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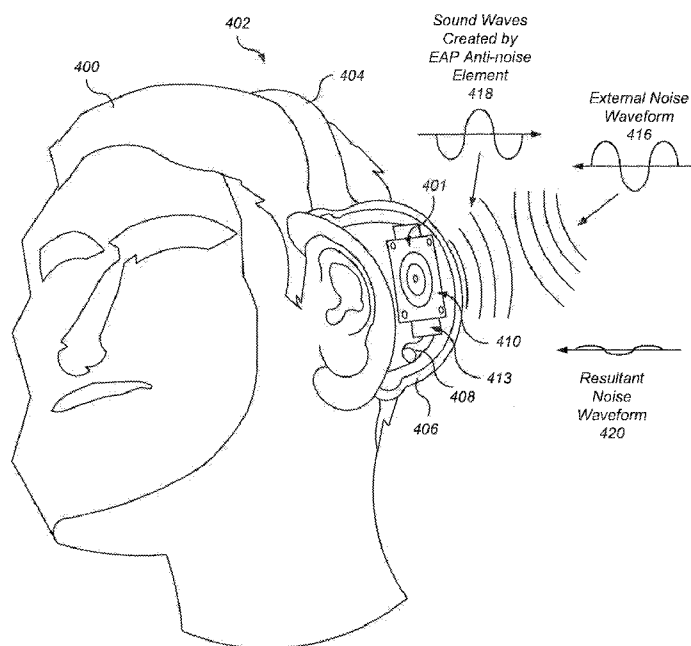
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[Continued on next page]

(54) Title: AUDIO DEVICES WITH ELECTROACTIVE POLYMER ACTUATORS NOISE CANCELLATION



(57) Abstract: A noise canceling system and method for an over-the-ear headphone is provided. The system and method provide a microphone configured to detect a first acoustic signal generated by a source external to the headphone and to produce a first electrical signal corresponding to the first acoustic signal, the first electrical signal having an amplitude, frequency, and phase representative of the first acoustic signal. An electroactive polymer actuator is electrically coupled to the microphone and configured to receive a second electrical signal having an amplitude and frequency substantially equal to the amplitude and frequency of the first electrical signal and a phase that is 180 degrees out-of-phase with the first electrical signal. The electroactive polymer actuator is configured to move in response to the second electrical signal and produce a second acoustic signal having an amplitude and frequency substantially equal to the first acoustic signal and a phase that is about 180 degrees out-of-phase with the first acoustic signal.



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AUDIO DEVICES WITH ELECTROACTIVE POLYMER ACTUATORS**NOISE CANCELLATION****CROSS REFERENCE TO RELATED APPLICATION**

[0001] This application claims the benefit, under 35 USC § 119(e), of United States provisional patent application numbers: 61/740,614, filed December 21, 2012, entitled "EAP LOW FREQUENCY NOISE CANCELLATION SYSTEM," the entire disclosure of which is hereby incorporated by reference.

FIELD OF THE INVENTION

[0002] In various embodiments, the present disclosure relates generally to electro-mechanical systems for cancelling noise in audio systems. More particularly, the present disclosure relates to audio devices equipped with electroactive polymer actuators or transducers to cancel noise in audio systems. In particular, the present disclosures relates to headphones equipped with electroactive polymer actuators configured to cancel noise by destructive interference.

BACKGROUND OF THE INVENTION

[0003] Conventional acoustic headphones include a pair of ear cups intercoupled by a headband. The ear cups include loudspeakers mounted within a housing portion of the ear cups and held in place close to a user's ears. The headphones include electrical wires to connect the loudspeakers to an audio signal source such as an audio amplifier, radio, CD player, portable media player, computer, tablet, mobile device, or gaming console. Some versions of conventional headphones also include electronic circuits for signal conditioning and processing the acoustic signal received from the audio signal source. Versions of audio headphones that do not include a headband and are specifically designed to be placed directly in the user's ear are also known as earphones or colloquially as earbuds.

[0004] Conventional audio signals include acoustical frequency components in the range of about 20 Hz to about 20 kHz. Most acoustic reproduction systems

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(home audio, headphones, earbuds, telephones, speakers) cannot cover the entire audio frequency range effectively and typically perform poorly at low frequencies (below about 200 Hz).

[0005] Unfortunately for music lovers, ambient sounds can interfere with the sounds coming through their headphones. This is most commonly manifested while listening to music on an airplane where the roar of the engines makes it difficult to hear the sound through the speakers situated in or over the ear. Noise-canceling headphones use microphones to listen to the incoming ambient sound, then signal processing techniques are employed to create inverse waves which are fed back into the headphones. These inverse waves cancel out the ambient sound, hence the term noise-canceling.

[0006] Of course, in reality conventional noise canceling systems are not quite so perfect. Noise canceling works best with low droning sounds, like car engines, airplane engines, air conditioners, etc. Noise-canceling headphones come in either active or passive types.

[0007] The best passive noise-canceling headphones are over the ear (circum-aural) types that are specially constructed to maximize noise-filtering properties.

[0008] Active noise-canceling headphones add an extra level of noise reduction by actively erasing lower-frequency sound waves. Noise-canceling headphones accomplish this by creating their own sound waves that imitate the incoming ambient noise sound waves except the headphone's sound waves are 180 degrees out of phase with the incoming ambient noise sound waves.

[0009] One way that conventional noise-canceling headphones accomplish this is by ensuring that the sound waves coming from the noise-canceling headphone and the sound waves associated with the ambient noise have the same amplitude and frequency, but are 180 degrees out-of-phase. In other words, the crests and troughs (compressions and rarefactions) of the desired and undesired sound waves are arranged so that the crests (compressions) of one wave line up with the troughs

(rarefactions) of the other wave and vice versa. Accordingly, the two waves cancel each other out, a phenomenon known as destructive interference.

[0010] Several components are required to achieve the noise-canceling effect. A microphone placed inside the ear cup to listen to external sounds that cannot be blocked passively. Noise-canceling electronic circuitry placed in the ear cup to sense the input from the microphone and generate an electrical impression of the noise, noting the frequency and amplitude of the incoming wave. The electrical circuitry then creates a new wave that is 180 degrees out of phase with the waves associated with the noise. A conventional diaphragm speaker that creates the anti-sound created by the noise-canceling circuitry is fed into the headphones' speakers along with the normal audio. The anti-sound erases the noise by destructive interference, but does not affect the desired sound waves in the normal audio. A battery adds energy to the system to produce the noise-canceling effect.

[0011] While conventional noise-canceling headphones do a relatively adequate job of distinguishing between desired and undesired audio they compromise in sound quality by muffling sounds. Also, conventional noise-canceling systems sized to fit an over the ear headphone are often incapable of yielding a suitable frequency response in the low audio frequency range (e.g. 10Hz - 250Hz) needed to cancel out the undesired low frequency audio signals.

SUMMARY OF THE INVENTION

[0012] In one embodiment, the present disclosure applies to noise canceling audio system. In one embodiment, a noise canceling system for an over-the-ear headphone is provided. The system comprises a microphone configured to detect a first acoustic signal generated by a source external to the headphone and to produce a first electrical signal corresponding to the first acoustic signal, the first electrical signal having an amplitude, frequency, and phase representative of the first acoustic signal. An electroactive polymer actuator is electrically coupled to the microphone and configured to receive a second electrical signal having an amplitude and frequency substantially equal to the amplitude and frequency of the

first electrical signal and a phase that is 180 degrees out-of-phase with the first electrical signal. The electroactive polymer actuator is configured to move in response to the second electrical signal and produce a second acoustic signal having an amplitude and frequency substantially equal to the first acoustic signal and a phase that is about 180 degrees out-of-phase with the first acoustic signal.

[0013] In another embodiment, a noise reduction system comprises a plurality of electroactive polymer transducers driven as described above and arranged to provide noise reduction in a volume of space where there is ambient background noise. The individual transducers may be controlled individually, in multiple groups, or as a single group. The noise reduction system may also include a plurality of microphones for better spatial optimization.

BRIEF DESCRIPTION OF THE FIGURES

[0014] The present invention will now be described for purposes of illustration and not limitation in conjunction with the figures, wherein:

[0015] FIG. 1 is a perspective view of a sensory enhanced headphone according to one embodiment of the present invention;

[0016] FIG. 2 is a perspective view of the left ear cup shown in FIG. 1 according to one embodiment;

[0017] FIG. 3 is a front view of the left ear cup shown in FIG. 1 according to one embodiment;

[0018] FIG. 4 is a perspective view of the right ear cup shown in FIG. 1 according to one embodiment;

[0019] FIG. 5 is a back view of the right ear cup shown in FIG. 1 according to one embodiment;

[0020] FIG. 6 is a sectional view of the right ear cup taken along section line 6—6 as shown in FIG. 4 according to one embodiment;

[0021] FIG. 7 is a sectional view of the right ear cup taken along section line 6—6 as shown in FIG. 4 according to one embodiment;

[0022] FIG. 8 is a front view of the ear cup shown in FIGS. 6 and 7 according to one embodiment;

[0023] FIG. 9 is a cutaway view of an electroactive polymer system to illustrate the principle of operation;

[0024] FIG. 10 is a schematic diagram of one embodiment of an electroactive polymer system to illustrate the principle of operation;

[0025] FIGS. 11A-11C diagrammatically illustrate the geometry and operation of frustum-shaped actuators in accordance with one embodiment;

[0026] FIG. 12 is a top view of a multi-phase frustum-shaped actuator in accordance with one embodiment;

[0027] FIG. 13A is an assembly view of another frustum shaped actuator, and FIG. 13B is a side view the same basic actuator with an alternate frame construction in accordance with one embodiment;

[0028] FIG. 14 is a sectional perspective view of a parallel-stacked type of frustum transducer in accordance with one embodiment;

[0029] FIG. 15 is a side-section view showing an optional output shaft arrangement with a frustum type transducer in accordance with one embodiment;

[0030] FIG. 16 is a side-section view of an alternate, inverted frustum transducer configuration in accordance with one embodiment;

[0031] FIG. 17 is a sectional perspective view of a coil spring-biased single frustum transducer in accordance with one embodiment;

[0032] FIG. 18 is an illustration of a user wearing a headphone having an electroactive polymer based noise cancellation system, where the left ear cup is shown in partial cutaway view to show the internal components thereof in accordance with one embodiment;

[0033] FIG. 19 is an illustration of the headphones shown in FIG. 18 having an electroactive polymer based noise cancellation device, where the left ear cup is

shown in partial cutaway view to provide a more detailed view of the internal components thereof in accordance with one embodiment;

[0034] FIG. 20 is a partial cutaway perspective view of a multi-diaphragm frustum type electroactive polymer noise canceling actuator in accordance with one embodiment;

[0035] FIG. 21 is a block diagram of a circuit configured to cancel noise generated by an external source by destructive interference utilizing a multi-diaphragm frustum type electroactive polymer actuator in accordance with one embodiment;

[0036] FIG. 22 is an illustrative representation of the concept of destructive interference, in accordance with one embodiment;

[0037] FIG. 23 is a block diagram of a circuit configured to cancel noise generated by an external source by destructive interference utilizing a diaphragm type electroactive polymer actuator in accordance with one embodiment;

[0038] FIG. 24 is a block diagram of a circuit configured to cancel noise generated by an external source utilizing a single-diaphragm frustum type electroactive polymer noise canceling actuator in accordance with one embodiment; and

[0039] FIG. 25 is a block diagram of a circuit configured to cancel noise generated by an external source utilizing a single-diaphragm frustum type electroactive polymer actuator in accordance with one embodiment.

[0040] FIG. 26 illustrates a device comprising a monolithic transducer for converting between electrical energy and mechanical energy in accordance with another embodiment of the present invention.

[0041] FIG. 27A is an exploded view of one embodiment of a single "tile" of the present invention.

[0042] FIG. 27B is the tile of FIG. 27A in assembled form.

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[0043] FIGS. 28-28A depict a cross-sectional view of an alternate embodiment of the transducer that is well-suited for manufacture by microfabrication techniques.

[0044] FIG. 29 illustrates the use of a soft foam biasing member for an alternate embodiment of an acoustic actuator of the present invention.

[0045] FIG. 30 illustrates an embodiment of an electroactive polymer flat panel diaphragm acoustic element.

DETAILED DESCRIPTION OF THE INVENTION

[0046] Before explaining the embodiments of the inventive noise canceling audio devices in detail, it should be noted that the disclosed embodiments are not limited in application or use to the details of construction and arrangement of parts illustrated in the accompanying drawings and description. The disclosed embodiments may be implemented or incorporated in other embodiments, variations and modifications, and may be practiced or carried out in various ways. Further, unless otherwise indicated, the terms and expressions employed herein have been chosen for the purpose of describing the embodiments for illustrative purposes and for the convenience of the reader and are not intended for the purposes of limiting any of the embodiments to the particular ones disclosed. Further, it should be understood that any one or more of the disclosed embodiments, expressions of embodiments, and examples can be combined with any one or more of the other disclosed embodiments, expressions of embodiments, and examples, without limitation. Thus, the combination of an element disclosed in one embodiment and an element disclosed in another embodiment is considered to be within the scope of the present disclosure and appended claims.

[0047] In various embodiments, the present invention provides a low frequency noise cancellation audio system comprising an electroactive polymer actuator and a circuit electrically coupled to the actuator system, wherein the circuit is to generate a drive signal to cause the actuator system to move according to the drive signal. The drive signal is 180 degrees out-of-phase with ambient sound waves

that can interfere with the sound waves produced by speaker elements of the headphones.

[0048] In one embodiment, the invention comprises an electroactive polymer actuator sized to fit an over the ear headphone, capable of yielding a frequency response in the low audio frequency range (e.g., 10Hz - 250Hz) combined with drive electronics and signal needed to cancel out the undesired low frequency audio signals.

[0049] In another embodiment, the present invention provides noise cancellation across the whole range of audio spectrum, e.g., 10 Hz to about 20 kHz.

[0050] In one embodiment, the electroactive polymer is capable of a very low frequency response in an actuator much smaller in form factor than a typical speaker required to yield similar low frequency response. A properly designed electroactive polymer actuator can be used directly across the full range of audio spectrum (10 Hz to about 20 kHz), or can be used exclusively for low frequency response (10 Hz to about 250 Hz).

[0051] Advantages of the invention include providing noise cancellation means in the low frequency audio range or across the full audio spectrum in a small package size, suitable for headphone applications, which is very desirable for people in high noise areas that have significant low frequency components which can be difficult to passively attenuate.

[0052] Prior to describing the various noise reduction techniques, the disclosure turns to FIG. 1, which is a perspective view of a noise canceling headphone 100 according to one embodiment. In the embodiment shown in FIG. 1, the headphone 100 comprises a right ear cup 102 and a left ear cup 104 intercoupled by a headband 106. The headband 106 may be any suitable conventional headband. The right and left ear cups 102, 104 each comprise a corresponding exemplary right and left circumaural cushion 108, 110. It will be appreciated that the circumaural cushions 108, 110 may have any shape although traditionally such cushions are circular or ellipsoid to encompass the ears. Because the circumaural

cushions 108, 110 completely surround the ear, these headphones 100 can be designed to fully seal against the head to attenuate any intrusive external noise, for example. The materials of the cushions 108, 110, may be chosen to modulate the degree of coupling between the headphone and the user. Each of the right and left ear cups 102, 104 may preferably comprise circumaural cushions 108, 110, perforated speaker grills 112 (right only shown), and housings 114 (left only shown). The housing 114 contains a speaker, an electroactive polymer actuator, a circuit board comprising circuits to drive the actuator, and in some embodiments and mechanical and/or electronic acoustic noise reduction components.

Embodiments of these elements are described hereinbelow. Despite best efforts in passive noise cancellation technology, it is not possible to completely eliminate external noise coupled through the ear cups 102, 104. Accordingly, as described hereinbelow, in one embodiment, the present invention provides active noise cancellation techniques. More particularly, in one embodiment, the present invention provides open loop active noise cancellation techniques utilizing electroactive polymer actuators that move along the axis of the headphone speaker in each cup 102, 104.

[0053] FIG. 2 is a perspective view of the left ear cup 104 and FIG. 3 is a front view of the left ear cup 104. As shown in FIGS. 2 and 3, the left ear cup 104 comprises a circumaural cushion 110 and a perforated speaker grill 116.

[0054] FIG. 4 is a perspective view of the right ear cup 102 and FIG. 5 is a back view of the right ear cup 102. As shown in FIGS. 4 and 5, the right ear cup 102 comprises a housing 118.

[0055] FIGS. 6 and 7 are sectional views of the right ear cup 102 taken along section line 6—6 as shown in FIG. 4. FIG. 8 is a front view of the ear cup 102 shown in FIGS. 6 and 7. Since the left ear cup 104 is substantially similar to the right ear cup 102, for conciseness and clarity of disclosure the remainder of this description provides focuses on the structure and function of the right ear cup 102 although such attributes may pertain equally to the left ear cup 104.

