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Beveridge [45] **June 6, 1972**

[54] ELECTROSTATIC LOUDSPEAKER

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[21] Appl. No.: **833,952**

[52] **U.S. Cl.** ....179/111 R
[51] **Int. Cl.** H04r 19/02
[58] **Field of Search** 179/111–115.511; 181/24, 31, 27

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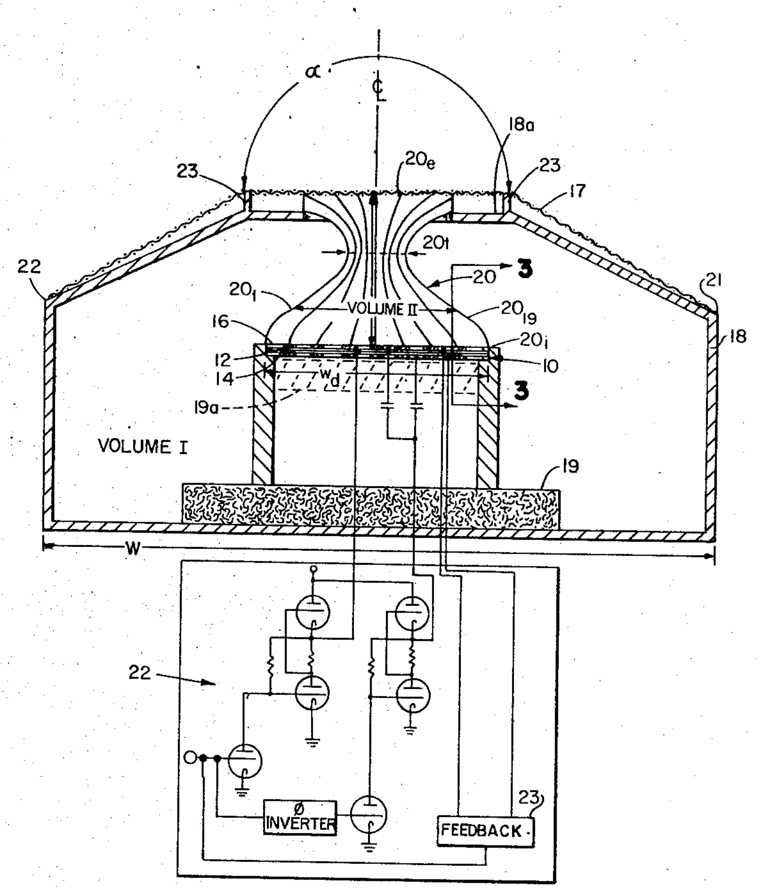
Primary Examiner—Kathleen H. Claffy
Assistant Examiner—Thomas L. Kundert
Attorney—John Noel Williams

[57] ABSTRACT

An electrostatic loud speaker system is shown which combines a balanced transducer, an amplifier and an enclosure each of unique construction which together permit the reproduction of frequencies over the full audio range. The electrostatic transducer is shown surrounded by an enclosure that has an outlet passage preferably significantly smaller than the transducer and an acoustic lens preferably guides the sound through the narrow outlet into a wave form of circular cross-section. By these provisions a low resonant frequency for the speaker and wide dispersal of the directional high frequencies are achieved in an enclosure of limited size. The fixed electrodes of the transducer are of substantial thickness and are formed of high dielectric constant material, achieved preferably by molding a lower K matrix with additives raising K and lowering volumetric resistivity. The amplifier is formed of series-connected active devices, one controlled by the other. A third active device amplifies the audio signal. Its output is connected to control the first of the series-connected devices and the output terminal of the amplifier is connected through a resistive feedback path to the output of the third device. A further feedback system employs a carrier wave applied to the diaphragm of the transducer. The resulting signal on the electrodes is differentiated and negatively fed back to damp speaker response at low frequency resonance.

22 Claims, 23 Drawing Figures



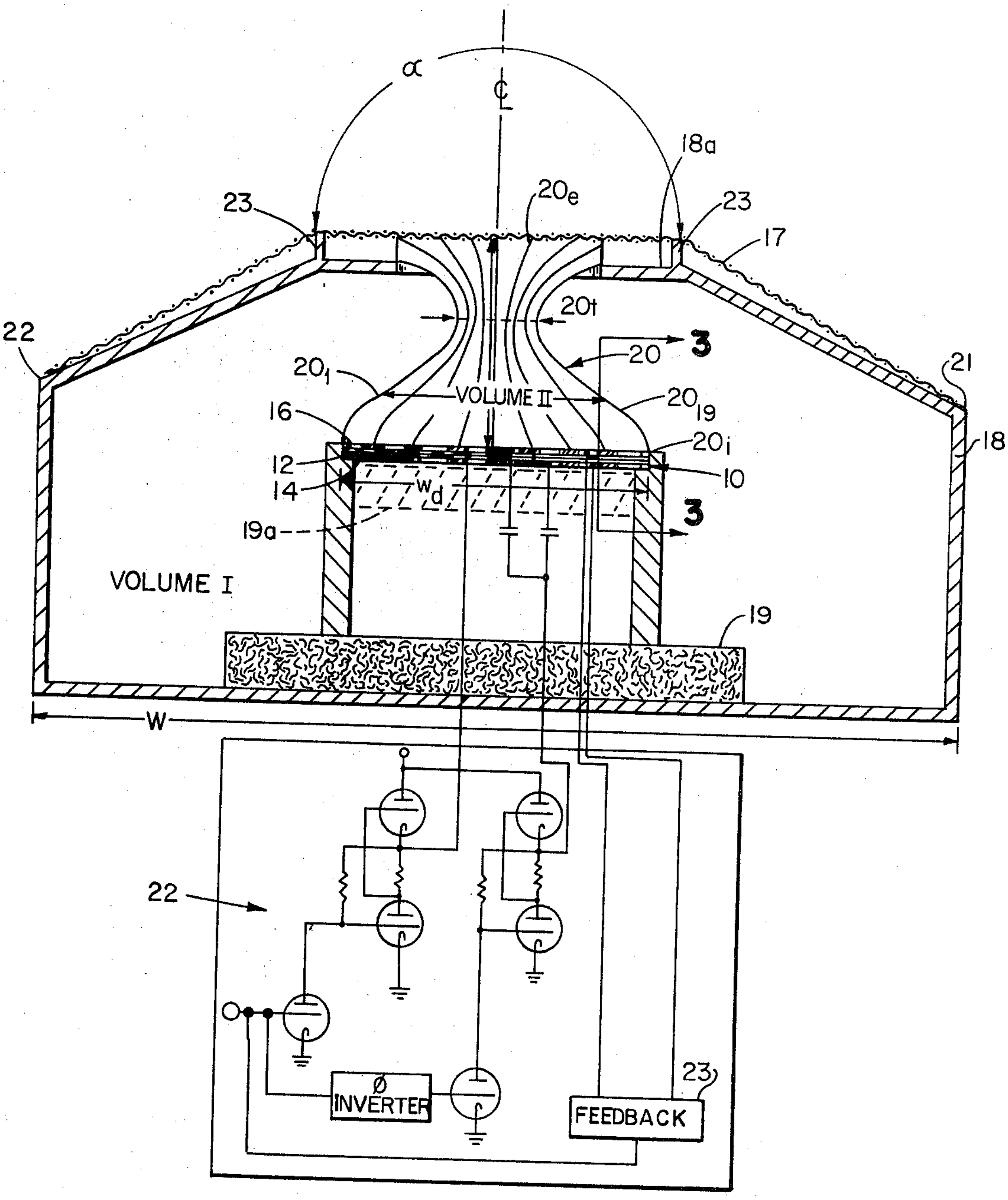
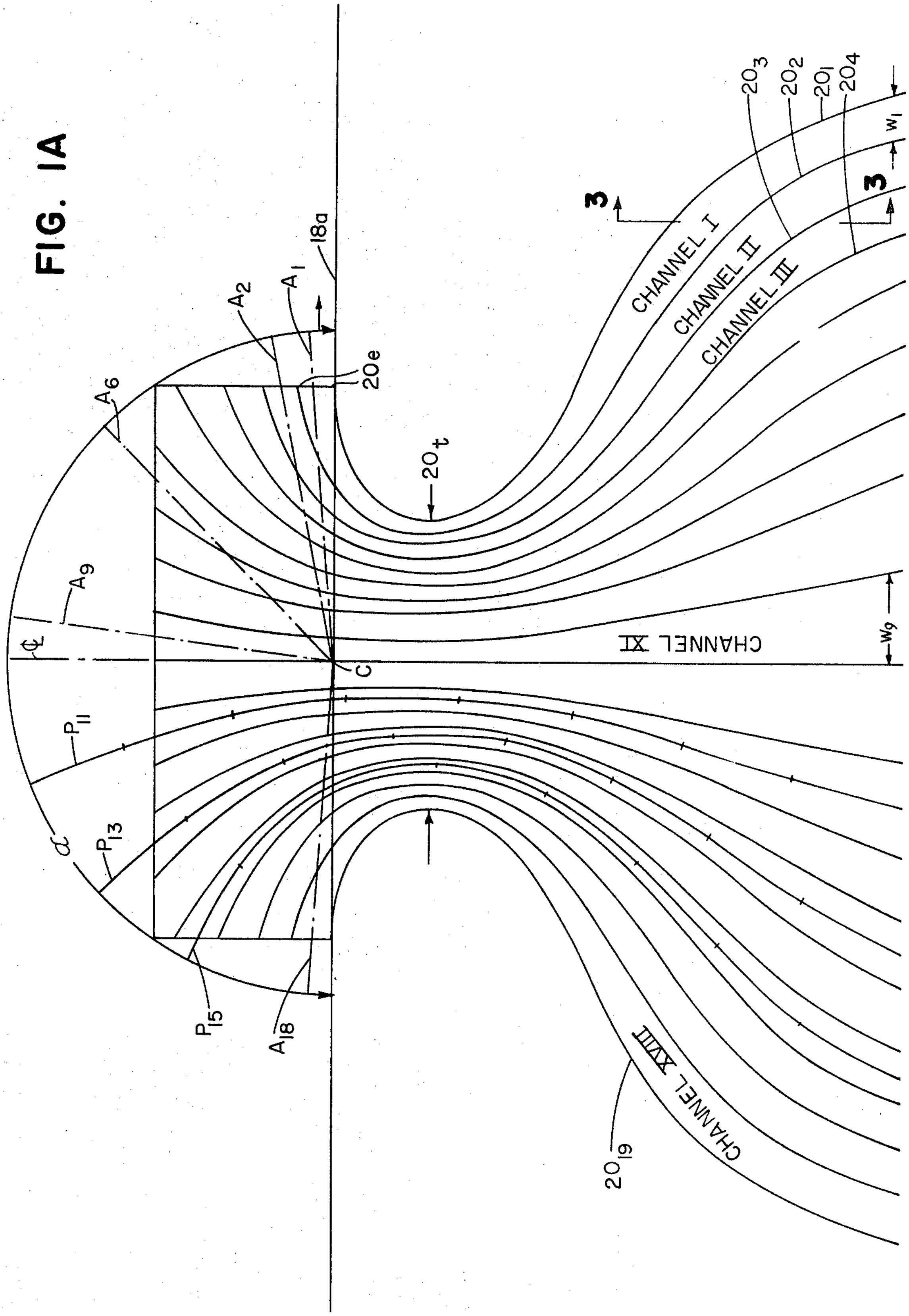

α
℄
18a
23
20e
23
17
20t
22
20
3
21
20₁
VOLUME II
20₁₉
18
16
20i
12
10
14
Wd
19a
3
VOLUME I
19
W
22
Ø INVERTER
FEEDBACK
23

FIG. I

FIG. 1A


20_3
20_2
20_1
20_4
W_1
3
3
CHANNEL I
CHANNEL II
CHANNEL III
18a
A_1
A_2
20e
A_6
20_t
A_9
℄
C
CHANNEL XI
W_9
P_{11}
α
P_{13}
P_{15}
A_{18}
CHANNEL XVIII
20_{19}

