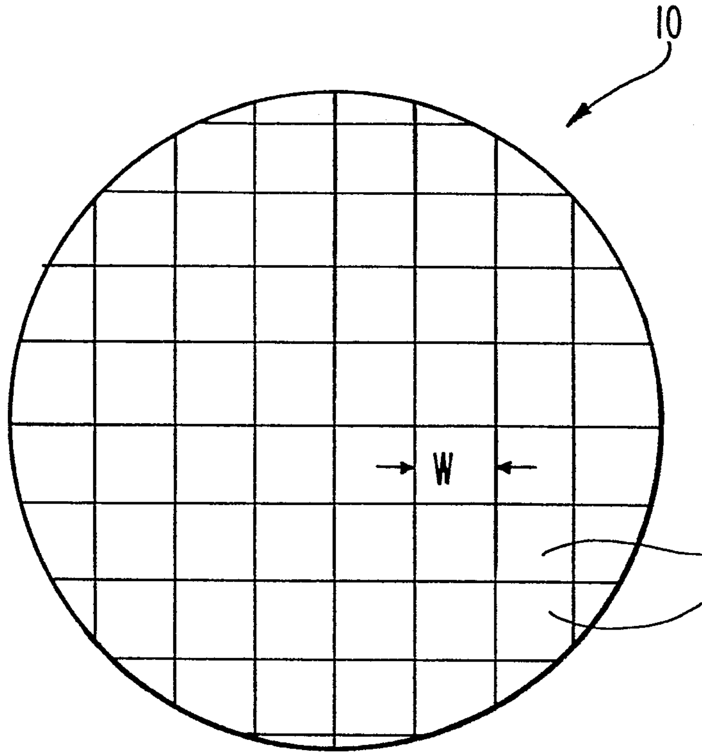
3. The improved ultrasonic transducer of Claim 2 wherein said saw kerfs are filled with a non-conductive material, and the surface of said piezoelectric material and said filler material is covered by a conductive electrode.

4. The improved ultrasonic transducer of Claim 3 wherein said conductive electrode is comprised of a tri-metal system comprising a first metal on the surface of said piezoelectric material, a second metal on the surface of said first metal, and a third metal on the surface of said second metal.

5. The improved ultrasonic transducer of Claim 4 wherein said first metal is chrome, said second metal is nickel, and said third metal is copper.

6. The improved ultrasonic transducer of Claim 1 wherein the transducer is an annular array transducer and said subelements are separated by saw kerfs which extend completely through said piezoelectric material.

