United States Patent

[11] 3,544,733

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[21] Appl. No. 646,219
[22] Filed June 15, 1967
[45] Patented Dec. 1, 1970
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[54] **ELECTROSTATIC ACOUSTIC TRANSDUCER**
11 Claims, 23 Drawing Figs.

[52] **U.S. Cl.** **179/111**, 29/594
[51] **Int. Cl.** **H04r 19/00**
[50] **Field of Search** 29/594; 179/111; 1/1

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ABSTRACT: A multilayer electrostatic transducer in the form of a pliable unitary structure for use in a fluid atmosphere having alternate relatively thin flexible conductive layers and relatively thin electrically leaky flexible dielectric layers which entrap relatively large bubbles of fluid between each conductive and dielectric layer is shown.

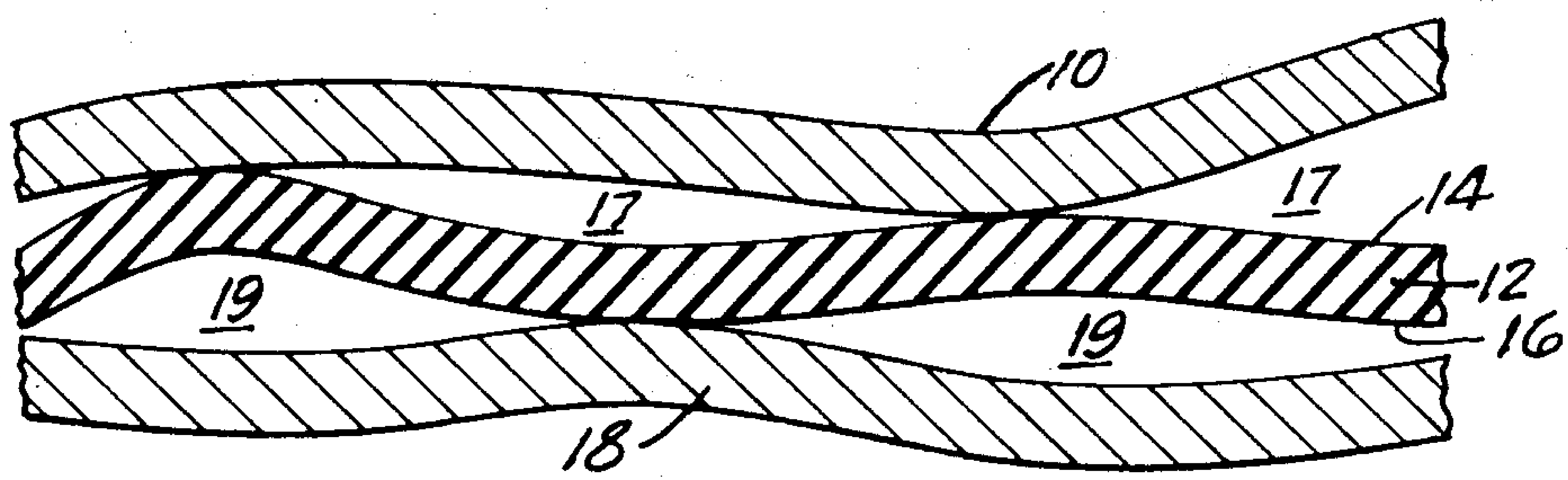

FIG. 1

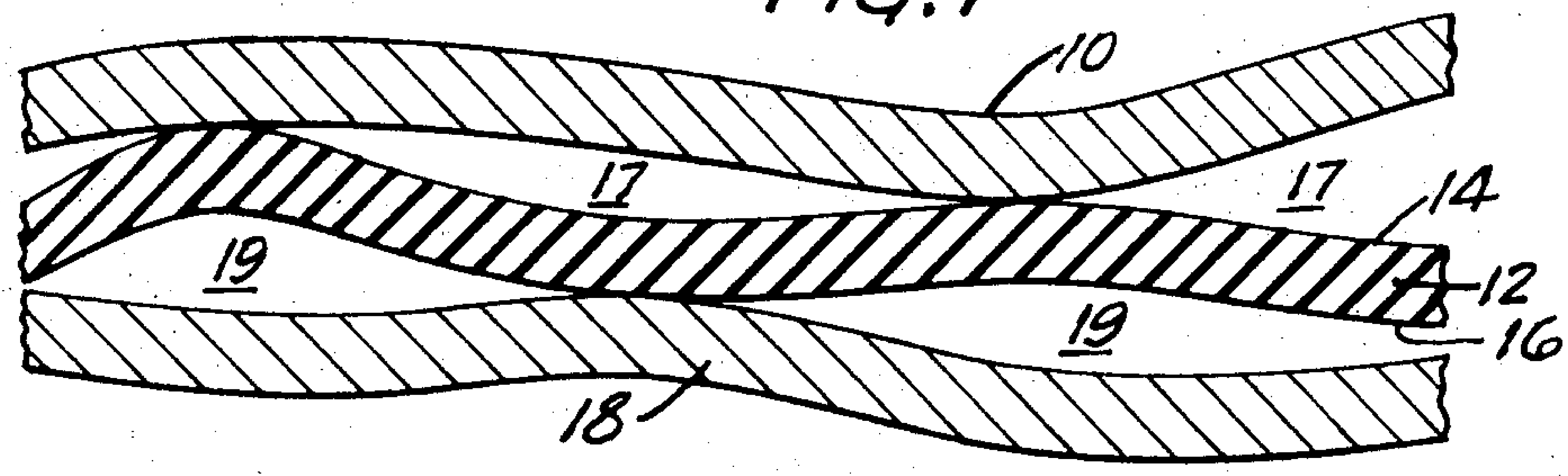

FIG. 2

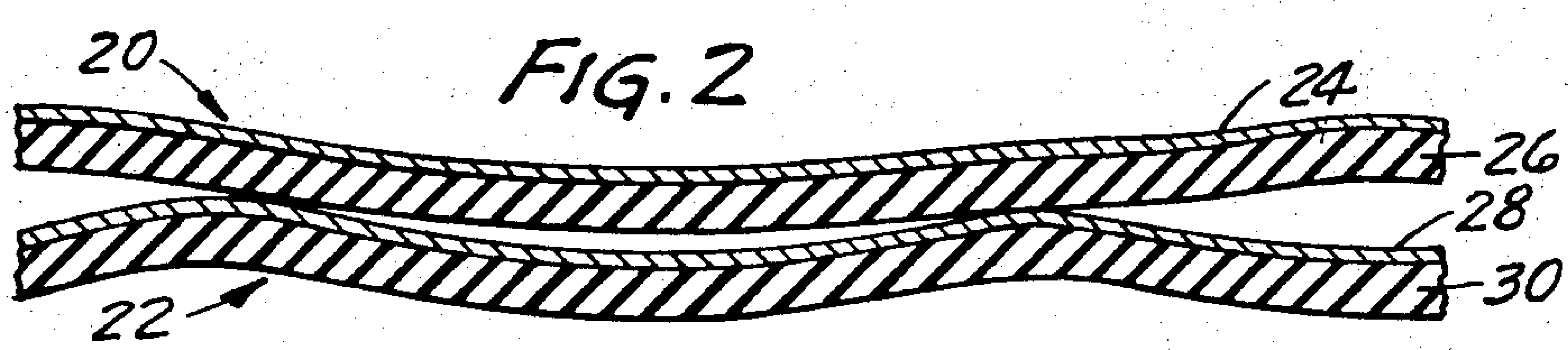

FIG. 3

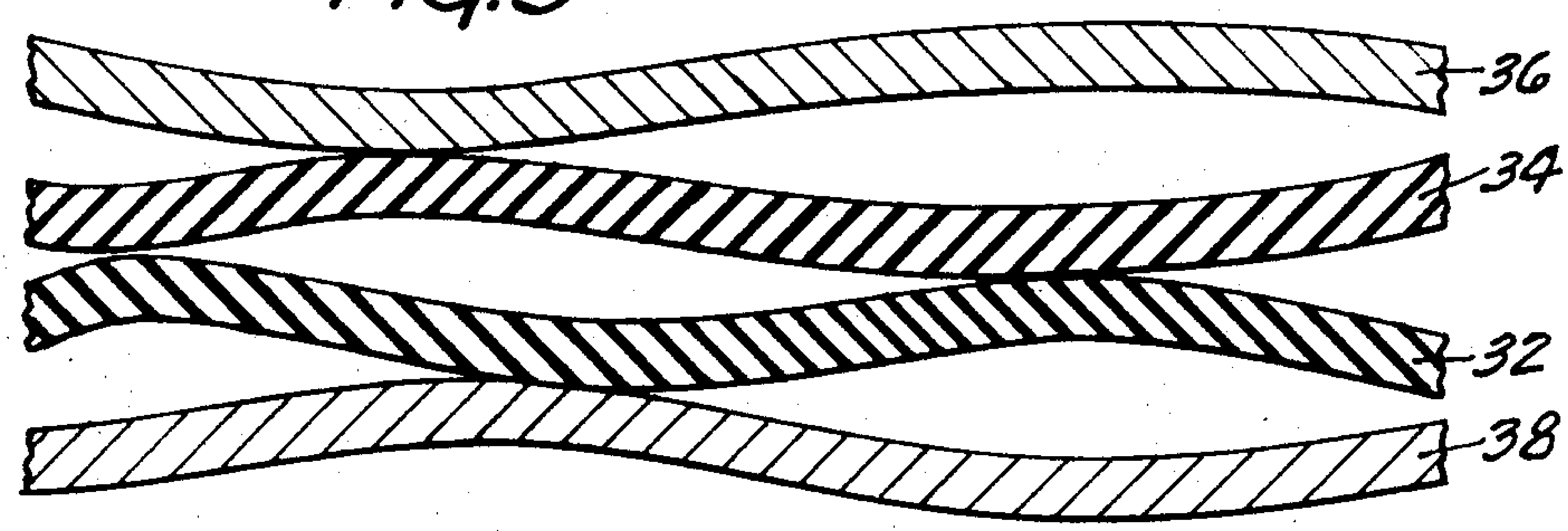

FIG. 4

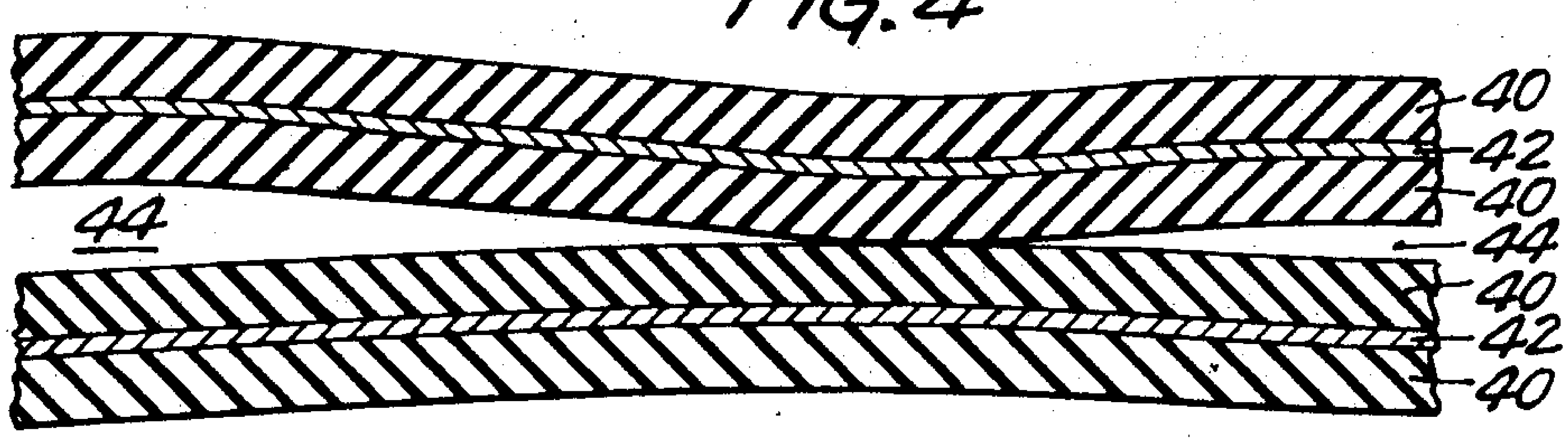

FIG. 5

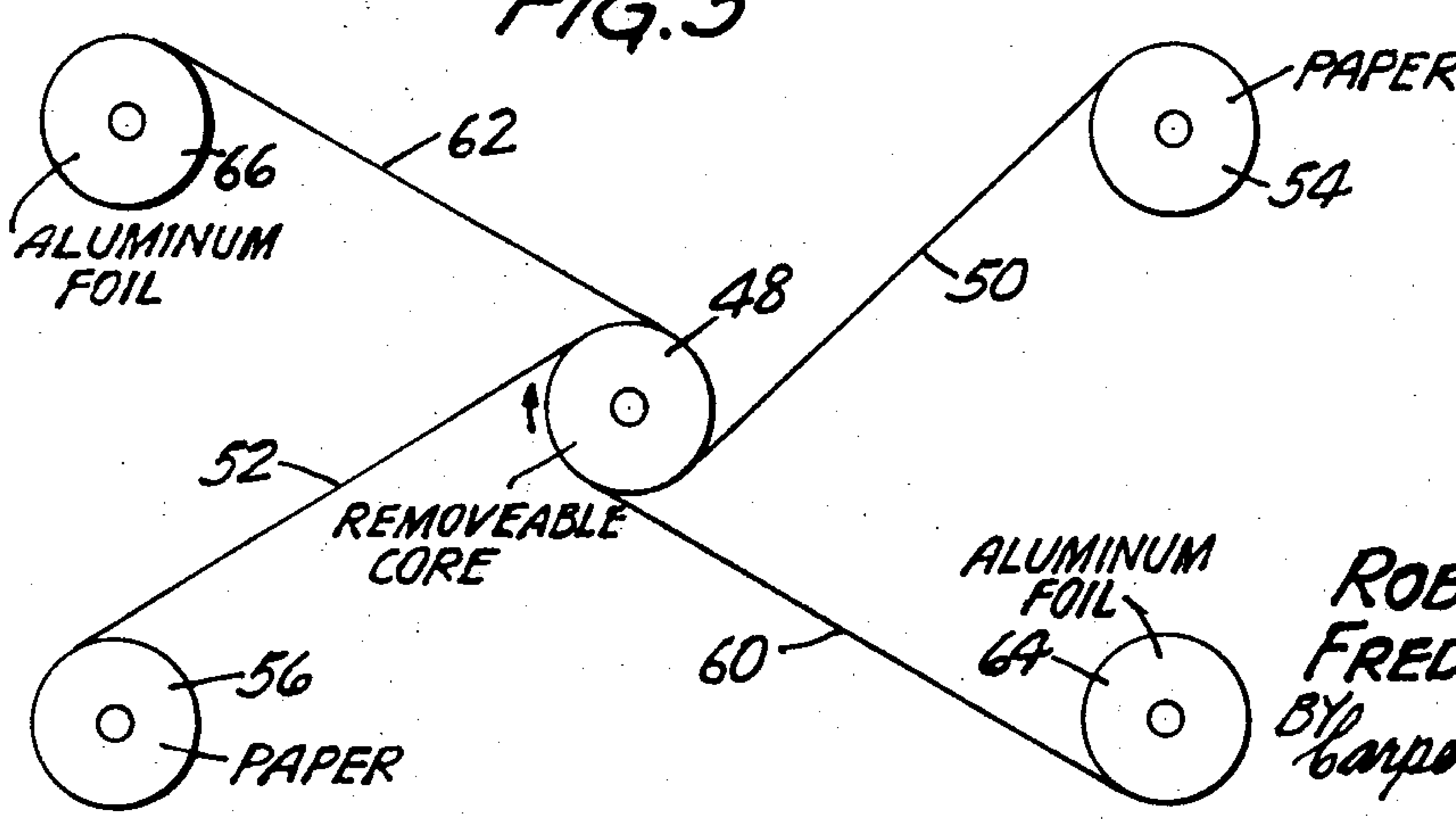

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FIG. 6B

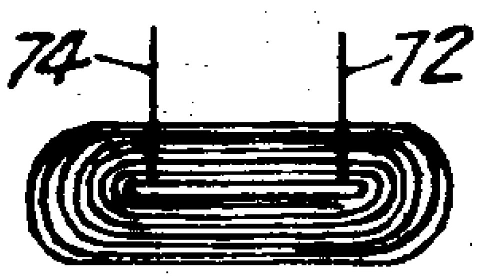

FIG. 7C

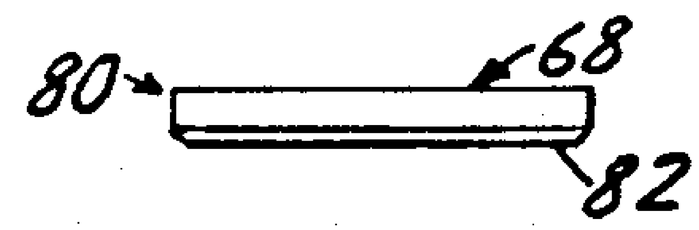

FIG. 8

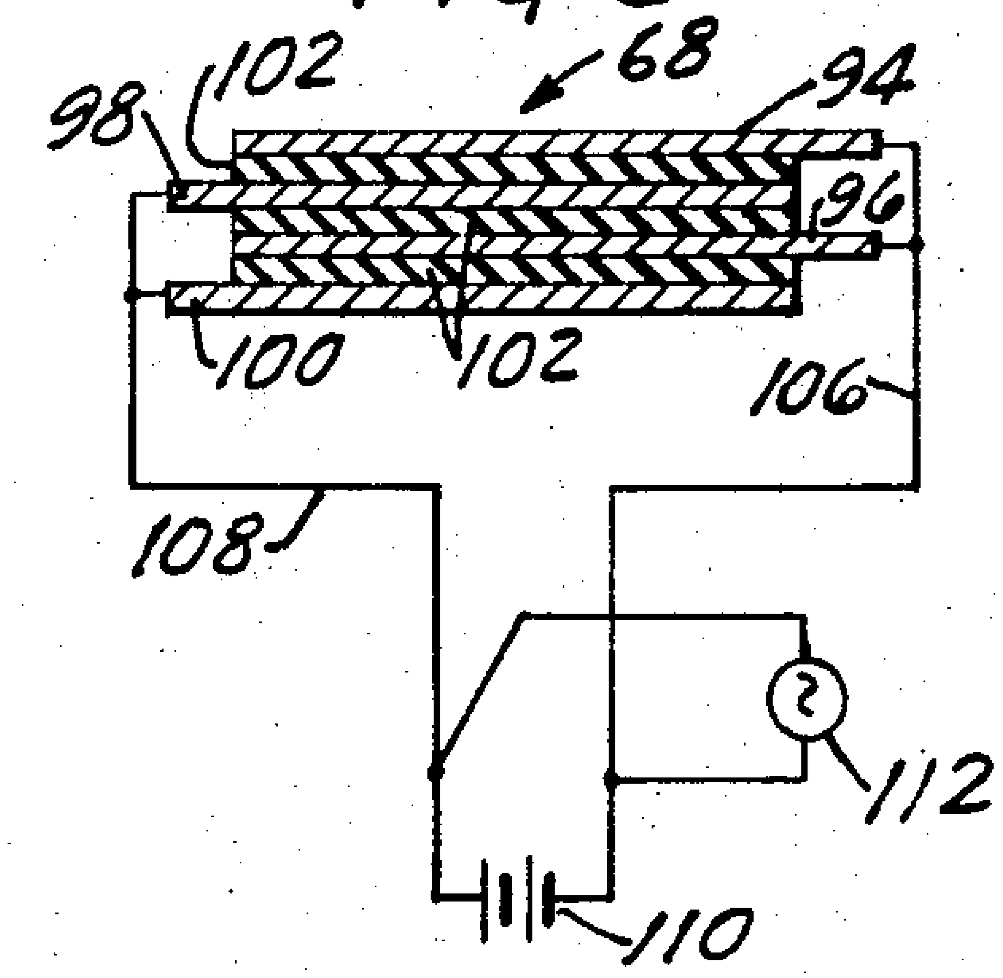

FIG. 6A

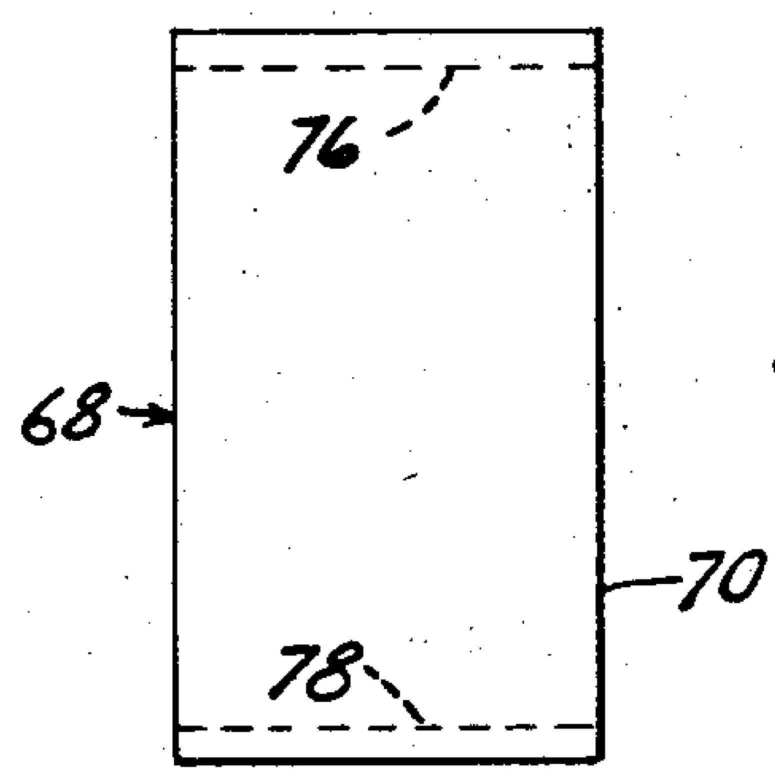

FIG. 7A

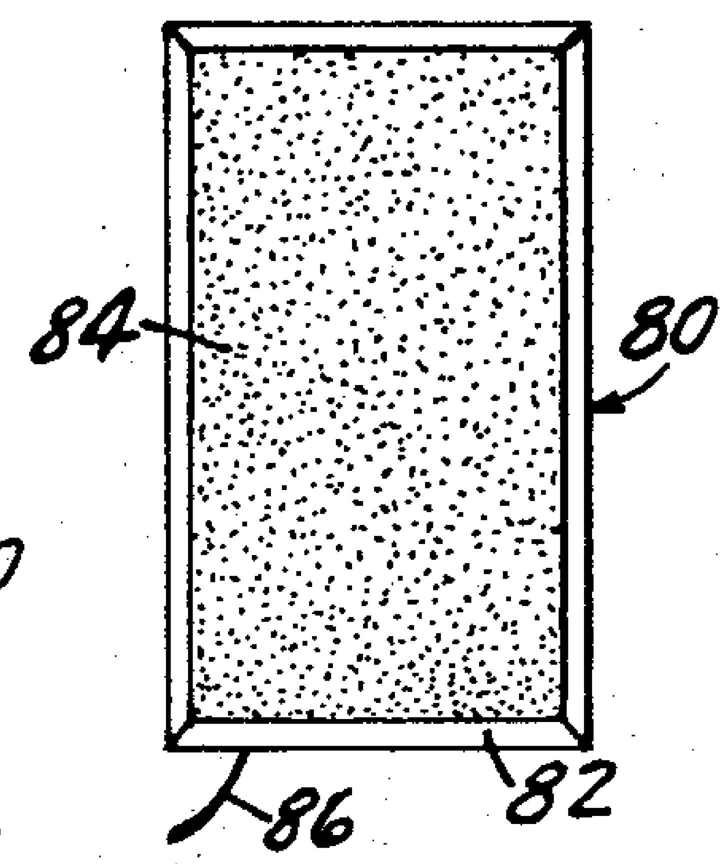

FIG. 7B

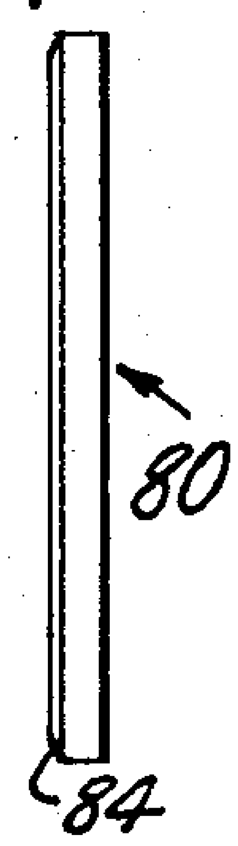

FIG. 9C

FIG. 11

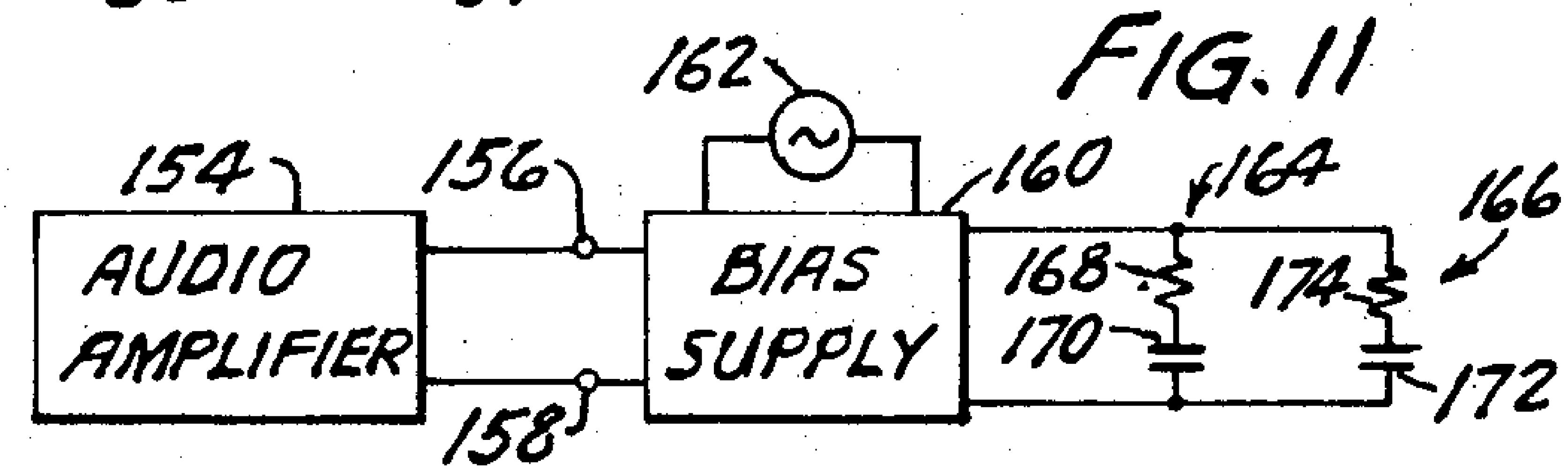

FIG. 9B

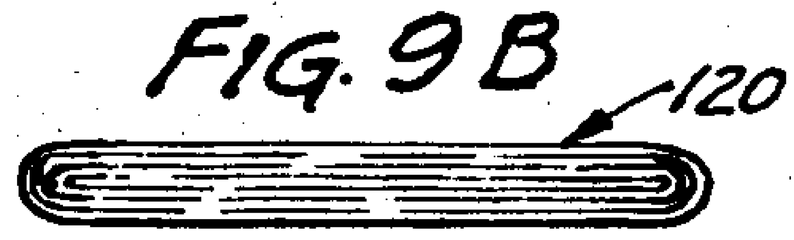

FIG. 9A

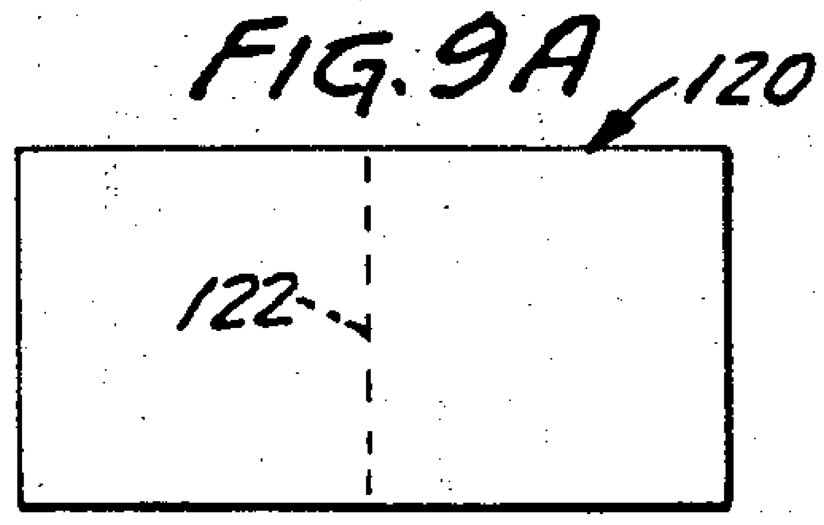

FIG. 12

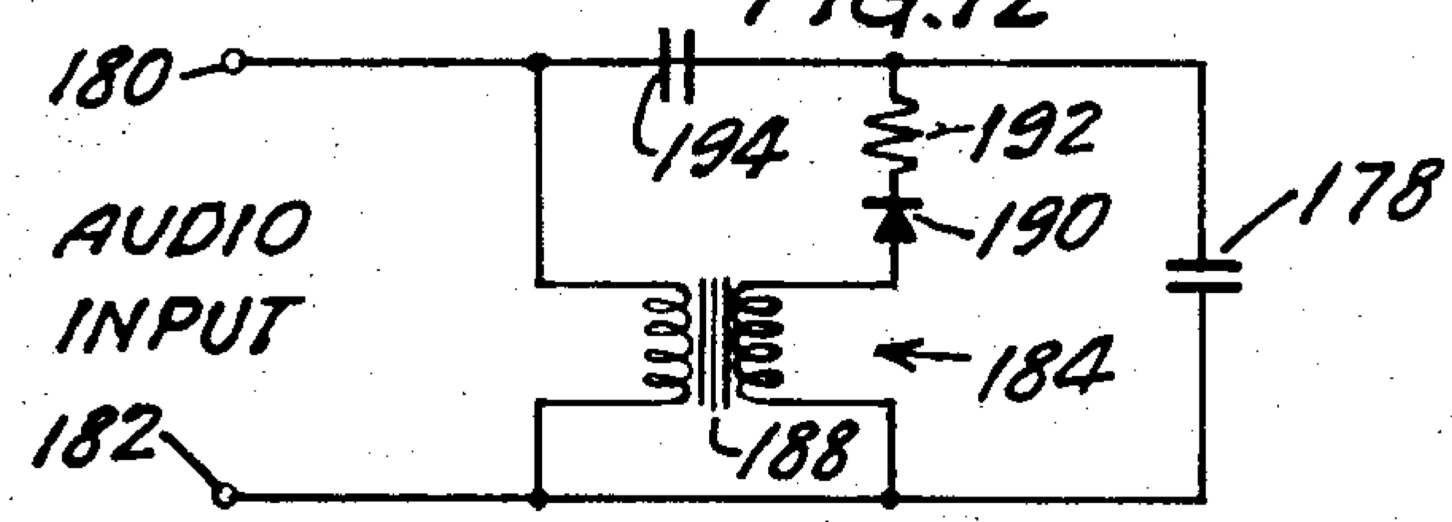

FIG. 10

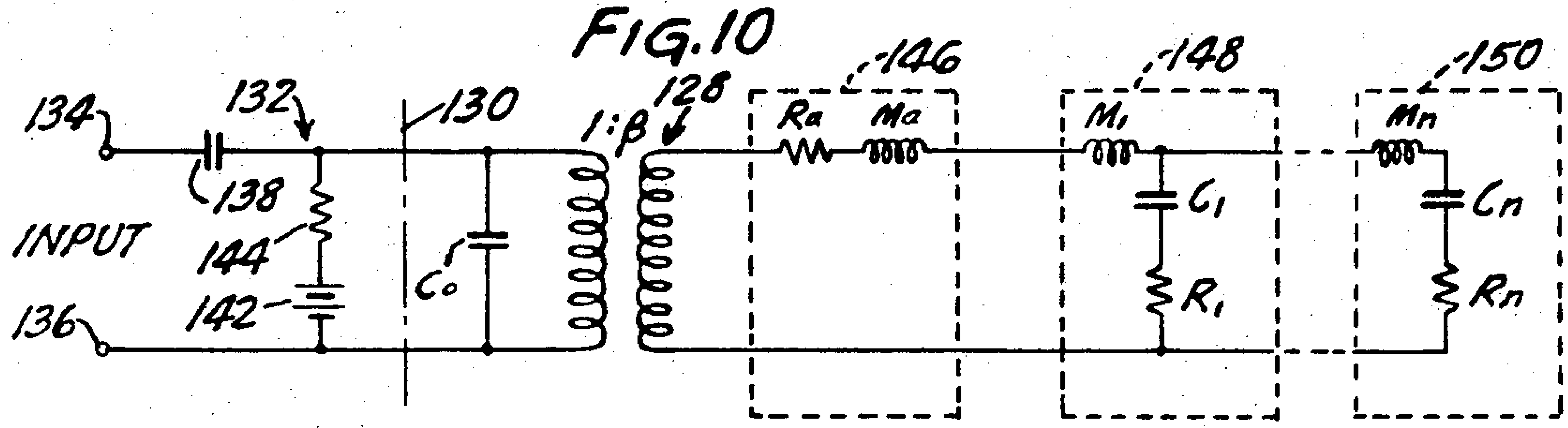

FIG. 16

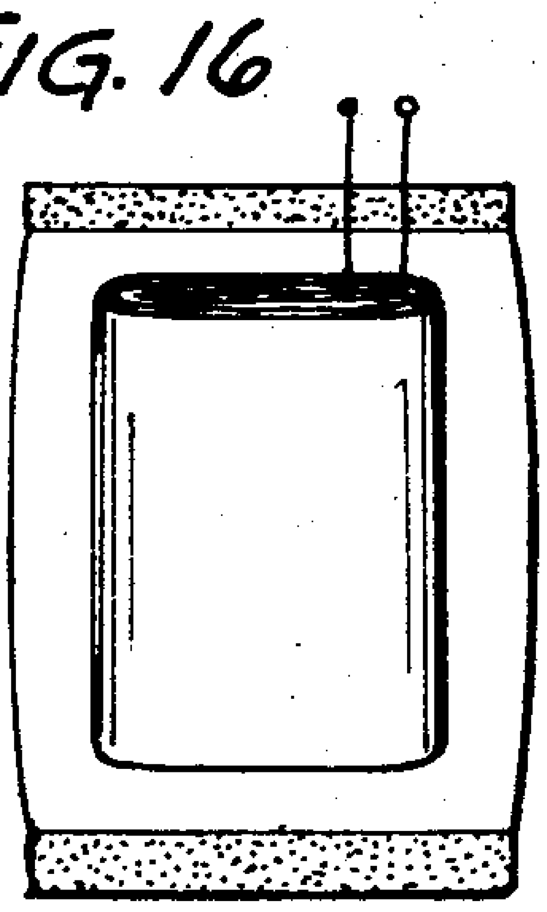

FIG. 15

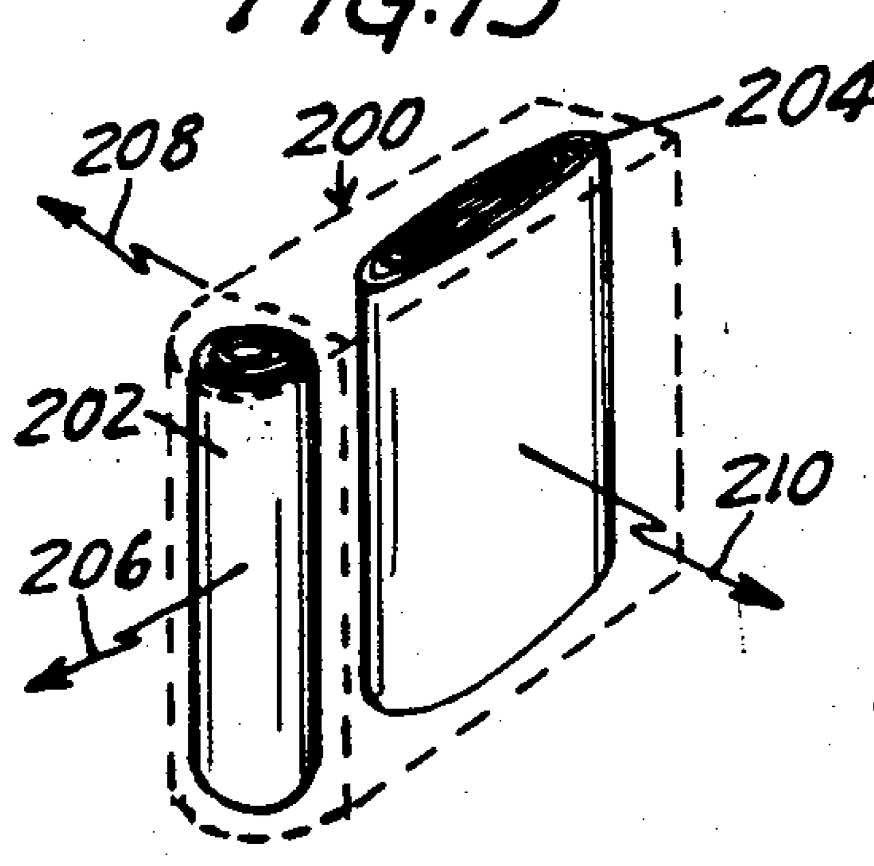

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FIG 13

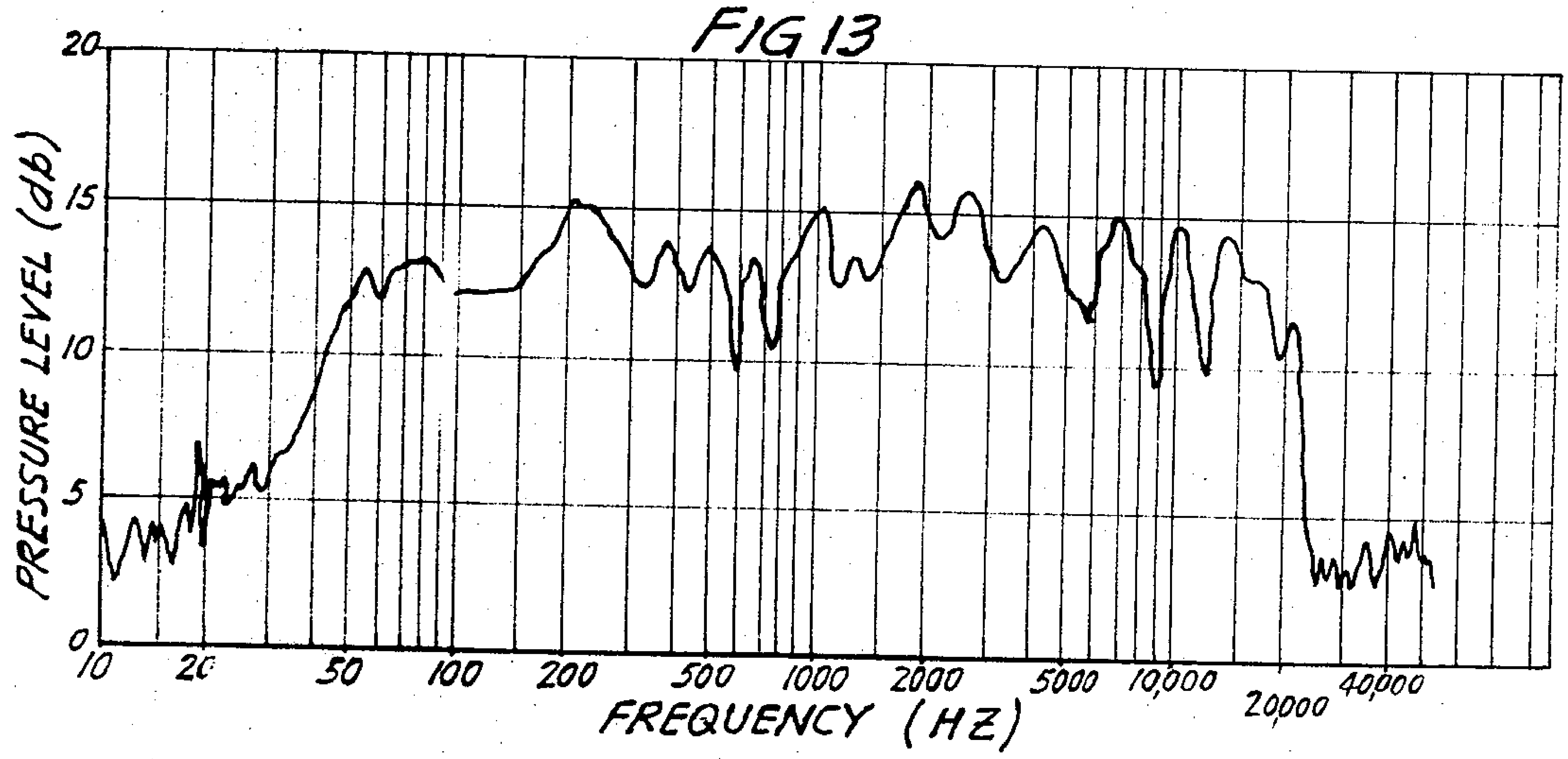


FIG. 14

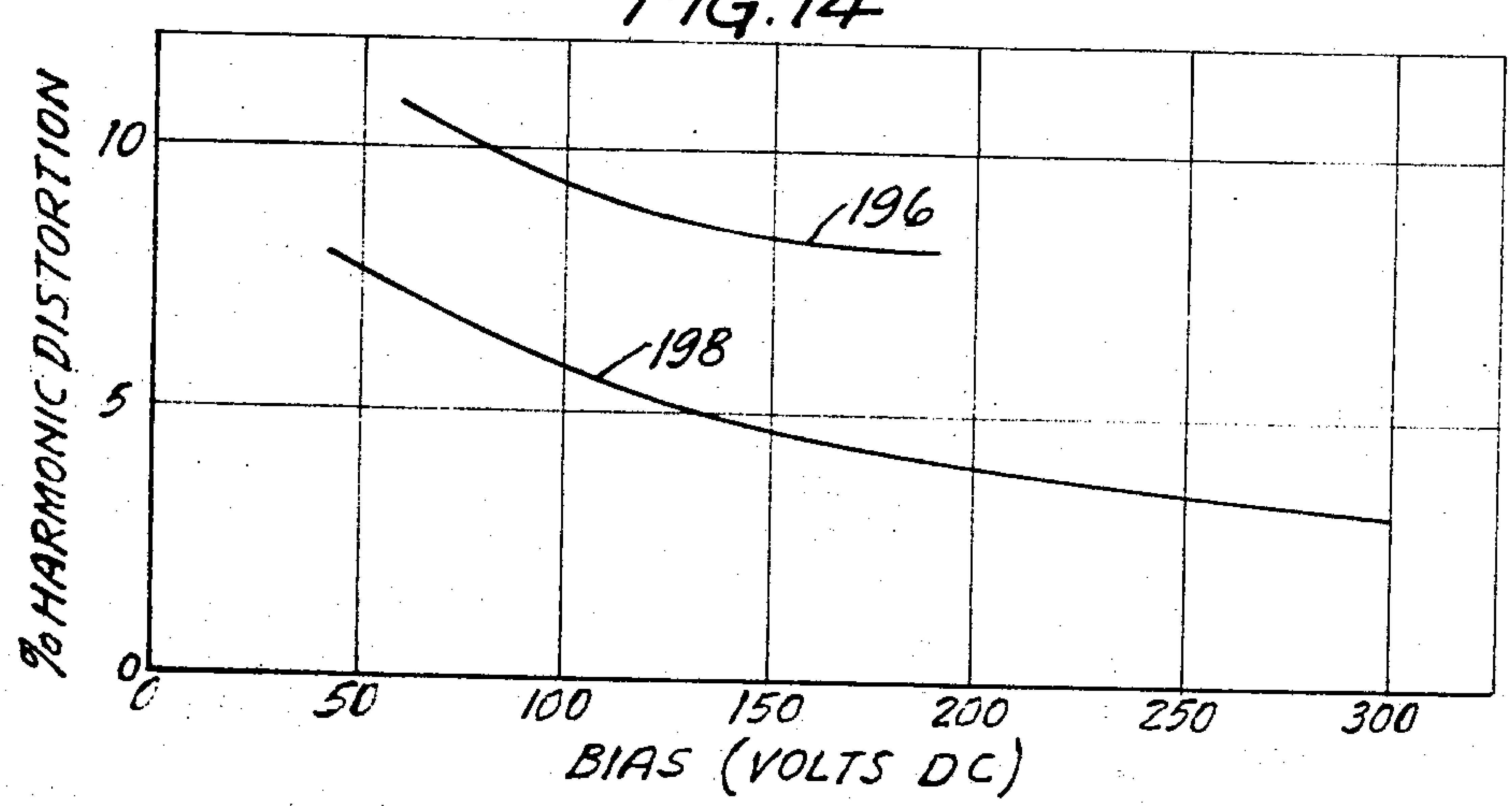


FIG. 18

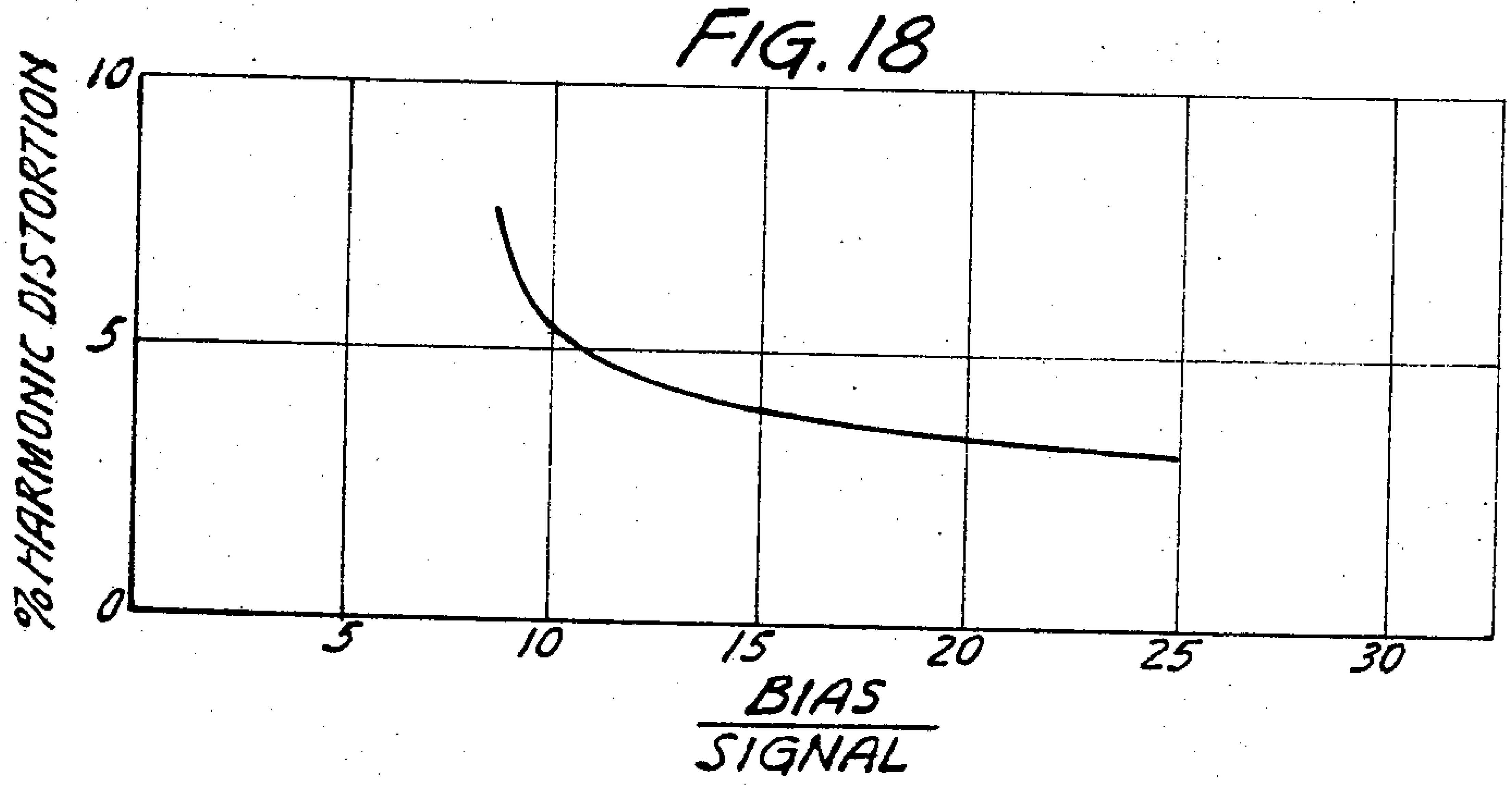
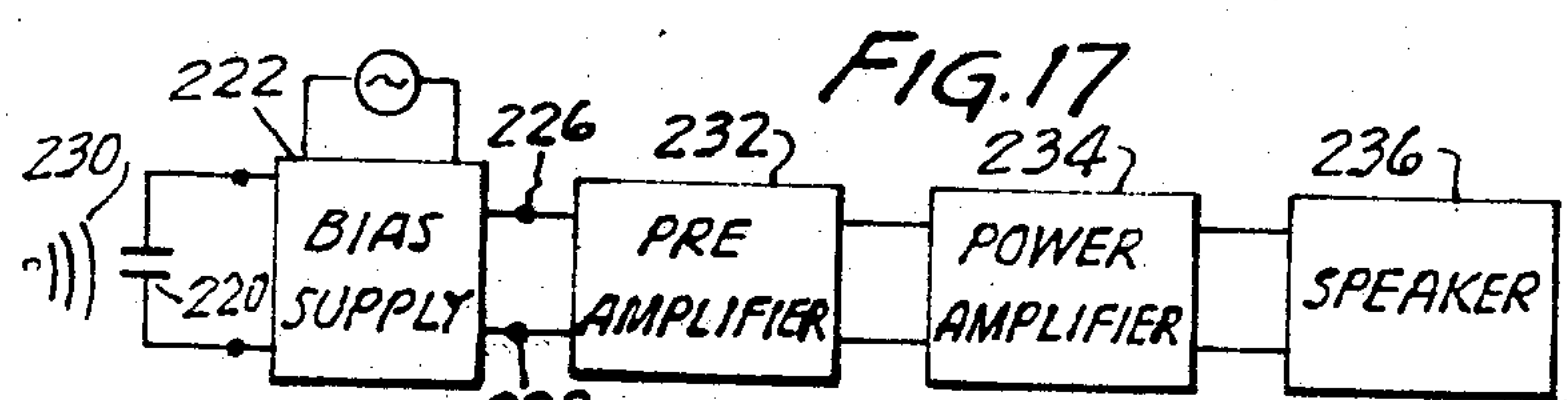


FIG. 17



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ELECTROSTATIC ACOUSTIC TRANSDUCER

Electrostatic transducers for generating a sound wave or an acoustical signal are known, for example U.S. Pat. Nos. 3,118,979,. 2,975,307, 1,978,200 and 1,544,001. These patents typify the known electrostatic acoustical transducers. Such transducers can generally be characterized as devices having a movable nonconductive dielectric material in juxtaposition to a movable conductive material wherein both the dielectric material and movable conductive material vibrate in unison.