[0056] With reference now in particular to FIGS. 6-8, in one embodiment the right ear cup 102 comprises a housing 118, which defines an opening 124 suitable for mounting a speaker 120 and an electroactive polymer actuator 122 therein. In the embodiment illustrated in FIGS. 6-8, the actuator 122 comprises several sub-components and thus may be occasionally referred to herein as an electroactive polymer module. In particular embodiments where the actuator 122 includes three bars, for example, the actuator 122 may be referred to as a 3-bar electroactive polymer module, without limitation. With reference now back to FIGS. 6-8, the speaker 120 can be mounted directly behind the perforated speaker grill 112, as shown. In other embodiments however, the location of the speaker 120 may vary and may be mounted in any suitable location within the opening 124 of the housing 118. In one embodiment, for example, the electroactive polymer actuator 122 can be mounted to an inner wall 132 portion of the housing 118. In one embodiment, the actuator 122 may comprise a tray 126, an electroactive polymer actuator array 128, and a mass 130. Electroactive polymer actuator arrays such as the actuator 128 also may be referred to herein as an “n-bar cartridge,” where “n” stands for the number of actuator bars in the array. Thus, a 3-bar standalone cartridge refers to an electroactive polymer actuator array comprising three actuator bars that is mounted in a tray with flexure elements. It will be appreciated that any of the disclosed headphone embodiments comprising a standalone actuator tray such as the tray 126 may be configured to move in a direction parallel with the vibration of the speaker 120, without limitation. Thus, if the electroactive polymer actuator 122 is configured to move 180 degrees out-of-phase with external noise waveform coupled into the ear cup 102, these vibrations will cancel out the vibrations caused by the external noise source.

[0057] With reference now to FIGS. 1-6, in one embodiment, the noise canceling headphones 100 comprising electroactive polymer actuators 122 according to the present disclosure are capable of producing mechanical vibrations in the audio frequency band (e.g., about 10 Hz to about 20 kHz) to counteract audio sensations produced by external noise sources that are coupled into the ear cup 102 without

being completely eliminated by passive techniques. Thus, the sound pressure generated by electroactive polymer actuator **122** counteracts the sound pressure from external noise sources coupled in to the ear cup **102** to eliminate the external noise in the user's ear. Of course, those skilled in the art will appreciate that cancellation accuracy is dependent upon many factors including, for example, the ability of internal circuitry to reproduce the amplitude of the external noise coupled inside the ear cup **102** and the ability to invert the waveform 180 degrees out-of-phase prior to driving the electroactive polymer actuator **122** to produce the counter audio pressure inside the ear cup **102**.

[0058] In one embodiment, a suitable acoustically isolated microphone located within the cup can be employed to detect the unwanted noise signal coupled in the ear cup **102**. In one embodiment, each of the ear cups **102**, **104** comprise the electroactive polymer actuator **122**. Each of the actuators **122** may comprise a small mass **130** (preferably from 1 to 50 g, more preferably 25 g) attached to the electroactive polymer actuator array **128** forming a simple mass/spring/damper resonant system. Portions of the incoming audio are passed to an audio amplifier that is connected to the actuators **122**. The electroactive polymer actuators **122** shake (vibrate) the ear cups **102**, **104**, the vibrations tracking the inverse of the incoming audio signals, thereby giving the sensation of noise cancellation. The electroactive polymer actuators **122** disclosed herein enhance the "listening" experience of conventional audio headphones. The elimination of low frequency (10 Hz - 250 Hz) vibrations from external noise sources enhances the user's experience of the noise canceling headphones **100**. Elimination of noise in the full audio frequency spectrum (10 Hz - 20 kHz) also enhances the user's experience.

[0059] The vibrations generated by the electroactive polymer actuators **122**, however, are non-linear in nature. In addition, electroactive polymer based actuators **122** may also produce acoustic vibrations that may, or may not, be desirable. In the case of undesirable acoustic vibrations, mechanical and electrical techniques may be employed to reduce the undesirable acoustic effects to acceptable levels. At times, the vibrations may be out-of-plane with the speaker

120. Vibrational augmentation may be added to the sensory enhanced noise canceling headphones **100**, if desired, by employing voice coils for driving suspended masses. These implementations, however, may result in high Q systems having low damping such that they move longer in the same axis as the acoustic radiator, thereby introducing undesirable acoustic artifacts. In various embodiments, however, the electroactive polymer actuators **122** disclosed herein may be oriented in such a manner that the plane of vibration is perpendicular to the acoustic radiator axis, thereby significantly reducing unwanted acoustic artifacts. These and other techniques are described in commonly assigned PCT international application number PCT/US12/26421, titled "AUDIO DEVICES HAVING ELECTROACTIVE POLYMER ACTUATORS," the disclosure of which is herein incorporated by reference in its entirety.

[0060] Before launching into a further description of various embodiments of the electroactive polymer actuator **122**, as shown in connection with FIGS. 6-8, for example, the description turns briefly to FIGS. 9-11 for a description of various integrated devices comprising electroactive polymer based modules suitable for use in audio devices such as the noise canceling headphones **100**. FIG. 9 is a partial cutaway view of an electroactive polymer system that may be integrally incorporated into the actuator **122** to provide the necessary vibratory motion to the headphone **100**. Accordingly, in one embodiment the system comprises an electroactive polymer module **200**. An electroactive polymer actuator **222** is configured to slide an output plate **202** (e.g., sliding surface) relative to a fixed plate **204** (e.g., fixed surface) when energized by a voltage "V." The plates **202**, **204** are separated by steel balls or bearings, and have features that constrain movement to the desired direction, limit travel, and withstand drop tests. The plates may alternatively be suspended using flexures.

[0061] For integration into a headphone device, the top plate **202** may be attached to an inertial mass, such as the mass **130** shown in FIGS. 6-8. In FIG. 9, the top plate **202** of the electroactive polymer module **200** includes a sliding surface configured to mount to an inertial mass or the back of a surface that can move bi-

directionally as indicated by arrow **206**. To adapt and configure the electroactive polymer module **200** for noise canceling applications, the direction of vibration indicated by arrow **206** must be converted such that the direction of vibration is orthogonal to direction **206** in the Z direction as indicated by arrow **207** such that the sound pressure waves generated by the moving electroactive polymer actuator **222** cancel the coupled noise sound pressure waves before they reach the user's ear.

[0062] One technique for vibrating the electroactive polymer module **200** in such a mode, in the Z direction, is to constrain the fixed plate **204** and the outer plate **202** such that the electroactive polymer actuator **222** moves in the Z direction like a diaphragm when driven by an alternating signal. Between the output plate **202** and the fixed plate **204**, the electroactive polymer module **200** comprises at least one electrode **208**, optionally at least one divider **210**, and at least one output bar **212** that attach to the sliding surface, e.g., the top plate **202**. Frame and divider segments **214** attach to a fixed surface, e.g., the bottom plate **204**. The module **200** may comprise any number of bars **212** configured into arrays to amplify the motion of the sliding surface. The electroactive polymer module **200** may be coupled to the drive electronics of an actuator controller circuit via a flex cable **216**. A voltage "V" potential difference of preferably about 1 kV (preferably anywhere up to 5 kV, more preferably between 100 V to 5 kV, more preferably between 300 V to 5 kV) may be applied to first and second electrically conductive elements **218A**, **218B** of the flex cable.

[0063] Segmenting the electroactive polymer actuator **222** within a given footprint into (n) sections is a convenient method for setting the passive stiffness and blocked force of the electroactive polymer system. A pre-stretched dielectric is held in place by the rigid material that defines an external frame such as the fixed plate **204** and one or more windows within the frame. Inside each window is an output bar **212** of the same rigid frame material, and on one or both sides of the output bar **212** are electrodes **208**. Alternatively, an adhesive may replace the rigid frame material as disclosed in co-assigned International PCT Patent

Application No. PCT/US2012/021511, filed January 17, 2012 entitled FRAMELESS ACTUATOR APPARATUS, SYSTEM AND METHOD; the entire disclosure of which is hereby incorporated by reference. Applying the potential difference (V) across the dielectric on one side of the output bar **212** creates electrostatic pressure in the elastomer which causes the electrode area to expand and exert force on the output bar **212**. This force scales with the effective cross section of the electroactive polymer actuator **222**, and therefore increases linearly with the number of segments, each of which adds to the effective width of the actuator. The passive spring rate scales with n^2 , as each additional segment effectively stiffens the device twice, first by shortening it in the stretching direction (X) and second by adding to the width (Y) that resists displacement. Both spring rate and blocked force scale linearly with the number of dielectric layers (m).

[0064] Advantages of electroactive polymer modules **200** include the ability to generate low frequency vibrations inside the ear cup housings that can be felt substantially immediately by the user. In addition, electroactive polymer modules **200** consume low power, and are well suited for customizable design and performance options. The electroactive polymer module **200** is representative of those developed by Artificial Muscle, Inc., of Sunnyvale, CA, USA.

[0065] Still with reference to FIG. 9, many of the design variables of the electroactive polymer module **200**, (e.g., thickness, footprint) may be fixed by the needs of module integrators while other variables (e.g., number of dielectric layers, operating voltage) may be constrained by cost. Because actuator geometry – the allocation of footprint to rigid supporting structure versus active dielectric – does not impact cost much, it may be a reasonable way to tailor performance of the electroactive polymer module **200** to an application where the module **200** is integrated with a headphone device, as shown in FIGS. 6-8.

[0066] Computer implemented modeling techniques can be employed to gauge the merits of different actuator geometries, such as: (1) Mechanics of the Headset/User System; (2) Actuator Performance; and (3) User Sensation.

Together, these three components provide a computer-implemented process for estimating the capability of candidate designs and using the estimated capability data to select an electroactive polymer design suitable for mass production. The model predicts the capability for two kinds of effects: long effects (gaming and music), and short effects (key clicks). “Capability” is defined herein as the maximum sensation a module can produce in service. Such computer-implemented processes for estimating the capability of candidate designs are described in more detail in commonly assigned International PCT Patent Application No. PCT/US2011/000289, filed February 15, 2011, entitled “ELECTROACTIVE POLYMER APPARATUS AND TECHNIQUES FOR QUANTIFYING CAPABILITY THEREOF,” the entire disclosure of which is hereby incorporated by reference.

[0067] FIG. 10 is a schematic diagram of an electroactive polymer system 300 designed to illustrate the principle of operation of electroactive polymer modules. The electroactive polymer system 300 comprises a power source 302, shown as a low voltage direct current (DC) battery for illustrative purposes, electrically coupled to an electroactive polymer module 304. In accordance with the present disclosure, the power source (V_{Batt}) represents the output of an audio signal source configured to generate low frequency audio signals below about 200 Hz, for example, and in one embodiment between about 2 Hz to about 200 Hz, where the term “about” stands for $\pm 10\%$. The electroactive polymer module 304 comprises a thin elastomeric dielectric element 306 disposed (e.g., sandwiched) between two conductive electrodes 308A, 308B. The conductive electrodes 308A, 308B are stretchable (e.g., conformable) and may be printed on the top and bottom portions of the elastomeric dielectric element 306 using any suitable technique, such as, for example screen printing. The electroactive polymer module 304 is activated by coupling the battery 302 (e.g., signal source) to an actuator circuit 310 by closing a switch 312. The actuator circuit 310 converts the low DC voltage V_{Batt} signal into a higher DC voltage V_{in} signal suitable for driving the electroactive polymer module 304. In accordance with the present disclosure, an additional circuit may

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be located within the opening **124** defined by the housing **118**, where the circuit is configured to convert the low voltage low frequency audio signal from the audio signal source, to a higher voltage signal suitable for driving the electroactive polymer actuator **122** (FIGS. 6-8). Returning to FIG. 10, when the voltage V_{in} is applied to the conductive electrodes **308A**, **308B** the elastomeric dielectric element **306** contracts in the vertical direction (V) and expands in the horizontal direction (H) under electrostatic pressure. The contraction and expansion of the elastomeric dielectric element **306** can be harnessed as motion. The amount of motion or displacement is proportional to the input voltage V_{in} . The motion or displacement may be amplified by a suitable configuration of electroactive polymer actuators

[0068] It will be appreciated that the description of the electroactive polymer actuator in connection FIGS. 9 and 10 serves primarily as general background on the operation of an electroactive polymer actuator. Although the device **200** shown in FIG. 9 can adapted and configured to provide the necessary motion in a direction parallel to the speaker **120** to cancel unwanted acoustical disturbances, a much better candidate for implementing such functionality is a diaphragm type electroactive polymer actuator. Diaphragm type electroactive polymer actuators can be configured with a single or multiple diaphragms, as discussed in more detail hereinbelow. The actuators can have one or more active areas defined by the electrode pattern. For a more general discussion of such diaphragm type electroactive polymer actuators, reference is made to commonly assigned U.S. Pat. No. 8,183,739, which is herein incorporated by reference in its entirety.

[0069] FIGS. 11A-11C diagrammatically illustrate the geometry and operation of frustum-shaped actuators in accordance with one embodiment. Specifically, FIGS. 11A-11C diagrammatically illustrate the manner in which these concave/convex or frustum shaped actuators function in a simplified two dimensional model. FIG. 11A illustrates the derivation of the transducer frustum shape. Whether conical, squared, ovaloid, etc. when viewed from above, from the side a truncated form **660** is provided by modifying existing diaphragm actuator

configurations by capping the top (or bottom) of the structure. When under tension, the cap 642 alters the shape the electroactive polymer layer/layers 10/10' would take. On the example where a point load stretches the film, the film would assume a conical shape (as indicated by dashed lines define a triangular top 662). However, when capped or altered to form a more rigid top structure, the form is truncated as indicated in solid lines 664 in FIG. 11A.

[0070] Modifying the structure fundamentally alters its performance. For one, it distributes stress that would otherwise concentrate at the center of structure 666 around a periphery 668 of the body instead. In order to effect this force distribution, the cap is affixed to the electroactive polymer layers. An adhesive bond may be employed. Alternatively, the constituent pieces may be bonded using any viable technique such as thermal bonding, friction welding, ultrasonic welding, or the constituent pieces may be mechanically locked or clamped together. Furthermore, the capping structure may comprise a portion of the film that is made substantially more rigid through some sort of thermal, mechanical or chemical techniques—such as vulcanizing.

[0071] Generally, the cap section will be sized to produce a perimeter of sufficient length to adequately distribute stress applied to the material. The ratio of size of the cap to the diameter of the frame holding the electroactive polymer layers may vary. Clearly, the size of disc, square, etc. employed for the cap will be larger under higher stress/force application. The relative truncation of the structure (as compared to point-loaded cones, pressure biased domes, etc.) is of further importance to reduce volume the aggregate volume or space the transducer occupies in use, for a given amount of pre-stretch to the electroactive polymer layers. Furthermore, in a frustum type diaphragm actuator, the cap or diaphragm 642 element may serve as an active component (such as a valve seat, etc. in a given system).

[0072] With the more rigid or substantially cap section formed or set in place, when electroactive polymer material housed by a frame is stretched in a direction

perpendicular to the cap, it produces the truncated form. Otherwise, the electroactive polymer film remains substantially flat or planar.

[0073] Still with reference to FIG. 11A, with the cap 642 defining a stable top/bottom surface, the attached electroactive polymer sides 10/10' of the structure assume an angle. The angle an electroactive polymer is set at when not activated may range between 15 and about 85 degrees. More preferably, it will range from about 30 to about 60 degrees. When voltage is applied so that the electroactive polymer material is compressed and grows in its planar dimensions, it assumes a second angle β in about the same range plus between about 5 and 15 degrees. Optimum angles may be determined based on application specifications.

[0074] Single-sided frustum transducers are within the contemplated scope of the present invention as well as double-sided structures. For preload, single sided devices employ any of a spring interfacing with the cap (e.g., a coil, a constant force or roll spring, leaf spring, etc.), air or fluid pressure, magnetic attraction, a weight (so that gravity provides preload to the system), or a combination of any of these means or others.

[0075] In double-sided frustum transducers, one side provides preload to the other. Still, such devices may include additional bias features/members. FIG. 11B illustrates the basic "double-frustum" architecture 670. Here, opposing layers of electroactive polymer material or one side of electroactive polymer film and one side of basic elastic polymer are held together under tension along an interface section 627. The interface section often comprises one or more rigid or semi-rigid cap element(s) 642. However, by adhering two layers of the polymer together at their interface, the combined region of material, alone, offers a relatively stiffer or less flexible cap region in the most basic manner to offer a stable interface portion of the transducer.

[0076] However constructed, the double-frustum transducer operates as shown in FIG. 11B. When one film side 674 is energized, it relaxes and pulls with less force, releasing stored elastic energy in the bias side 674 and doing work through

force and stroke. Such action is indicated by dashed line in FIG. 11C. If both film elements comprise electroactive polymer film, then the actuator can move in/out or up/down relative to a neutral position (shown by solid line in each of FIGS. 11A and 11B) as indicated by double-headed arrow 680.

[0077] If only one active side 674 / 676 is provided, forced motion is limited to one side of neutral position 682. In which case, the non-active side of the device may simply comprise elastic polymer to provide preload/bias (as mentioned above) or electroactive polymer material that is connected electrically to sense change in capacitance only or to serve as a generator to recover motion or vibration input: in the device in a regenerative capacity.

[0078] Further optional variation for transducers according to the present invention includes provision for multi-angle/axis sensing or actuation. FIG. 12 is a top view of a multi-phase frustum-shaped actuator in accordance with one embodiment. FIG. 12 shows a circular electroactive polymer cartridge 690 configuration with three (692, 694, 696) independently addressable zones or phases. When configured as an actuator, by differential voltage application, the sections will expand differently causing cap 642 to tilt on an angle. Such a multi-phase device can provide multi-directional tilt as well as translation depending on the manner of control. When configured for sensing, input from a rod or other fastener or attachment to the cap causing angular deflection can be measured by way of material capacitance change.

[0079] The electroactive polymer section shown in FIG. 12 is round. FIG. 13A is an assembly view of another frustum shaped actuator, and FIG. 13B is a side view the same basic actuator with an alternate frame construction in accordance with one embodiment. FIG. 13A provides an assembly view of a round-frustum transducer 6100. The body frame member 624 employed is solid, resembling that used in the combination or convertible type actuator. However, the device shown in FIG. 13A is a dedicated diaphragm type actuator (though it may employ a multiphase structure shown in FIG. 12). An alternative construction for such an

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actuator is shown in FIG. 13B. Here, the monolithic frame element **624** is replaced by simple frame spacers **624'**.

