(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number : **0 620 049 A2**

(12) EUROPEAN PATENT APPLICATION

(21) Application number : **94302655.9**

(51) Int. Cl.[5] : **B06B 1/06**

(22) Date of filing : **14.04.94**

(30) Priority : **16.04.93 US 48604**

(43) Date of publication of application : **19.10.94 Bulletin 94/42**

(84) Designated Contracting States : **DE FR GB IT NL**

(71) Applicant : **Hewlett-Packard Company**
3000 Hanover Street
Palo Alto, California 94304 (US)

(72) Inventor : **Greenstein, Michael**
860 Covington Road
Los Altos, CA 94024 (US)
Inventor : **Lum, Paul**
690 Templebar Way
Los Altos, CA 94022 (US)
Inventor : **Yoshida, Henry**
5663 Glen Haven Court
San Jose, CA 95129 (US)
Inventor : **Melton, Hewlett E., Jn.**
1138 Royal Ann Drive
Sunnyvale, CA 94087 (US)

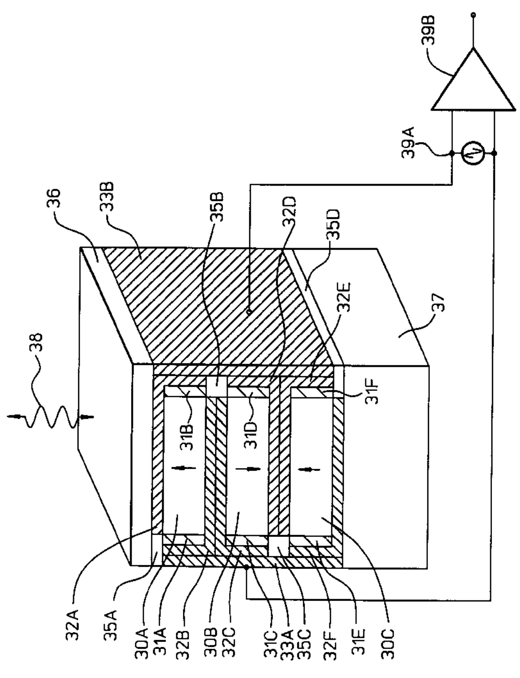
(74) Representative : **Powell, Stephen David et al**
WILLIAMS, POWELL & ASSOCIATES
34 Tavistock Street
London WC2E 7PB (GB)

(54) Multilayer acoustic transducer.

(57) An acoustic transducer apparatus comprises a piezoelectric resonator stack which contains active piezoelectric layers (20,20B,20C,20D, 20E,20F), internal conductive electrodes (22A, 22B,22C,22D,22E,22F), internal bonding layers (25A,25B,25C,25D), and an optional internal dielectric layer (24A,24B). The electrodes may be connected to provide alternating polarization directions, or any other desired sequence of polarization directions, in the sequence of piezoelectric layers. An optional edge dielectric layer (21A,21B,21C,21D,21E,21F), positioned between side electrodes (23A, 23B) and adjacent piezoelectric layers, controls the fringe electrical fields and the lateral piezoelectric modes that would otherwise develop. The piezoelectric layers may have uniform thicknesses with independently selected polarization direction within each piezoelectric layer.

Alternatively, the individual piezoelectric layers may have non-uniform thicknesses tn and independently selected polarization direction within each layer.

FIG. 3



EP 0 620 049 A2

This invention relates to acoustic transducers for medical imaging using multilayer piezoelectric materials, and to improvements in acoustic signal definition and bandwidth.

A diagnostic ultrasonic imaging system forms images of tissues inside the human body by electrically exciting a transducer or array of transducers to generate short ultrasonic pulses, which then travel into the body. A transducer or array of transducers then converts the ultrasonic echoes from the tissues into electrical signals which are amplified and used to form a cross sectional image of the tissue. Most often, transducers used for medical imaging consist of a single layer of piezoelectric material that requires excitation with a high voltage for generating short ultrasonic pulses. The echo signals are often amplified with low voltage integrated circuit electronics.

Currently, the high excitation voltage is an impediment to integrating low voltage, high density circuitry with a transducer or an array of transducers. For example, a two-dimensional acoustic array with a large number of acoustic elements requires local integrated electronics to achieve acceptable performance. It is both desirable and beneficial to strive for use of a low voltage transducer that can be excited by standard low voltage integrated circuit electronics. Use of low voltage transducers also reduces the potential of electrical hazard to the patient.

From an electrical point of view, achieving the required electric field within the piezoelectric material at low applied voltage requires a relatively thin layer of piezoelectric material. Achieving the desired operating frequency of the resonator requires a thickness of one half wavelength (or odd integer multiples thereof) or a thickness of one quarter wavelength (or odd integer multiples thereof). In addition, a uniform poling field throughout the lateral extent of the piezoelectric resonator and a uniform electric field without fringing fields during operation is required. In the prior art, these requirements have not been anticipated in the embodiments nor in the teachings.

Berlincourt, et al. disclose use of two or more piezoelectric layers in a stack on a substrate, with an independent common electrode being positioned between any two adjacent piezoelectric layers, in U.S. Patent No. 3,590,287. The objective is to provide improved filters and transformers for signal processing applications. Two adjacent piezoelectric layers are chosen to have the same or opposite electrical polarities, and two adjacent piezoelectric layers are chosen to have the same or different piezoelectric properties. Piezoelectric layer thicknesses are chosen to achieve a particular fixed resonant frequency for the structure. No discussion is presented of the issue of fringe fields poling or operation.