In U.S. Pat. Nos. 3,118,979 and 2,975,307, the electrostatic transducers utilize a thin layer of Mylar film as the dielectric material. The Mylar film is spaced from the surface of an adjacent conductive plate or conductive foil by means of staggered and discretely placed spacers or performed dimples forming an air space or air gap of a predetermined and controlled thickness. The conductive foil may or may not be secured in a tensioned relationship.

In the prior art transducers, separate spacers are employed for forming predetermined air gaps for two reasons: first, to permit packing or assembling of the layers together as tightly as possible so as to avoid the entrapment of large air bubbles; and second, to provide an air gap having a thickness such that large signal excursions will not cause the vibrating dielectric material to contact an adjacent conductive foil layer. In these devices, if the dielectric material physically engages the conductive foil, mechanical distortion occurs due to restricting of the vibrating dielectric material. For these reasons, the prior art teaches that the number and placement of points of physical contact between the dielectric material and an adjacent conductive foil is determined as a function of the dielectric vibration amplitude and the fluctuations of the thickness of the air layer due to irregularities in adjacent surfaces. Further, under some circumstances the natural adhesion between Mylar film and an engaged foil causes the Mylar film to stick thereby contributing to the restriction of the vibrating dielectric material.

U.S. Pat. No. 1,978,200 relates to an acoustic device comprising a relatively thick, stiff, corrugated or folded dielectric material, such as rubber, paper or the like, sandwiched between loosely disposed metal foil sheets. This device exhibits electrical characteristics of a low pass filter. The electrical impedance of the device when utilized as a speaker is substantially uniform for all frequencies within the limited audio range of signals which the speaker is to reproduce. The relatively large spacing occurring between adjacent metal foil sheets due to the folded dielectric material requires that a relatively high polarizing potential be applied between the foil sheets to establish an adequate electric field gradient sufficient to drive the dielectric material into vibration.

The transducer of U.S. Pat. No. 1,544,00l requires that the metallic plates be insulated from each other either by an air gap or by comparatively thin sheets of elastic material, such as rubber. In either case, a predetermined spacing between the plates is established without use of a combination air gap and dielectric material. In U.S. Pat No. 1,544,001, the transducer is connected to a movable stylus forming a reproducing device. Comparatively thick sheets of elastic material are arranged in a loosely stacked relationship between each movable metal plate except that the last plate is a rigid