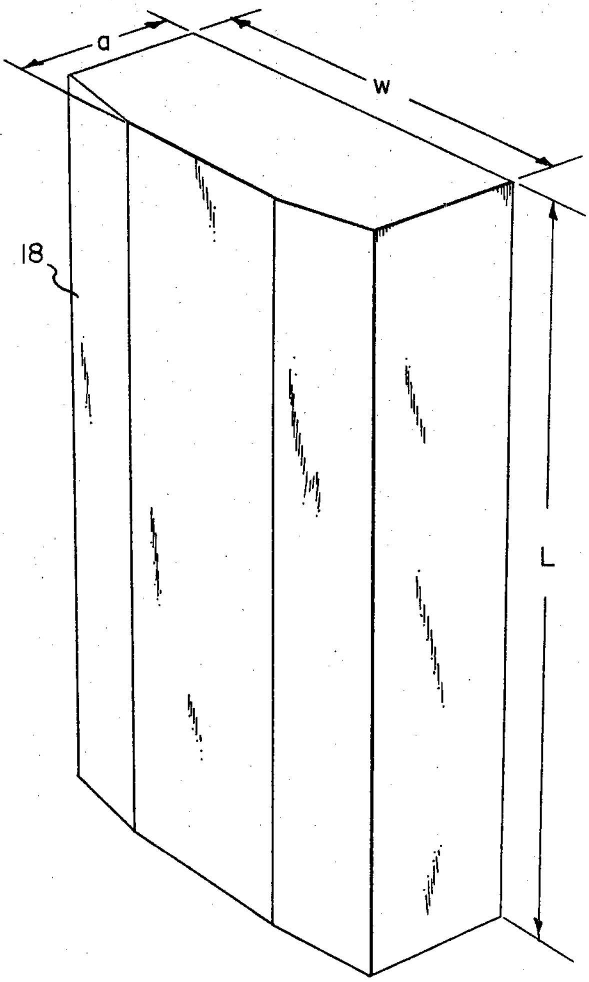


FIG. 2

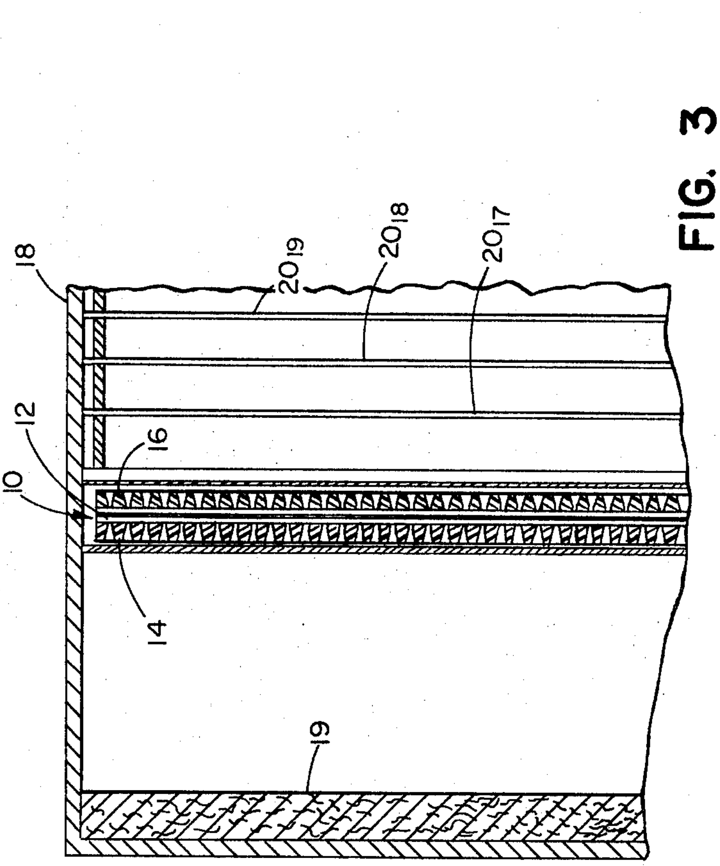


FIG. 3

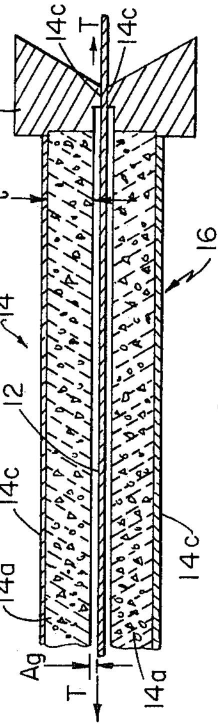


FIG. 9

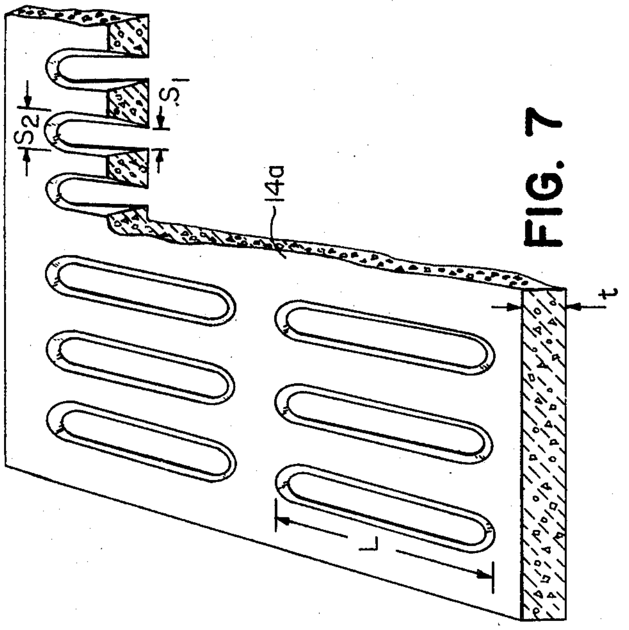


FIG. 7

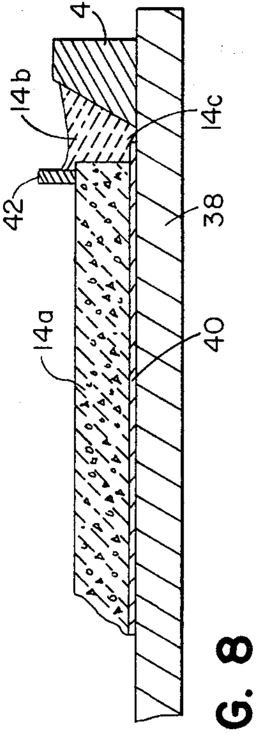


FIG. 8

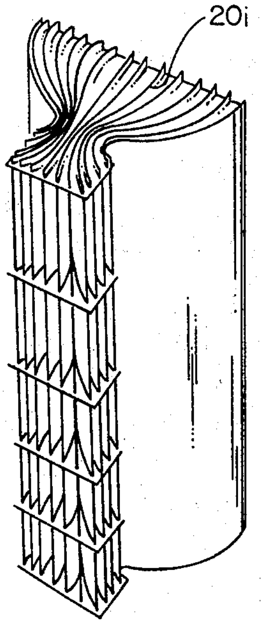


FIG. 4

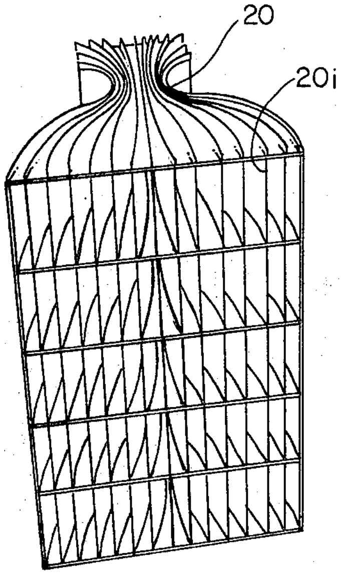


FIG. 5

FIG. 6a

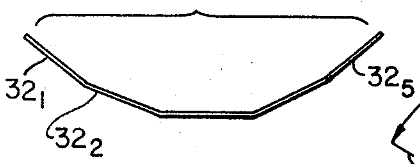
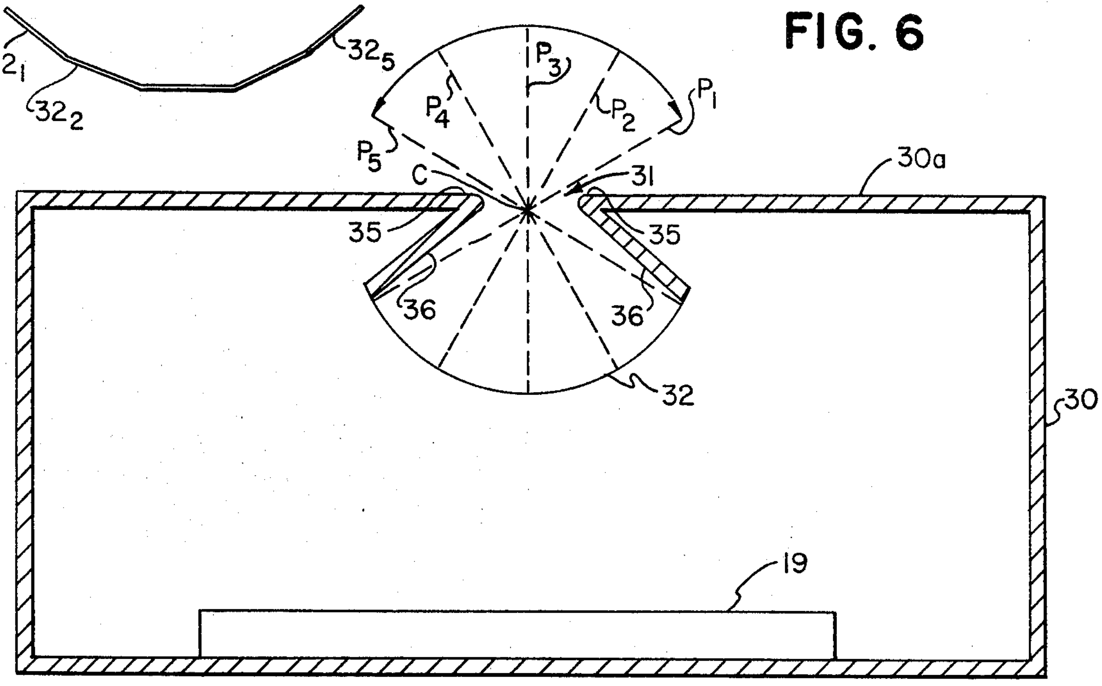