In U.S. Patent No. 4,087,716, Heywang discloses use of a multilayer stack of piezoelectric layers, with two interdigitated sets of electrode fingers being provided so that an electrode finger lies between each two adjacent piezoelectric layers of a co-fired ceramic structure. The polarization directions of any two adjacent piezoelectric layers are opposite to one another. The two sets of electrode fingers are driven by a time-varying voltage source, and electrode fingers from the first set and from the second set do not completely overlap laterally. The potential problem of shorting during operation and stress-induced cracking at the periphery of the multilayer is recognized, but no discussion is presented the problems with fringe field effects.

Glenn, in U.S. Patent No. 4,477,783, discloses an ultrasonic transducer, based on a piezoelectric polymer, that includes a multilayer stack of piezoelectric materials, with an electrode pair flanking each piezoelectric layer. Each such electrode pair has a controllable electronic delay means associated with it, and the time delay selected depends on the time interval required for propagation of an ultrasonic wave across the associated piezoelectric layer thickness. Adjacent piezoelectric layers may have electrical field polarization directions that are the same or are reversed. Internal electrodes on adjacent piezoelectric layers may be electrically shorted or isolated. Again, no discussion is presented of the issue of fringe fields during poling or operation.

The concept of impedance reduction for ultrasonic medical imaging was recognized in the context of signal to noise reduction by S. Saitoh, M. Izumi and K. Abe in "A Low-Impedance Ultrasonic Probe Using a Multilayer Piezoelectric Ceramic", Japan. Jour. App. Phys.,vol. 28, pp. 54-56, 1989. These authors do not comment on the utility of a multilayer transducer for reducing the required drive voltage of a transducer, nor on the effect of fringe fields on the performance of the transducer.

What is needed is an acoustic transducer for medical imaging with improved signal definition, efficiency and bandwidth. Preferably, the transducer should operate at low voltages and should control the development of spurious lateral modes that arise from fringe electric fields in the piezoelectric material which originate from poling the assembled resonator stack as well as the operation of the transducer with side electrodes.

These needs are met by the invention, which provides for fabrication of one or an array of low voltage, multilayer transducers, each transducer having side or external electrodes using a controllable, uniform poling field for an assembled acoustic resonator stack and using a static or time-dependent electrical field during operation.

In accordance with a first aspect of the present invention there is provided an array of acoustic transducers for producing an electrical signal in response to passage of an incident acoustic wave therethrough and for producing an acoustic wave in response to receipt of an electrical signal, each transducer comprising:

a plurality of N piezoelectric layers numbered consecutively $n = 1, 2, ..., N$, of selected thickness, each layer having two exterior surfaces, and being oriented approximately perpendicular to a selected path of an incident acoustic wave when the acoustic wave passes through the layer;

a plurality of M electrically conductive electrode layers spaced apart and facing each other, numbered consecutively $m = 1, 2, ..., M$, where $M \geqq N+1$, where at least one electrode layer is positioned between piezoelectric layers numbers j and j+1 for $j = 1, 2, ..., N-1$, where piezoelectric layer number 1 is positioned between electrode layers number 1 and 2, and where piezoelectric layer number N is positioned between electrode layers number M-1 and M;

a plurality of K electrically conductive external electrodes numbered consecutively $k = 1, 2, ..., K$ ($K \geqq 2$), with external electrode number k being electrically connected to a selected kth group of the electrode layers, where any two of these selected groups of electrode layers have no electrode layers in common; and

a plurality of K voltage signal transceivers with each external electrode layer being electrically connected to one of the voltage signal transceivers, to impress a selected time-dependent voltage signal on an electrode layer connected to a voltage signal transceiver and to allow a voltage signal transceiver to receive a time-dependent voltage signal from an electrode layer connected to that voltage signal transceiver.

The number of piezoelectric layers may be two, and they may have approximately equal thickness t_1 and t_2, or unequal thicknesses t_1 and t_2. One of said thicknesses t_1 and t_2 may be approximately twice as large as the other of said thicknesses.

Alternatively the number of piezoelectric layers may be three, and they may have approximately equal thicknesses t_1,t_2 and t_3 in which the thickness ratios t_1, t_2 and t_3 may be approximately 1:3:2 or 2:3:1.

The voltage signals impressed upon the electrode layers by said voltage signal transceivers may be changeable dynamically.

In accordance with a second aspect of the present invention there is provided an array of J acoustic transducers ($J \geqq 1$) for producing an electrical signal in response to passage of an incident acoustic wave there through, for producing an acoustic wave in response to receipt of an electrical signal, and for suppressing development of a trapped mode resonance that arises within the transducer in response to passage of an acoustic wave therethrough, each transducer being characterised by: a plurality of N piezoelectric layers, numbered consecutively $n = 1, 2, ..., N$, where each layer has two exterior surfaces, and being oriented approximately perpendicular to a selected path of an incident acoustic wave passing through the layer, where N is an even positive integer; a plurality of M electrically conductive electrode layers, spaced apart and facing each other, numbered consecutively $m = 1, 2, ..., M$, where at least one electrode layer is positioned between piezoelectric layers number j and j+1 for $j = 1, 2, ..., N-1$, where piezoelectric layer number 1 is positioned between electrode layers number 1 and 2, and where piezoelectric layer number N is positioned between electrode layers number M-1 and M; a plurality of P ($P \geqq N$) edge dielectric layers numbered consecutively $p = 1, 2, ..., P$, where each edge dielectric layer is positioned adjacent to at least one exterior surface of one of the piezoelectric layers and isolates two electrode layers from each other but does not lie in the acoustic wave path;

a plurality of K electrically conductive external electrodes numbered consecutively $k = 1, 2, ..., K$ ($K \geqq 2$), with external electrode number k being electrically connected to a selected kth group of the electrode layers, where any two of these selected groups of electrode layers have no electrode layers in common; and

a plurality of K voltage signal transceivers with each external electrode layer being electrically connected to one of these voltage signal transceivers, to impress a selected time-dependent voltage signal on an electrode layer connected to a voltage signal transceiver and to allow a voltage signal transceiver to receive a time-dependent voltage signal from an electrode layer connected to that voltage signal transceiver.