plate supporting the stylus. The loosely stacked elastic material is compressed between the plates in response to movement of the rigid plate and stylus. The resilient compressed elastic sheet expands and returns the metallic plates to the uncompressed position as the rigid plate and stylus move into an uncompressed position. Movement of the conductive plates and interposed dielectric sheets in response to the compression and expansion forces varies the capacitance of the reproducing device causing variations in current flowing to a receiver.

The electrostatic transducer of the present invention has several important advantages over the prior art devices including those disclosed in the patents noted above. In the present invention, a multilayer electrostatic transducer is formed from a pliable unitary structure adapted for use in a fluid atmosphere. The transducer has a plurality of relatively thin flexible conductive layers and a plurality of thin flexible electrically leaky dielectric layers alternately distributed between the conductive layers to form a pliable unitary structure.

In one embodiment, the pliable unitary structure has utility as an electrostatic acoustic transducer. In the present invention, the pliable unitary body comprises a plurality of dielectric layers and a plurality of conductive layers, at lease one of which has slight undulations, positioned in a predetermined relationship whereby two conductive layers have at least one dielectric layer sandwiched therebetween. The pliable unitary body entraps, either randomly or nonrandomly, relatively large bubbles of fluid in the slight undulations.

In one embodiment, the dielectric material having slight undulations is placed in releasable engagement with at least one surface of a conductive layer and randomly entraps relatively large bubbles of fluid therebetween. The fluid bubbles are compressed by the conductive layers being brought closer together due to a varying electric field. Compression of the fluid bubbles effectively permits the dielectric layers and the conductive layers sandwiching the dielectric layers to vibrate in unison such that the vibrations are mechanically additive.

The teachings of the present invention provide a surprising and unexpected result when considered in light of the prior art transducers and teachings. Notably, the electrostatic transducers of the prior art having attempted to uniformly space the dielectric layers from the conductive layer. The present invention does not require a predetermined and controlled uniform air space or air gap between the conductive material and the dielectric material, either or both of which may have slight undulations. Elimination of a uniform air gap permits the conductive layers to be urged into intimate contact at a plurality of separate