FIG. 6



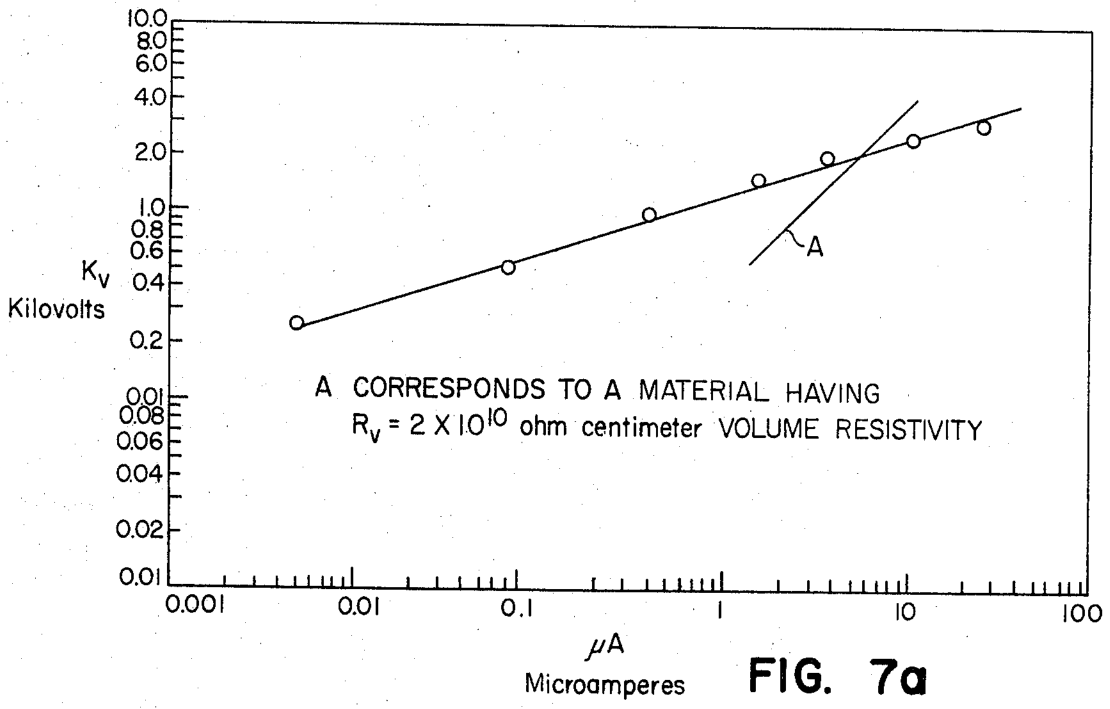

10.0
8.0
6.0
4.0
2.0
1.0
0.8
0.6
K_V
Kilovolts
0.4
0.2
0.01
0.08
0.06
0.04
0.02
0.01
0.001
0.01
0.1
1
10
100
μA
Microamperes
A
A CORRESPONDS TO A MATERIAL HAVING
R_V = 2 X 10^10 ohm centimeter VOLUME RESISTIVITY

FIG. 7a

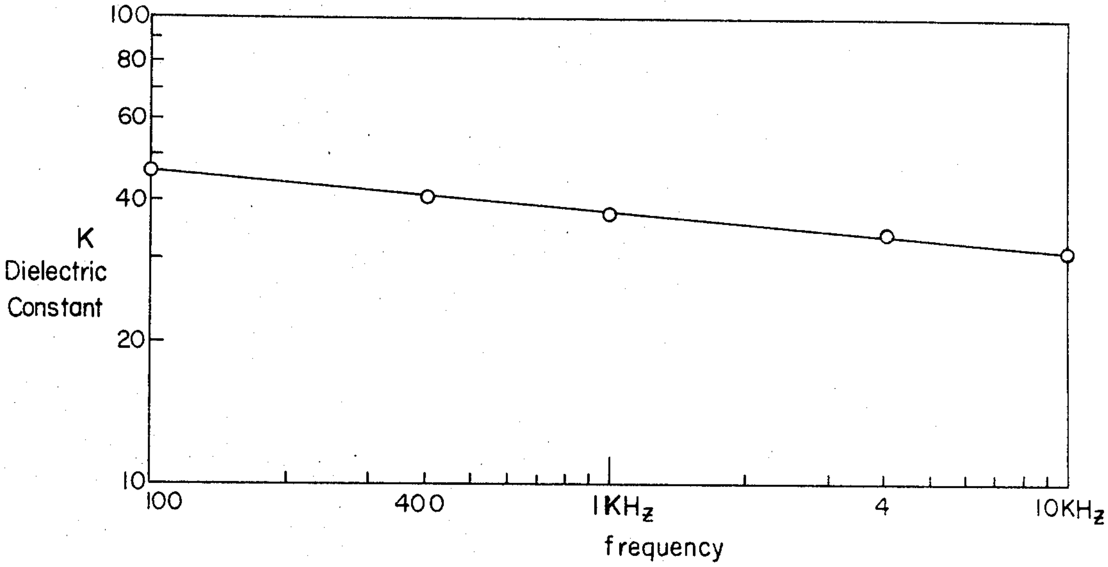

100
80
60
40
K
Dielectric
Constant
20
10
100
400
1KHz
4
10KHz
frequency

FIG. 7b

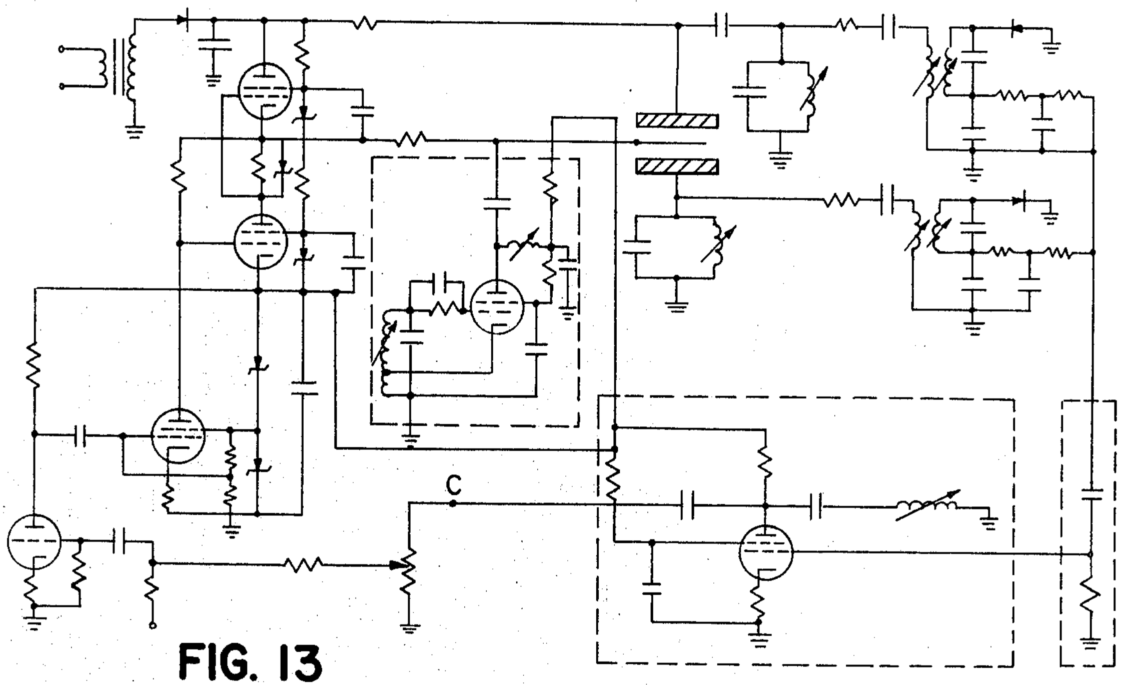


FIG. 13

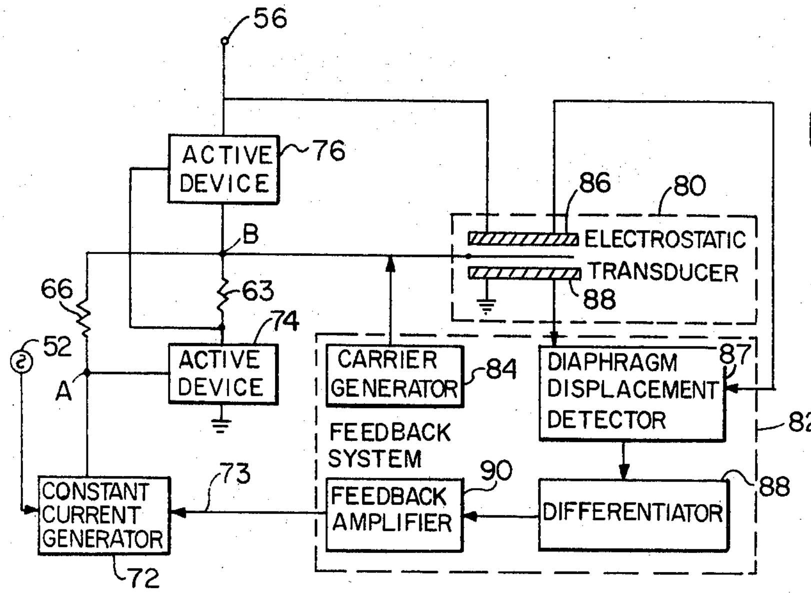


FIG. 12

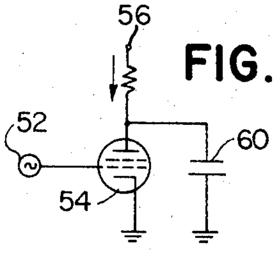


FIG. 10

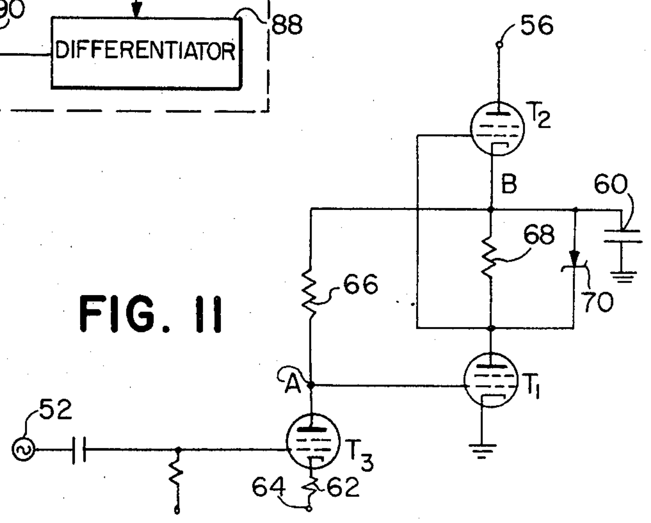
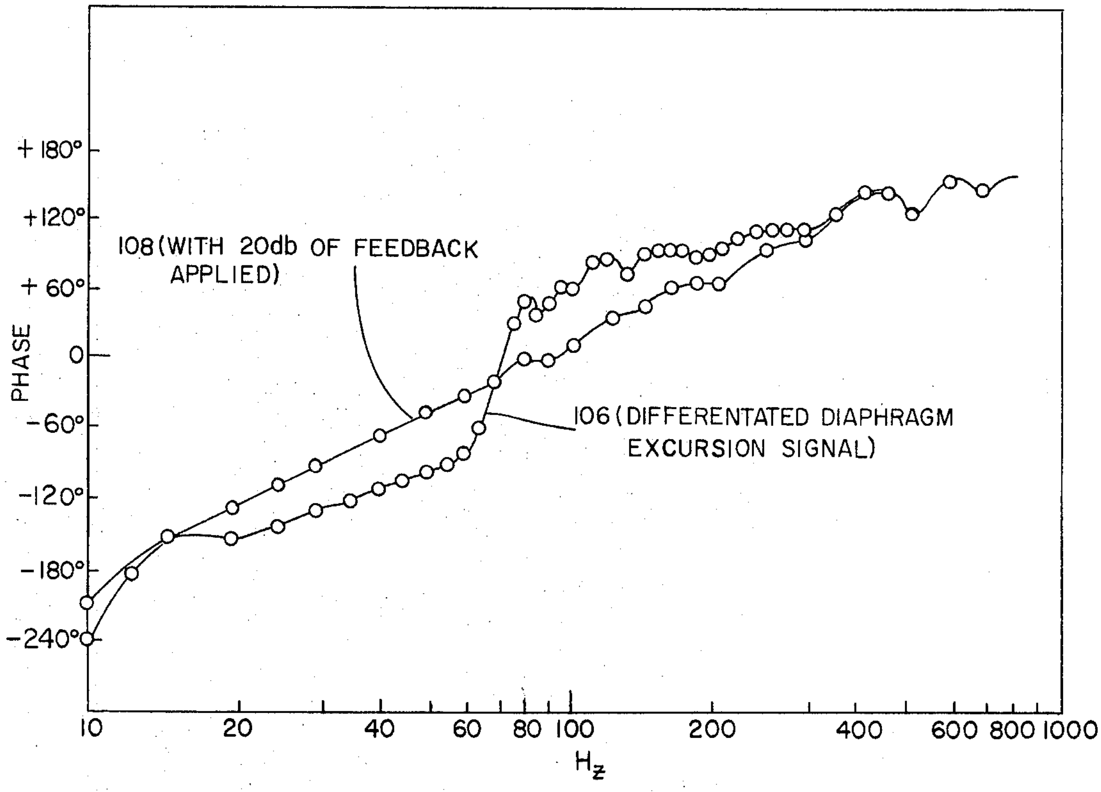