In one embodiment, the invention provides a multilayer acoustic transducer including a plurality of N piezoelectric layers (of equal or unequal thicknesses), in a piezoelectric resonator stack, each with top and bottom electrode layers. An optional adjacent matching layer and with an optional backing layer are provided. The requirements for the properties of the matching and the backing layers are well known by those skilled in the art.

Electrical connections are provided from each electrode layer to a time-varying voltage source for transmitting acoustic signals, and to an amplifier that receives acoustic echoes. The total thickness of the piezoelectric resonator stack is an odd multiple of $\lambda/4$ or $\lambda/2$ for a predetermined wavelength λ of an acoustic wave passing through the transducer. Adjacent piezoelectric layers have their poling directions oriented in the same direction or in opposite directions. Each piezoelectric layer has one or two edge dielectric layers that controls fringe electric fields and lateral modes that would otherwise develop. The electrodes for each piezoelectric layer are independently addressable from a multiplexer circuit, and the electrodes are electrically isolated from each other by internal dielectric layers positioned in the acoustic wave path. Side electrodes can be used to connect the piezoelectric layers electrically in parallel.

Multifrequency operation of the transducer is achieved with a multilayer transducer, including a plurality of equal or unequal thickness piezoelectric layers, with an optional matching layer and with an optional backing layer. This arrangement, mechanically in series and electrically in parallel, provides impedance control as well as voltage control. A single transducer or an array of transducers positioned side-by-side can be provided. In a second embodiment, the number N of piezoelectric layers is even, which allows some structural simplifications.

In a third embodiment, impedance normalization for different area transducer elements in a two-dimensional acoustic array is achieved with a multilayer transducer, including a plurality of N piezoelectric layers (of equal or unequal thicknesses), with an optional matching layer and an optional backing layer. The electrodes for the piezoelectric layers are arranged in either dedicated or dynamically variable series-parallel combinations to maintain the ratio of the electrical impedance to the element area as a constant across a two-dimensional acoustic array including elements of varying areas. Alternatively, the transverse areas of the piezoelectric layers in each stack are selected to maintain the same impedance across a two-dimensional transducer array.

Figures 1A, 1B and 1C illustrate a portion of an embodiment of the invention with a single piezoelectric layer and an edge dielectric layer.

Figures 2A and 2B illustrate the difference between an even number of layers (N=2) and an odd number of layers (N=3) in a resonator stack.

Figure 3 illustrates the multilayer resonator stack assembled into a transducer.

Figure 4 illustrates use of a curvilinear interface for an edge dielectric layer and adjacent electrodes.

Figures 5A and 5B illustrate achievement of reduced impedance for multilayer transducers according to the invention.

Figures 6A and 6B illustrate achievement of voltage reduction and multi frequency operation for multilayer transducers according to the invention.

Figures 7A, 7B, 7C and 7D illustrate the effect of poling direction on two-layer and three-layer structures.

Figure 8 illustrates a cylindrical multilayer transducer structure.

Figures 9A and 9B illustrate multifrequency operation of a transducer using isolated internal electrode layers and a multiplexer circuit.

Figures 10A-10F illustrate multifrequency operation using the largest nonredundant integer resonator stack.

Figures 11A-11D illustrate achievement of impedance control based on series/parallel interconnection combinations.

Figure 12 illustrates one embodiment for achievement of impedance normalization for two-dimensional arrays based on impedance control.

Figures 1A, 1B and 1C illustrate one embodiment of the invention, the piezoelectric layer, including an active piezoelectric layer 10, edge dielectric layers 11A and 11B, and conductive electrode layers 12A and 12B. In the version of Figure 1A, an edge dielectric layer 11A or 11B does not completely surround the active piezoelectric layer. In other embodiments, as shown in Figure 1B, an edge dielectric layer 11 may completely surround the active piezoelectric layer. Figure 1C is a cross sectional end view of the combination of layers. A typical thickness of the conductive electrode is in the range of 100 to 5000 Å. However, the conductive electrodes 12A and 12B are shown with exaggerated thickness for clarity.

The presence and positioning of each of the edge dielectric layers 11A and 11B in Figure 1C, physically separates the electrode layers 12A and 12B from each other and minimizes excitation of undesirable lateral modes within the piezoelectric layer 10 in the transmit mode, which arise from fringe electrical fields for previously poled piezoelectric material or from fringe fields for multilayer piezoelectric resonator stacks poled in situ. If pairs of side electrodes that contact a given piezoelectric layer directly on two parallel sides of the piezoelectric layer were used here, lateral modes could be excited in that piezoelectric layer. The type and properties of the dielectric chosen for the edge dielectrics 11A and 11B will determine the magnitudes of the fringe electric fields. In general, for the reduction of the magnitude of the lateral modes, use of dielectrics with dielectric constants much smaller than the dielectric constant of the piezoelectric layer will increase the effective separation of the side electrode from the piezoelectric layer. The distance of separation between the first electrode layer 12A and the second electrode layer 12B, provided by an edge dielectric such as 11B, lies in the range 10-250 mm. This separation must nominally stand off both the poling voltages and the operational applied voltages. Suitable dielectric materials for the edge dielectric layers and for optional internal dielectric layers discussed below include: oxides, such as SiO_z ($z \geqq 1$); ceramics, such as Al_2O_3 and PZT; refractory materials, such as Si_xN_y, BN and AlN; semiconductors, such as Si, Ge and GaAs; and polymers, such as epoxy and polyimide.