physical points with the relatively thin flexible electrically leaky dielectric layers. Also, use of an electrically leaky dielectric material in a multilayer transducer is novel and unique. Further, since the dielectric material and conductive material are both relatively thin, the electrostatic transducer of the present invention provides a means for constructing a relatively thin, compact, acoustical transducer. The transducer structure can be formed into any desired shape, such as a planar or curved shaped transducer, without significantly affecting the electrical or operational characteristics of the transducer. One other advantage of the present invention is that an electrostatic transducer having good low frequency response and a small physical dimensions relative to prior art transducers can be constructed.

Therefore, one advantage of the present invention is that an electrostatic transducer can be constructed which is relatively compact in physical size.

Another advantage of the present invention is that the conductive layers which form the electrodes need not be constrained, such as for example in tension, thereby permitting any desired layer geometry without requiring a predetermined and uniform air gap between the conductive layers and dielectric layers.

An additional advantage of the present invention is that a relatively low magnitude direct current voltage can be used for biasing the transducer thereby eliminating a high biasing voltage.

Yet another advantage of the present invention is that an electrostatic transducer loudspeaker having extremely good frequency response over the audio range of frequencies which it is to reproduce can be constructed using at least two electrostatic transducers. In one electrostatic acoustic loudspeaker, the frequency response was relatively flat within ±5 db from about 50 to about about 20,000 hertz.

Another advantage of the present invention is that the electrostatic transducer can be used either as a microphone or a loudspeaker.

A further advantage is that an electrostatic acoustic transducer of the present invention can be constructed by a simple winding process or alternatively by a stacking or folding process.

An additional advantage of the present invention is that a transducing system having good frequency response, a low voltage biasing potential and low distortion characteristics can be constructed in accordance with the teachings of the present invention.

These and other advantages of the present invention become apparent by reference to the following description of one embodiment and by reference to the attached drawing wherein:

FIG. 1 is a diagrammatic exploded cross-sectional view of an incremental transducer section wherein one dielectric layer is sandwiched between two conductive layers;