FIG. 11

FIG. 15


+180°
+120°
+60°
0
-60°
-120°
-180°
-240°
PHASE
108 (WITH 20db OF FEEDBACK APPLIED)
106 (DIFFERENTATED DIAPHRAGM EXCURSION SIGNAL)
10
20
40
60
80
100
200
400
600
800
1000
Hz

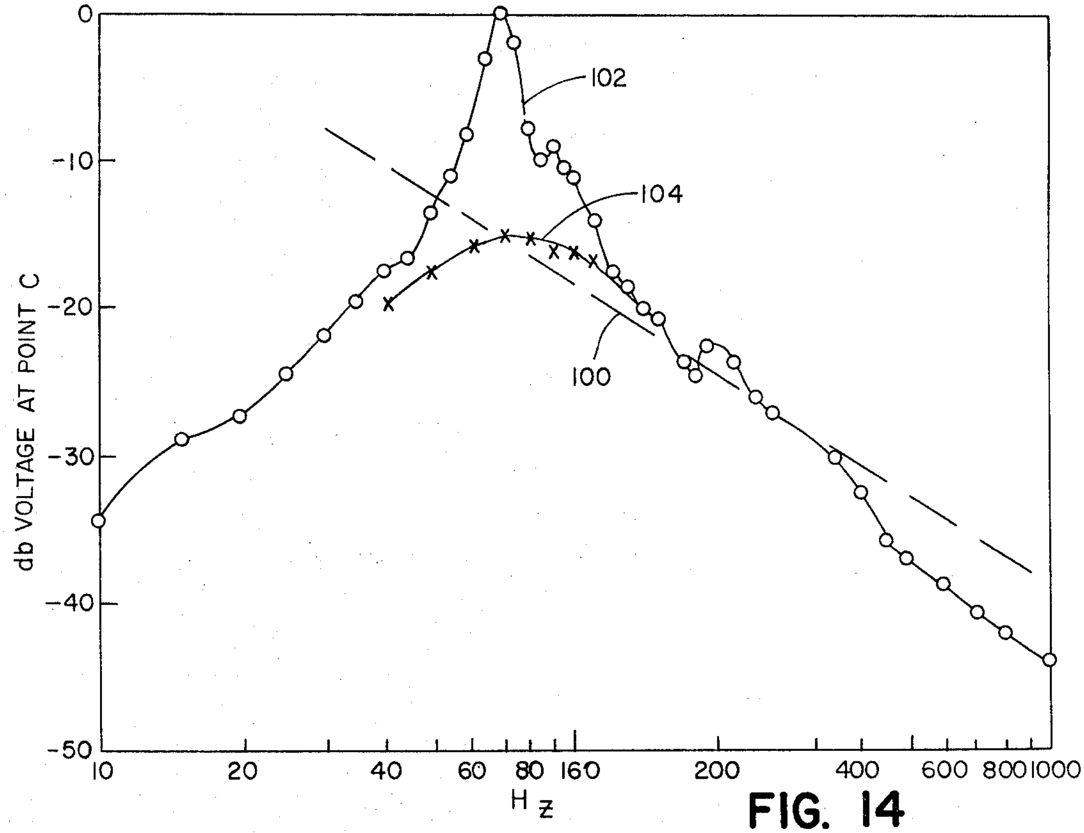

0
-10
-20
-30
-40
-50
db VOLTAGE AT POINT C
102
104
100
10
20
40
60
80
160
200
400
600
800
1000
Hz

FIG. 14

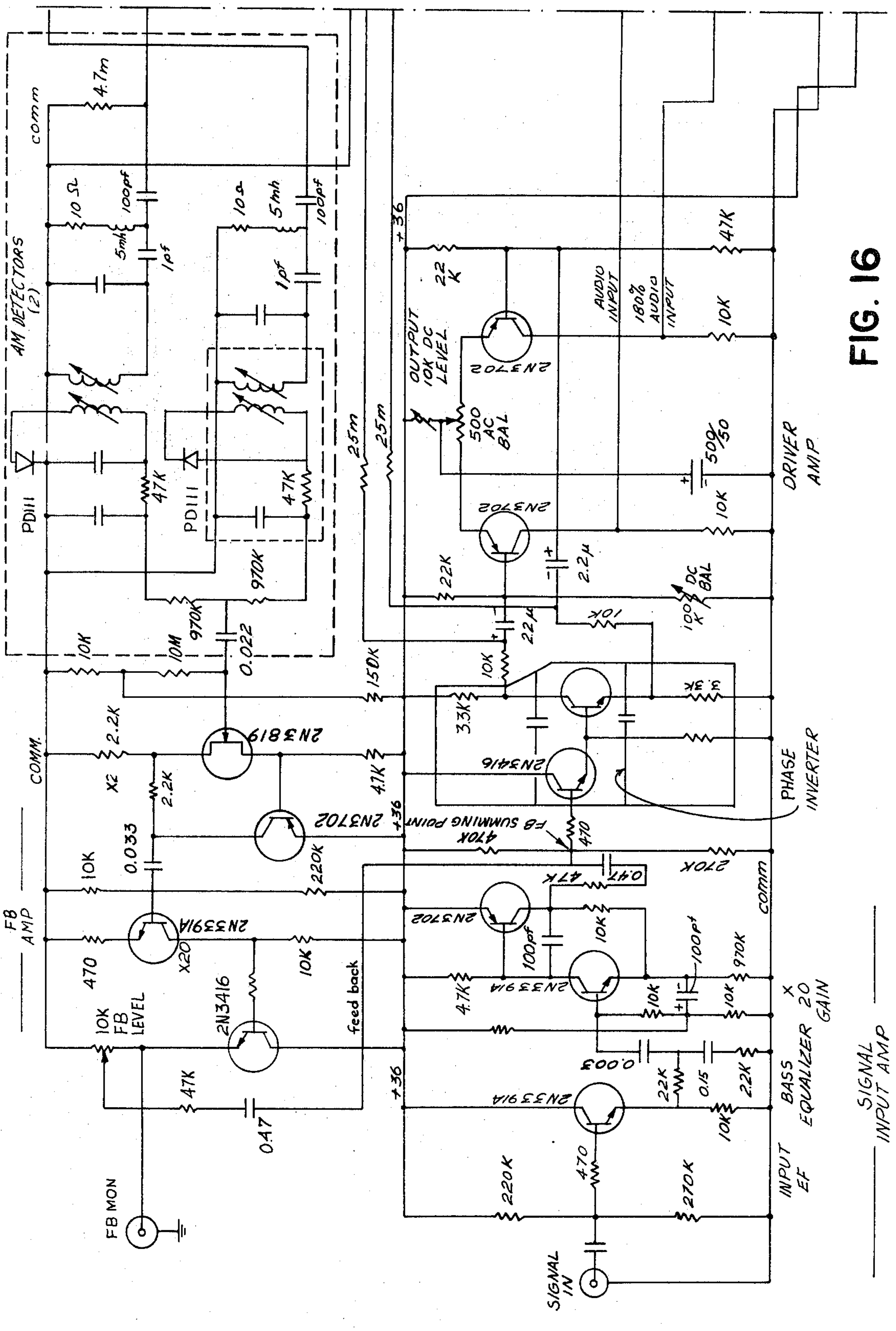

AM DETECTORS (2)
comm
4.7m
10 Ω
5mh
100pf
1pf
10 Ω
5mh
100pf
1pf
PD111
47K
PD111
47K
970K
970K
0.022
10K
10M
COMM.
2.2K
X2
2.2K
2N3819
150K
4.7K
2N3702
+36
0.033
10K
220K
FB AMP
470
2N3391A
X20
10K
2N3416
10K FB LEVEL
47K
0.47
feed back
FB MON
+36
25m
25m
+36
22K
2N3702
OUTPUT 10K DC LEVEL
500 AC BAL
2N3702
22K
2.2µ
22µ
10K
3.3K
2N3416
3.3K
10K
100K DC BAL
FB SUMMING POINT
470K
470
0.47
47K
270K
2N3702
100pf
10K
2N3391A
4.7K
100pf
970K
10K
10K
0.003
22K
0.15
2.2K
2N3391A
10K
470
220K
270K
SIGNAL IN
AUDIO INPUT
180° AUDIO INPUT
47K
10K
500/50
10K
DRIVER AMP
PHASE INVERTER
comm
X 20 GAIN
BASS EQUALIZER
INPUT EF
SIGNAL INPUT AMP

FIG. 16

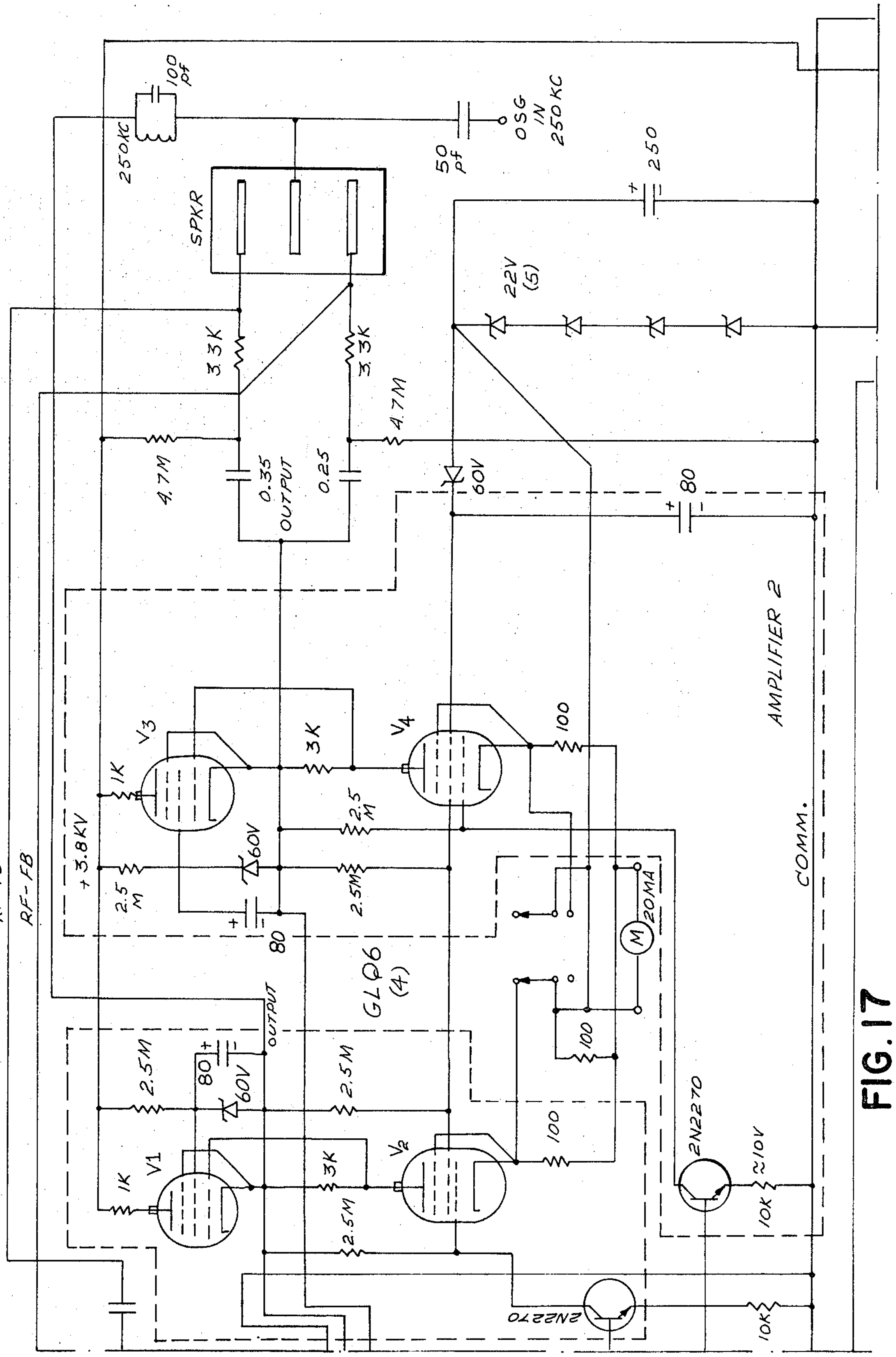

100 pf
250KC
OSG IN 250 KC
50 pf
250
SPKR
22V (5)
3.3K
3.3K
4.7M
4.7M
0.35
OUTPUT
0.25
60V
80
AMPLIFIER 2
RF-FB
RF-FB
+3.8KV
V3
1K
3K
V4
100
2.5 M
60V
2.5M
2.5 M
80
GLQ6 (4)
M
20MA
COMM.
OUTPUT
2.5M
80
60V
2.5M
100
100
V1
1K
3K
V2
2.5M
2N2270
≈10V
10K
2N2270
10K