[0080] FIG. 14 is a sectional perspective view of a parallel-stacked type of frustum transducer in accordance with one embodiment. FIG. 14 shows another construction variation in which the transducer comprises multiple cartridge layers **622** on each side of a double-frustum device **6100**. Individual caps **642** are ganged or stacked together. To accommodate the increased thickness, multiple frame sections **624** may likewise be stacked upon one another.

[0081] Recall that each cartridge **622** may employ compound electroactive polymer layers **10'**. Either one or both approaches—together—may be employed to increase the output potential of the subject device. Alternatively, at least one cartridge member of the stack (on either one or both sides of the device) may be setup for sensing as opposed to actuation to facilitate active actuator control or operation verification. Regarding such control, any type of feedback approach such as a PI or PID controller may be employed in such a system to control actuator position with very high accuracy and/or precision.

[0082] FIG. 15 is a side-section view showing an optional output shaft arrangement with a frustum type transducer in accordance with one embodiment. FIG. 15 is a side-section view showing an optional output shaft arrangement with a frustum type transducer **6110**. Threaded bosses **6112** on either side of the cap pieces provide a means of connection for mechanical output. The bosses may be separate elements attached to the cap(s) or may be formed integral therewith. Even though an internal thread arrangement is shown, external threaded shaft may be employed. Such an arrangement may comprise a single shaft running through the cap(s) and secured on either side with a nuts in a typical jam-nut arrangement. Other fastener or connection options are possible as well.

[0083] FIG. 16 is a side-section view of an alternate, inverted frustum transducer configuration in accordance with one embodiment. FIG. 16 is a side-section view of an alternate transducer **6120** configuration, in which instead of employing two

concave structures facing away from one another, the two concave/frustum sections **6122** face towards each other. The preload or bias on the electroactive polymer layers to force the film into shape is maintained by a shim or spacer **6124** between caps **642**. As shown, the space comprises an annular body. The caps may too include all opening in this variation of the invention as well as others. Note also that the inward-facing variation of the invention in FIG. 16 does not require an intermediate frame member **624** between individual cartridge sections **622**. Indeed, the electroactive polymer layers on each side of the device can contact one another. Thus, in situations where mounting space is limited, this variation of the invention may offer benefits. Further uses of this device configuration are also discussed below. Other biasing approaches for frustum-type actuators are, however, first described.

[0084] FIG. 17 is a sectional perspective view of a coil spring-biased single frustum transducer in accordance with one embodiment. Specifically, FIG. 17 provides a sectional perspective view of a coil spring-biased single frustum transducer **6130**. Here, a coil spring **6132** interposed between cap **642** and a baffle wall **6134** associated with the frame (or part of the frame itself) biases the electroactive polymer structure.

[0085] FIG. 18 is a schematic of a user **400** wearing a headphone **402** with ear cups **406** (only the left ear cup **406** is shown) intercoupled by a headband **404**. The headphones **402** comprise an electroactive polymer based noise cancellation system **410**. The left ear cup **406** is shown in partial cutaway view to show the internal components of the system in accordance with one embodiment. The noise cancellation system **410** comprises a microphone **408** located within a cavity defined by the ear cup **406**, and is preferably acoustically isolated from the speaker element. The system **410** further comprises circuitry **413** and an electroactive polymer actuator **401**.

[0086] The microphone **408** detects external noise waveform **416** such as low droning sounds, like car engines, airplane engines, air conditioners, etc. and feeds the signal into the circuitry **413**. The circuitry **413** inverts the phase of the

microphone 408 signal by 180 degrees. The inverted signal is used to drive the electroactive polymer actuator 401, which produces sound waves 418, which are equal in magnitude and inverted (180 degrees out-of-phase) from the external noise waveform 416. Accordingly, the sound pressure waves 418 generated by the electroactive polymer actuator 401 substantially cancel the sound pressure waves 416 detected by the microphone 408 by destructive interference as indicated by resultant noise waveform 420. In one embodiment, the microphone 408 is located within the cavity defined by the ear cup 406 and is acoustically isolated from both the electroactive polymer actuator 401 as well of the headphone speaker element. Locating the microphone 408 within the cavity defined by the ear cup 406 takes advantage of any passive noise cancellation provided by the construction of the ear cup 406, but would require careful acoustic isolation from the headphone 402 speaker and the electroactive polymer actuator 401. In one embodiment, the microphone 408 can be located external to the ear cup 408 with the advantage of being acoustically isolated from the headphone 402 speaker and the electroactive polymer actuator 401.

[0087] FIG. 19 is a schematic of the headphone 402 shown in FIG. 18 having an electroactive polymer based noise cancellation system 410, where the left ear cup 406 is shown in partial cutaway view to provide a more detailed view of the internal components thereof in accordance with one embodiment. The ear cups 406, 407 are intercoupled by the headband 404. As shown in FIG. 19, the microphone 408 is located within the cavity defined by the ear cup 406 and the circuitry 413 is located below the electroactive polymer actuator 401. Although only the details of the left ear cup 406 are shown, it will be appreciated that each ear cup 406, 407 includes identical noise cancellation systems 410.

[0088] In the embodiment illustrated in FIG. 19, the electroactive polymer actuator 401 is a multi-phase frustum-shaped diaphragm type actuator similar to those described in connection with FIGS. 11-17. Returning now to FIG. 19, accordingly, the electroactive polymer actuator 401 comprises a rigid frame 412 to support a first electroactive polymer membrane 438 and a diaphragm or cap 441.

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A second electroactive polymer membrane 439 and cap 443 (shown in FIG. 20) are located on the other side of the frame 412 to form the frustum shape previously discussed in FIGS. 11-17. Returning now to FIG. 19, the first electroactive polymer membrane 438 is coupled to the second electroactive polymer membrane by the top cap 441, the bottom cap, and a fastener 440 located therethrough. The first electroactive polymer membrane 438 and the second electroactive polymer membrane are electrically coupled to the driver electronic circuits by way of terminals 430, 432, 434, 436. To achieve proper action, first electroactive polymer membrane 438 and the second electroactive polymer membrane are driven by drive signals that are 180 degrees out-of-phase such that the membranes move in opposite directions. As shown, the first electroactive polymer membrane 438 is electrically coupled to terminals 432 (-A) and 436 (GND). The second electroactive polymer membrane is electrically coupled terminals 430 (+A) and 434 (GND). Thus, each membrane is driven by signals +A and -A that are out-of-phase with each other.

[0089] FIG. 20 is a partial cutaway perspective view of a multi-diaphragm frustum type electroactive polymer noise canceling actuator 401 in accordance with one embodiment. The multi-diaphragm frustum type electroactive polymer noise canceling actuator 401 comprises a rigid frame 412, 413 to support the first electroactive polymer membrane 438 and the second electroactive polymer membrane 439. The membranes 438, 439 are electrically coupled to terminals 432, 434 (the others 430, 436 shown in FIG. 19). First and second diaphragms or caps 441, 443 couple the two membranes in the center and are fastened by a fastener 440. Accordingly, as out-of-phase drive alternating current signals are applied to the membranes 438, 439, the diaphragms 441, 443 vibrate according to the amplitude and frequency of the drive signals. If properly tailored, the vibrations of the diaphragms 441, 443 are equal in amplitude but opposite in phase relative to the undesired ambient noise sensed by the microphone 408 (FIGS. 18, 19).

[0090] FIG. 21 is a block diagram of a circuit 410 configured to cancel noise generated by an external source 502 by destructive interference utilizing a multi-diaphragm frustum type electroactive polymer actuator 401 in accordance with one embodiment. Undesired background noise (either in the low frequency range 10Hz to 250Hz or the full audio frequency spectrum 10Hz to 20kHz) from an external noise source 502, such as car engines, airplane engines, air conditioners, etc. is coupled inside a cavity defined within the ear cup 406, 407. The microphone 408 is acoustically isolated from the electroactive polymer actuator 401 and the headphone speaker 524 by acoustic isolation wall 415 provided within the ear cup 406, 407.

[0091] Within the acoustically isolated chamber 506 the signal produced by the microphone 408, which represents the undesired background noise, is coupled to a first electroactive polymer driver circuit 510. The electroactive polymer actuator 401 is driven by first and second driver circuits 510, 514 that are 180 degrees out-of-phase. A phase inverter circuit 512 coupled between the output of the first driver circuit 510 and the input of the second driver circuit 514 provides the necessary phase inversion to suitably drive the electroactive polymer actuator 401. Accordingly, the electroactive polymer actuator 401 counteracts the effects of the background noise by destructive interference. Accordingly, the electroactive polymer actuator 401 actuator is sized to fit in the ear cups 406, 407 of an over the ear headphone and is capable of yielding frequency response in the low audio frequency range (e.g., 10Hz - 250Hz) combined with drive electronics 510, 512, 514 and signal needed to cancel out the undesired low frequency audio signals by destructive interference.

[0092] FIG. 22 is an illustrative representation of the concept of destructive interference, in accordance with one embodiment. The destructive interference results when sound pressures produced from a noise source characterized as a noise waveform 416 are combined with sound pressures produced by an electroactive polymer actuator characterized as anti-noise waveform 418 having the same amplitude and being 180 degrees out-of-phase from the noise waveform

416. Ideally, the destructive interference would completely eliminate the noise, however, due to real world limitations in frequency response of the various components of the noise reduction / elimination system, the resultant noise waveform 420 drops substantially, but could never be completely attenuated.

[0093] FIG. 23 is a block diagram of a circuit 410 configured to cancel noise generated by an external source by destructive interference utilizing a diaphragm type electroactive polymer actuator 401 in accordance with one embodiment. The diagram illustrated in FIG. 23, further shows the audio source 520 input into the ear cup 406, 407. The audio source 520 is coupled into an audio amplifier 522 which drives the headphone speaker element 524. The anti-noise vibrations produced by the electroactive polymer actuator 401 in response to the anti-noise waveform 418 destructively interfere with the external noise 416 coupled into the ear cups 406, 407.

[0094] FIG. 24 is a block diagram of a circuit 411 configured to cancel noise generated by an external source utilizing a single-diaphragm frustum type electroactive polymer noise canceling actuator 501 in accordance with one embodiment. Undesired background noise from an external noise source 502, such as car engines, airplane engines, air conditioners, etc. is coupled inside a cavity defined within the ear cup 406, 407. The microphone 408 is acoustically isolated from the electroactive polymer actuator 501 and the headphone speaker 524 by acoustic isolation wall 415 provided within the ear cup 406, 407. Within the acoustically isolated chamber 506 the signal produced by the microphone 408, which represents the undesired low frequency background noise, is coupled first to a phase inverter circuit 512 to obtain the necessary signal inversion and the inverted signal is coupled to the driver circuit 510. The electroactive polymer actuator 501 has either a single or a stack of membranes that are driven by a single driver source. Accordingly, the electroactive polymer actuator 401 counteracts the effects of the background noise by destructive interference. Accordingly, the electroactive polymer actuator 401 is sized to fit in the ear cups 406, 407 of an over the ear headphone and is capable of yielding frequency response in the low

audio frequency range (e.g., 10Hz - 250Hz) combined with drive electronics **510**, **512**, **514** and signal needed to cancel out the undesired low frequency audio signals by destructive interference.

[0095] FIG. 25 is a block diagram of a circuit configured to cancel noise generated by an external source utilizing a single-diaphragm **526** frustum type electroactive polymer actuator **501** actuator in accordance with one embodiment. The diagram illustrated in FIG. 25, further shows the audio source **520** input into the ear cup **406**, **407**. The audio source **520** is coupled into an audio amplifier **522** which drives the headphone speaker element **524**. The anti-noise vibrations produced by the single diaphragm **526** electroactive polymer actuator **501** in response to the anti-noise waveform **418** destructively interfere with the external noise **416** coupled into the ear cups **406**, **407**.

[0096] It is to be appreciated that the embodiments described herein illustrate example implementations, and that the functional elements, logical blocks, program modules, and circuit elements may be implemented in various other ways which are consistent with the described embodiments. Furthermore, the operations performed by such functional elements, logical blocks, program modules, and circuits elements may be combined and/or separated for a given implementation and may be performed by a greater number or fewer number of components or program modules. As will be apparent to those of skill in the art upon reading the present disclosure, each of the individual embodiments described and illustrated herein has discrete components and features which may be readily separated from or combined with the features of any of the other several embodiments without departing from the scope of the present disclosure. Any recited method can be carried out in the order of events recited or in any other order which is logically possible.

[0097] Although certain modules and/or blocks may be described by way of example, it can be appreciated that a greater or lesser number of modules and/or blocks may be used and still fall within the scope of the embodiments. Further, although various embodiments may be described in terms of modules and/or

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blocks to facilitate description, such modules and/or blocks may be implemented by one or more hardware components (e.g., processors, digital signal processors, programmable logic devices, application-specific integrated circuits, circuits, registers), software components (e.g., programs, subroutines, logic) and/or combination thereof.

[0098] While the examples above have referred to use of the present invention in headphones, other audio applications can also benefit from the electroactive polymer actuator noise cancellation. The present invention is particularly advantageous to large area audio applications such as office cubicles, automobile interiors, and aircraft cabins, which are subject to significant ambient or background noise. In such cases, a plurality of electroactive polymer transducers may be arranged across a surface or in multiple locations to provide noise reduction throughout a larger space such as an office cubicle or at a particular location such as the region around the head of the driver of an automobile. The transducers may be operated as one group, as multiple groups, or individually. It may be desirable to use a plurality of microphones in the latter two cases. The signals from microphones in different locations may be combined to optimize the noise cancellation response.

[0099] One embodiment of a transducer design that can be used in large area applications is shown in FIG. 26 which illustrates a cross-sectional side view of a monolithic diaphragm device **1130** comprising a monolithic polymer **1131** before deflection in accordance with one embodiment of the present invention. The polymer **1131** is attached to a frame **1132**. The frame **1132** includes apertures **1133A** and **1133B** that allow deflection of polymer portions **1131A** and **1131B** perpendicular to the area of the apertures **1133A** and **1133B**, respectively. The diaphragm device **1130** comprises electrodes **1134A** and **1134B** attached on either side of the portion **1131A** to provide a voltage difference across the portion **1131A**. Electrodes **1136A** and **1136B** are deposited on either side of the portion **1131B** to provide a voltage difference across the portion **1131B**. The electrodes **1134** and **1136** are compliant and change shape with polymer **1131** as it deflects.

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In the voltage-off configuration, polymer **1131** is stretched and secured to frame **1132** with tension to achieve pre-strain.

[0100] Using electrodes **1134** and **1136**, portions **1131A** and **1131B** are capable of independent deflection. For example, upon application of a suitable voltage between electrodes **1134A** and **1134B**, portion **1131A** expands away from the plane of the frame **1132**. Each of the portions **1131A** and **1131B** is capable of expansion in both perpendicular directions away from the plane. In one embodiment, one side of polymer **1131** comprises a bias pressure that influences the expansion of the polymer film **1131** to continually actuate upward in the direction of arrows **1143**.

[0101] The transducers shown in FIG. 26 may be arranged in an array suitable for large area applications as shown in an exploded perspective view in FIG. 27A and in an assembled, perspective view in FIG. 27B. A single film **56** of silicone rubber of uniform thickness is placed over a matrix or grid **58** of circular holes. Alternatively, the holes may be other shapes such as slots or squares. The size and shape of the holes is determined by the application, but they typically range in size from 1-5 millimeters. The rubber film is coated with compliant electrodes. Other elastomeric dielectric polymers, for example, fluorosilicone, polyurethane fluoroelastomer, natural rubber, polybutadiene, nitrile rubber, isoprene, polyurethane, and ethylene propylene diene may be used in place of silicone.

[0102] The whole grid is made of a lightweight material, such as a plastic that is much stiffer than the silicone rubber. Alternatively, it may be an elastomer itself, provided it is sufficiently stiff to support the polymer film actuator with negligible deflection during actuation.

[0103] The vacuum plenum allows for the imposition of a bias pressure while simultaneously acting as a resonance cavity. Elastomeric gaskets **62** and **64** seal the film and grid **58** to the face plate **66** and plenum plate **68**, respectively. When assembled, the plenum **70** defined by the plenum plate **68** and the membrane may be evacuated by a vacuum or negative pressure source to provide the bias

pressure. Only a slight reduction in the internal pressure of plenum is generally needed relative to the surrounding atmosphere.

[0104] Multiple small assemblies of the type in FIG. 27B may be tiled to cover a larger area. The components in FIG. 27 may be shaped or conformable to enable non-planar configurations.

[0105] FIG. 28 shows an alternate embodiment of the present invention. In this case, the desired bias pressure is positive rather than negative relative to the surrounding atmosphere, and can be supplied, for example, using a positive pressure source rather than a vacuum source. More particularly, the membrane 72 is attached to a support structure 74 having a plurality of apertures 76. The support structure 74 is attached to a plenum plate 78 to form the plenum 80 behind the bubbles 82.

[0106] Although thinner films would allow for lower operating voltages, their fragility becomes an issue for a practical transducer. However, by using a film stack of multiple layers separated by electrodes, the low voltage operation of a thin film and the ruggedness and greater energy output of a thicker film can be combined. FIG. 28A is a magnified view of a section 85 (FIG. 28) illustrating this "sandwich" structure of alternating conductive layers 84 and dielectric layers 86.