FIG. 2 is a diagrammatic exploded cross-sectional view of an incremental transducer section wherein a conductive layer is vacuum-metallized onto a dielectric layer;

FIG. 3 is a diagrammatic exploded cross-sectional view of an incremental transducer section of the present invention wherein two dielectric layers are sandwiched between two conductive layers;

FIG. 4 is a diagrammatic exploded cross-sectional view of an incremental transducer section of the present invention using composite layers comprising a laminate of dielectric layer-conductive layer-dielectric layer;

FIG. 5 is a pictorial representation of a method of winding an electrostatic transducer having only two dielectric strips;

FIGS. 6A and 6B are diagrammatic front and top views of an electrostatic transducer made in accordance with the method illustrated in FIG. 5;

FIGS. 7A, 7B and 7C are pictorial representations of the transducer of FIG. 6B fabricated into a thin, picture frame loudspeaker;

Fig. FIG. 8 is a pictorial representation of a multilayer transducer illustrating electrical connections for the conductive layers;

FIGS. 9A, 9B and 9C are pictorial representations of another embodiment of the present invention wherein an electrostatic transducer is folded into a compact loudspeaker;

FIG. 10 is a schematic diagram representing by means of an analogous electrical circuit the electrical properties of an electrostatic transducer;

FIG. 11 is a schematic diagram of an electrostatic loudspeaker having a low frequency transducer and a high frequency transducer operatively connected by a crossover network and driven from a conventional audio amplifier;

FIG. 12 is a schematic diagram illustrating a circuit for developing a biasing voltage by rectifying an electrical signal containing an audio frequency signal which is concurrently driving the electrostatic transducer;

FIG. 13 is a graph illustrating the frequency response of one embodiment of this invention obtained by plotting sound pressure level in decibels as a function of frequency;

FIG. 14 is a graph illustrating for one embodiment the relationship between the ratio of bias voltage to modulated voltage and the percent distortion for a particular frequency;

FIG. 15 is a pictorial representation of a book-type speaker;

FIG. 16 is a pictorial representation of an electrostatic transducer packaged in a heat-sealed package having an fluid atmosphere and adapted for use as an underwater microphone;

FIG. 17 is a block diagram of a typical reproducing system using an electrostatic transducer of the present invention as a microphone; and

FIG. 18 is a graph illustrating percent harmonic distortion plotted as a function of the ratio of bias voltage to signal voltage for an electrostatic speaker having a zinc conductive layer vapor-coated onto a dielectric layer.