FIG. 17

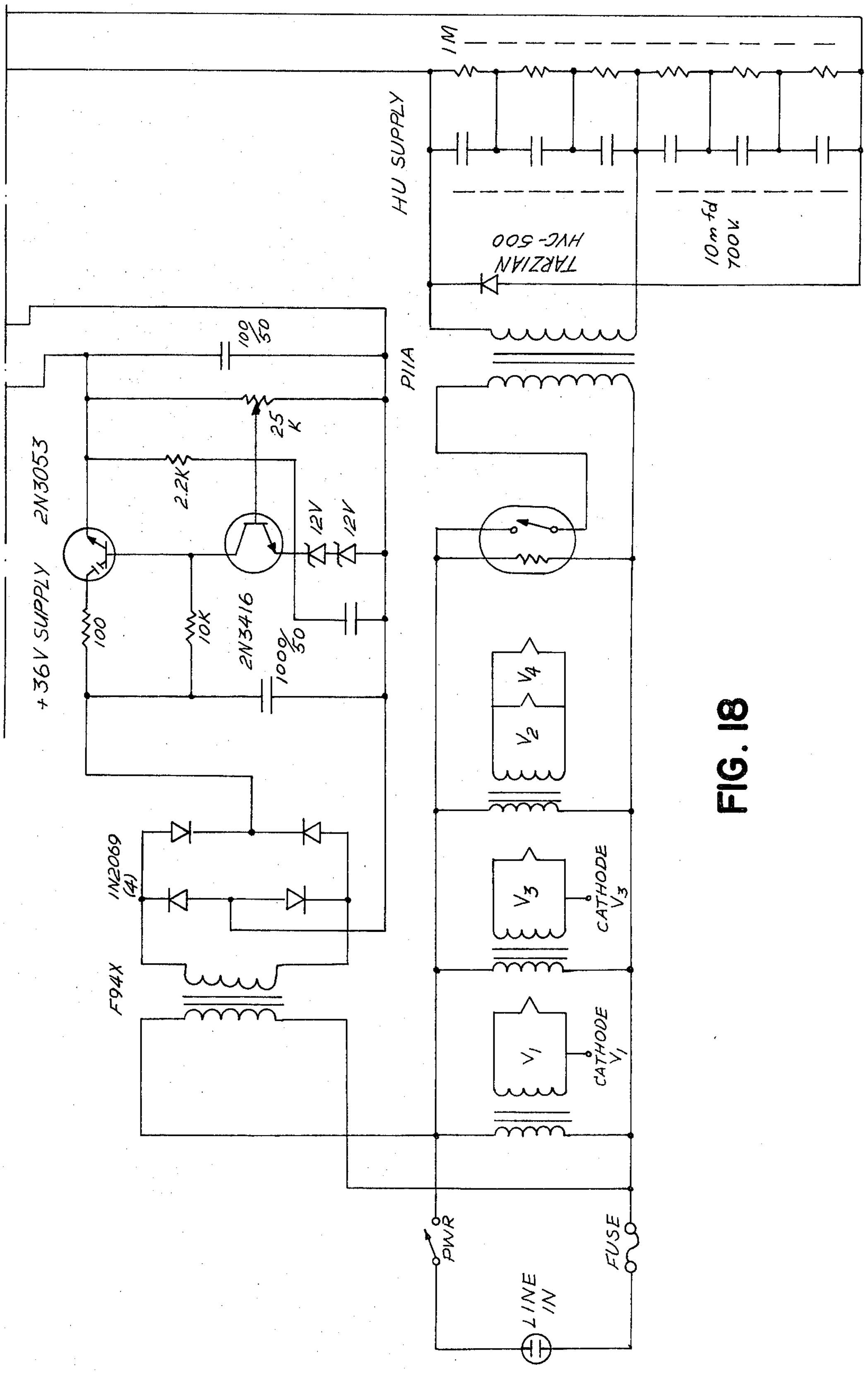

1M
HV SUPPLY
TARZIAN
HVC-500
10 mfd
700V.
100/50
P11A
25 K
2N3053
2.2K
12V
12V
+36V SUPPLY
100
10K
2N3416
100/50
1N2069
(4)
F94X
V4
V2
V3
CATHODE V3
V1
CATHODE V1
PWR
FUSE
LINE IN

FIG. 18

ELECTROSTATIC LOUDSPEAKER

This invention relates to electrostatic loudspeakers.

A principal object of the invention is to provide an electrostatic speaker system and components which solve or avoid in a practical way the various problems which exist for such speakers.

Another object is to provide an electrostatic loudspeaker capable of accurately reproducing sounds down to 40 to 50 Hz with ample volume and which is sufficiently compact as to be acceptable for use in homes.

Another object is to provide an electrostatic loudspeaker capable of accurately reproducing high frequency sound, frequencies from 1,000 to about 10,000 Hz and dispersing it over a wide solid angle (e.g. angles up to 180°).

Another object is to provide a full range electrostatic loudspeaker capable of accurate reproduction of both low and high frequencies.

Another object is to provide an electrostatic loudspeaker having an electrode construction and power source capable of achieving each and all of the foregoing objects as well as providing better performance generally for electrostatic speakers.

The invention features the combination of an electrostatic transducer with particular components to achieve the above objects. Featured is an electrostatic transducer surrounded by a rigid enclosure and having a constricted outlet throat smaller than the transducer, using the principle of the Helmholtz resonator, enabling the achievement of an acceptably low figure (e.g. below 50 Hz) for the natural frequency of resonance of the mechanical system in an enclosure which is sufficiently small to enable use in the home. Preferably, the volume of the enclosure exposed to the back side of the diaphragm is at least four times greater than the volume exposed to the front.

The invention further features an electrostatic transducer with means establishing equal length paths from various diaphragm portions terminating on the arc of a circle having a center on the sound path some distance from the diaphragm portions, the speaker thus being capable of dispersing high frequencies in a wide solid angle. A further feature of the invention is the combination in which the constricted throat of the enclosure outlet, which contributes to lowering the natural frequency of resonance of the system, also forms part of the geometry of the dispersing system. The invention also features a plurality of side-by-side narrow channels leading from corresponding portions of the transducer, and bending to disperse the entire range of audio frequencies. The inlet width of those channels which bend is generally less than the length of the shortest wave length sound to be dispersed, generally less than 1 ½ inches and on the order of two-third inch for speakers having high frequency capability.

The invention further features a high voltage power system, with peak voltages exceeding 3,000 volts, employing thick electrodes of high dielectric constant (e.g. $30<K<60$) and a relatively low volume resistivity (e.g. R_r within the range of 10^8 and 10^{11}, preferably on the order of 10^{10} ohm centimeters.

Thick electrodes according to the invention may be considered to be those whose dielectric portions are more than about 3 times that of the air gap involved. While large air gaps, electrode thicknesses on the order of one-fourth inch, and peak voltages in the range of 6,000 volts are employed for the preferred full range speaker, in its broader aspect this thick electrode feature of the invention applies to constructions in which both the air gap and the dielectric dimensions are scaled to smaller values. Such thick electrode systems avoid power arcs while achieving a relatively high energy output per unit diaphragm area, judged against other electrostatic speakers. The electrodes concentrate the electrostatic field in the air gap between the electrodes, protect the conductive diaphragm from arcing and enable voltage differences across the thickness of the electrodes to be rapidly eliminated, should such voltage differences occur. The transducer can present a capacitance on the order of 750 to 1,000 pf per square foot of diaphragm area and total capacitance ranging up to 2,000 pf and above, with virtually no resistive impedance in the operative frequency range, thus providing ample capability for the full range speaker of the invention.

To provide the high K electrodes the invention features an electrode molded of a dielectric matrix material in which is dispersed a substance of relatively much higher dielectric constant, e.g. $K>500$, to achieve an electrode K advantageously greater than 30. A further additive is useful to lower the volume resistivity of the electrode to preferably on the order of 10^{10} ohm centimeters to achieve appropriate time constants.

Also featured is an amplifier capable of powering this system, the amplifier having active devices series-connected across a large DC voltage, with the output terminal for the electrostatic transducer located between the active devices. A third active device having high impedance (constant current generator) characteristics is controlled by the audio signal source and its output is connected to control one of the active devices, while it is also connected through a resistive feedback path to the output terminal. This achieves a high-voltage, low-impedance amplifier directly coupled to the electrostatic transducer.

Further featured is an electronic feedback loop which dampens the response of the speaker in the low frequency range. This feedback loop employs a carrier signal applied to the moving diaphragm, and detector circuits for both electrodes of a balanced speaker, the dielectric portion of the electrodes having a high K, e.g. $K>15$, at the carrier frequency. Demodulation recovers a signal that varies with displacement of the diaphragm and differentiation of the signal provides an effective feedback signal proportional to diaphragm velocity and of proper phase.

These features, in combination, complement each other in a very interrelated way to achieve full audio range capability in a practical form. It is believed that certain versions of the system are capable of better sound reproduction in the home than any full range speaker system heretofore proposed; and that other versions permit a good level of quality to be achieved inexpensively.

While these features and others which will appear herein lead to a full frequency range electrostatic loudspeaker, they have use individually and in various subcombinations, as will be apparent to those skilled in the art.

In the drawings:

FIG. 1 is a horizontal cross-sectional view of a full audio range electrostatic speaker according to the invention, including schematically an amplifier system;

FIG. 1*a* shows in greater detail the configuration of the lens walls for the loudspeaker of **FIG. 1**;

FIG. 2 is a perspective view of the loudspeaker of **FIG. 1**;

FIG. 3 is a partial vertical cross-sectional view of the speaker of **FIGS. 1** and **2** taken on line **3—3** thereof;

FIG. 4 is a perspective view of the front portion of the lens system of **FIGS. 1** and **1*a***, showing the outlet;

FIG. 5 is a perspective view similar to **FIG. 4** viewed from the back to reveal the inlet of the lens system;

FIG. 6 is a cross-sectional view of an alternate form of lens construction;

FIG. 6*a* is a horizontal cross-sectional view of a transducer for use in the embodiment of **FIG. 6**;

FIG. 7 is a partially broken away perspective view of a preferred electrode plate;

FIGS. 7*a* and **7*b*** are plots of electrical characteristics of electrode material according to the invention;

FIG. 8 is a cross-sectional view showing an edge member being formed on the electrode plate of **FIG. 7**;

FIG. 9 is a cross-sectional view of a balanced electrostatic transducer being formed from two electrodes in accordance with **FIG. 8**;

FIG. 10 is a schematic utilized to illustrate the difficulty of using conventional amplifier circuitry to drive a capacitive load;

FIG. **11** is a simplified schematic of an amplifier of the type provided by the present invention;

FIG. **12** is a block diagram of an entire loudspeaker system according to the invention; and

FIG. **13** is a detailed schematic of the electronic components of one practical embodiment of the invention.