[0107] In one embodiment shown in FIG. 29, an alternative to a plenum pressurized with air is to apply a bias pressure to the polymer film using a soft foam 88. The foam is closed-cell with the cell size much less than the diameter of the film bubble 90. The foam is pressed against the undersurface 92 of the polymer film 94. A backing plate or sheet 96 is located under the foam. Bolts, rivets 98, stitching or adhesives would attach the backing plate 96 to the grid and thereby squeeze the foam against the polymer film. The holes 100 through the polymer film of sheet 96 for these rivets 98 can be seen in FIG. 29. The holes are provided to prevent the rivets from creating electrical shorts in the membrane 94. The rivets are located at a spacing sufficient to provide a uniform pressure on the foam and are located between active bubbles. The amount of bias pressure

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applied by the foam is selected to give the desired initial bubble shape and can be selected based on the stiffness of the foam and the amount of foam compression. An extremely soft, low-creep foam, such as made from silicone or natural rubber, is preferred because it is desirable that the bubble shape not change significantly over time.

[0108] The acoustic transducer of the present invention may be manufactured as a single block, tile or panel. Many of such tiles can be combined into a sheet and applied to a surface to form a conformal covering. The size of the tiles is determined by manufacturing considerations, and may be quite small (e.g. 1 cm²) or relatively large (e.g. 100 cm²). A tile therefore includes a number of acoustic elements (e.g. "bubbles") in a related physical structure. Individual tiles may be electrically coupled to adjacent tiles, or may be electrically isolated from adjacent tiles.

[0109] If the plenum is relatively flexible, such as sheet metal or sheet plastic, and the grid is correspondingly made of a flexible material, then a single larger tile can be used to conformally cover simple curved surfaces such as a cylinder. Further, if both the grid and plenum can be stretched (e.g. they are elastomeric materials), then conformal coverings of relatively large areas can be made on even complex curved surfaces such as spheres.

[0110] FIG. 30 shows a cross-sectional view of a flat panel diaphragm acoustic element comprising electroactive polymer diaphragm transducers 367 where the electroactive polymer diaphragms are biased using an insert of open pore foam 397. The speaker 365 comprises a grid plate 369, six diaphragm transducers 367 and a substrate 368 enclosed in a frame 316. Substrate 368 may be a screen which allows air exchange between the lower chamber 387 and the bias material 397. The grid plate 369 includes apertures for accommodating the diaphragms. The substrate 368 is used to hold the foam in place. In one embodiment, the foam may extend to the bottom of a lower chamber 387 and the screen may not be used.

[0111] While the examples above all show simple diaphragm transducers, the frustum and double frustum configurations described previously may also be used. The multiple transducers may be arranged as a regular array as shown or may be located as necessary to optimize the noise cancellation response. In some cases, it may be possible to combine the responses through constructive or destructive interference to optimize the noise cancellation response. The individual transducers in a noise cancellation system may have different properties such as size, film thickness, or stiffness, to optimize their response for different frequency ranges.

[0112] Numerous specific details have been set forth herein to provide a thorough understanding of the embodiments. It will be understood by those skilled in the art, however, that the embodiments may be practiced without these specific details. In other instances, well-known operations, components and circuits have not been described in detail so as not to obscure the embodiments. It can be appreciated that the specific structural and functional details disclosed herein may be representative and do not necessarily limit the scope of the embodiments.

[0113] It is worthy to note that any reference to “one embodiment” or “an embodiment” means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. The appearances of the phrase “in one embodiment” or “in one aspect” in the specification are not necessarily all referring to the same embodiment.

[0114] Also worthy of note is that some embodiments may be described using the expression “coupled” and “connected” along with their derivatives. These terms are not intended as synonyms for each other. For example, some embodiments may be described using the terms “connected” and/or “coupled” to indicate that two or more elements are in direct physical or electrical contact with each other. The term “coupled,” however, may also mean that two or more elements are not in direct contact with each other, but yet still co-operate or interact with each other.

[0115] It will be appreciated that those skilled in the art will be able to devise various arrangements which, although not explicitly described or shown herein, embody the principles of the present disclosure and are included within the scope thereof. Furthermore, all examples and conditional language recited herein are principally intended to aid the reader in understanding the principles described in the present disclosure and the concepts contributed to furthering the art, and are to be construed as being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, embodiments, and embodiments as well as specific examples thereof, are intended to encompass both structural and functional equivalents thereof. Additionally, it is intended that such equivalents include both currently known equivalents and equivalents developed in the future, i.e., any elements developed that perform the same function, regardless of structure. The scope of the present disclosure, therefore, is not intended to be limited to the exemplary embodiments and embodiments shown and described herein. Rather, the scope of present disclosure is embodied by the appended claims.

[0116] The terms “a” and “an” and “the” and similar referents used in the context of the present disclosure (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. Recitation of ranges of values herein is merely intended to serve as a shorthand method of referring individually to each separate value falling within the range. Unless otherwise indicated herein, each individual value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., “such as,” “in the case,” “by way of example”) provided herein is intended merely to better illuminate the invention and does not pose a limitation on the scope of the invention otherwise claimed. No language in the specification should be construed as indicating any non-claimed element essential to the practice of the

invention. It is further noted that the claims may be drafted to exclude any optional element. As such, this statement is intended to serve as antecedent basis for use of such exclusive terminology as solely, only and the like in connection with the recitation of claim elements, or use of a negative limitation.

[0117] Groupings of alternative elements or embodiments disclosed herein are not to be construed as limitations. Each group member may be referred to and claimed individually or in any combination with other members of the group or other elements found herein. It is anticipated that one or more members of a group may be included in, or deleted from, a group for reasons of convenience and/or patentability.

[0118] While certain features of the embodiments have been illustrated as described above, many modifications, substitutions, changes and equivalents will now occur to those skilled in the art. It is therefore to be understood that the appended claims are intended to cover all such modifications and changes as fall within the scope of the disclosed embodiments and appended claims.

[0119] Various aspects of the subject matter described herein are set out in the following numbered clauses:

[0120] 1. A noise canceling system, the system comprising, at least one microphone configured to detect a first acoustic signal generated by a source external to the headphone and to produce a first electrical signal corresponding to the first acoustic signal, the first electrical signal having an amplitude, frequency, and phase representative of the first acoustic signal, and at least one electroactive polymer transducer electrically coupled to the microphone and configured to receive a second electrical signal having an amplitude and frequency substantially equal to the amplitude and frequency of the first electrical signal and a phase that is 180 degrees out-of-phase with the first electrical signal, wherein the electroactive polymer actuator is configured to move in response to the second electrical signal and produce a second acoustic signal having an amplitude and

frequency substantially equal to the first acoustic signal and a phase that is about 180 degrees out-of-phase with the first acoustic signal.

[0121] 2. The noise canceling system according to clause 1, wherein the at least one electroactive polymer transducer has a frequency response in the range of about 10Hz to about 250Hz.

[0122] 3. The noise canceling system according to clause 1, wherein the at least one electroactive polymer actuator has a frequency response in the range of about 10Hz to about 20kHz.

[0123] 4. The noise canceling system according to any one of clauses 1 to 3, wherein the at least one electroactive polymer transducer comprises at least one selected from the group consisting of a diaphragm supported by a frame, a frustum-shaped diaphragm supported by a rigid frame, and a pair of frustum-shaped diaphragms supported by a rigid frame and joined in a center portion of the diaphragms by oppositely positioned caps and a fastener therebetween.

[0124] 5. The noise canceling system according to any one of clauses 1 to 4, further comprising a driver circuit coupled between the microphone and the electroactive polymer transducer, the driver circuit configured to receive the second electrical signal and produce an electrical drive signal to electroactive polymer actuator.

[0125] 6. The noise canceling system according to any one of clauses 1 to 5, further comprising a phase inverter circuit coupled between the microphone and the driver circuit, the phase inverter circuit the first electrical signal and produce the second electrical signal.

[0126] 7. The noise canceling system according to any one of clauses 1 to 6, further comprising, at least two frustum-shaped diaphragms supported by a rigid frame and joined in a center portion of the diaphragms by oppositely positioned caps and a fastener therebetween, a first driver circuit coupled to the microphone and to at least one of the at least two frustum-shaped diaphragms of the electroactive polymer actuator, the first driver circuit configured to receive the

first electrical signal and to generate a first electrical drive signal to drive at least one of the at least two frustum-shaped diaphragms with the first electrical drive signal, and a second driver circuit coupled to a phase inverter circuit and to the at least one other of the at least two frustum-shaped diaphragms of the electroactive polymer actuator, the second driver circuit configured to receive an electrical signal that is 180 degrees out-of-phase with the first electrical drive signal and to generate a second electrical drive signal to drive at least one other of the at least two frustum-shaped diaphragms with the second electrical drive signal, wherein the first and second electrical drive signals are 180 degrees out-of-phase with each other.

[0127] 8. The noise canceling system according to any one of clauses 1 to 7, further comprising a plurality of electroactive polymer transducers wherein the plurality of electroactive polymer actuators is arranged to optimize the noise cancellation response.

[0128] 9. The noise canceling system according to clause 8, wherein individual transducers in the plurality of electroactive polymer transducers have been optimized to have different frequency responses.

[0129] 10. The noise canceling system according to any one of clauses 1 to 9, further comprising a plurality of microphones wherein the signals from the plurality of microphones are combined to optimize the noise cancellation response.

[0130] 11. A headphone including the noise canceling system according to any one of clauses 1 to 10.

[0131] 12. The headphone according to clause 11, wherein the electroactive polymer actuator is configured to move in a direction that is parallel with the displacement of a speaker element of the headphone.

[0132] 13. The headphone according to one of clauses 11 and 12, further comprising an ear cup defining a cavity.

[0133] 14. The headphone according to any one of clauses 11 to 13, wherein the microphone is located within a cavity defined by the ear cup.

[0134] 15. The headphone according to any one of clauses 11 to 14, further comprising an acoustic isolation wall located within a cavity defined by the ear cup.

[0135] 16. The headphone according to clause 15, wherein the acoustic isolation wall is configured to isolate the microphone from at least one chosen from the group of the electroactive polymer actuator and a speaker element of the headphones.

[0136] 17. A method of canceling noise in an over-the-ear headphone, the method comprising, receiving, at a microphone, a first acoustic signal, producing a first electrical signal corresponding to the first acoustic signal, the first electrical signal having an amplitude, frequency, and phase representative of the first acoustic signal, producing a second electrical signal having an amplitude and frequency substantially equal to the amplitude and frequency of the first electrical signal and a phase that is 180 degrees out-of-phase with the first electrical signal; and driving an electroactive polymer actuator with the second electrical signal to move the electroactive polymer actuator in response to the second electrical signal and produce a second acoustic signal having an amplitude and frequency substantially equal to the first acoustic signal and a phase that is about 180 degrees out-of-phase with the first acoustic signal.

[0137] 18. The method according to clause 17, further comprising driving the electroactive polymer actuator at a frequency in the range of about 10Hz to about 250Hz.

[0138] 19. The method according to clause 17, further comprising driving the electroactive polymer actuator at a frequency in the range of about 10Hz to about 20kHz.

[0139] 20. The method of canceling noise according to any one of clauses 17 to 19, wherein a phase inverter circuit is coupled between the microphone and the

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electroactive polymer actuator, the method comprising, receiving the first electrical signal by a phase inverter circuit coupled between the microphone and the electroactive polymer actuator, and inverting the phase of the first electrical signal to produce the second electrical signal that is 180 degrees out-of-phase relative to the first electrical signal.

WHAT IS CLAIMED IS:

1. A noise canceling system, the system comprising:
at least one microphone configured to detect a first acoustic signal generated by a source external to the headphone and to produce a first electrical signal corresponding to the first acoustic signal, the first electrical signal having an amplitude, frequency, and phase representative of the first acoustic signal; and
at least one electroactive polymer transducer electrically coupled to the microphone and configured to receive a second electrical signal having an amplitude and frequency substantially equal to the amplitude and frequency of the first electrical signal and a phase that is 180 degrees out-of-phase with the first electrical signal, wherein the electroactive polymer actuator is configured to move in response to the second electrical signal and produce a second acoustic signal having an amplitude and frequency substantially equal to the first acoustic signal and a phase that is about 180 degrees out-of-phase with the first acoustic signal.
2. The noise canceling system according to Claim 1, wherein the at least one electroactive polymer transducer has a frequency response in the range of about 10Hz to about 250Hz.
3. The noise canceling system according to Claim 1, wherein the at least one electroactive polymer actuator has a frequency response in the range of about 10Hz to about 20kHz.
4. The noise canceling system according to any one of Claims 1 to 3, wherein the at least one electroactive polymer transducer comprises at least one selected from the group consisting of a diaphragm supported by a frame, a frustum-shaped diaphragm supported by a rigid frame, and a pair of frustum-shaped diaphragms supported by a rigid frame and joined in a center portion of the diaphragms by oppositely positioned caps and a fastener therebetween.

5. The noise canceling system according to any one of Claims 1 to 4, further comprising a driver circuit coupled between the microphone and the electroactive polymer transducer, the driver circuit configured to receive the second electrical signal and produce an electrical drive signal to electroactive polymer actuator.

6. The noise canceling system according to any one of Claims 1 to 5, further comprising a phase inverter circuit coupled between the microphone and the driver circuit, the phase inverter circuit the first electrical signal and produce the second electrical signal.

7. The noise canceling system according to any one of Claims 1 to 6, further comprising:

at least two frustum-shaped diaphragms supported by a rigid frame and joined in a center portion of the diaphragms by oppositely positioned caps and a fastener therebetween;

a first driver circuit coupled to the microphone and to at least one of the at least two frustum-shaped diaphragms of the electroactive polymer actuator, the first driver circuit configured to receive the first electrical signal and to generate a first electrical drive signal to drive at least one of the at least two frustum-shaped diaphragms with the first electrical drive signal; and

a second driver circuit coupled to a phase inverter circuit and to the at least one other of the at least two frustum-shaped diaphragms of the electroactive polymer actuator, the second driver circuit configured to receive an electrical signal that is 180 degrees out-of-phase with the first electrical drive signal and to generate a second electrical drive signal to drive at least one other of the at least two frustum-shaped diaphragms with the second electrical drive signal; wherein the first and second electrical drive signals are 180 degrees out-of-phase with each other.

8. The noise canceling system according to any one of Claims 1 to 7, further comprising a plurality of electroactive polymer transducers wherein the plurality

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of electroactive polymer actuators is arranged to optimize the noise cancellation response.

9. The noise canceling system according to Claim 8, wherein individual transducers in the plurality of electroactive polymer transducers have been optimized to have different frequency responses.
10. The noise canceling system according to any one of Claims 1 to 9, further comprising a plurality of microphones wherein the signals from the plurality of microphones are combined to optimize the noise cancellation response.
11. A headphone including the noise canceling system according to any one of Claims 1 to 10.
12. The headphone according to Claim 11, wherein the electroactive polymer actuator is configured to move in a direction that is parallel with the displacement of a speaker element of the headphone.
13. The headphone according to one of Claims 11 and 12, further comprising an ear cup defining a cavity.
14. The headphone according to any one of Claims 11 to 13, wherein the microphone is located within a cavity defined by the ear cup.
15. The headphone according to any one of Claims 11 to 14, further comprising an acoustic isolation wall located within a cavity defined by the ear cup.
16. The headphone according to Claim 15, wherein the acoustic isolation wall is configured to isolate the microphone from at least one chosen from the group of the electroactive polymer actuator and a speaker element of the headphones.

17. A method of canceling noise in an over-the-ear headphone, the method comprising:

receiving, at a microphone, a first acoustic signal;

producing a first electrical signal corresponding to the first acoustic signal, the first electrical signal having an amplitude, frequency, and phase representative of the first acoustic signal;

producing a second electrical signal having an amplitude and frequency substantially equal to the amplitude and frequency of the first electrical signal and a phase that is 180 degrees out-of-phase with the first electrical signal; and

driving an electroactive polymer actuator with the second electrical signal to move the electroactive polymer actuator in response to the second electrical signal and produce a second acoustic signal having an amplitude and frequency substantially equal to the first acoustic signal and a phase that is about 180 degrees out-of-phase with the first acoustic signal.

18. The method according to Claim 17, further comprising driving the electroactive polymer actuator at a frequency in the range of about 10Hz to about 250Hz.

19. The method according to Claim 17, further comprising driving the electroactive polymer actuator at a frequency in the range of about 10Hz to about 20kHz.

20. The method of canceling noise according to any one of Claims 17 to 19, wherein a phase inverter circuit is coupled between the microphone and the electroactive polymer actuator, the method comprising:

receiving the first electrical signal by a phase inverter circuit coupled between the microphone and the electroactive polymer actuator; and

inverting the phase of the first electrical signal to produce the second electrical signal that is 180 degrees out-of-phase relative to the first electrical signal.