Figure 2A illustrates one embodiment of the invention, the piezoelectric resonator stack, for fixed electrically parallel excitation of equal thickness piezoelectric layers with opposite poling vector direction. The poling vectors for the electrical fields impose across the piezoelectric layers are indicated by the vertically directed arrows. Figure 2A illustrates a situation where the number of layers N is even (N=2), and the external electrodes 22A and 22D have the same polarity. Figure 2B illustrates a situation where the number of layers N is odd (N=3), and the ixternal electrodes 22A and 22F have opposite polarity. The active piezoelectric layers 20A, 20B and 20C have adjacent edge dielectric layers 21A/21B, 21C/21D and 21E/21F, respectively, and adjacent conductive electrodes 22A/22B, 22C/22D and 22E/22F, respectively, with external side conductive electrodes 23A and 23B as shown. Alternatively, a single edge dielectric layer, such as 21B, 21D and 21E, can be provided adjacent to each piezoelectric layer.

The individual piezoelectric layers 20A, 20B and 20C in Figures 2A and 2B are attached together with internal dielectric layers 24A and 24B (optional), and respective bonding layers 25A/25B and 25C/25D (optional). The thicknesses of the electrode layers 22A-22D, the bonding layers 25A-25D and the internal dielectric layers 24A-24B are shown in Figures 2A and 2B with exaggerated thicknesses for clarity. Typical thicknesses of a bond layer and of an internal dielectric layer are less than 1 μm, and less than 100 μm, respectively. Side electrodes 23A and 23B are optionally provided, or each electrode layer 21A-21F can be electrically connected to one terminal of a group of one or more voltage signal sources 29A or signal amplifiers 29B. If the internal dielectric layers 24A-24B and the bonding layers 25A-25D are deleted, some of the intermediate electrode layers, such as 22B and 22D, can be optionally deleted so that the transducer requires as few as N+1 electrode layers for an N-layer stack.

The total thickness T of the piezoelectric resonator stack includes the thicknesses of the piezoelectric layers t_i, the thickness of the internal dielectric layers h_i, and the thicknesses of the bonding layers k_i. The thicknesses of the conductive electrodes are negligible here. For $\lambda/2$ and $\lambda/4$ resonator stacks, where h_i, k_i << t_i, T satisfies the relation

$$T = \sum_{i=1}^{N} (t_i + h_i + k_i + c_i) = (2m + 1)\lambda / Q, \qquad (1)$$

where λ is the acoustic wavelength in the piezoelectric layers, Q=2 for piezoelectric resonator stacks of thickness $\lambda/2$, Q=4 for piezoelectric resonator stacks of thickness $\lambda/4$, and m is a selected non-negative integer. If the internal dielectric layers and/or the bonding layers are deleted from the transducer, the respective variables h_i and/or k_i do not appear in Eq. (1).

If the thicknesses t_i, h_i, k_i and c_i are expressed non-dimensionally in terms of the acoustic wavelength, λ, the normalized relations

$$t_i = (\lambda/Q)\,\tau_i, \qquad (2)$$
$$h_i = (\lambda/Q)\,\delta_i, \qquad (3)$$
$$k_i = (\lambda/Q)\beta_i, \qquad (4)$$
$$c_i = (\lambda/Q)\gamma_i \qquad (5)$$

are operative, where τ_i, δ_i, β_i and γ_i are non-dimensional parameters. A total normalized thickness T' of the piezoelectric resonator stack then may be written as

$$T' = \sum_{i=1}^{N} (\tau_i + \delta_i + \beta_i + \gamma_i) = (2m + 1). \qquad (6)$$

A multilayer resonator stack may also be constructed from layers that are limited (by other constraints) in their individual maximum thicknesses. This situation may occur with layers deposited in situ by sputtering or evaporation or sol-gel deposition, for example. In this situation, each layer might be restricted to a maximum thickness, t_{max}, which may be of the order of 1-10 μm, while the resonator has a desired thickness $\lambda/2 >> t_{max}$. The required numbers of layers N is given approximately by the ratio $N = \lambda/2t_{max}$ (>> 1).

Figure 3 illustrates a complete acoustic transducer for fixed electrical parallel excitation according to the invention, with opposite poling directions for three consecutive piezoelectric layers. This transducer includes: three parallel, spaced apart piezoelectric layers 30A, 30B and 30C; three pairs 31A/31B, 31C/31D and 31E/31F of side dielectric layers flanking the piezoelectric layers 30A, 30B and 30C, respectively; three pairs 32A/32B, 32C/32D and 32E/32F of individually controlled electrodes that surround the respective piezoelectric layers 30A, 30B and 30C; an internal dielectric layer (not shown in Figure 3) separating the electrodes 31B and 31C; an internal dielectric layer (not shown in Figure 3) separating the electrodes 31D and 31E; end electrodes 33A and 33B that flank all other components on the left and right, respectively; two dielectric end spacers 35A and 35D; a dielectric spacer 35B that separates the electrodes 32A, 32B, 32C and 32D; a dielectric spacer 35C that separates the electrodes 32C, 32D, 32E and 32F; an optional matching layer 36; an optional backing layer 37; an amplifier 39B connected to the two end electrodes 33A and 33B; and a voltage source 39A connected between the two end electrodes 33A and 33B to impose a selected external voltage difference between these two end electrodes. An acoustic wave 38 is received by the apparatus in the receive mode, or issued by the apparatus in the transmit mode. A single dielectric edge layer, such as 31A, 31C and 31E, can be provided in place of the pairs of flanking edge dielectric layers 31A-31F. Alternatively, one can delete the edge dielectric layers.