FIG. **14** and **15** are plots of characteristics of a preferred embodiment of the invention.

FIGS. **16**, **17** and **18** together comprise a detailed schematic of another circuit according to the invention.

Referring to FIGS. **1–3** there is shown an embodiment of a full range electrostatic loudspeaker in accordance with the invention. The basic components comprise an electrostatic transducer **10** (including a large flexible diaphragm **12** e.g. of metal coated mylar, and a pair of rigid planar high K electrodes **14**, **16**), a rigid-walled enclosure **18** surrounding the transducer **10**, an outlet passage, here in the form of a lens **20** and an amplifier **22** including a diaphragm-tracking feedback circuit **23**.

The electrostatic transducer **10** extends across one third of the full width W of the enclosure **18**, having a width W_d of **13** inches. The electrode assembly of the transducer has a height of 23 inches. A number of these can be mounted above each other if desired.

The electrostatic transducer of this embodiment is of the balanced type in which the flexible diaphragm **12** is held in taut condition between two apertured electrodes **14**, **16**. The sound absorbent material **19** (effective down to about 300 H_z) and the rigid walled enclosure **18** prevent backward moving radiation emitted by diaphragm **12** back through electrode **14** from escaping and causing cancellation of the forward radiation.

The forward electrode **16** is disposed immediately adjacent the inlet 20_i of the lens structure **20** (see FIG. **5**). The lens is composed of a series of walls 20_1, 20_2, ...20_{19} (see FIG. *1a*) which are straight in the vertical direction (see FIGS. **4** and **5**) but are spaced apart and curved in accordance with a special pattern in the horizontal direction to define a series of channels (see FIGS. **1** and *1a*). Thus outer wall 20_1 and the next adjacent wall 20_2 define a channel (channel I) having an inlet of width W_1 exposed to a corresponding outer portion of diaphragm **12** (through the apertures *16a* of the outer electrode **16**). The walls 20_1 and 20_2 converge together in the direction outwardly and simultaneously curve toward the centerline of the lens, to the lends throat region 20_t.

Near this region the channels begin a re-entrant curve so that at the throat 20_t the channel is again substantially perpendicular to the diaphragm, although displaced significantly toward the centerline. Beyond this region the walls 20_1 and 20_2 curve outwardly from the centerline and diverge from each other, terminating in ends *20e* which, in this example, are disposed outside of the front wall *18a* of enclosure **18**. The axis A_1 of the outlet of channel **1** is thus directed outwardly at a substantial angle from its direction of the channel axis at the inlet. In like manner the other side of wall 20_2 and wall 20_3 define channel II. It is disposed to receive the sonic output of the next adjacent portion of the diaphragm. It curves and converges and diverges similarly to channel I while its output axis A_2 is disposed at a lesser angle to the normal to the diaphragm. Channel II provides the next adjacent segment of the solid angle α achieved by the lens. Channel III is likewise defined by the walls 20_3 and 20_4, and so on to Channel IX, along which extends the centerline. The lens structure is symmetrical about the centerline, and thus the right hand outer channel XVIII curves in like manner, but in opposite direction, to Channel I.

The outer portion of the walls $20_1 - 20_{19}$ are shaped to establish the series of outlet axes $A_1 - A_{18}$, such that projections of these axes intersect at a common inward point C spaced substantially (e.g. 1 foot) from the diaphragm. Since a dispersed angle α of about one half a circle is desired for this embodiment center C lies on the plane projected through the front surface *18a* of the enclosure. Preferably, as shown, the curvatures of the walls are arranged so that the sound path P along each of the channels and outwardly to a circle projected from the common center C of the outlets is the same length for all channels.

Thus $P_1 = P_2 = P_3 = \ldots . P_{17} = P_{18}$.

The effect of these features is to emit a circular wave front even though the sound emitting diaphragm is both planar and extremely directional for the high frequencies. With a suitable shaping of the walls, the wave form can be spherical, however in the preferred embodiment shown, the speaker retains the same circular horizontal cross-section throughout its height, hence the output sound wave is of cylindrical form, which can spread to fill a room with high frequency sound. The walls may be made of various conventional speaker materials, e.g. paper stock of appropriate grade. The outer channels may be of lesser width than the inner channels (e.g. $W_1 < W_9$) taking advantage of the fact that the smaller the filament of sound, the more it can be bent without distortion. For outer channels especially, the channel width should be based upon the shortest audio wave length of interest and in general should be less than 1 ½ inches. Practical limits exist however because too narrow a channel introduces too much resistance to the travel of the sound. Thus it is found that channel width on the order of two-thirds of an inch for the channels is suitable. A practical rule, for channels which turn significantly, is that the inlet width of the channel should approximate the wave length of the highest frequency of interest.

The potential mid frequency mismatch resulting from reflected waves of the channels is believed to be overcome by varying from channel to channel the distance from the diaphragm to the point (20_t) at which the constricted throat occurs. Referring still to FIGS. **1** and *1a* it will be observed that although the throat 20_t for the various channels occurs at the same plane parallel to the diaphragm, this represents different path lengths to the diaphragm. Thus the path length of channel I from its portion of the diaphragm to the throat 20_t is longer than the corresponding path of the next adjacent channel II.

The throat 20_t is sized, in relation to the given enclosure, to provide a sufficiently low natural frequency of resonance (e.g. below the frequencies of bass organ and bass drum) in accordance with the laws relating to Helmholtz resonators, and in general will be less than half as wide as the transducer for enclosures of suitably limited size.

Also the volume of the enclosure exposed to the back side of the transducer (Volume I, FIG. **1**) should be a plurality of times greater than the volume of the enclosure exposed to the front side of the transducer, as measured from the diaphragm **12** to the outlet (Volume II, FIG. **1**). Advantageously the ratio of Volume I to Volume II should be greater than **4**.

In this embodiment the restricted throat is 3 inches wide contrasted to the 1-foot width of the sound-emitting diaphragm which is surrounded by this enclosure, and the lens outlet has a width of about 7 inches. The enclosure width W is 36 inches, depth *d* is 18 inches and height *h* is 72 inches, the front edges of the enclosure being chamfered as shown. Volume I bears the ratio to volume II of about **10** to **1**.

In this embodiment the ends *20e* of the walls defining the channels protrude beyond front wall *18a* and the axes A_1 and A_{18} of the outlets of channels I and XVIII on the extremities are substantially parallel to front wall *18a*, see FIG. *1a*, in order to achieve a solid angle of dispersion α approximately 180°. The ends *20e* are hidden from view in a simple manner by grill cloth **17**. In this case the cloth is anchored at points **21** and **22** at the beginning of the chamfer of the front edges of the enclosure (the chamfers decrease the bulky appearance of the enclosure). The grill cloth extends at a substantially similar angle to the chamfers to stand-off projections **23** located at the intersection of the chambers and the front panel *18a*, these projections being acoustically transparent. The projections **23** extend as far from the front panel *18a* as do the ends *20e* of the channel-forming walls, and the grill cloth stretched between these projections covers these ends and gives the speaker a finished appearance.

It may be noted that in the instance of using such a speaker as this merely as a woofer, only the outside walls 20_1 and 20_{19} of the lens, FIG. **1***a*, would be required, still keeping the constricted throat. However, high and low frequency component mismatch, cross-over network difficulties and other significant problems are avoided and economies achieved by the full range speaker of the present embodiment.

To illustrate that the concept for reducing the frequency of low frequency resonance and dispersal of high frequencies by a restricted aperture lens system may not be limited to the preferred channeled lens construction, reference is made to FIGS. **6** and **6***a*. There is shown an enclosure **30** surrounding an electrostatic driver **32**. The principle of this speaker would be the same as that of the preceding figures in this respect: a restricted aperture **31**, or throat which is substantially narrower than the surrounded driver **32** provides (by the principle of the Helmholtz resonator) a natural frequency of resonance of the mechanical system below the lowest frequencies (e.g. bass organ and bass drum) that are to be reproduced, and the backward radiation of the transducer is contained by the enclosure. At the same time the transducer is arranged so that its sounds seem to emanate from a center C spaced from the diaphragm and near the front wall **30***a* of the enclosure. The paths P from adjacent portions of the diaphragm ($32_1, 32_2 \ldots 32_5$) radiate from this center so as to disperse the high frequency sounds through a wide solid angle. The lengths of the paths (e.g. $p_1, p_2, \ldots p_5$) from the respective portions of the diaphragm to a circle centered on C are substantially of the same length.

Referring to the specific structure of FIGS. **6** and **6***a*, the form of the transducer **32** approximates the arc of a circle and the concave portion of the transducer is directed toward the aperture **31**. (Although a single circular line is shown in FIG. **6**, it will be understood that the transducer preferably comprises opposed apertured electrodes with a flexible diaphragm disposed therebetween in a balanced construction.) The transducer is arranged with the focal point (the point of intersection of the normals to the diaphragm surface) at the position of the desired center for radiation C, e.g. near the plane **30***a* of the front of the enclosure. Thus the high frequency radiations, in following paths normal to the diaphragm portions, pass through the center, adjacent paths crossing each other. Since the normals of adjacent surface portions lie at angles to each other, the net effect is a circular wave form emanating from the aperture. FIG. **6** is a horizontal cross-section of the speaker. The speaker can have uniform cross-section throughout a substantial height, so it generates a cylindrical wave form, to disperse high frequency radiation in a wide solid angle α.

As illustrated in FIG. **6***a*, it may be possible to approximate a circular cross-section transducer by a number of planar units $32_1, 32_2 \ldots 32_5$ disposed as chords of a circle, thus to take advantage of the simplifications attendant with the use of planar members. It also may be advantageous to employ rounded transition surfaces **35** between the front wall **30***a* of the enclosure and the guide walls **36** which extend from each outer diaphragm portion to the aperture **31**. This lens construction could be used in tweeter and mid-range speakers as can the lens system of FIG. **1–3**, but one of its virtues, like that of the system of FIG. **1–3**, would be the possibility of use in lower range and full frequency range speakers in which a lowered resonant frequency and avoidance of cancellation and reinforcement due to the back wave would be achieved.

Referring to FIG. **9**, in the preferred embodiment of the invention a conductive diaphragm **12** is employed. With such diaphragms the use of a bare conductive fixed electrode would lead to power arcs that can destroy the diaphragm. It is realized that coating of the electrodes with high dielectric strength coatings would still leave the problem of imperfection and pinholes permitting destructive power arcs. This whole class of problem is avoided according to the invention by using thick high dielectric constant electrodes, i.e. dielectric portions about 3 or more times greater in thickness than the air gap on the respective side of the diaphragm, assuming the diaphragm to be in mid-position.

The electrode featured by the invention for meeting these unusual dielectric requirements is a molded member comprised of a dielectric matrix in which a substance of relatively higher dielectric constant (preferably $K>500$) has been dispersed. The result is an electrode whose construction permits tailor-made electrical properties with high K values. Such electrodes permit sufficient force per unit of diaphragm area to be applied to power the loudspeaker being described.

The matrix material may be selected from the various moldable dielectric substances that are available, but particularly good results are achieved using epoxy, which has dielectric constants below 10, e.g. $K = 4$ to 6. To this material is added, previous to molding, a dispersion of a substance selected for having a much higher dielectric constant (such as barium titanate, $K = 1,000$ to 1,500). Advantageously, also a dispersion of semi-conductive substance (such as carbon) is added, having a lower volume resistivity than the matrix material to achieve a volume resistivity in the range of 10^8 to 10^{11} ohm centimeters, the preferred value being about 10^{10} ohm centimeters.