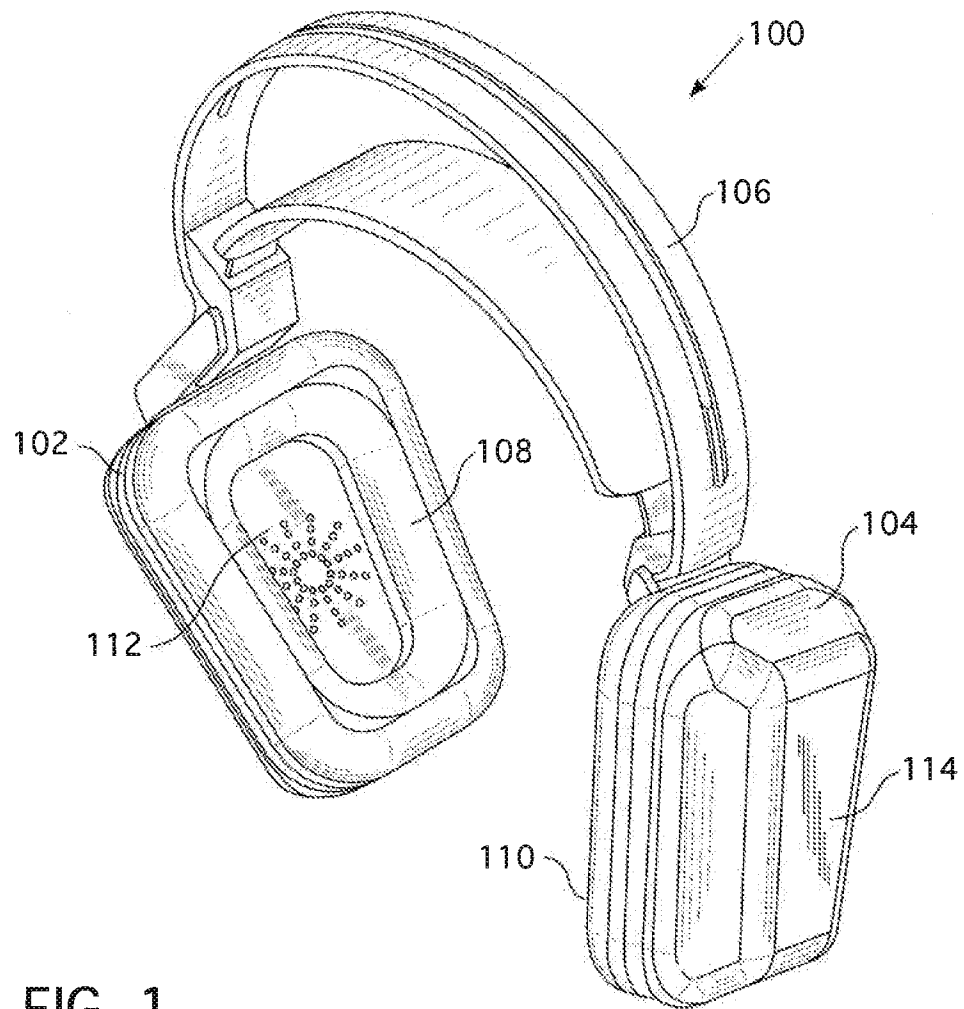


FIG. 1

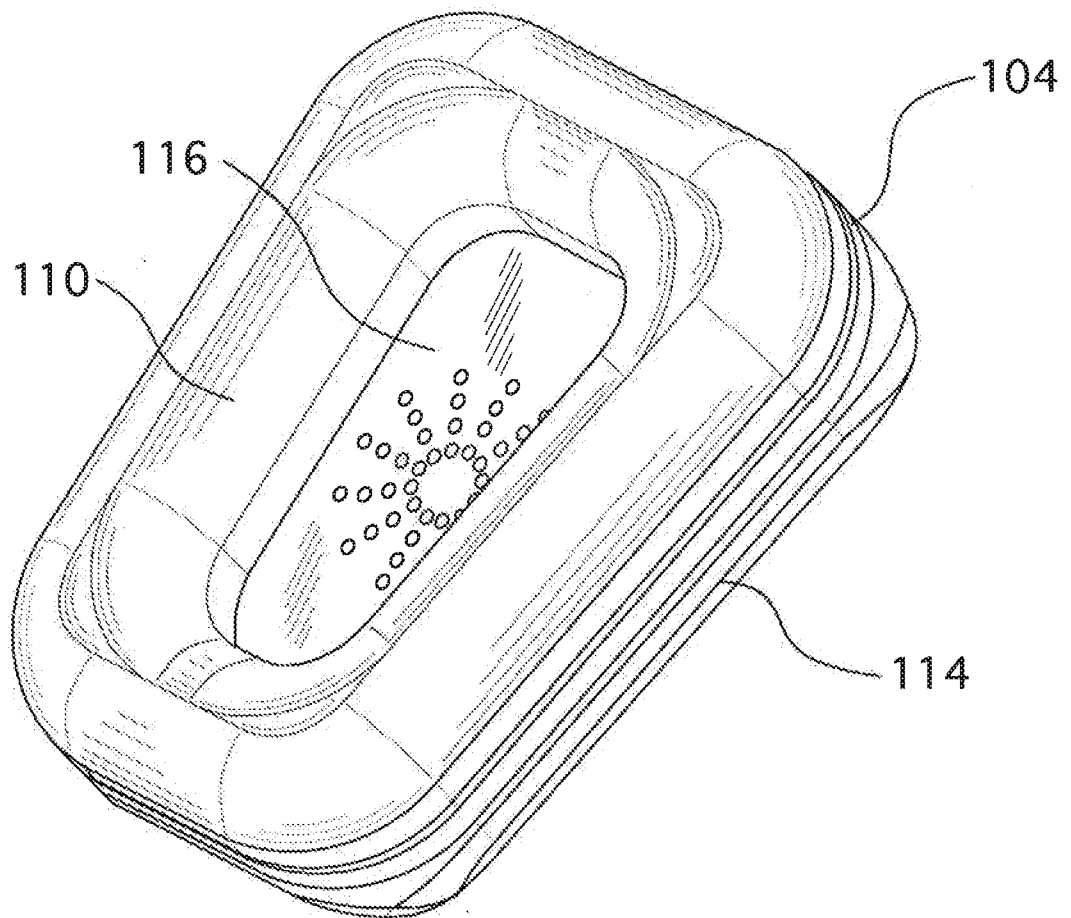


FIG. 2

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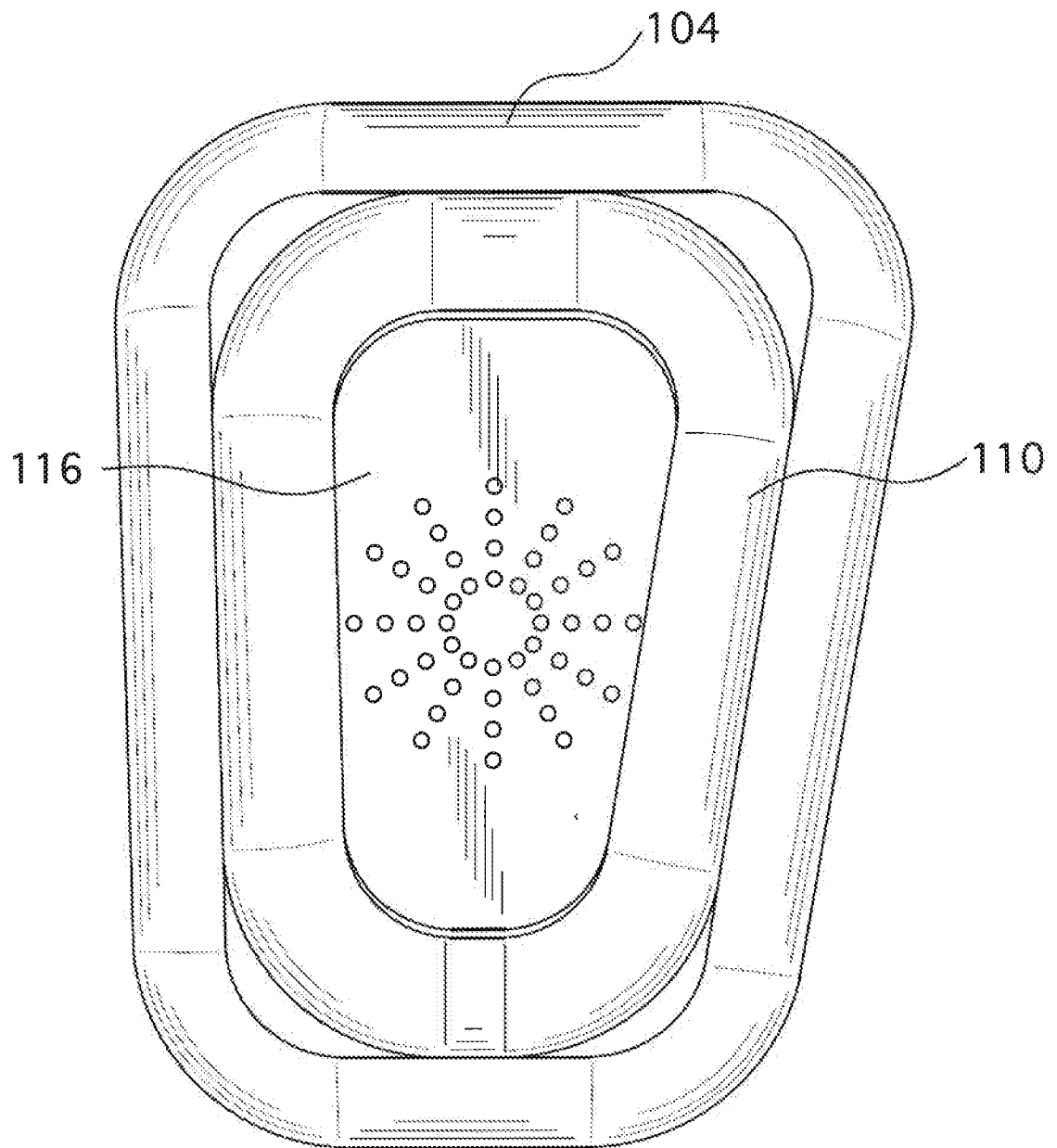
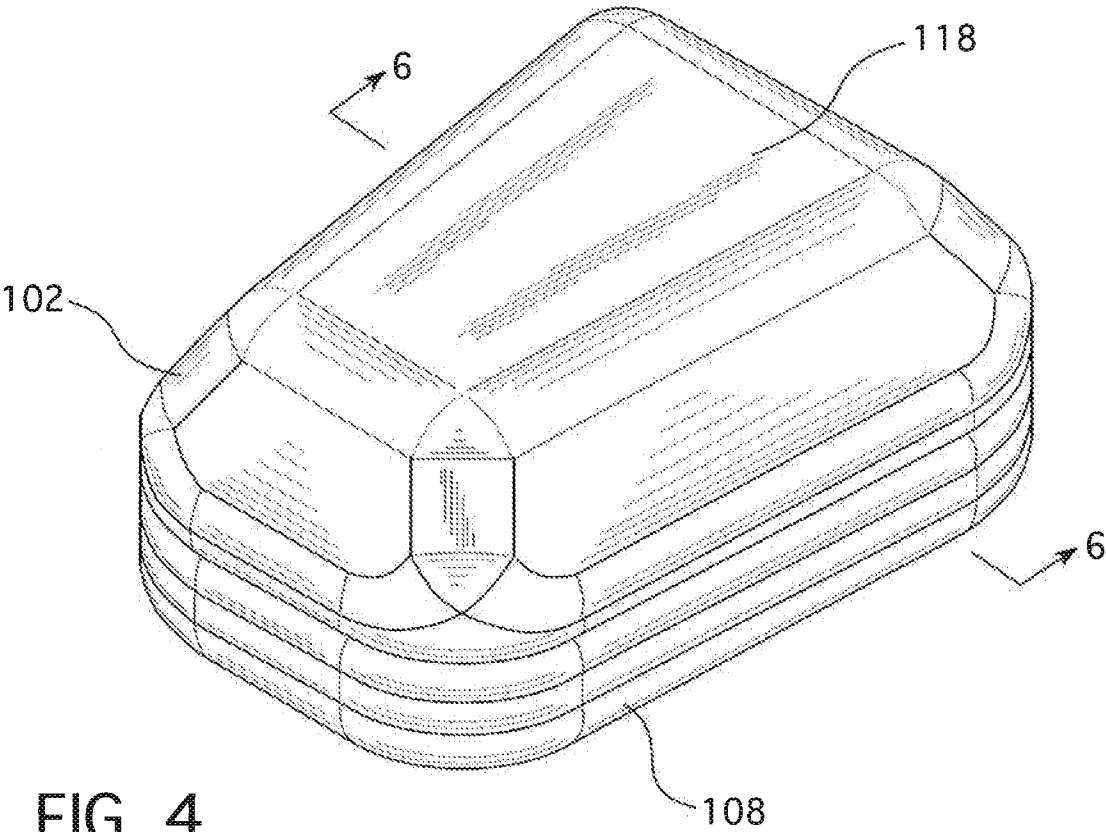


FIG. 3



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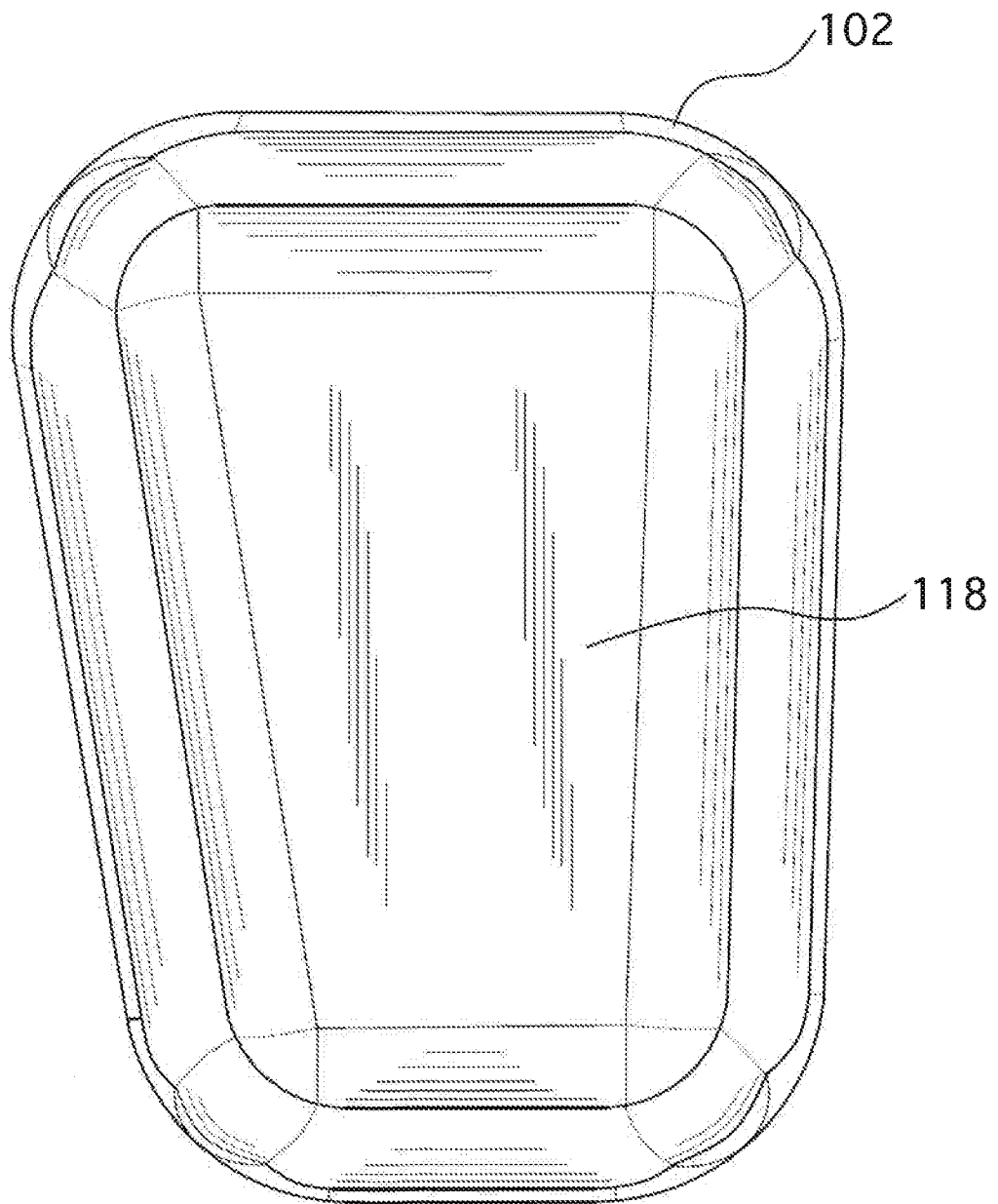


FIG. 5

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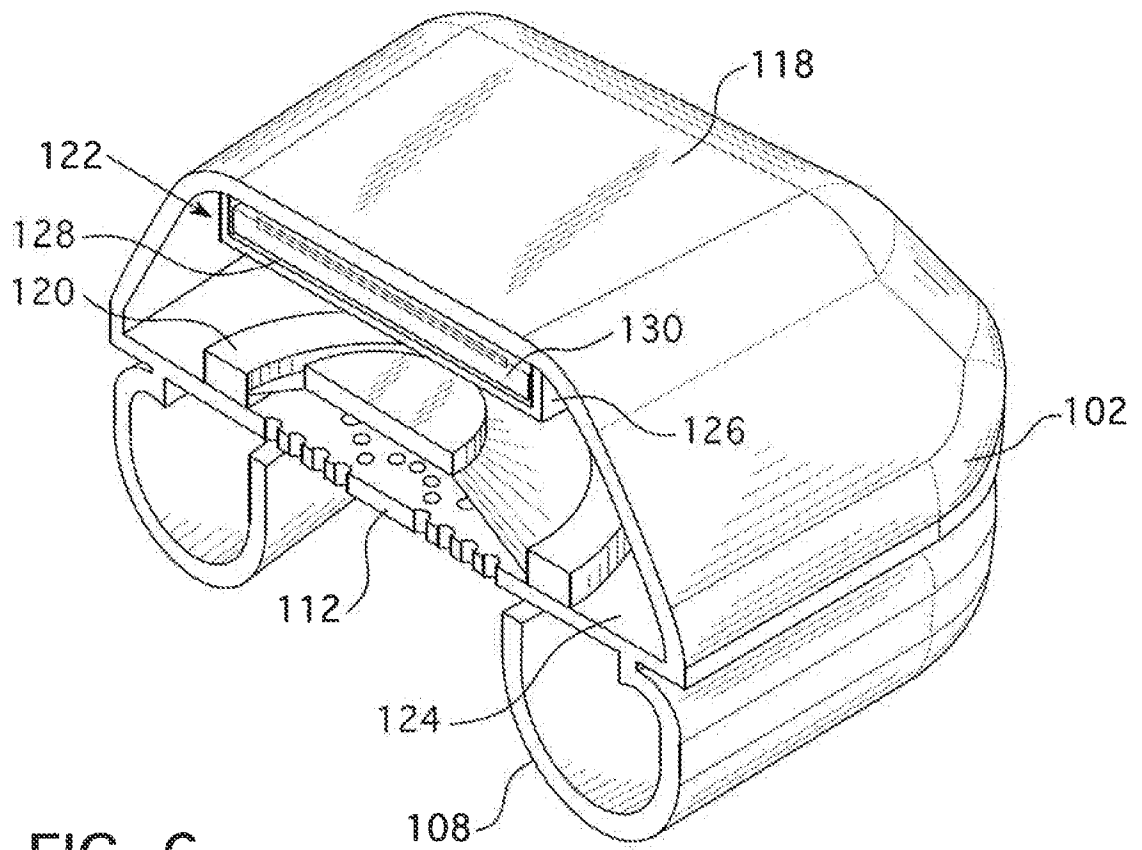