The optional matching layer 36 is provided to suppress or minimize losses experienced by the acoustic wave 38 as the wave passes from the ambient-matching layer interface into and through the matching layer-piezoelectric layer interface. The material for the matching layer 36 may be graphite, epoxy, Mylar, polyimide or other similar compounds, with an acoustic impedance between that of the piezoelectric and that of the ambient medium, preferably being the geometric mean of the acoustic impedances of the two adjacent layers. The optional backing layer 37 of material is provided to suppress backward traveling waves produced by the acoustic wave 38. The material for the backing layer 37 may be a heavy metal, such as tungsten, in a lighter matrix such a polymer or a ceramic.

Figure 4 illustrates a further refinement of the electrical connection between first and second conductive electrodes 42A or 42B, and an external or side electrode 43. The reliability of the electrical contact can be improved by providing rounded or arcuate surfaces 44A and 44B on the adjacent edge dielectrics 41A and 41B and rounded or arcuate surfaces 45A and 45B at the interface of the two conductive electrode layers 42A and 42B with the external electrode 43. The external side conductive electrode 43 is deposited after the piezoelectric layers 40A and 40B and the edge dielectric layers 41A and 41B are bonded together, thus allowing the side electrode to conform to the geometry of the rounded corners as shown.

A multilayer piezoelectric resonator stack has several useful features, if the individual piezoelectric layers are of uniform thickness, ti, and the adjacent piezoelectric layers have opposite poling directions. In this configuration, the piezoelectric layers act mechanically in series, but act electrically in parallel. Figure 5 illustrates how impedance reduction can be achieved for a multilayer transducer, where the piezoelectric layers are electrically connected in parallel. For a piezoelectric layer of capacitance $C_0=\varepsilon A/t$, where ε is the layer dielectric constant, A is the layer area, and t is the layer thickness, the electrical impedance is given by $Z_0 = 1/(j\omega C_0)$, where $\omega= 2\pi f$ is the angular frequency of interest. For N piezoelectric layers, each having capacitance Z_0, the total electrical impedance Z_T is

$$Z_T = Z_0/N^2. \quad (7)$$

Thus, use of an N-layer transducer with parallel electrical connections can reduce the electrical impedance by a multiplicative factor of N^2.

If a single piezoelectric layer of thickness T (the "comparison layer") requires an applied voltage of V_0, a multilayer resonator stack of N piezoelectric layers, also of total thickness T, constructed as indicated in Figures 2A and 2B, with parallel electrical connections, requires an applied voltage of only V_0/N to achieve an equivalent piezoelectric stress field. This occurs because of the reduced piezoelectric layer thickness between adjacent electrodes. If the required applied transmit voltage for the comparison layer is 50-200 Volts, the required applied voltage for a multilayer resonator stack can easily be reduced to the range 5-15 Volts, which is suitable for integration with high density integrated circuits.

The electrical bandwidth of an N-layer resonator stack can also be increased relative to the bandwidth of the comparison layer with N = 1. Each piezoelectric layer in the multilayer resonator stack is a $\lambda/2$ resonator operating at N times the fundamental frequency f_0 for the comparison single layer resonator, neglecting the effect of strong coupling between the piezoelectric layers. With an appropriate choice of series and parallel electrical connections to the individual electrodes between the piezoelectric layers, a multilayer resonator stack can also operate as a multifrequency acoustic transducer with a plurality of discrete fundamental frequencies.

Figures 6A and 6B illustrate how voltage reduction can be achieved for a multilayer transducer where the piezoelectric layers are electrically connected in parallel, and how multifrequency operation occurs when the piezoelectric layers are electrically connected individually. For a single piezoelectric layer 60, an applied voltage of V_0 gives a resonance frequency of f_0, for a thickness of $\lambda/2$. For N=3 piezoelectric layers 61A, 61B and 61C, of total thickness $\lambda/2$ and connected in parallel, the required voltage to achieve the equivalent total electric field in the three-layer resonator stack is $V_0/3$. For independent electrical connections to the piezoelectric layers, the possible resonance frequencies are f_0, $3f_0/2$, and $3f_0$., using three, two or one piezoelectric sub-layers in combination, respectively.

Figures 7A, 7B, 7C and 7D illustrate the effect on the spatial distribution of the electric field E and the fundamental resonant frequency of the piezoelectric resonator stack for parallel electrical connections for both parallel and opposite poling directions in adjacent piezoelectric layers. Positioned below each transducer configuration is a plot of the electric field as a function of distance x, measured from front to back (or inversely) through a multilayer piezoelectric stack. These plots follow the approach of M. Redwood, "A Study of Waveforms in the Generation and Detection of Short Ultrasonic Pulses, Advanced Materials Research, 1963, pp. 76-84. Figure 7A illustrates the situation of N=2 layers, where the piezoelectric layers 71A and 71B are have opposite or anti-parallel poling directions. Figure 7B illustrates the situation of N=2 layers, where the piezoelectric layers 72A and 72B have parallel poling directions. The configurations of Figures 7A and 7B produce resonant frequencies of f_0 and $2f_0$, respectively. Figure 7C illustrates the situation of N=3 layers, where three piezoelectric layers 73A, 73B and 73C have opposite poling directions for adjacent piezoelectric layers. Figure 7D illustrates the situation of N=3 layers, where adjacent piezoelectric layers 74A, 74B and 74C have parallel poling directions. Figures 7C and 7D produce resonant frequencies of f_0 and $3f_0$, respectively.

Figure 8 illustrates an embodiment where the transducer is a right circular cylinder in form for the situation of N=3 layers. A matching layer and a backing layer (both optional) are omitted for clarity. An acoustic wave 88 is shown for both transmit and receive modes of operation. Three piezoelectric layers 80A, 80B and 80C are shown without internal conductive electrodes and bonding layers for clarity. Two side electrodes 83A and 83B of opposite polarity wrap around the bottom and the top, respectively, of the cylinder. Insulating dielectric layers 85A and 85B isolate the two electrodes 83A and 83B. A voltage source 89A for the transmit mode and an differential amplifier 89B for the receive mode are also incorporated.