Briefly, the multilayer electrostatic transducer of the present invention is in the form of a pliable unitary structure for use in a fluid atmosphere. The transducer comprises a plurality of superimposed relatively thin flexible conductive layers. Alternate conductive layers are electrically connected to a first terminal and the other conductive layers are electrically common to a second terminal to provide first and second electrodes of an electrostatic transducer. At least one relatively thin flexible electrically leaky dielectric layer is disposed between and separates adjacent conductive layers. Adjacent layers are in contact with each other to form a pliable, unitary, multilayer structure in which lateral movement of the layers is constrained. At least one of either the conductive or dielectric layers has slight undulations and a compressible fluid is disposed between the conductive and dielectric layers and entrapped between opposing surfaces of the undulating layer and contiguous layers as a large number of fluid bubbles. The compressible fluid permits movement of the layers normal to their contiguous surfaces in response to changes in the potential difference between the first and second electrostatic transducer electrodes.

FIG. 1 is a pictorial representation of an exploded cross-sectional view of a section of one embodiment of an electrostatic transducer. In this embodiment, a first relatively thin flexible conductive layer **10** having at least one surface, such as its inner surface, is utilized as one conductive electrode of the electrostatic transducer. Positioned adjacent the conductive layer **10** is a relatively thin flexible electrically leaky dielectric material or layer **12**, which layer has slight undulations. In this example of FIG. 1, both the conductive layers and dielectric layers are illustrated as containing slight undulations. Also, the surfaces of both the dielectric layer and conductive layers are of normal roughness or have normal surface irregularities for such materials. It is contemplated that either the dielectric material or conductive material only may have the undulations. But in any event, at least one of the two materials, or both, has undulations in which fluid bubbles can be entrapped.

In FIG. 1, the layer **12** is depicted to have two surfaces **14** and **16**. The electrically leaky dielectric material should be selected to ideally have a low volume resistivity, say in the range of about 10^8 to about 10^{14} ohm-cm and preselected dielectric constant. In one embodiment, a dielectric constant in the range of about 2 to 3 was utilized, but it is desirable and contemplated to have the dielectric constant as high as possible. Mylar film, having a high resistivity in the order of 10^{18} ohm-cm, cannot be used in the present invention

However, it is anticipated that Mylar film, polyethylene, polypropylene and the like could be used as the electrically leaky dielectric material if the ratio of surface resistivity-to-volume resistivity is made sufficiently large thereby providing a dielectric material having acceptable characteristics noted above. The ratio of surface resistance (sometimes referred to as insulation resistance) to the resistance derived directly from the thickness of the dielectric material can be improved by the following techniques. The surface resistance can be increased, e.g. cleaning the surface, the resistance derived directly from the dielectric material thickness can be decreased by reducing the material thickness or the resistivity of the dielectric material can be changed by selectively doping or by the addition of a conductive material to the dielectric material.

The dielectric layer **12** has a surface area and geometry substantially the same as the first conductive layer **10** and is positioned to have one of its surfaces having slight undulations, for example surface **14**, in releasable engagement with at least one of the generally planar surfaces of the conductive layer **10**. The surface **14** and the inner surface of conductive layer **10** entrap therebetween relatively large bubbles of fluid, such as for example air **17**. In a preferred embodiment, the fluid bubbles are randomly entrapped between the conductive layer surface and the dielectric layer surface.

A second relatively thin flexible conductive layer **18** having a surface area and geometry substantially the same as that of the first conductive layer **10** is positioned to have one surface thereof in releasable engagement with the other surface **16** of dielectric layer **12**. The surface **16** and the inner surface of conductive layer **18** similarly entrap therebetween in the slight undulations relatively large bubbles of fluid **19**. When multilayers of both dielectric layers interposed between conductive layers are loosely stacked together, or alternatively wound together, the dielectric layer is loosely sandwiched between a first and second conductive layer in a manner similar to dielectric layer **12** being sandwiched between conductive layers **10** and **18**.

The above example of FIG. **1** illustrates the use of solid conductive sheets and solid dielectric sheets. However, it is contemplated and anticipated that several modifications may be made to increase the efficiency of the transducer. For example, the conductive metal sheets may be spaced strips or the dielectric material may be perforated. In any event, by using such techniques either in this example or the other examples disclosed herein, a more efficient transducer can be constructed using the teachings of this invention.

A potential gradient is established between the conductive layers **10** and **18** to produce the desired electric field. The electric field causes the pliable unitary structure to contract resulting in an overall decrease in thickness which is obtained by the conductive layers **10** and **18** compressing the entrapped fluid bubbles between the dielectric layer **12** and conductive layer **10** and the dielectric layer **12** and conductive layer **18**. In any event, it appears that the magnitude of a direct current biasing voltage must be less that the breakdown voltage or potential of the dielectric medium and fluid layer. Typical values for conductive layers, for dielectric layers and diameters of fluid bubbles would be in the order of .00025 inch (about 10μ). Also, the diameter of the fluid bubbles, may be either greater than or less than the thickness of the dielectric layer.

The conductive foil layer alternatively could be vacuum-metallized onto one surface of the dielectric layer forming composite layers, such as for example composite layers of FIG. 2. Composite layer **20** comprises a metallic layer **24** deposited onto a dielectric material or layer **26**. Composite layer **22** has a metallic layer **28** deposited onto a dielectric layer **30**. When the pliable unitary structure is assembled, the uncoated dielectric surface having slight undulations cooperates with the metallic surface to entrap bubbles of fluid therebetween.

Other obvious and known variations of metal layers and dielectric layers resulting in a composition similar to FIG. 2 may be used in practicing this invention. For example, the dielectric material could be a porous foam having the necessary electrical properties and the thin conductive foil could be a metal vapor-coated onto one surface thereof.

FIG. **3** is a pictorial representation of yet another embodiment of an electrostatic transducer wherein two dielectric layers **32** and **34** are sandwiched between two conductive layers **36** and **38**. In this arrangement, dielectric layers **32** and **34** entrap relatively large bubbles of fluid therebetween. The addition of an extra dielectric layer between each conductive layer adds an additional stratum of bubbles. Additionally, the characteristics of the transducer are changed, such as for example the frequency response and the magnitude of the biasing voltages required for acceptable transducer operation.

FIG. **4** is a pictorial representation of another embodiment of an electrostatic transducer wherein two composite layers are used to form a pliable unitary structure. Each composite layer comprises a thin conductive layer **42** having laminated on each surface thereof a dielectric layer **40**. Importantly, at least one of the composite layers has slight undulations to permit entrapment of fluid bubbles between contiguous surfaces of the two composite layers.

Typical combinations which may be used in making the composite layer illustrated in FIG. **4** may be, for example, a paper-foil-paper laminate or a polymer-foil-polymer laminate. The paper or polymer used as the dielectric material would have the necessary electrical properties as described herein. For purposes of example, one polyurethane dielectric material may be made by combining a polyurethane resin sold by the B. F. Goodrich Company under the trade name "Estane" identified as 05740-2 with a vinyl chloride vinyl acetate copolymer resin sold by the B. F. Goodrich Company under the trade name "Geon" identified as 0427. One useful ratio of resins may comprise two-thirds of "Estane" to one-third of "-Geon". The dielectric constant of the dielectric material may be raised by adding barium titanate to the resin in a ratio of 2.4 barium titanate by weight to 1 by weight of resin comprising two-thirds "Estane" and one-third "Geon." The dielectric material may be laminated in a layer having a thickness of about .0004 inch (about 15μ) using known techniques onto each surface of an aluminum foil about .00025 inch (about 10μ) in thickness.

FIG. **5** illustrates one method for constructing or assembling an electrostatic transducer to produce a device illustrated in FIG. **1**. A removable support, such as for example a removable or collapsible core **48** in the form of a cylinder having an outer surface about which the various layers are wound, is used as a mandrel or spindle. Alternately, the mandrel could be in the form of a bifurcated member or a forked mandrel.

In this method, dielectric materials, for example paper **50** and **52**, are unwound from separate supply rolls, for example paper supply rolls **54** and **56** respectively. The leading ends of dielectric material **50** and of dielectric material **52** are releasably secured in opposed alined positions on the outer surface of core **48**. Conductive layer, such as for example thin aluminum foil **60** and **62**, are unwound from foil supply rolls **64** and **66** respectively. The leading ends of foil **60** and **62** respectively are releasably secured in opposed alined relationship on the outer periphery of core **48**. Concurrently, each foil end is arranged to overlap and be brought into intimate contact with the surface of its adjacent dielectric layer. For example, the leading end of foil **60** is secured such that it is substantially parallel to that of paper **50**. Upon movement of the core **48** in a clockwise direction, foil **60** comes into intimate engagement with paper **50** on one side thereof and paper **59** on the other side thereof.

In a similar manner, the leading end of foil **62** is releasably secured to the periphery of core **48** in alignment with the leading end of paper **62**. Also, the end of foil **62** is positioned such that it overlaps the end of paper **52**. As the core **48** is rotated in the clockwise direction, foil **62** comes into intimate contact first with paper **52** and then into contact with paper **50**.

Alternatively, the core **48** could be held stationary and the foil and paper could be wound around the core. Also, it is envisioned that the core **48** could be rotated in one direction while the foil and paper concurrently are wound in the opposite direction about the rotating core **48**.

By using the above described winding method, a transducer having two strata of air bubbles between conductive layers, such as illustrated in FIG. **1**, is formed. Use of the above winding process where two dielectric layers are between adjacent conductive layers results in a transducer having three strata of air bubbles, as illustrated in FIG. **3**. If the process is used to wind two strips of dielectric material each having metalized foil deposited thereon, the resulting transducer has only one stratum of air bubbles as shown in FIG. **2**.

Referring again to FIG. **5**, after the predetermined number of layers have been wound, the removable core **48** is withdrawn from the wound unitary structure and the structure is physically deformed into a generally planar rectangular shape as illustrated in FIGS. **6A** and **6B**. In this example, the axial length of the wound transducer exceeds the length of the major axis of the resulting elliptically shaped end. Spacing between metal foils and average air gap thickness seems to depend on the stiffness of the material, weight of the transducer and tension during winding.

In FIG. **6A**, the wound unitary structure **68** is constructed such that the last outer layer **70** is a dielectric layer or paper. This is done for safety reasons, viz. to prevent a person from receiving a shock if he inadvertently contacts an outer layer comprising a conductive foil. FIG. **6B** illustrates that the collapsed transducer has an elliptically shaped end. However, the transducer is in the form of a pliable unitary structure wherein each dielectric layer of paper is sandwiched between two conductive layers.

Every other conductive layer is electrically connected together by a first lead **72**. Similarly, the remaining conductive layers are electrically terminated by a second lead **74**. A direct current biasing voltage is impressed between leads **72** and **74**. The unitary structure responds to the biasing voltage by contracting as described.

An electrical signal containing audio frequency information may be impressed across leads **72** and **74**. This electrical signal modulates the biasing voltage by varying the electric field between adjacent conductive layers causing the dielectric layers of paper and foil to vibrate in unison and produce a sound wave having a frequency in the audio range. The frequency of vibration is determined by the audio frequency information within the electrical signal.

The wound unitary structure forming the electrostatic transducer illustrated in FIGS. **6A** and **6B** can be packaged for use as a loudspeaker in a variety of ways and shapes. For example, the wound unitary structure **68** can be attached to a generally rectangular picture frame illustrated in FIGS. **7A**, **7B** and **7C**. The picture frame loudspeaker is designated as **80** has a decorative border **82** formed around the periphery thereof. The picture frame **80** has a decorative fabric, say for example a grid cloth **84** or a light, relatively thin, nonporous material which may or may not have a pictorial representation thereon, thereby truly giving the appearance of a framed picture. Typical exterior dimensions would be about a 10-inch (about 25 cm.) width, about a 15-inch (about 40 cm.) height and a relative thickness of about one-half inch (about 1.25 cm.).