FIG. 6

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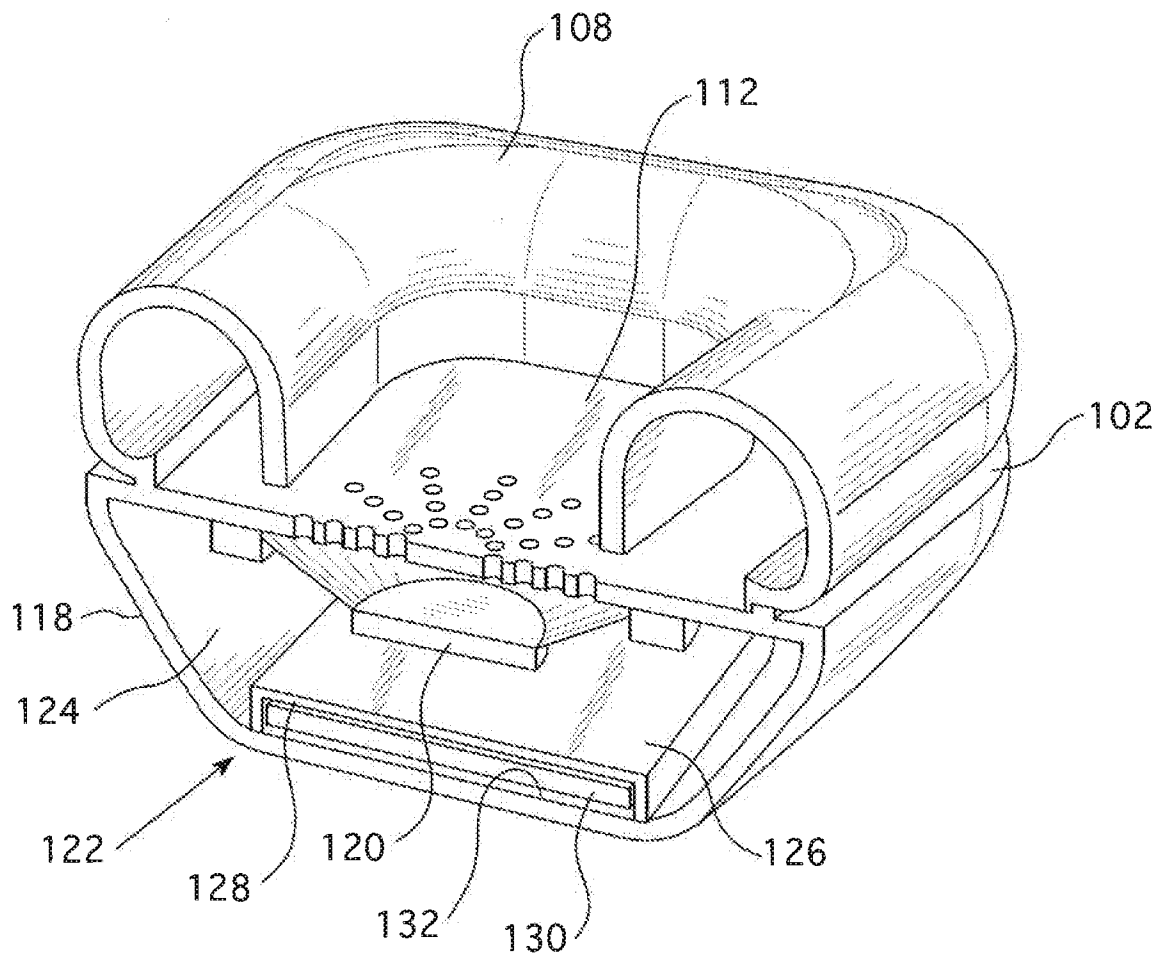


FIG. 7

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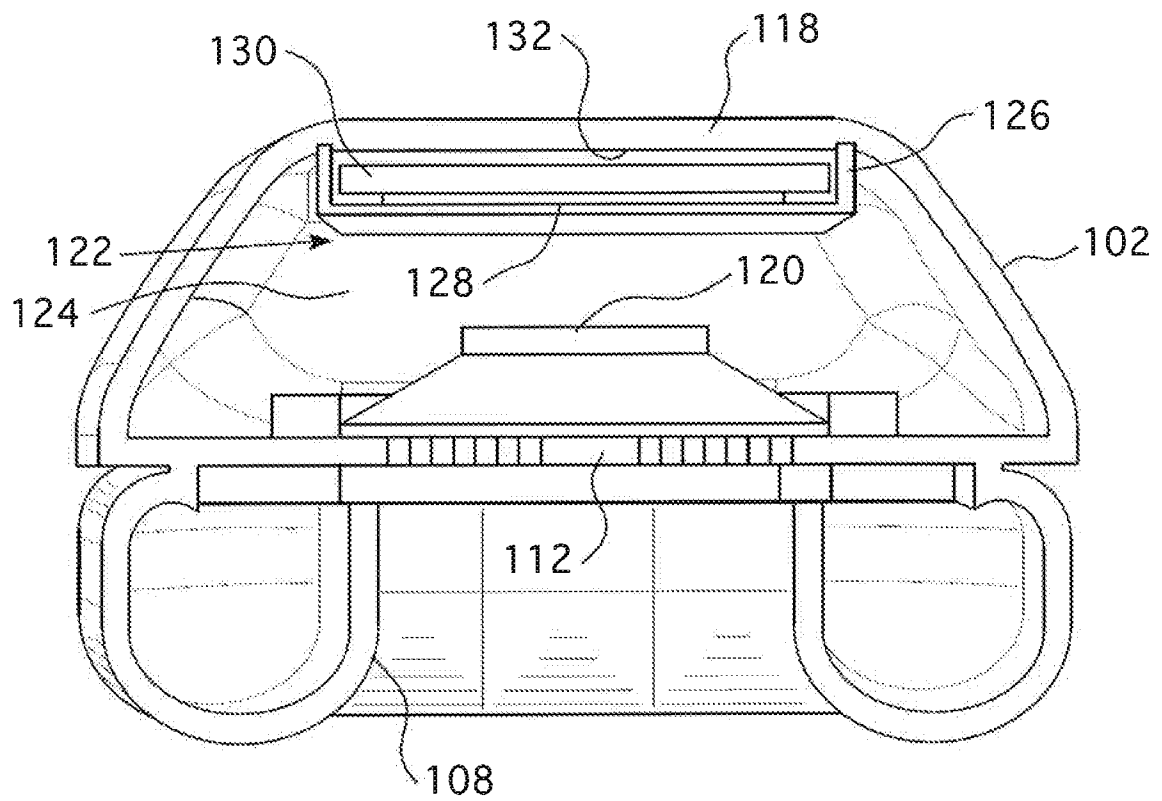


FIG. 8

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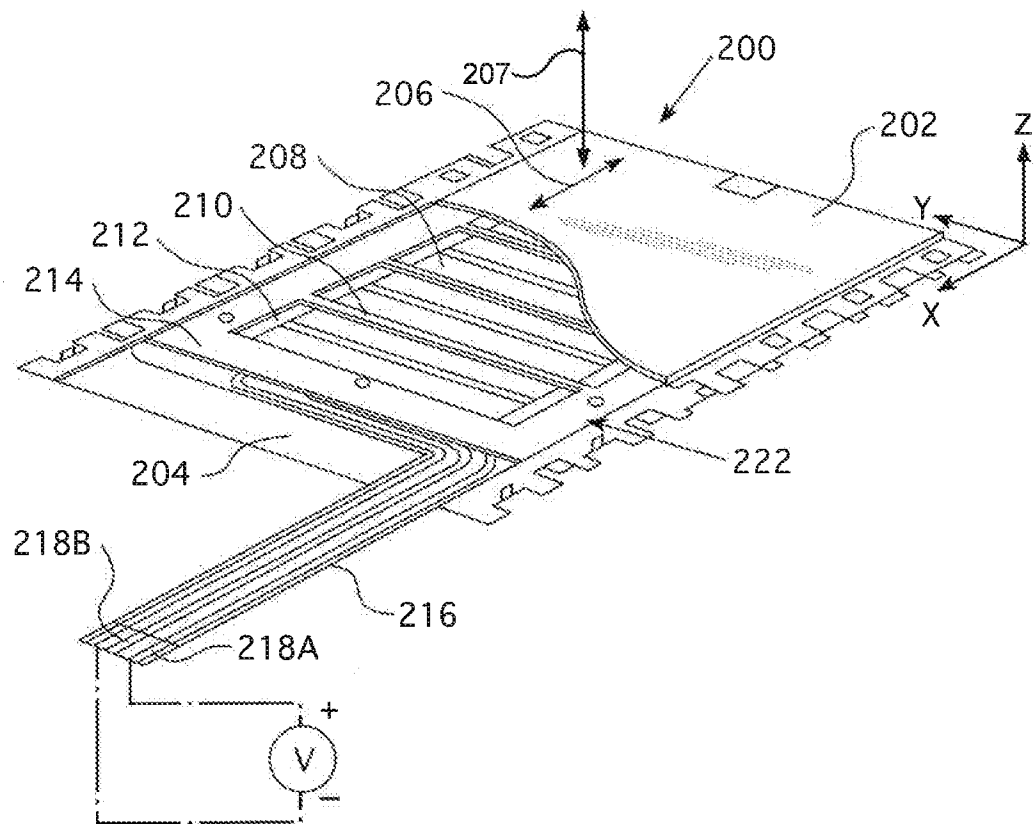


FIG. 9

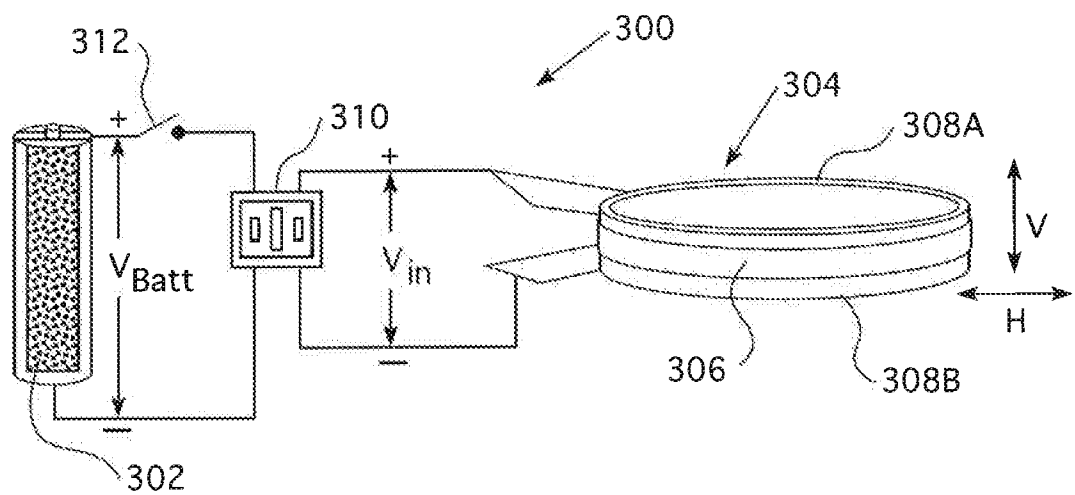


FIG. 10

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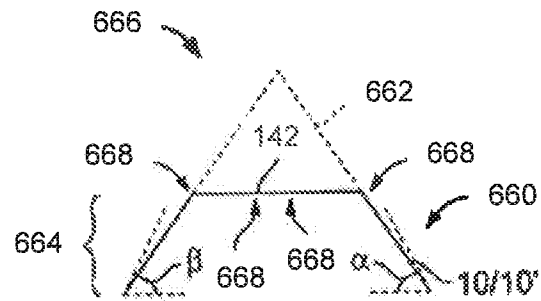


FIG. 11A

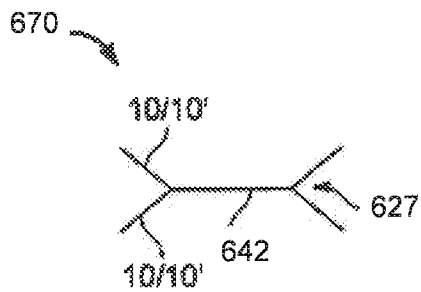


FIG. 11B

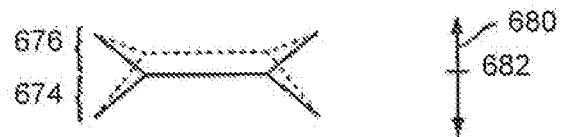


FIG. 11C

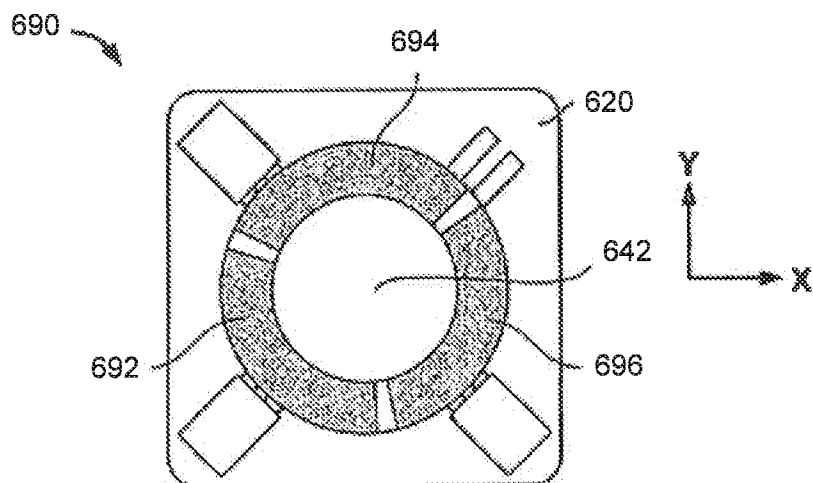


FIG. 12

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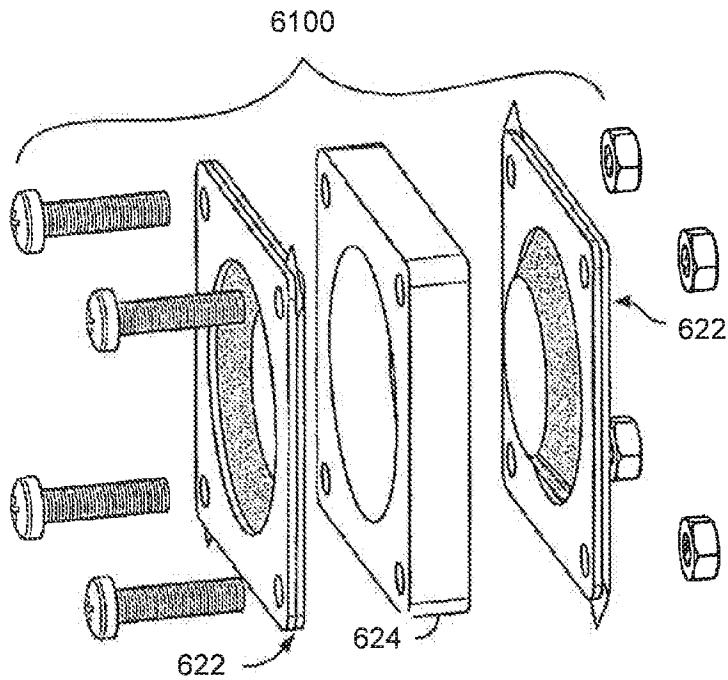