Multifrequency operation may be achieved if the electrodes are individually addressable. This requires use of thin electrical isolation layers that minimally perturb an acoustic wave that passes therethrough. Figures 9A and 9B illustrate an embodiment for the situation N=3 layers where multifrequency operation is achieved, using isolated internal electrodes and a multiplexer circuit. Piezoelectric layers 90A, 90B and 90C have respective conductive electrode pairs 92A/92B, 92C/92D and 92E/92F, respective edge dielectric pairs 91A/91B, 91C/91D and 91E/91F, and bonding layers 95A, 95B, 95C and 95D as shown in Figure 9A. The internal electrodes 92B, 92C, 92D and 92E are isolated with internal dielectric layers 94A and 94B. Each of the electrodes 92A, 92B, 92C, 92D, 92E and 92F is connected to an individual signal line 93A, 93B, 93C, 93D, 93E and 93F, respectively, all of which are connected to a multiplexer circuit 97. A voltage source 99A, for the transmit mode, and an amplifier 99B, for the receive mode, are also provided. The table shown in Figure 9B exhibits the various voltage assignments required for the signal lines 93A-93F to produce resonance frequencies of f_0, $3f_0/2$, and $3f_0$. For example, an assignment of voltage V_0 to signal lines 93B, 93C and 93F will produce a resonant frequency f_0.

A multifrequency transducer may also be constructed by use of non-uniform thicknesses for the piezoelectric layers. These non-uniform thickness piezoelectric layers may be assembled from uniform thickness layers that are permanently connected together to form non-uniform thickness layers.

Figures 10A-10F illustrate achievement of multifrequency operation from the largest nonredundant integer resonator stack, a stack having N=3 piezoelectric layers. This is the largest resonator stack whose members have integer ratios of thickness, and for which there are no redundant frequencies. This resonator stack can produce resonant frequencies of f_0, $1.2f_0$, $1.5f_0$, $2f_0$, $3f_0$ and $6f_0$.

Figure 10A produces a resonant frequency f_0 with piezoelectric layers 100A, 100B and 100C, all connected in series. Figure 10B produces a resonant frequency $1.2f_0$ result using piezoelectric layers 102A, 102B and 102C, where only the piezoelectric layers 102A and 102B are connected in series. Figure 10C produces a resonant frequency $1.5f_0$ result using the piezoelectric layers 104A, 104B and 104C, where only the piezoelectric layers 104B and 104C are connected in series. Figure 10D produces a resonant frequency $2f_0$ result using piezoelectric layers 106A, 106B and 106C, where only the piezoelectric layer 106B is connected. Figure 10E produces a resonant frequency $3f_0$ result using piezoelectric layers 108A, 108B and 108C, where only the piezoelectric layer 108A is connected. Figure 10F produces a resonant frequency $6f_0$ result using piezoelectric layers 110A, 110B and 110C, where only the piezoelectric layer 110C is connected . All N-layer resonator stacks ($N \geqq 4$) with integer ratios of thicknesses generate a sequence of frequencies, using adjacent layers, that contains redundant frequencies. The ratio of individual layer thicknesses for a multilayer, multifrequency transducer is not restricted to integral multiples of a single thickness.

Figures 11A-11D illustrate embodiments for impedance control using various series/parallel electrical interconnection combinations, for an example N=3 layers. Four different electrical impedance values may be achieved: Z_0, $Z_0/2$, $2Z_0/9$, $Z_0/9$ for the embodiments of Figures 11A, 11B, 11C and 11D, respectively. Each interconnection combination for the Figures 11A-11D is shown with an accompanying electrical circuit diagram for clarity. Figure 11A illustrates the series combination, with piezoelectric layers 120A, 120B and 120C, edge dielectrics 121A and 121B, external electrodes 122A and 122B, and internal electrodes 122C and 122D. Figure 11B illustrates a series-parallel combination, with the same components. Figure 11C illustrates a second series-parallel combination, with the same components. Figure 11D illustrates a parallel combination, with the same components This set of impedances is shown with a dedicated set of electrical connections, but may also be achieved with a dynamically configurable set of electrical connections.

The ability to control the electrical impedance of a multilayer resonator stack by arrangement of the electrical connections between the layers can be used to approximately equalize the impedances of different multilayer resonator stacks. This ability can , for example, be usefully applied to a coarsely sampled two-dimensional array, where the elevation aperture is divided into separate elements of various sizes. The smaller area elevation elements will have a higher associated electrical impedance (inversely proportional to area of an element) than a larger area elevation element. Equalization of electrical impedance is useful because the driving electronics then senses that all electrical loads are approximately the same.

The preceding discussions and illustrative figures have focused on a single transducer stack of piezoelectric layers and associated electrode and dielectric layers. The invention also contemplates an array of J such transducers ($J \geqq 1$), positioned side by side, with an incident acoustic wave passing through one, several or all of the J transducers in the usual manner. Two or more transducer elements j1 and j2 ($1 \leqq j1 < j2 \leqq J$) may have different transverse areas A_{j1} and A_{j2} presented to the acoustic wave, to provide other control parameters for shaping or analyzing an acoustic wave.

Figure 12 illustrates this approach with N = 3 layers, with J = 7 stacks or elevation elements, and with 32 azimuth elements. It is assumed here that the seven elevation elements are wired symmetrically into four elevation groups so that, for example, the two elements of elevation height Y4 are wired in parallel; the two stacks of elevation height Y4 effectively form a single independent stack. The area for each elevation element, indicated at the right in Figure 12, is chosen to maintain the ratio of electrical impedance to transverse area as a constant for each independent stack. Therefore, if the total area of an elevation group scales with the electrical impedance for that group, achieved by resonator stack wiring such as shown in Figures 11A-11D, the electrical load seen by the driving electronics will be equalized across all elevation groups or stacks.