The properties of the resulting electrode are not linear. That is, whereas a linear resistor has a slope of one in the IE plot, for the actual material the slope is on the order of one-third. Also the dielectric constant at high frequency drops to approximately two-thirds of its low frequency value. Some idea of the operational properties of the material may be seen by computing a pseudo time constant for mid-range values, with the assumption of linearity of these properties. Referring to FIGS. **7***a* and **7***b*, curves of a typical embodiment, the material is seen at midfrequency range to have a dielectric constant of about 40 and a volume resistivity of 2×10^{10} ohm centimeters. This corresponds to a pseudo time constant of 0.2 seconds. In actuality the time constant at this particular frequency will be somewhat longer due to the lesser slope of the volume resistivity curve of the actual material.

It is found that time constants considerably greater than 1 second make recovery of operation of the speaker in the event of overload unduly long. On the other hand, if volume resistivity is too low, in the case of the diaphragm touching the electrode, too large a current flows which can impair the tension of the mylar diaphragm.

With the dielectric constant K in the preferred range of 30 to 60 and with the volume resistivity lying within the range of about 10^8 and 10^{11} ohm centimeters, satisfactory performance is obtained.

The dielectric constant of the material according to this invention remains substantially high into the range of several hundred kilocycles permitting the use of a carrier frequency for measuring diaphragm movement and velocity for negative feedback purposes, discussed further below.

According to a suitable procedure for preparing the electrode barium titanate and carbon powders are mixed together with a suitably proportioned mass of epoxy in the liquid state, prior to reaction. The mixture is then cast into a mold in the desired form and cured.

Referring to FIG. **7** a broken away portion of the preferred electrode plate is shown, formed by the casting procedure. The matrix material illustrated by the dashed cross-hatching is No. 2038 epoxy; and No. 3416 hardener, manufactured by Houghton Laboratories of Olean, New York, in the ratio of 1 part by weight hardener to 10 parts 2038.

The triangles shown in the cross-section of FIG. **7** diagrammatically suggest the uniform dispersion of fine barium titanate particles and the circles shown in the cross-section similarly suggest the uniform dispersion of carbon particles. Employing substantially equal amounts of barium titanate and 2038, with carbon approximately 5 percent of the weight of the epoxy produces a suitable electrode construction with dielectric constant in the range of $K= 30$ to 40 and volume resistivity in the region of $R_r = 10^{10}$ ohm centimeters.

In one preferred embodiment the electrode plate consists of the following percentages, of the various ingredients:

epoxy 2038	100 parts by weight
barium titanate	100 parts by weight

epoxy hardener 3416	10 parts by weight
carbon	5.3 parts by weight (being 4.8 percent of the total epoxy)

Referring again to FIG. **7**, the slots molded integrally into the electrode plate **14** have length L on the order of 2 inches, inlet width S_1 of 1 1/16 inch, and the slot walls diverge to an outlet width S_2 of one-eighth inch. Each land between the slots has a width on the inlet side of three-sixteenth inch and converges to a width of one-eighth inch on the outlet side. The electrode thickness *t* is on the order of one-fourth inch.

The inlet surface of the electrode is cast precisely planar and smooth. The outlet surface is smooth and after formation is coated with a conductive layer **14***c*, FIG. **9**, e.g. an epoxy containing a dispersion of fine silver-coated particles. Thereafter, the electrode plate may be baked for curing, e.g. 140° F. for a few hours.

After formation the electrode plate **14***a* is appropriately jigged, see FIG. **8**, and an edge member **14***b* is molded integrally therewith. A planar casting plate **38**, e.g. of plate glass forms the inside edge surface **14***c* of the edge member **14***b*. A removable spacer **40** of uniform thickness approximating one-half the thickness of the desired air gap rests upon the casting plate **38** and directly supports the inlet surface of the electrode during this operation. Jig members **42** and **44** form the outline of the edge member **14***b*. The edge member may be formed of the same material as the matrix of the electrode plate, however omitting the additives.

Referring to FIG. **9**, two such electrode members **14** and **16** are brought together, inner surfaces directed toward each other and frame surfaces **14***c* aligned. A thin flexible conductive diaphragm **12** (e.g. a polyester film such as Dupont's Mylar, of between one-fourth to one-half mil thickness, carrying on each side a vacuum-deposited aluminum coating) is disposed between the electrodes. Tension T (of several thousand p.s.i.) is applied to the diaphragm beyond the electrode whereupon the electrodes are permanently clamped to the diaphragms, e.g. by means of adhesive applied to mating surfaces **14***c* or by bolting the two electrodes together. The thus formed electrostatic driver is then ready for mounting within the speaker enclosure, see FIGS. **1–3**.

For full range electrostatic speakers the polarizing voltage across the fixed electrodes may range between about 2 to 8 kilovolts. The air gap between the diaphragm (in midposition) and either fixed electrode ranges between one-twentieth to one-tenth inch and it is found that the thickness of the electrode preferably should be of the order of one-fourth inch.

The signal voltage is divided across the electrode thickness and the air gap. To lose as little signal voltage across the electrode and to concentrate the signal voltage to the air gap the electrode of high dielectric constant (e.g. greater than 30) is employed. A maximum limit on electrode thickness is found to exist because of lowering of the slot resonant frequency with increasing thickness. A minimum thickness limit is found to exist because of the need to avoid power arcs. For higher K, lower conductance is needed, but R_r too low is found to give problems, for example greater tendency for the diaphragm to stick to the electrode should contact be made, and localized heating and resultant damage to the diaphragm.

The desired level of leakiness (i.e. (i.e. the volume resistivity) is advantageously achieved by the addition of a dispersion of carbon, as noted above.

In the example of the preferred embodiment, see FIG. **9**, the polarizing voltage together with the audio peak is established at 6,000 volts between diaphragm and electrode, the air gap A_g is 0.070 inch, the effective dielectric constant of the electrode material averages K = 40 (varying little with frequency), the thickness *t* of the electrode is about one-fourth inch. The volume resistivity of the electrode is adjusted by the amount of carbon present in the electrode matrix, (between 10^8 and 10^9 ohm centimeters) to establish a time constant of less than 1 second, preferably less than 0.1 second. By this is meant that less than 1 or 0.1 second is required for a voltage between the inner and outer faces of the electrode to drop to one-third of its value.

The electrostatic speaker of the invention imposes severe operating requirements upon the associated amplifier system. To obtain the requisite levels of audio output without requiring an unduly large diaphragm, the audio drive voltage must be quite high, a peak drive potential of 4,000 volts being employed. The speaker impedance is almost entirely capacitive (3,000 to 6,000 pf.) and peak currents in excess of 300 ma. are sometimes required implying a peak output requirement of many hundreds of bolt amperes. The output transformers generally used to drive conventional moving-coil speakers (which have a relatively low and essentially resistive impedance, e.g. 8 ohms) are peculiarly ill suited to the demands of the electrostatic speaker. Transformers having the requisite output are cumbersome, expensive, and present resonance problems when used to drive a capacitive load.

A simple schematic is presented in FIG. **10** to illustrate the difficulties of driving an electrostatic speaker directly from the output of a conventional resistance-coupled amplifier. An audio input signal **52** is applied to amplifying tube **54** and a plate supply voltage of + 4,000 volts is applied to terminal **56**. If capacitive load **60** is 3,000 pf. its impedance at 10 KHz is about 5,500 ohms. For the loss in response at that frequency to be limited to 3 db. plate resistor **58** can be no larger than 5,500 ohms. The plate supply would then have to furnish about 375 ma. or 1,500 watts to terminal **56**. This "brute force" method of driving a speaker is, of course, highly inefficient and impractical.

The inventor has devised a low-impedance amplifier circuit that produces the required output with efficiency, stability, linearity, and a relatively low-level input. A simplified schematic of this circuit is shown in FIG. **11**. An audio input signal **52** of about 10-volt amplitude is applied to the grid of pentode **T3**. (Like elements are designated with identical reference numerals throughout all the figures.) The terminal **56** plate supply of pentode **T2** is +4,000 volts. Capacitor **60**, representing the load presented by the electrostatic speaker, has a value of 3,000 pf. A −100 volt potential is applied to 10 K cathode resistor **62** at terminal **64**. The output signal at point B ranges from a value close to ground to almost +4,000 volts, and may furnish a peak current of over 300 ma. in either direction to load **60**.

In the quiescent no-input state, pentode **T3** develops a well defined plate current of slightly over 1 ma. through the 2M feedback resistor **66**. About 2,040 volts is developed over resistor **66** so that point B settles at a quiescent voltage of about +2,000 volts, while point A settles at about −40 volts. About 6 ma. flows from terminal **56** through pentode **T2**, 7 K resistor **68** and pentode **T1**.

Point B is held stable at +2,000 volts by feedback resistor **66**. Should it tend to rise to a higher voltage, the voltage increase would be applied through resistor **66** to the grid of pentode **T1**, causing **T1** to conduct more heavily and thus lowering the output voltage at point B. Conversely, were the voltage at point B to tend to fall to a lower value, the drop would also be fed back through resistor **66**, reducing the conduction through pentode **T1** and increasing the plate voltage of **T1** and decreasing the voltage between grid and cathode of pentode **T2** (the grid of **T2** is directly coupled to the plate of **T1**). The resulting increase in conduction through **T2** causes the voltage at point B to rise restoring the equilibrium output value of +2,000 volts.

The small-signal output impedance of the circuit is extremely low. Assume, for example, that pentodes **T1** and **T2** each have a transconductance of 1,000 microhms and that a 1-volt incremental voltage is applied to point B. This incremental voltage is fed back through resistor **66** to the grid of **T1**, resulting in a 1 ma. increase in the plate current of **T1** and a 7-volt increase in the drop across resistor **68**. The resulting 7-volt increase in the grid bias of **T2** reduces the cathode current of **T2** by 7 ma. The total change in current at point B (as seen by the load) is thus the increase in the plate current of **T1** plus the decrease in the cathode current of T2 (1 ma. + 7 ma. = 8 ma.). The small-signal output impedance of the amplifier is therefore only 1 volt/8 ma. = 125 ohms.

Only a few tens of volts of drive are required from the plate of pentode T3 which, in driving point A, closely approximates a very linear constant current generator. The large unbypassed cathode resistor **62** increases the effective output impedance of the T3 stage. (The effective resistance looking into the plate of T3 can be as high as 1 M.) Series-connected pentodes T1 and T2 function essentially as class B amplifiers, but the linearity of their operation is greatly increased by the 40 to 50 db. of negative feedback provided by resistor **66**. Further linearity improvement can be achieved by customary feedback from point B to **52**.

For large signal inputs, the amplifier can furnish very high peak currents, both positive and negative, to load **60**. When pentode T2 conducts, the output current is limited only by the current capacity of T2 at low or zero bias, and peak currents of many hundreds of ma. can be furnished to the load.

When pentode T1 conducts, the output current is, in first instance, limited by the 7 K resistor **68**. However, by shunting a 100-volt Zener diode **70** across resistor **68**, the voltage drop can be limited to 100 volts and the current which T1 can supply to the load can then, for all practical purposes, be limited only by the current capacity of pentode T1 rather than by resistor **68**.

A block diagram showing the entire electronic section of the system is presented in FIG. **12**. This block diagram incorporates amplifier elements similar to those shown in FIG. **11** and in addition shows the audio feedback system used to damp the low frequency resonance of the system.

An audio input signal **52** is applied to input amplifier **72**, a high-impedance, constant current stage or set of stages (which may even be solid state) serving the function of pentode T3 in FIG. **11**, and also serving to combine the audio input **52** with a feedback signal on line **73**. Active devices **74** and **76**, which occupy roles similar to those of pentodes T1 and T2 respectively, (but of course need not necessarily be pentodes) are connected in series between a high voltage source at terminal **56** and ground. Diaphragm **78** of electrostatic transducer **80** is electrically connected to Point B, the junction of active devices **74** and **76**, as is feedback resistor **66**.