When a picture frame loudspeaker is mounted onto a rigid solid wall , the fidelity of the sound being produced is improved. This improvement occurs due to the elimination of an out-of-phase backwave commonly associated with cone-type speakers. In the picture frame speaker the sound wave emanates entirely from the front surface of the speaker thereby completely eliminating the generation of a backwave.

Other speakers constructed in accordance with this invention, when used in a spaced relationship from a solid surface, generate a backwave which is in phase with the frontwave. Thus, in the absence of a solid surface, the acoustical waves emanating from the speaker are radiated in opposite directions but are in phase.

Alternatively, it is possible to form the unitary structure **68** into a curved pliable unitary structure. For example, a curved speaker which could easily be attached to a curved wall or into the dashboard or ceiling of a motor vehicle could be formed. In FIGS. **7A** and **7B**, a lead **86** is used to connect the speaker to the output state of an audio amplifier and to a source of biasing voltage.

FIG. **8** is a pictorial representation showing an alternate construction of the unitary structure **68**. The pliable unitary structure **68** can be assembled by using a stacking process as illustrated. In FIG. **8**, every other conductive layer, for example conductive layers **94** and **96**, are staggered relative to the other conductive layers, for example layers **98** and **100**, whereby the edges of the structure are uneven. The staggered relationship may be obtained during the winding process of FIG. **5** by utilizing a conductive foil which has a surface dimension slightly larger than that of the dielectric material.

Referring again to FIG. **8**, the dielectric layers, generally designated as **102**, are sandwiched between the conductive layers forming the unitary structure. A first lead **106** is electrically connected to the overlapping edges of foils **94** and **96** and a second lead **108** is similarly connected to the overlapping edges of the foils **98** and **100**. A biasing voltage, for example a battery **110**, is electrically connected between the leads **106** and **108** to form an electric field therebetween. The dielectric material amplitude and frequency of vibration is determined by the electrical signal containing audio signal information from a source **112** which modulates the biasing voltage.

Electrostatic transducers of various geometrical dimensions can be constructed in accordance with the process described in FIG. **5**. FIGS. **9A**, **9B** and **9C** illustrate a unitary structure **120** which differs in shape and geometry from the transducer of FIG. **6A** and **6B**. In this particular embodiment, the unitary structure **120** has a length which is approximately twice its width when the structure is physically collapsed as illustrated in FIG. **9B**. The unitary structure **120** is folded at approximately its midpoint as illustrated by dashed line **122** in FIG. **9A** resulting in an electrostatic transducer having a folded elliptical end view as illustrated in FIG. **9C**. Leads **124** and **126** are electrically connected to alternate conductive layers in a manner similar to that described in FIG. **8**. The electrostatic transducer represented by FIGS. **9A**, **9B** and **9C** differs from that of FIGS. **6A** and **6B** in that the thickness of structure **120** is approximately equal to twice that of structure **68** in FIG. **6B**. Another difference is that the structure **120** of FIG. **9A**, when folded, has a generally square planar dimension while that of structure **68** in FIG. **6A** is generally rectangular with unequal side dimensions.

FIG. **10** is an approximate analogous electrical circuit of the physical or mechanical properties of a typical electrostatic transducer. The portion of the circuit designated generally as **128**, to the right of dashed line **130**, is the analogous circuit for an electrostatic transducer used as a loudspeaker. The portion of the circuit designated as **132**, to the left of dashed line **130**, represents the input terminal and biasing circuitry for electrostatic transducer used as a loudspeaker. Generally, input terminals **134** and **136** are operatively connected to and energized from an output stage of an audio signal amplifier (not shown). An electrical signal containing audio signal information is coupled via a coupling capacitor **138** to the speaker circuitry **128**. The d.c. biasing voltage can be obtained from any suitable source such as, for example, a battery designated generally as **142** which is applied through a current limiting resistor **144** to the circuitry designated as **128**. Generally, the electrical signal containing the audio signal information is impressed upon and modulates the d.c. biasing voltage emanating from the battery **142**.

The transducer analogous circuit **128** has a capacitance which is represented by capacitor C_o. The circuit contains an ideal transformer having a turn ratio of $1:\beta$ to convert the electrical signal to its equivalent mechanical signal. The loading of an ambient fluid such as, for example, air is represented by dashed area **146** having therein a resistive-type element R_a and an inductive-type element M_a representing the radiation resistance and the mass loading of a fluid. Each of the dielectric layers and electrodes has its mechanical properties represented in terms of analogous electrical components as illustrated in dashed area **148** for layer 1 and dashed area **150** for layer *n*. In area **148**, inductive-type element M_1 represents the effective mass of the first dielectric layer and the first electrode C_1 represents the compliance of the first dielectric layer and R_1 represents the damping of the first dielectric layer. In a similar manner, area **150** contains the analogous circuitry for dielectric layer *n* wherein M_n represents the effective mass of the *n* dielectric layer and electrode, C_n represents the compliance of the *n* dielectric layer and R_n represents the damping of the *n* dielectric layer. By controlling the number of layers of a transducer, the physical characteristics of the resulting transducer can be predicted from the analogous circuit of FIG. **10**.

The circuitry of FIG. **11** illustrates in a partial block diagram and in a partial schematic diagram the use of two electrostatic transducers assembled into an extended range loudspeaker. Each transducer is designed to reproduce frequencies in a particular frequency range and the speakers are selectively connected by means of a crossover network. Generally, an audio amplifier such as, for example, an audio amplifier designated generally as **154** is operatively coupled via an appropriately selected output tap to input terminals **156** and **158** of the loudspeaker. In the particular loudspeaker illustrated in FIG. **11**, the bias supply **160** is energized by a separate a.c. source **162**, such as for example, 110 volts, 60 cycle, a.c. voltage. The bias supply receives electrical signals containing the audio signal information at terminals **156** and **158**. The electrical signals modulate the biasing voltage, which biasing voltage is energizing a loudspeaker having a low frequency transducer 164 and a high frequency transducer 166. Transducer 164 has a capacitance which is represented by capacitor 168. The capacitor 168 is electrically connected in series with a resistor 170 to determine the cutoff frequency of the audio signal information to be applied to the transducer 164. Similarly, the other transducer 166 is represented by a capacitor 172 electrically connected in series with a resistor 174 for determining the cutoff frequency of the audio signal information to be applied to the transducer 166. It is contemplated that any known crossover network, such as for example an inductive crossover network, may be utilized for selectively determining which frequencies are to be applied to which speakers.

FIG. 12 illustrates in an electrical schematic diagram a biasing supply, generally designated as 184, wherein the biasing voltage for a speaker, represented by capacitor 178; is generated from the electrical signal containing audio frequency information. The electrical signal is applied to input terminals 180 and 182 of the biasing supply 184. In this biasing supply 184, a step-up transformer 188 increases the voltage of the audio input signal to a relatively high voltage which is sufficient for biasing the speaker. The transformed voltage is passed through a diode 190 and a resistor 192. Diode 190 and resistor 192 function to rectify the transformed electrical signal and apply the same as a direct current biasing voltage to establish an electric field within the speaker represented by capacitor 178. The level or magnitude of the biasing signal varies as a function of the average level of the audio signal. However, the minimum level is determined by the turns ratio of the transformer. Coupling capacitor 194 couples the electrical signal which is to modulate the electric field onto the direct current biasing voltage generated by means of transformer 188, diode 190 and resistor 192.

Several embodiments of electrostatic transducers having excellent frequency response were constructed according to the teachings of this invention. Several of the transducers are described in the following examples.

EXAMPLE I

A loudspeaker having a low frequency electrostatic transducer and a high frequency electrostatic transducer was constructed. The low frequency transducer was constructed using the method illustrated in FIG. 5. Two rolls of aluminum foil approximately 12 inches (about 30 cm.) wide and approximately .0005 inch (about 15μ) thick and two rolls of capacitor tissue paper approximately 13 inches (about 33 cm.) wide and approximately .001 inch (about 25μ) thick were used as starting materials. The paper used was White Jupiter type paper manufactured by Peter Schweitzer Paper Company. As is apparent from the above dimensions, the width of the paper slightly exceeded that of the aluminum foil to avoid edge arcover. The transducer was wound around a forked mandrel with approximately a 24-inch (about a 60-cm.) spacing. One hundred twenty-five complete turns of foil and paper were wound on the mandrel to produce 500 layers each of paper and of aluminum foil. Typical gap thickness between foil layers was measured to be approximately .00188 inch (about 50μ) with the solid dielectric layer being approximately, .001 inch (about 25μ) and the average thickness of an air bubble stratum being approximately .00088 inch (about 25μ). The ends of the foil layers were connected electrically such that every other layer from one side was connected to one output terminal. The alternate foil layers were similarly connected on the other side to a second separate output terminal such that the output voltage could be applied thereto for speaker operation. The 125-turn transducer was then flattened into a transducer having the geometry shown in FIGS. 9A and 9B. The resulting flattened transducer had exterior planar dimensions of approximately 13 inches by 26 inches (about 33 cm. by 66 cm.) and a total thickness of approximately 1.75 inches (about 5 cm.). The flat coil speaker was then folded upon itself, as illustrated in FIG. 9C, to produce a 2000-layer loudspeaker having a planar dimension of approximately 13 inches by 14 inches (about 33 cm. by 35 cm.) and approximately a 3½-inch (about a 10-cm.) thickness. The resulting speaker had excellent bass response combined with desirable geometry and dimensions.

The high frequency transducer was made in a manner similar to that for the low frequency transducer except that the resulting wound structure was not folded. The high frequency transducer contained five complete turns or 20 layers each of paper and of aluminum in a flattened device. The resulting loudspeaker was assembled and connected together, with appropriate resistors, i.e. a resistor of 50 ohms for the low frequency transducer and a resistor of 500 ohms for the high frequency transducer, to form a crossover network as the circuit illustrated in FIG. 10. The assembled loudspeaker total thickness comprised about 1.5 inches (about 4 cm.) attributed to aluminum and paper and about 2 inches (about 5 cm.) attributed to trapped air.

A direct current biasing voltage in the order of 200 volts was applied between the terminals electrically connected to the aluminum foil layers as described above.

This loudspeaker had a frequency response between 50-—20,000 Hz. which frequency response was relatively flat to ±5 db when tested in an anechoic chamber by stacking the high frequency transducer and the low frequency transducer on a massive lead plate (having planar dimensions of approximately 12 inches by 12 inches [about 30 cm. by 30 cm.] and weighing approximately 50 lbs. [about 120 kg.]).

The frequency response of the loudspeaker of example I is illustrated in the graph of FIG. 13. The sound pressure level in decibels (db) is plotted as a function of output frequency of the loudspeaker formed from the connection of the first and second transducer operatively connected by means of a crossover network. From FIG. 13, below 50 Hz., the db level drops off relatively quickly when the frequency is less than 50 Hz. However, in the frequency range of about 50 Hz.—20,000 Hz., the db level is substantially flat varying only in the order of ±5 db. At frequencies in excess of about 20,000 Hz., the db level begins to drop off. Thus, as is apparent from the graph of FIG. 13, the resulting loudspeaker has excellent frequency response over the audible range.

A most important factor in determining sound distortion is the ratio of the biasing voltage to the amplitude of the audio signal modulating voltage. The graph of FIG. 14 illustrates a first curve 196 depicting percent harmonic distortion plotted as a function of biasing voltage with a 3:1 ratio between the biasing voltage and audio signal voltage for the speaker of example I. Curve 198 depicts the same relationship as curve 196 except for a 5:1 ratio of biasing voltage to audio signal voltage.

Based on the curves 196 and 198 of FIG. 14, the following relationships exist. For both a 3:1 ratio between the and 5:1 ratio of biasing voltage to audio signal voltage, at high biasing voltages, the percent harmonic distortion is relatively low. At low biasing voltages, the percent harmonic distortion increases with the percentage being a function of the above-noted voltage ratios. If, for example, it is determined that a 7½ percent harmonic distortion is acceptable and a biasing voltage in the order of 50 volts is desirable, a 5:1 ratio satisfactorily provides this desired condition using the speaker of example I. In one experiment, a 150-volt biasing voltage and a 5:1 ratio of biasing voltage to audio signal voltage generated sound waves of acceptable quality and having less than 5 percent harmonic distortion.