Claims

1. An array of acoustic transducers for producing an electrical signal in response to passage of an incident acoustic wave therethrough and for producing an acoustic wave in response to receipt of an electrical signal, each transducer comprising:

   a plurality of N piezoelectric layers (20A,20B,20C), numbered consecutively n = 1, 2, ...,N, of selected thickness, each layer having two exterior surfaces, and being oriented approximately perpendicular to a selected path of an incident acoustic wave (38) when the acoustic wave passes through the layer;

   a plurality of M electrically conductive electrode layers (22A,22B,22C,22D,22E,22F), spaced apart and facing each other, numbered consecutively m = 1, 2,..., M, where $M \geqq N+1$, where at least one electrode layer is positioned between piezoelectric layers numbers j and j+1 for j = 1, 2, ..., N-1, where piezoelectric layer number 1 is positioned between electrode layers number 1 and 2, and where piezoelectric layer number N is positioned between electrode layers number M-1 and M;

   a plurality of K electrically conductive external electrodes (23A,23B), numbered consecutively k = 1, 2, ..., K ($K \geqq 2$), with external electrode number k being electrically connected to a selected kth group of the electrode layers, where any two of these selected groups of electrode layers have no electrode layers in common; and

   a plurality of K voltage signal transceivers (29A,29B), with each external electrode layer being electrically connected to one of the voltage signal transceivers, to impress a selected time-dependent voltage signal on an electrode layer connected to a voltage signal transceiver and to allow a voltage signal transceiver to receive a time-dependent voltage signal from an electrode layer connected to that voltage signal transceiver.

2. An apparatus according to claim 1 wherein there is provided a plurality of P ($P \geqq N$) edge dielectric layers (21A,21B,21C,21D,21E,21F), where each edge dielectric layer is positioned adjacent to at least one exterior surface of one of the piezoelectric layers and isolates two electrode layers from each other but does not lie in the acoustic wave path.

3. An apparatus according to claim 2, wherein the edge dielectric layers (21A, 21B, 21C, 21D, 21E, 21F)

include a material selected from the class of electrically insulating materials consisting of SiOz(z≧1), $A1_2O_3$, Si_xN_y(x,y≧1), BN, A1N, epoxy and polyamide.

4. An apparatus according to any preceding claim, wherein at least two consecutive piezoelectric layers (20A, 20B, 20C) number i and i+1 (1≦ i≦M-1) have oppositely directed poling directions applied in the direction of propagation of said incident acoustic wave in said piezoelectric layers number i and i-1.

5. An apparatus according to any preceding claim, wherein N is an even integer and said electrode layers (22A, 22B, 22C, 22D, 22E, 22F) number 1 and M have the same voltage impressed thereon.

6. An apparatus according to any of claims 1 to 4 wherein N is an odd integer and said electrode layers (22A, 22B, 22C, 22D, 22E, 22F) number 1 and M have different voltages impressed thereon.

7. An apparatus according to any preceding claim, wherein at least one of said electrode layers (42A, 42B) has an interface with one of said external electrodes (43) that is curvilinear in shape.

8. An apparatus according to any preceding claim and further including a plurality of N-1 internal dielectric layers (24A, 24B), numbered consecutively i=1, 2, ..., N-1, of selected thicknesses h_1 (i = 1, 2, ..., N-1) lying in the acoustic wave path, with internal dielectric layer number i being positioned between piezoelectric layers number i and i+1.

9. Am apparatus according to claim 8, wherein said internal dielectric layers (24A, 24B) include a material selected from the class of electrically insulating materials consisting of SiOz(z≧1), $A1_2O_3$, Si_xN_y (x,y≧ 1), PZT, BN, A1N, epoxy and polyamide.

10. An array of J acoustic transducers (J ≧ 1) for producing an electrical signal in response to passage of an incident acoustic wave there through, for producing an acoustic wave in response to receipt of an electrical signal, and for suppressing development of a trapped mode resonance that arises within the transducer in response to passage of an acoustic wave therethrough, each transducer being characterised by: a plurality of N piezoelectric layers,(20A, 20B, 20C) numbered consecutively n = 1, 2,...,N, where each layer has two exterior surfaces, and being oriented approximately perpendicular to a selected path of an incident acoustic wave passing through the layer, where N is an even positive integer; a plurality of M electrically conductive electrode layers (22A, 22B, 22C, 22D, 22E, 22F), spaced apart and facing each other, numbered consecutively m = 1, 2, ..., M, where at least one electrode layer is positioned between piezoelectric layers number j and j+1 for j = 1, 2,..., N-1, where piezoelectric layer (20A, 20B, 20C) number 1 is positioned between electrode layers number 1 and 2, and where piezoelectric layer number N is positioned between electrode layers number M-1 and M; a plurality of P (P≧N) edge dielectric layers (21A, 21B, 21C, 21D, 21E, 21F) numbered consecutively p = 1, 2, ..., P, where each edge dielectric layer is positioned adjacent to at least one exterior surface of one of the piezoelectric layers and isolates two electrode layers from each other but does not lie in the acoustic wave path;

a plurality of K electrically conductive external electrodes (23A, 23B) numbered consecutively k = 1, 2, ..., K (K ≧ 2), with external electrode number k being electrically connected to a selected kth group of the electrode layers, where any two of these selected groups of electrode layers have no electrode layers in common; and

a plurality of K voltage signal transceivers (29A, 29B), with each external electrode layer being electrically connected to one of these voltage signal transceivers, to impress a selected time-dependent voltage signal on an electrode layer connected to a voltage signal transceiver and to allow a voltage signal transceiver to receive a time-dependent voltage signal from ane electrode layer connected to that voltage signal transceiver.