FIG. 13A

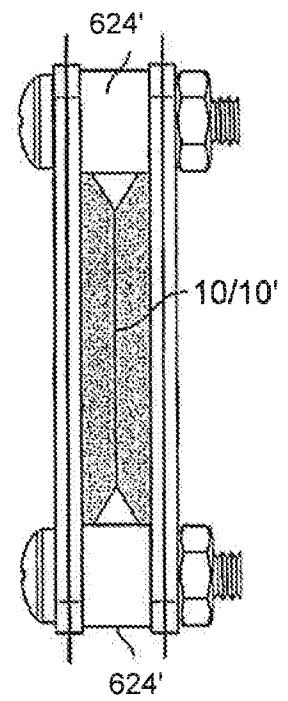


FIG. 13B

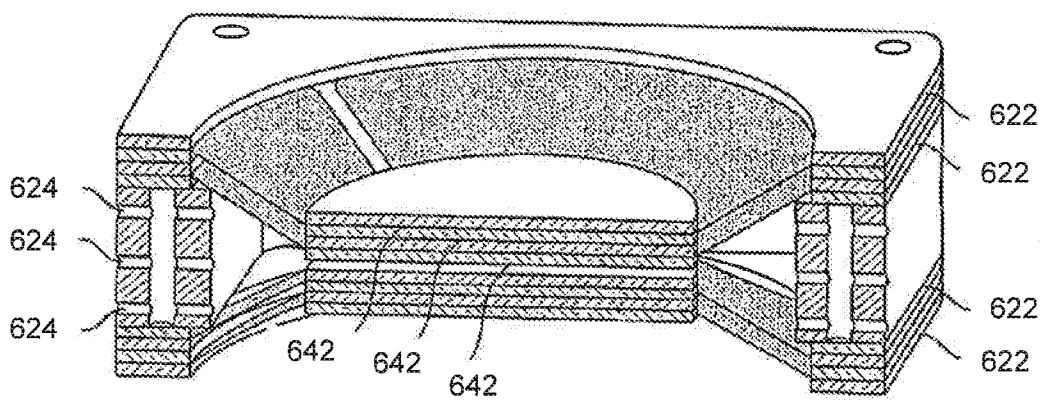


FIG. 14

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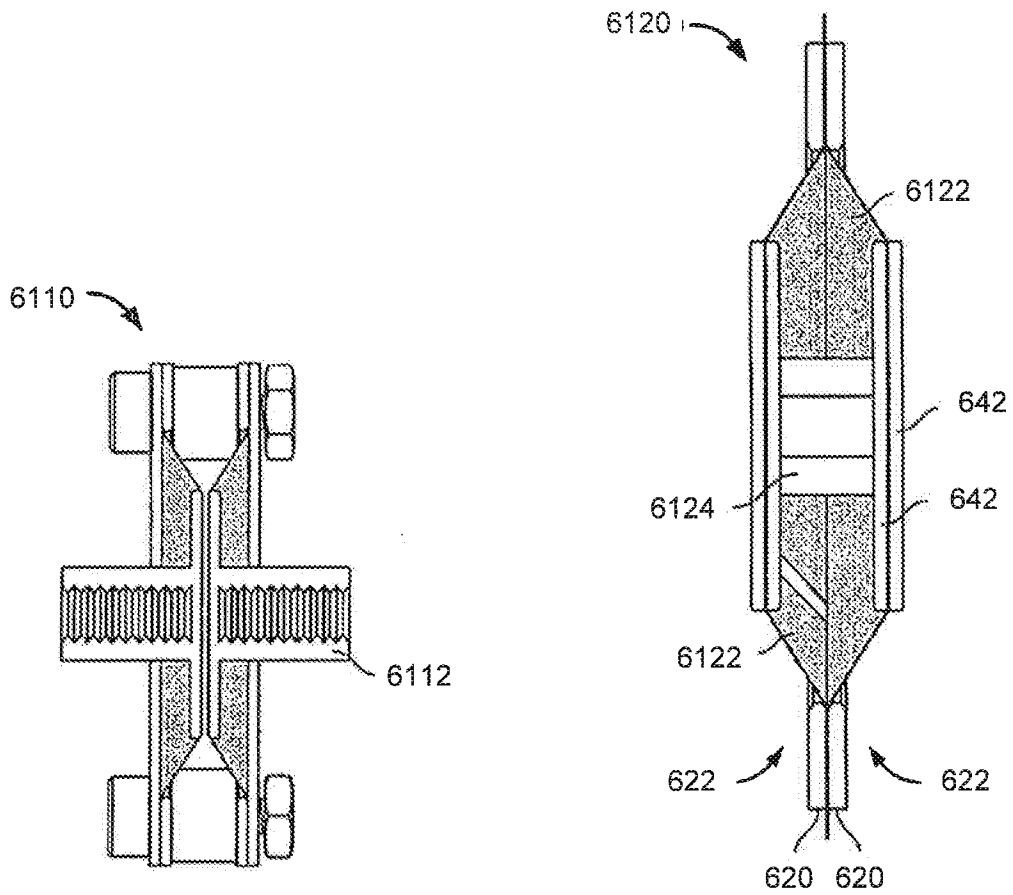


FIG. 15

FIG. 16

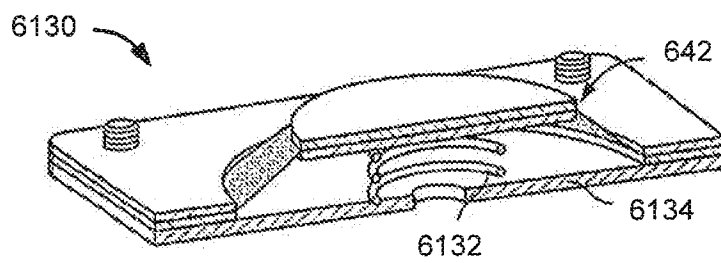


FIG. 17

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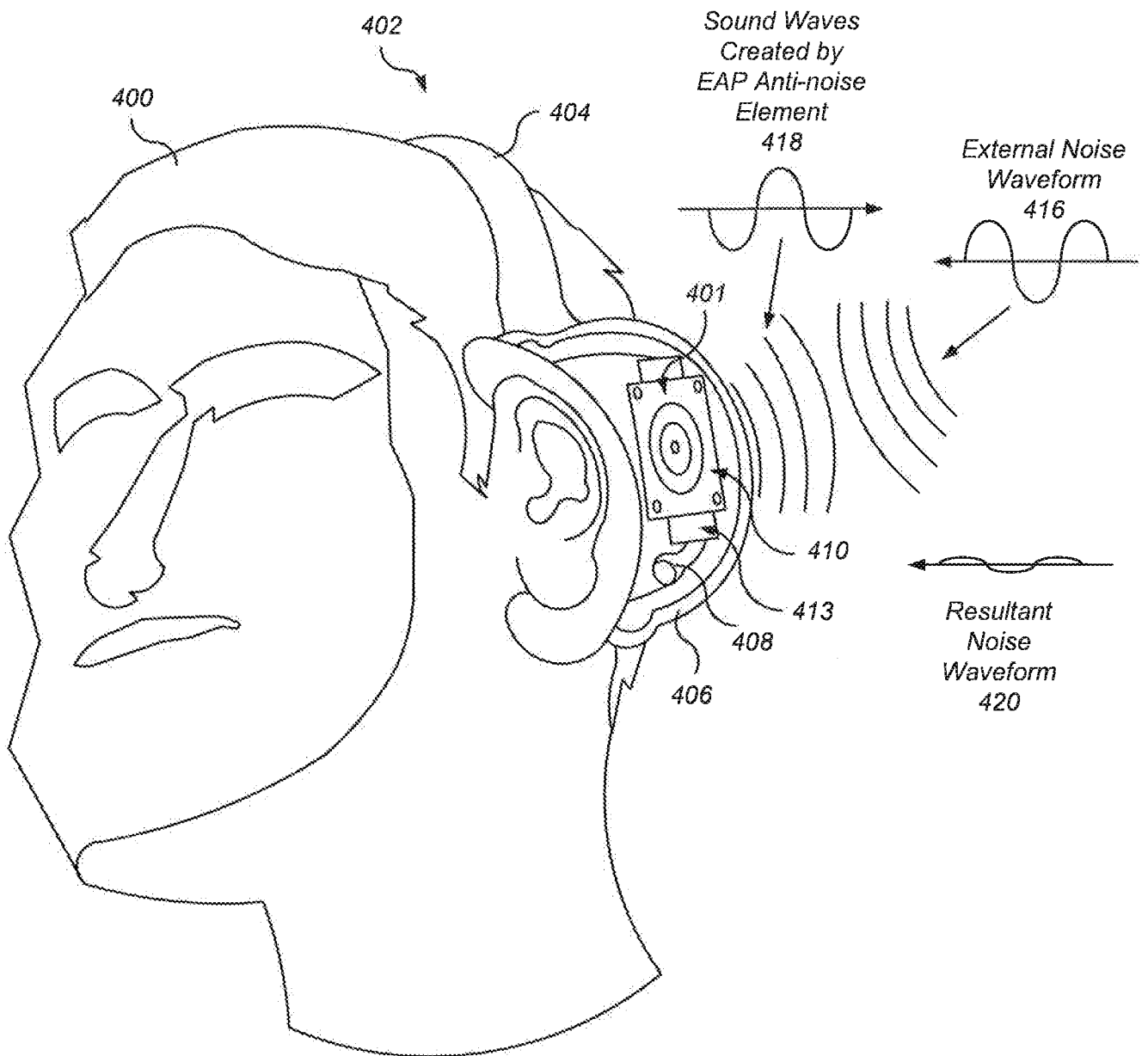


FIG. 18

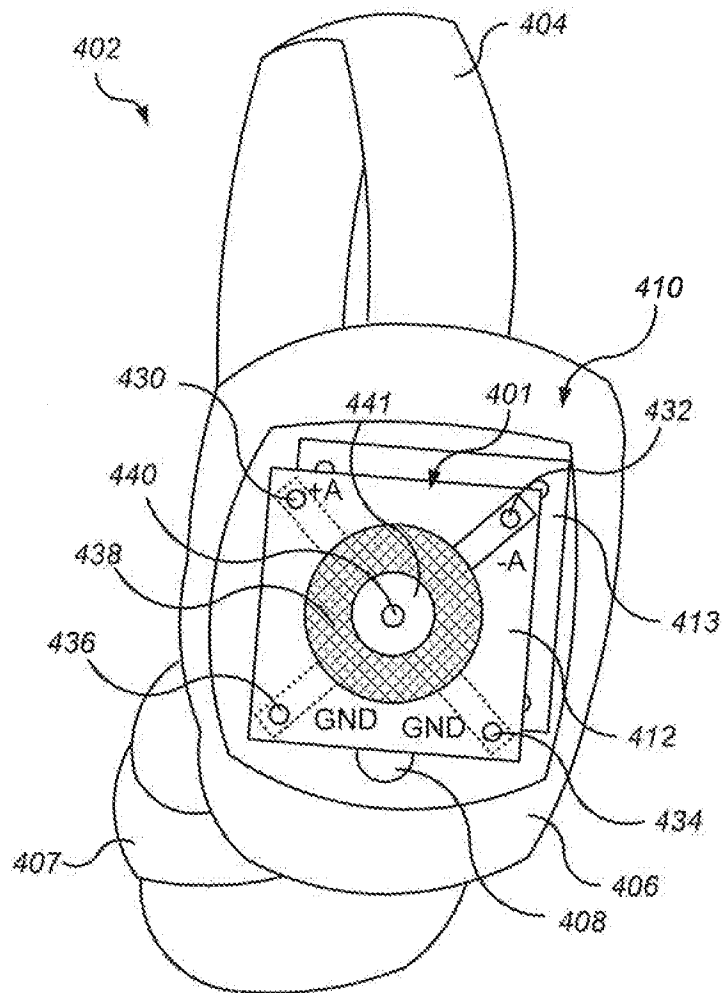


FIG. 19

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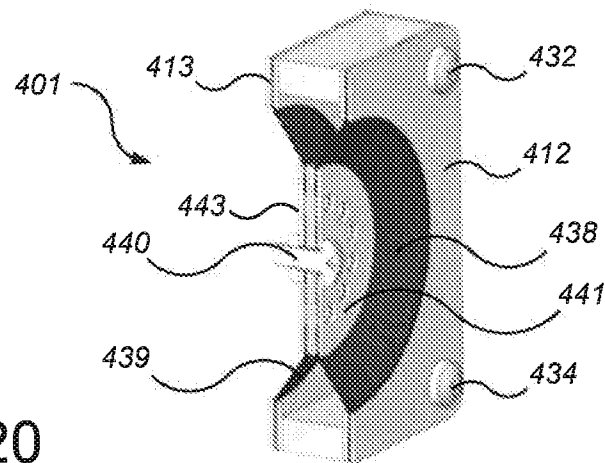