EXAMPLE II

In another embodiment, a book-type electrostatic transducer or loudspeaker, illustrated in FIG. 15 as 200, was constructed in the following manner. A high frequency transducer 202 or "tweeter" is constructed of 30 turns each of paper and of aluminum foil producing a transducer having external dimensions of about 10 inches by 2 inches (about 25 cm. by 5 cm.) and a thickness of about one-half inch (about 1.25 cm.).

A low frequency transducer **204** or "woofer" is constructed having 150 turns each of aluminum foil and of capacitor paper forming a transducer having planar dimensions of about 9 inches by 10 inches (about 23 cm. by 25 cm.) and a thickness of about 2 inches (about 5 cm.). Typical gap thickness between foil layers was measured to be approximately .00284 inch (about 70μ) with the solid dielectric layer being approximately .001 inch (about 25μ) and the average thickness of an air bubble stratum was measured to be approximately .00184 inch (about 45μ).

The "tweeter" is fixed in place of the spine of the book with the "woofer" being used as the pages of the book. The transducer, when formed into the book-type loudspeaker and mounted onto a shelf, radiated sound outward from the bookshelf in a direction perpendicular to the surface of the book spine as indicated by arrow **206**. The "woofer" comprising the book pages radiated in-phase sound waves outwardly in opposed directions indicated as **208** and **210** respectively. The frequency response of this book-type loudspeaker, when taken from 100—15 KHz., was ±14 db at 60° angle off the front of the book-type loudspeaker and ±7 db from 150—13,000 Hz. on an axis in front of approximately a 6-foot by 8-foot (about a 1.8-m by 2.5-m) wall in an anechoic chamber with ordinary books on either side of the book-type loudspeaker.

EXAMPLE III

In another embodiment, a transducer was constructed according to the teachings of this invention and sealed in a container of flexible material. Such a transducer is illustrated in FIG. **16**. The electrostatic portion of the transducer was constructed from 100 turns each of aluminum foil and of capacitor paper and then enclosed in a package of heat-sealable film, the properties of which are described in U.S. Pat. Nos. 3,188,265 and 3,188,266, in a gas atmosphere, such as for example air. It is envisioned and contemplated that an inert gas such as argon could to be used for a gas atmosphere. Also, the internal pressure may be selectively increased or decreased relative to the exterior ambient atmosphere to establish a pressure differential therebetween whereby the dimension of the strata of fluid bubbles would be a function of the pressure differential. Also, the physical properties of the transducer, such as for example the mechanical compliance, would vary as a function of pressure differential. The sealed transducer has utility, for example, as a means for detecting and generating vibrations under water.

EXAMPLE IV

A mechanically-rigid 200-turn transducer was constructed in accordance with the teachings of this invention. In this transducer two approximately .0005-inch (about 15μ) layers of Schweitzer capacitor paper were used as the dielectric material while each electrode comprised approximately .0005-inch (about 15μ) aluminum foil. The 200-turn transducer has an exterior planar dimension of approximately 12 inches by 12 inches (about 30 cm. by 30 cm.) and a thickness of approximately 3 inches (about 8 cm.). The mechanical rigidity of the 200-turn transducer was increased by dipping each open end into paraffin wax up to a depth of approximately one-half inch (about 1.25 cm.). The paraffin wax penetrated the gaps between the aluminum foil and capacitor paper and solidified. For example, the transducer of FIG. **6A** has dashed lines **76** and **78** illustrating the ends dipped according to this step. When the 200-turn loudspeaker was tested, the motion at the center of the transducer remained essentially unconstrained as evidenced by only a slight modification of the response curve before and after the wax dipping. Additionally, it was found that the rigidizing process has the advantage of maintaining layer spacing and transducer shape. The rigid transducer could be electrically connected to the output of an audio amplifier and could be used as a loudspeaker. Alternatively, the rigid transducer could be used as a microphone and be operatively connected to either a preamplifier or to the input of an amplifier. A typical circuit for using the electrostatic transducer as a microphone is illustrated schematically in FIG. **17**.

For example, in FIG. **17**, the electrostatic microphone appears as a capacitor shown generally as a capacitor **220**. The capacitor **220**, i.e. electrostatic microphone, has a biasing voltage applied thereto from a bias supply **222**. The bias supply **222** has output terminals **226** and **228** which produce an electrical output signal containing the audio frequency information generated by capacitor **220** in response to a sound wave **230**. The electrical signal containing audio frequency information from terminals **226** and **228** is applied to a preamplifier **232**. Preamplifier **232** applies the amplified signal to a power amplifier **234**, which amplifier **234** then drives a speaker **236**. Speaker **236** could well be an electrostatic transducer described herein.

EXAMPLE V

An electrostatic transducer adapted for use with a transistorized audio amplifier requiring a relatively low biasing voltage was constructed. The audio signal input to the electrostatic transducer or loudspeaker would have a maximum amplitude of about 20 volts. The transducer was constructed by using the method illustrated in FIG. **8**. In this speaker, an approximately .00025-inch (about 7μ) Kraft capacitor tissue manufactured by Peter Schweitzer Paper Company was vapor-coated with zinc having a thickness in the order of 300 Angstroms to obtain a surface resistivity in the order of 2 ohms per square. The transducer was wound with 400 turns of two strips of vapor-coated capacitor tissue to make a 3200-layer speaker having a surface dimension of approximately 5 inches by 7 inches (about 12 cm. by 18 cm.) and a thickness of about 1 inch (about 3 cm.).

FIG. **18** is a graph illustrating a curve depicting percent harmonic distortion plotted as a function of the ratio of bias voltage to audio signal voltage wherein the measurements were taken at a distance of 1 foot in front of the speaker for an 80 db sound level 2400 Hz. signal with the bias voltage fixed at 50 volts direct current. The graph illustrates that a high ratio of bias voltage to audio signal voltage yields the least distortion. However, when the audio signal voltage was increased to about 5 volts direct current to obtain a ratio of about 10:1, the percent harmonic distortion was about 5 percent. Thus, the electrostatic speaker of example V is capable of responding to low direct current voltages generally associated with transistorized circuitry.

It was determined from the speaker of example V that a biasing voltage in the order of 120 volts provided good response with minimum distortion. When the biasing voltage was reduced to approximately 60 volts, a slight increase in distortion was observed but the overall loudspeaker operation was acceptable. Such a speaker has been found to have utility in background music systems having transistorized amplifiers.

EXAMPLE VI

In the above examples, the conductive foil layers had a direct current biasing voltage or an external polarizing bias applied thereto to establish the electric field between foil layers. However, it is contemplated and deemed within the teachings of this invention to replace the unpolarized conductive layers with a dielectric material in which a permanent state of electrostatic polarization has been established and wherein the material will remain polarized for a prolonged period of time. Such a device is generally known as an "electret" and the use thereof in electroacoustic transducers is described in U.S. Pat. No. 3,118,022. An electret is a dielectric material, such as for example .00025 inch (about 7μ) Mylar film foil which has been treated with an electric field and a heating process in a known manner, which is capable of being permanently polarized in a predetermined direction.

In summary, the present invention teaches a method of constructing a multiple layer electrostatic transducer, an article of manufacture comprising a multilayer pliable unitary structure formed into a desired electrostatic transducer and a transducing system utilizing the electrostatic transducer of the present invention.

All modifications, changes and the like of the above multilayer electrostatic transducer are deemed within the spirit of this invention and within the scope of the appended claims.

We claim:

1. A pliable, unitary, multilayer electrostatic transducer comprising:

a plurality of superimposed relatively thin flexible conductive layers, alternate ones of which are electrically connected to a first lead and the others of which are electrically connected to a second lead;

at least one relatively thin flexible electrically leaky dielectric layer disposed between and separating adjacent conductive layers;

said layers being in contact with each other to form a pliable unitary multilayer structure in which lateral movement of the layers is constrained;

at least one of said layers having slight undulations; and

a compressible fluid disposed between layers and entrapped between opposing surfaces of said undulating layer and contiguous layers as a large number of fluid bubbles which permit relative movement of the layers normal to their contiguous surfaces in response to changes in the potential difference between said first and said second terminals.

2. A transducer according to claim **1**, wherein said layers are windings in a flat coil and wherein said conductive layers comprise two strips adjacent to each other throughout their length.

3. A transducer according to claim **1**, wherein each layer is an individual sheet.

4. A transducer according to claim **2**, wherein said flat coil is folded upon itself at least once.

5. A transducer according to claim **2**, further comprising:

a source of d.c. biasing potential coupled across said first and said second terminals; and

a source of electrical signals containing audio frequency information coupled in parallel with said source of d.c. biasing potential.

6. An electrostatic transducer according to claim **5**, wherein each conductive layer and each dielectric layer has randomly occurring slight undulations to provide a unitary structure entrapping said compressible fluid as a large number of bubbles between contiguous layers.

7. An electrostatic transducer according to claim **6**, wherein each conductive layer is a metallic foil.

8. An electrostatic transducer according to claim **6**, wherein each conductive layer is a conductive element vacuum metalized onto one surface of a dielectric layer.

9. An electrostatic transducer according to claim **6**, wherein each conductive layer has a thickness on the order of 10 microns and each dielectric layer has a thickness on the order of 10 microns.

10. A loudspeaker comprising:

a first electrostatic transducer having a relatively large number of superimposed relatively thin flexible conductive layers, alternate ones of which are electrically connected to a first terminal and the others of which are electrically connected to a second terminal; at least one relatively thin flexible electrically leaky dielectric layer disposed between and separating adjacent conductive layers; said layers being in contact with each other to form a pliable unitary multilayer structure in which lateral movement of the layers is constrained; at least one of said layers having slight undulations; and a first compressible fluid disposed between said layers and entrapped between opposing surfaces of said undulating layer and contiguous layers as a large number of fluid bubbles to permit relative movement of the layers normal to their contiguous surfaces in response to changes in the potential difference between said first and said second terminals;

a second electrostatic transducer having relatively few superimposed relatively thin flexible conductive strata, alternate ones of which are electrically connected to a third terminal and the others of which are electrically connected to a fourth terminal; at least one relatively thin flexible electrically leaky dielectric strata disposed between and separating adjacent conductive layers; said strata being in contact with each other to form a pliable unitary multilayer structure in which lateral movement of the layers is constrained; at least one of said strata having slight undulations; and a second compressible fluid disposed between said strata and entrapped between opposing surfaces of said undulating strata and contiguous strata as a large number of fluid bubbles to permit relative movement of the strata normal to their contiguous surfaces in response to changes in the potential difference between said third and said fourth terminals;

a source of d.c. potential connected between said first and second terminals and between said third and fourth terminals to provide a potential difference between adjacent conductive layers and between adjacent conductive strata; and

a source of electrical signals containing audio frequency information connected in parallel with said biasing means.

11. A loudspeaker according to claim **10**, wherein said source of electrical signals comprises crossover means connected between said source of electrical signals and said first transducer and said second transducer for applying audio signals of a low frequency to said first transducer and audio signals of a high frequency to said second transducer.

PO-1050
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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,544,733 Dated December 1, 1970

Inventor(s) Robert S. Reylek and Frederick W. Zachau

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 1, line 16, change "performed" to -- preformed --. Column 2, line 9, change "lease" to -- least --; Column 2, line 47, cancel "a". Column 3, line 33, cancel "Fig.", first occurrence. Column 4, line 34, after "and" insert -- a --. Column 5, line 22, change "that" to -- than --. Column 6, line 21, change "alined" to -- aligned --. Column 6, line 22, change "layer" to -- layers --; column 6, line 25, change "alined" to -- aligned --; column 6, line 32, change "59" to -- 52 --. Column 10, line 53, after "3:1" cancel -- ration between the --.

Signed and sealed this 6th day of July 1971.

(SEAL)
Attest:

EDWARD M.FLETCHER, JR.
Attesting Officer

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Commissioner of Patents