It is realized that damping of the low frequency resonance peak is desired. To a certain degree this is possible by viscous damping, e.g. using glass wool disposed immediately adjacent to the back of the transducer as suggested in dotted lines at **19***a* in FIG. **1**. Electronically this same damping is well achieved by feedback system **82**. Carrier generator **84** applies a 260 KC signal to diaphragm **78**. This signal induces corresponding signals at electrodes **86** and **88** of electrostatic transducer **80**. The amplitude of each of these signals varies with the distance of the diaphragm from the electrode; the closer the diaphragm, the stronger the signal. The induced carrier signals on the two electrodes are detected and summed at diaphragm displacement detector **87**. Successful operation is made possible by the fact that with the dielectric electrode made as described above, a substantial K (believed to be greater than about **15**) exists at the frequency of the carrier wave.

The resulting signal, centered around a zero voltage and ranging positive or negative depending upon the direction of diaphragm displacement from the center position, is proportional to diaphragm displacement and is in quadrature with the transducer drive voltage at the resonant frequency. Diaphragm excursion should be inversely proportional to the frequency squared (i.e. displacement decreases 12 db. for each octave of frequency increase). The output of diaphragm displacement detector **86** is applied to differentiator **88**, which generates a signal advanced in phase by 90° (and thus approximately in phase with the drive voltage). The amplitude of this differentiated signal is inversely proportional to frequency and so decreases 6 db. for each octave of frequency increase.

The differentiator output signal is applied to feedback amplifier **90** which introduces a further 180° phase shift in the signal. The output from the feedback amplifier is returned through line **74** to constant current generator **72** and there summed with audio input signal **52**. (The feedback system **82** is designed so that the line **74** feedback signal is significant only from about 20 Hz to about 200 Hz; its phase at those frequencies is such as to oppose the drive voltage.) To produce constant sound energy throughout the frequency range of the system (with constant drive amplitude) the system response curve should drop about 6 db. per octave, ideally approaching line **100** in FIG. **14**. The characteristics of the electrostatic speaker are such that there would, without feedback, be about a 15 db. resonant peak **102** in the response corresponding to the acoustic resonance of the speaker. The use of the feedback system **82** not only flattens out this peak as shown at **104**, but also renders the phase response of the system far more linear. The phase response without feedback is shown in FIG. **15** at **106**; phase response with feedback is shown at **108**.

A detailed schematic drawing is shown in FIG. **13** of those system components represented in block form in FIG. **12**. This practical circuit illustrates one presently preferred implementation of the electronic portions of the electrostatic speaker system.

A further schematic drawing is shown in FIG. **16** of a system employing certain of the elements in solid state, and thus constituting a reduction to practice using components that are practical for production. In this embodiment two amplifiers of identical construction are employed, one connected to the diaphragm and the other to the fixed electrodes as shown, with a 180° phase shift between the two. The arrangement is generally suggested in FIG. **1** as well. For a given amount of audio signal a considerably more powerful output is obtained, relative to a one-amplifier embodiment.

Numerous variations in the specific details are possible within the spirit and scope of the invention.

What is claimed is:

1. An electrostatic loudspeaker comprising an electrostatic transducer having diaphragm surface portions which produce backward and forward moving sound radiation, an enclosure surrounding said transducer and adapted to contain the backward moving sound, an outlet passage for forward moving sound, said outlet passage having a throat that is substantially less in cross-sectional area than the collective area of said diaphragm surface portions, said outlet passage constructed and arranged with respect to said diaphragm surface portions to cause forward moving sound from each of said portions to pass through substantially equal length paths terminating beyond said throat at a projected common circle centered on said passage, the path for adjacent diaphragm surface portions terminating at adjacent segments of the arc of said projected circle, and wherein said passage is provided by a set of channels defined by walls, each channel associated with a predetermined diaphragm surface portion, channels associated with neighboring surface portions having their outlets in neighboring relation, the channels having constricted throat portions of cross-sectional area less than the area of their respective inlets.

2. The loudspeaker of claim **1** in which said channels extend outwardly from said throat portions to outlets that are larger than the respective throat portions.

3. An electrostatic loudspeaker comprising an electrostatic transducer having diaphragm surface portions which produce backward and forward moving sound radiation, an enclosure surrounding said transducer and adapted to contain the backward moving sound, an outlet passage for forward moving sound, said outlet passage having a throat that is substantially less in cross-sectional area than the collective area of said diaphragm surface portions, said outlet passage constructed and arranged with respect to said diaphragm surface portions to cause forward moving sound from each of said portions to pass through substantially equal length paths terminating beyond said throat at a projected common circle centered on said passage, the path for adjacent diaphragm surface portions terminating at adjacent segments of the arc of said projected circle, and wherein said diaphragm surface portions are arrayed within said enclosure to form substantially a segment of a circle, the inside surface of said circular array aligned with a spaced apart outlet aperture of said enclosure, said aperture being substantially smaller in width than the chord of said segment, and walls connecting the sides of said circular array to the corresponding sides of said aperture, whereby the paths normal to adjacent surface portions cross each other substantially at a common point and emanate radially therefrom to provide a circular wave front.

4. An electrostatic loudspeaker comprising an electrostatic transducer having diaphragm surface portions which produce backward and forward moving sound radiation, an enclosure surrounding said transducer and adapted to contain the backward moving sound, an outlet passage for forward moving sound, said outlet passage having a throat that is substantially less in cross-sectional area than the collective area of said diaphragm surface portions, said passage is provided by a set of channels defined by walls, each channel associated with a predetermined diaphragm surface portion, channels associated with neighboring surface portions having their outlets in like relation, the channels having constricted throat portions of cross-sectional area less than the area of their respective inlets.

5. The loudspeaker of claim **4** wherein said diaphragm portions and the cooperating outlet passage are each of elongated form in the direction perpendicular to said circle thereby adapted to generate substantially a cylindrical waveform dispersion of high frequency sound.

6. The loudspeaker of claim **4** wherein said diaphragm is at least about twice as wide as the minimum width of said throat.

7. The loudspeaker of claim **4** wherein said diaphragm surface portions are defined by an integral planar diaphragm, and said channels comprise middle channels extending substantially straight from middle portions of said planar diaphragm to their respective outlets and outer channels extending along curved paths from outer portions of the diaphragm, said outer channels having first portions gradually reducing in cross-sectional area and curving toward said middle channels and second portions gradually increasing in cross-sectional area and curving away from said middle channels toward their respective outlets.

8. The loudspeaker of claim **4** wherein the portions of said channels immediately adjacent said outlets have centerlines substantially intersecting at a point.

9. The loudspeaker of claim **8** wherein said point of intersection lies substantially in the plane of the front of said enclosure and said outlets are arranged substantially through a semicircular arc.

10. An electrostatic loudspeaker capable of emitting high frequencies comprising a diaphragm mounted adjacent at least a first electrode to form an electrostatic transducer in combination with a lens system adapted to convert the directional high frequency sound from said diaphragm into a substantially curved wave, said lens system comprising walls defining a set of channels, each channel associated with a predetermined portion of said diaphragm, channels associated with neighboring portions having their outlets in like relation, said channels comprising middle channels extending substantially straight from middle portions of said planar diaphragm to their respective outlets and outer channels extending along curved paths from outer portions of the diaphragm, first portions of said outer channels near said diaphragm having gradually reducing cross-sectional area and curving toward said middle channels and second portions of said channels having gradually increasing cross-sectional area and curving away from said middle channels toward the outlets of said channels for dispersing said high frequency sound.

11. The loudspeaker of claim **10** wherein the minimum cross-sections of said channels occur at varying distances from said diaphragm thereby tending to reduce detrimental effects from reflections of sound passing through said channels.

12. The loudspeaker of claim **10** wherein said parts of said diaphragm surface and the entrances to the corresponding outer channels have widths corresponding generally to the length of the shortest wave length desired to be dispersed without distortion, said width being less than 1½ inches.

13. The loudspeaker of claim **10** wherein said channels are constructed and arranged to cause forward moving sound from each of said parts of said diaphragm surface to pass through substantially equal length paths terminating at a common circle, the outer portions of said channels lying substantially on axes that intersect, defining the center of said circle.

14. The loudspeaker of claim **10** wherein said diaphragm and the channels defined by walls are each of elongated form in the direction perpendicular to said circle, thereby adapted to generate substantially a cylindrical wave for dispersion of high frequency sound.

15. An electrostatic loudspeaker capable of emitting low frequencies down to around 50 Hz comprising a wide diaphragm mounted adjacent to at least a first electrode to form an electrostatic transducer, an enclosure surrounding said transducer and adapted to contain the backward moving sound radiation, an extended air column defining outlet passage from said transducer adapted to conduct forward moving sound radiation out of said enclosure, said outlet passage having an entrance sized and positioned to conduct sound from a wide effective area of said diaphragm, said passage tapering gradually down to a throat of cross-sectional area substantially less than said area of said diaphragm, said passage provided by a set of channels defined by walls, each channel associated with a predetermined diaphragm surface portion, channels associated with neighboring surface portions having their outlets in neighboring relation, the channels having constricted throat portions of cross-sectional area less than the area of their respective inlets, said enclosure sized to define an air volume exposed to the back of the diaphragm which is a plurality of times greater than the air volume confined by said outlet passage, said enclosure and throat adapted to establish a low frequency of resonance for said loudspeaker.

16. The loudspeaker of claim **15** wherein the portion of the volume of said enclosure that is exposed to the back surface of said diaphragm is at least about four times greater than the portion of the volume of said enclosure exposed to the front surface of said diaphragm.

17. An electrostatic loudspeaker wherein two electrodes are provided, one on each side of a diaphragm mounted under self-restoring tension in a balanced transducer construction, each of said electrodes being comprised of a dielectric portion directed toward said diaphragm and a conductive layer disposed on the outer side of said dielectric portion, each electrode comprising a matrix of dielectric material and a dispersion through said matrix of a substance having a dielectric constant greater than about 500, each electrode having molded therein a plurality of apertures through which sound can escape from said diaphragm, each of said dielectric portions having a thickness greater than about 3 times the thickness of the air gap between the respective electrode and the diaphragm in mid-position, the dielectric portions having a dielectric constant greater than about 30, and means for applying a polarizing voltage between said conductive layers of said electrodes, and an audio amplifier connected to apply amplified audio signals between said diaphragm and the electrodes.

18. The loudspeaker of claim **17** wherein said electrode has a volumetric resistivity in the range of 10^8 to 10^{11} ohm centimeters.

19. An electrostatic loudspeaker transducer comprising a flexible diaphragm mounted under self-restoring tension, at least one rigid electrode facing the diaphragm and having a conductive surface on its opposite side, energization means for applying a polarizing voltage and an audio signal to cause corresponding vibration of the diaphragm to produce sound, the electrode comprising a matrix of dielectric material and a dispersion through said matrix of a substance having a dielectric constant greater than about 500, said electrode having molded therein a plurality of apertures through which sound can escape from said diaphragm, said electrode having an overall dielectric constant greater than about 30.

20. The electrostatic loudspeaker of claim **19** wherein said electrode contains a dispersion of another substance having a lower volume resistivity than said matrix material, thereby reducing the volume resistivity of said electrode below that of said matrix material.

21. The loudspeaker transducer of claim **19** including a second electrode of like construction assembled with said first electrode and said diaphragm to provide a balanced construction with the diaphragm disposed between said electrodes, an enclosure surrounding said transducer constructed to contain backward moving radiation from said diaphragm, an outlet throat from said enclosure for sound from said diaphragm, said throat being substantially narrower than said diaphragm, said energization means adapted to apply a voltage greater than 2,000 volts across said electrodes.

22. The electrostatic loudspeaker of claim **15** wherein, with respect to adjacent surface portions of said diaphragm, said outlet passage is constructed and arranged to cause forward moving sound from each of said adjacent surface portions of said diaphragm to pass through substantially equal length paths terminating beyond said throat at a projected common circle centered on said passage, the paths for adjacent diaphragm surface portions terminating at adjacent segments of the arc of said projected circle.

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