FIG. 20

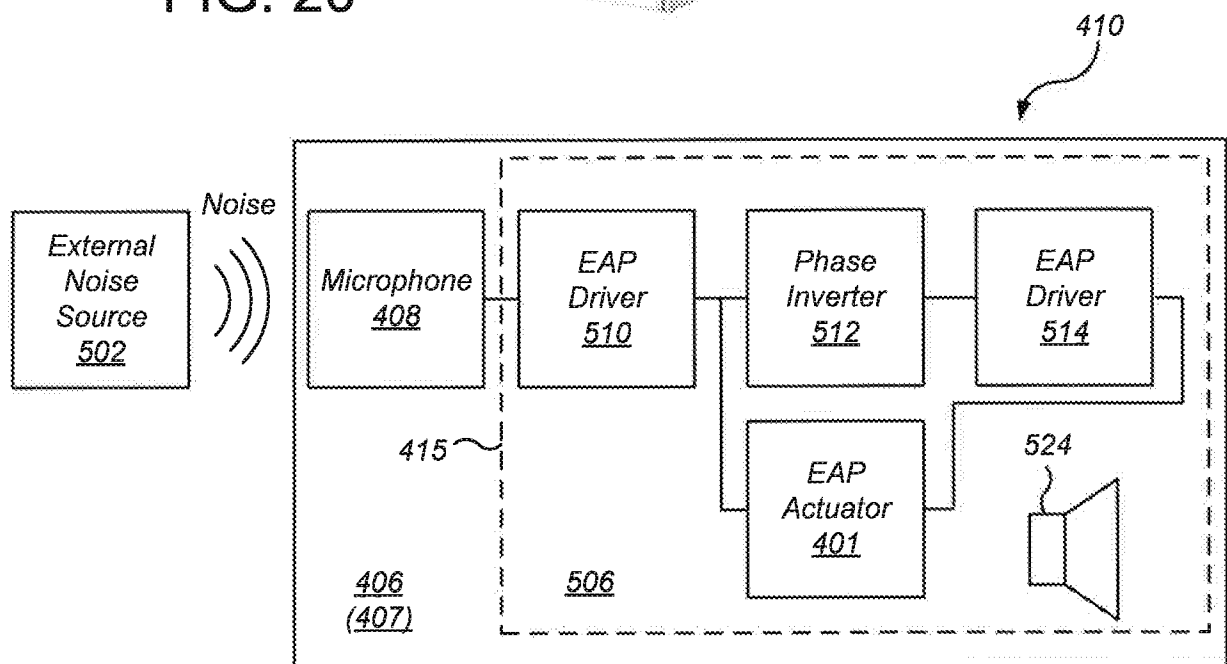


FIG. 21

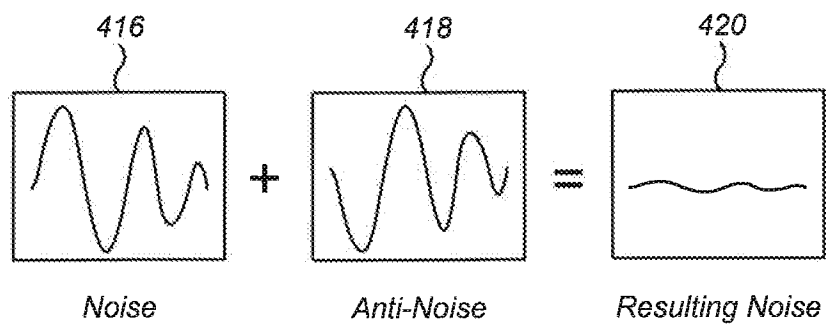


FIG. 22

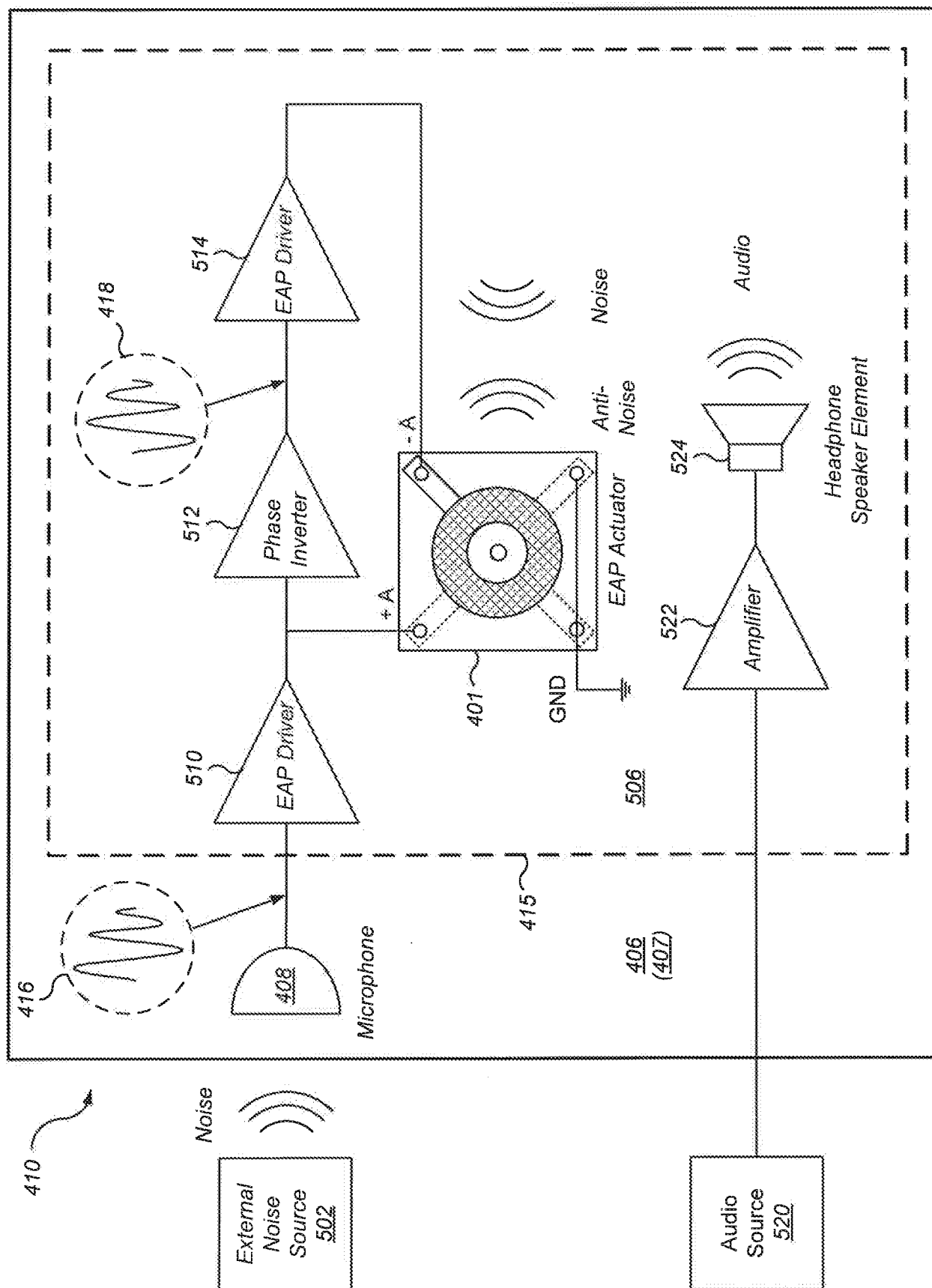


FIG. 23

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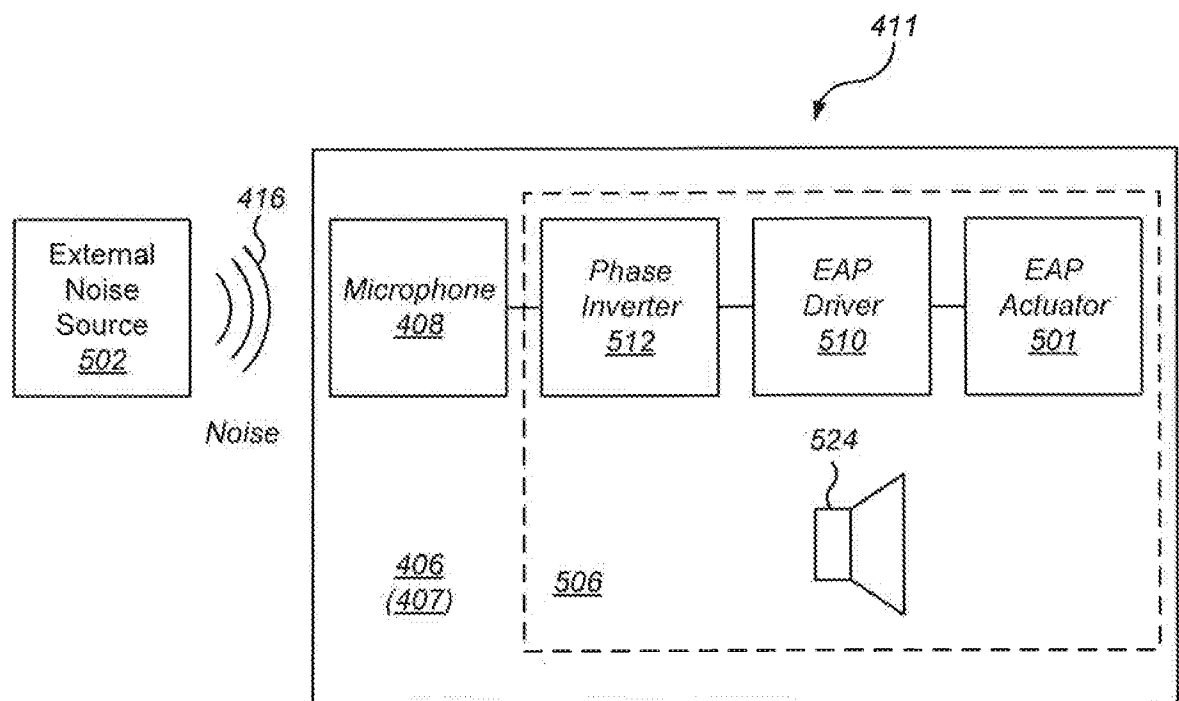


FIG. 24

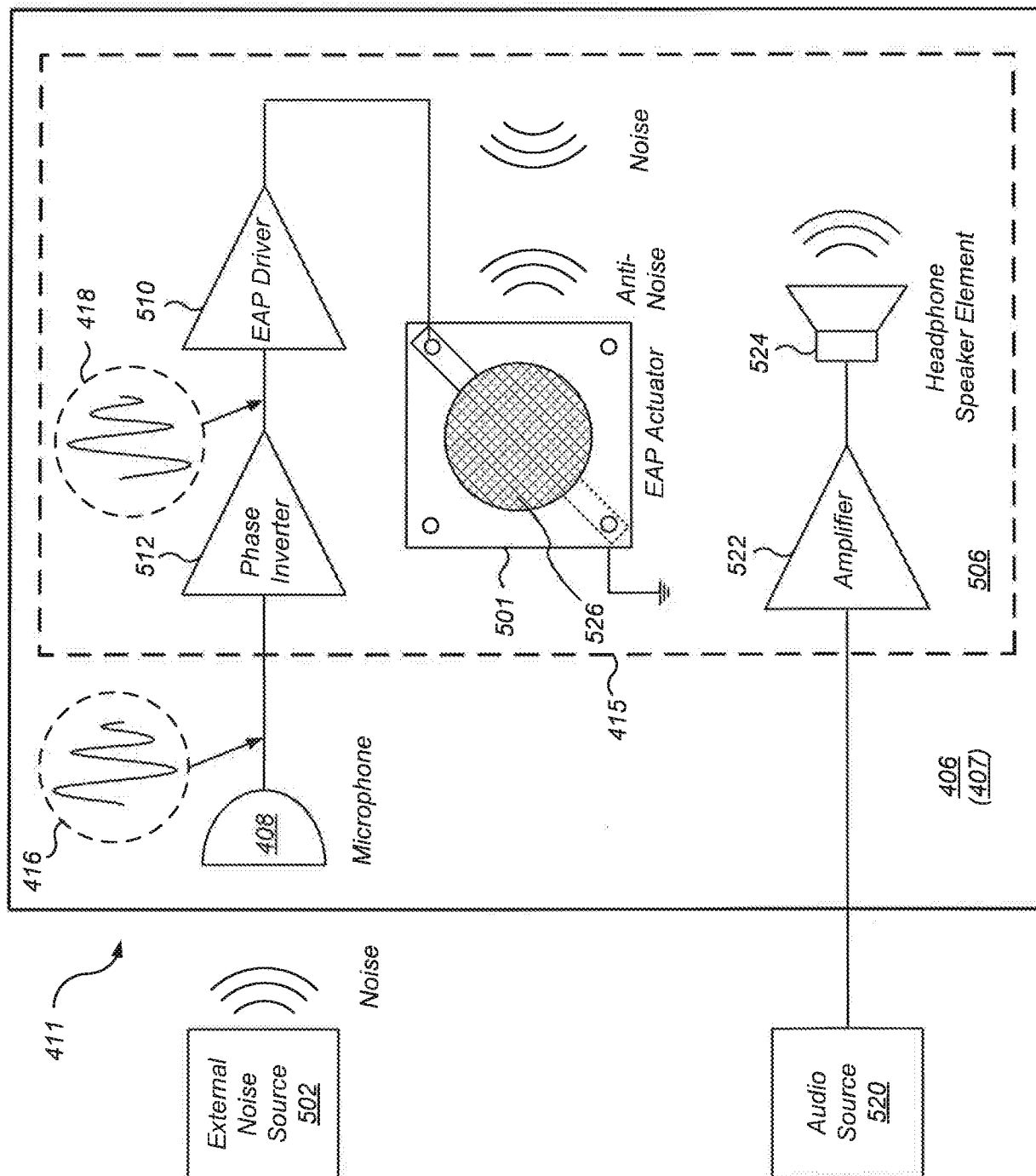


FIG. 25

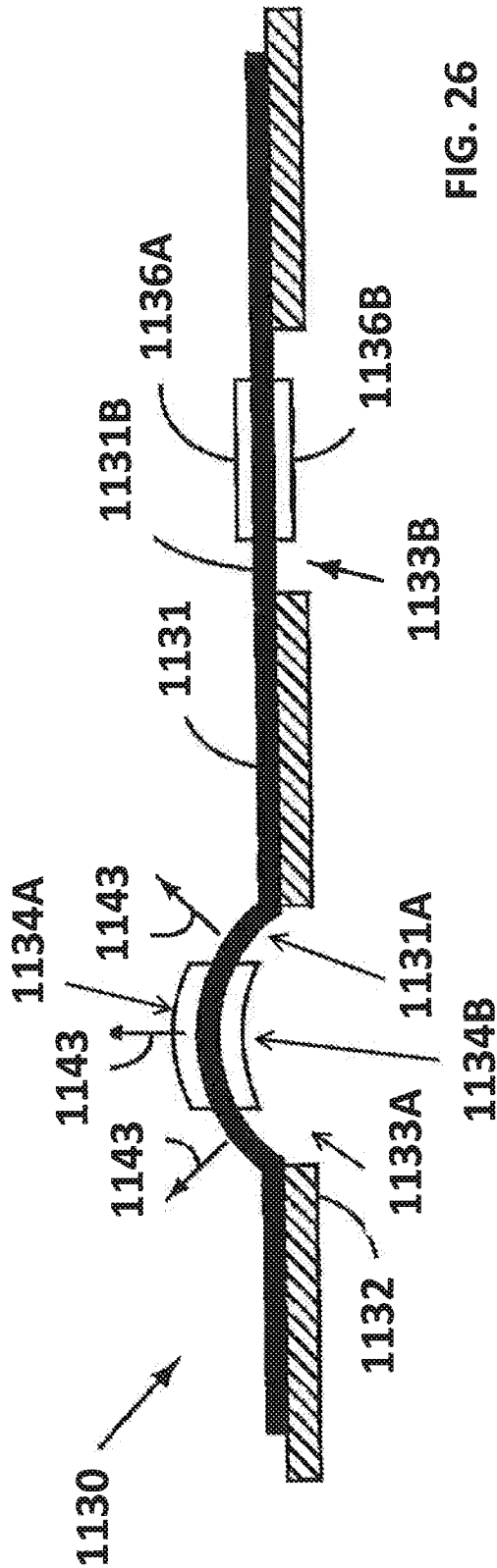


FIG. 26

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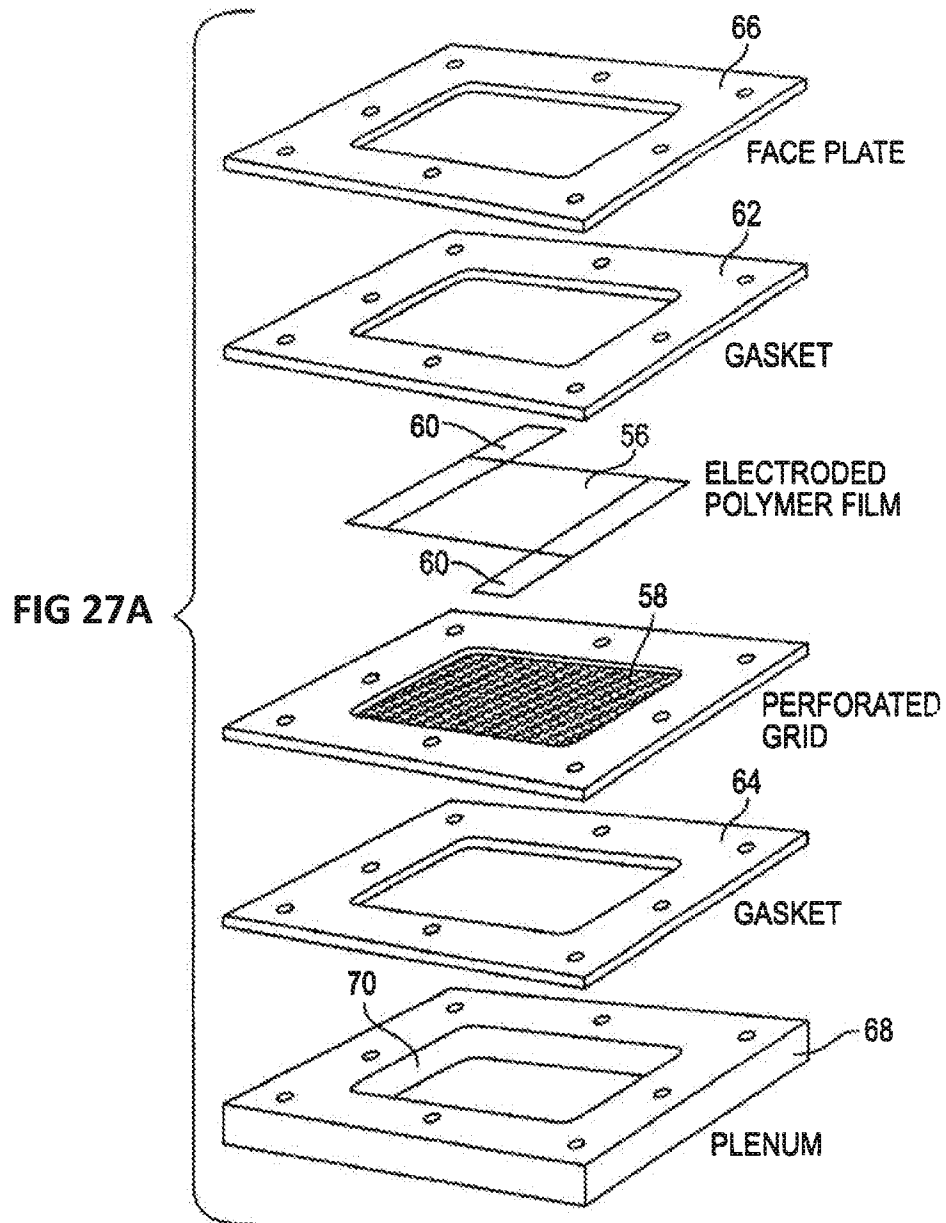


FIG 27B

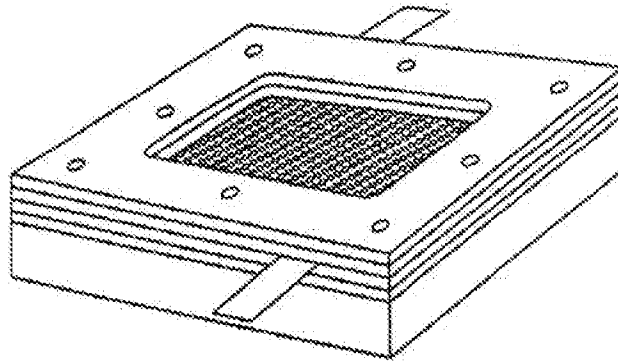


FIG. 28A

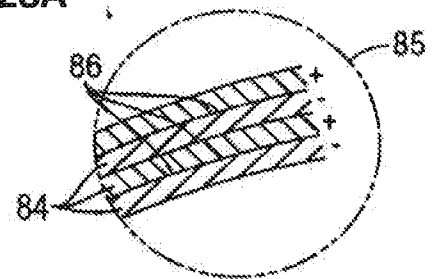
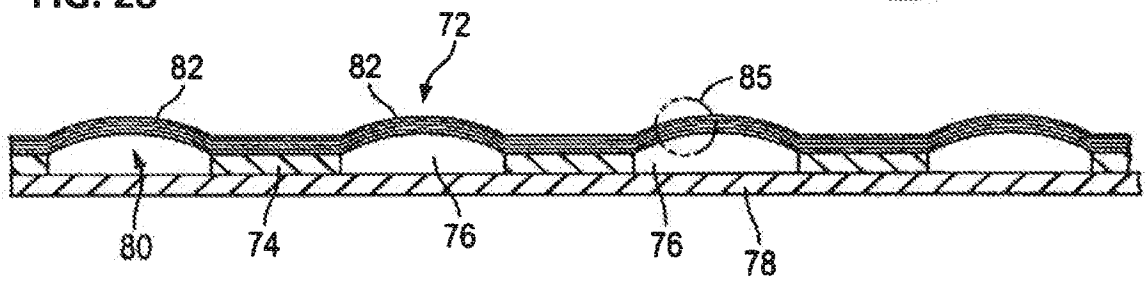


FIG. 28



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FIG. 29

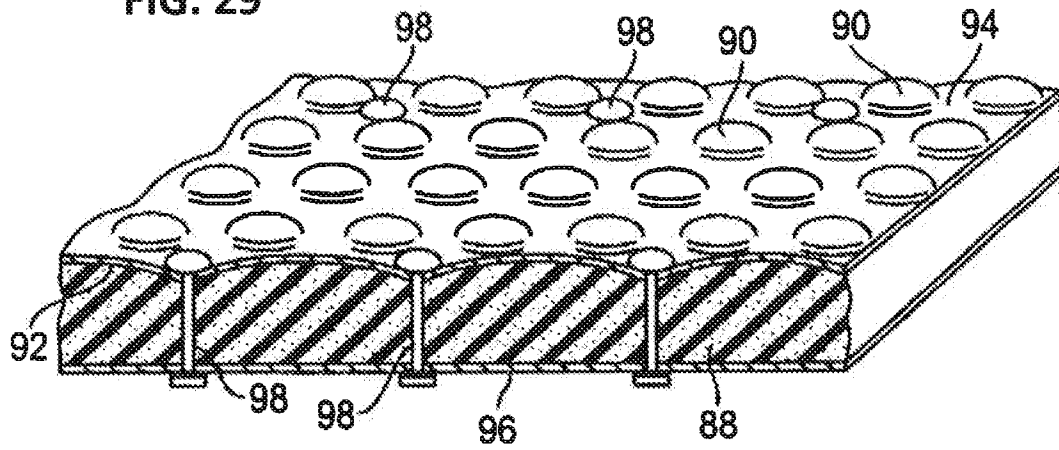


FIG. 30