Fig. 1



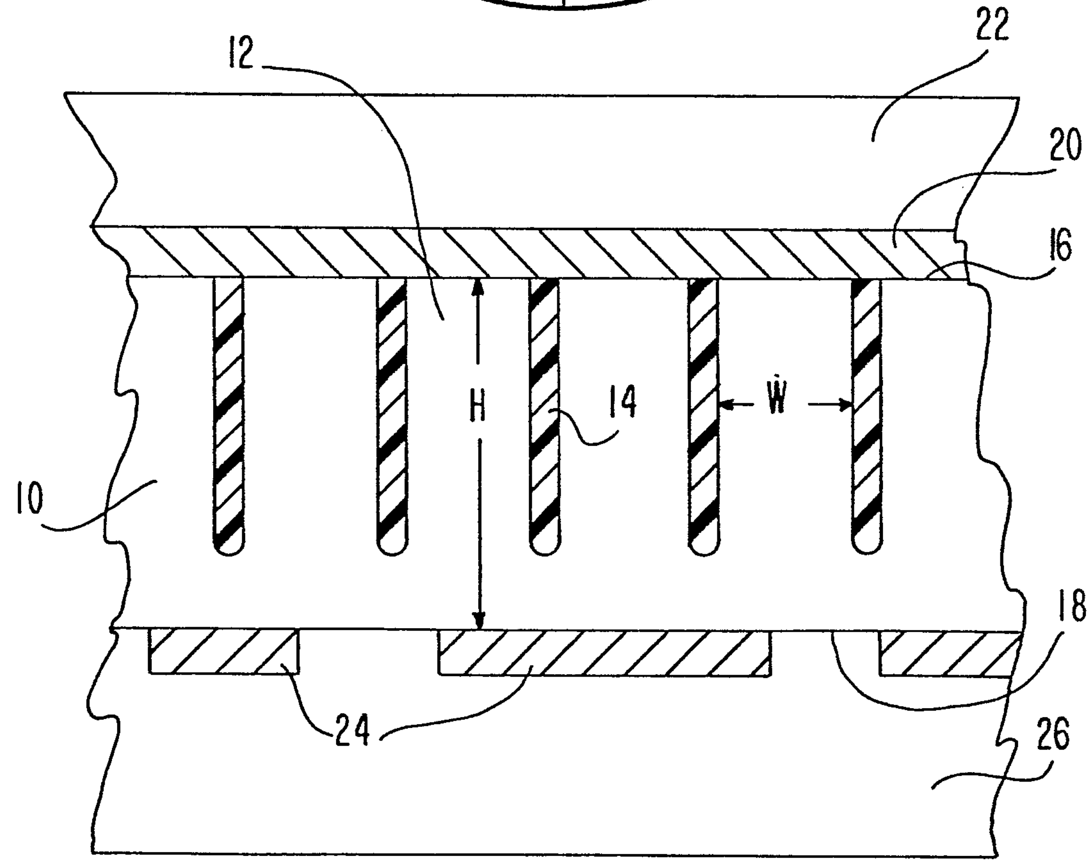


Fig. 2

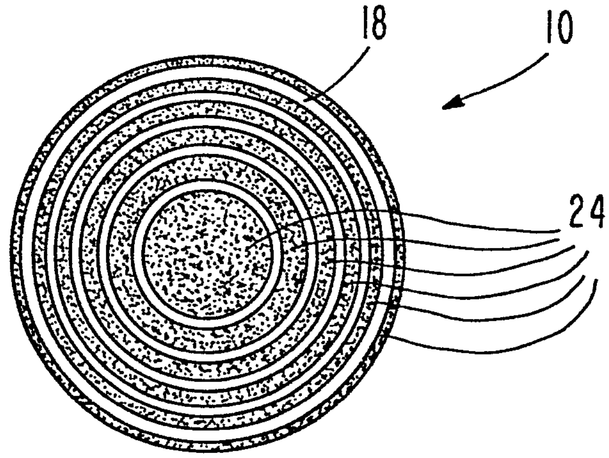


Fig. 3

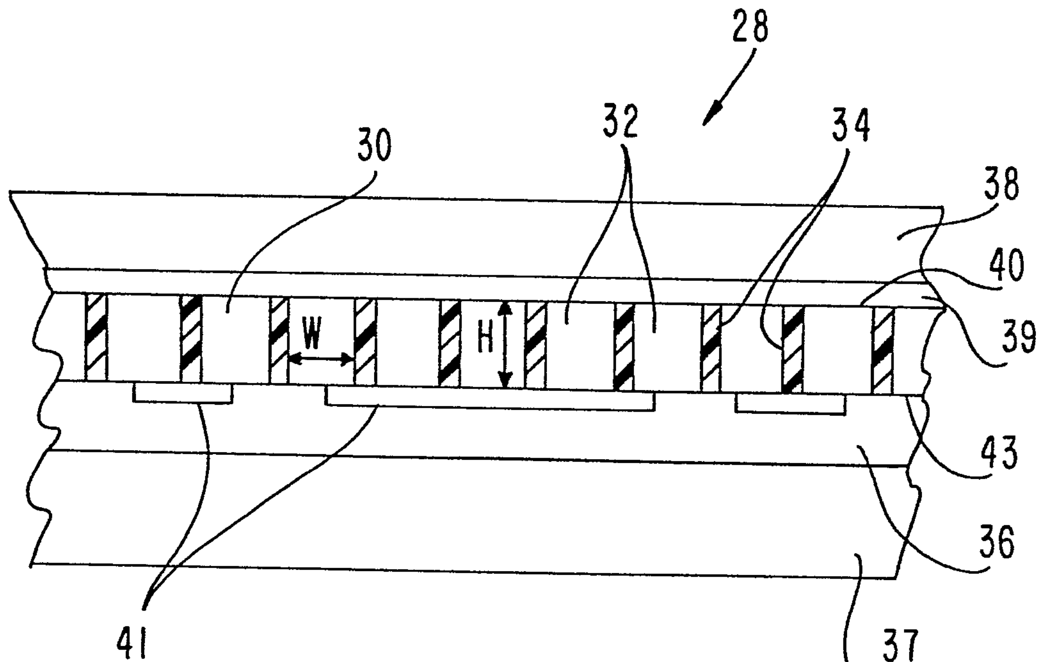


Fig. 4