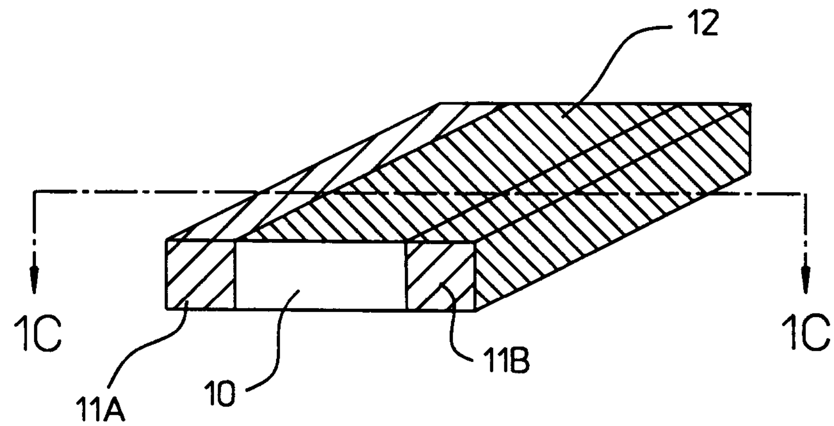


FIG. 1A

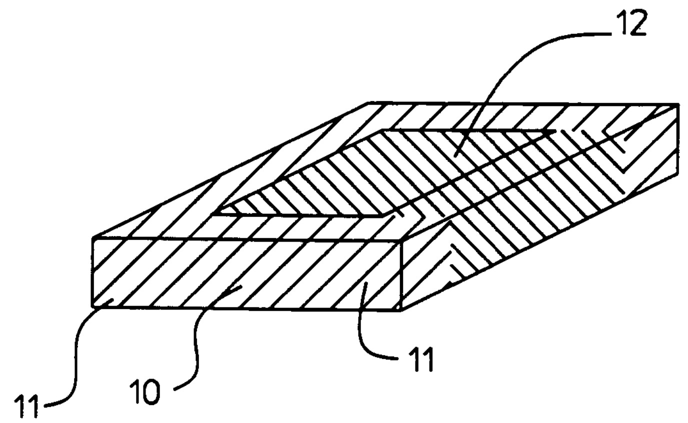


FIG. 1B

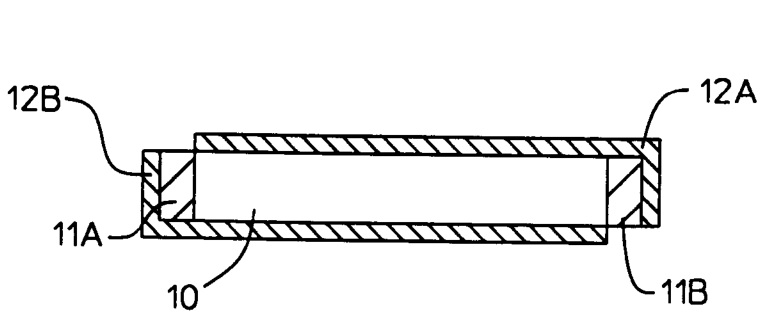


FIG. 1C

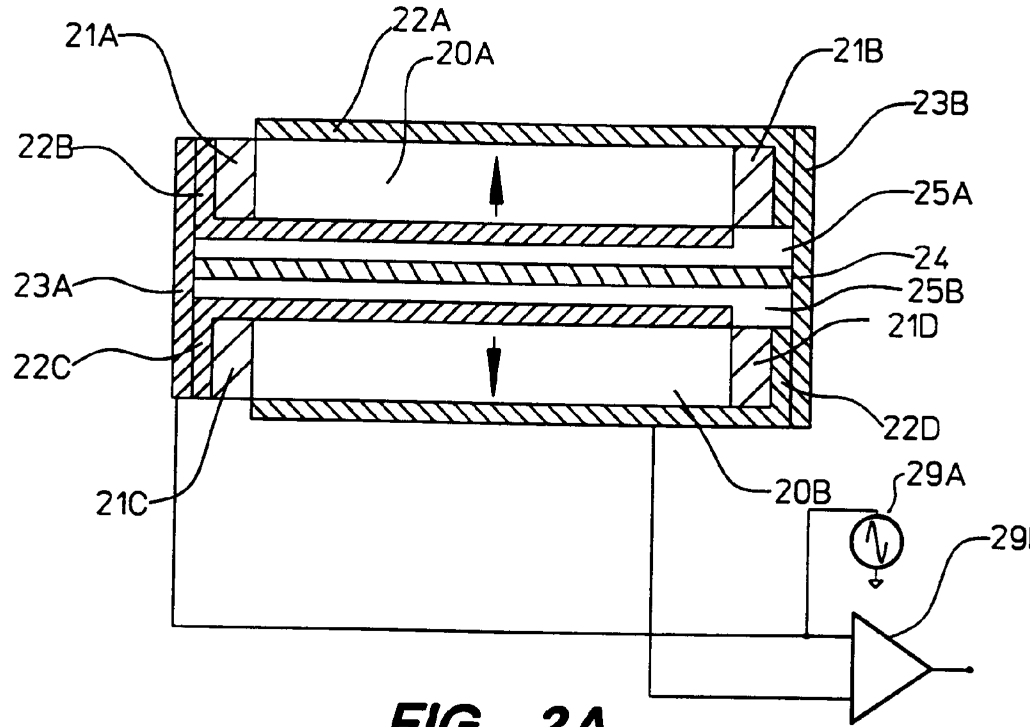

22A
20A
21A
21B
23B
22B
25A
24
23A
25B
21D
22C
22D
21C
20B
29A
29B

FIG. 2A

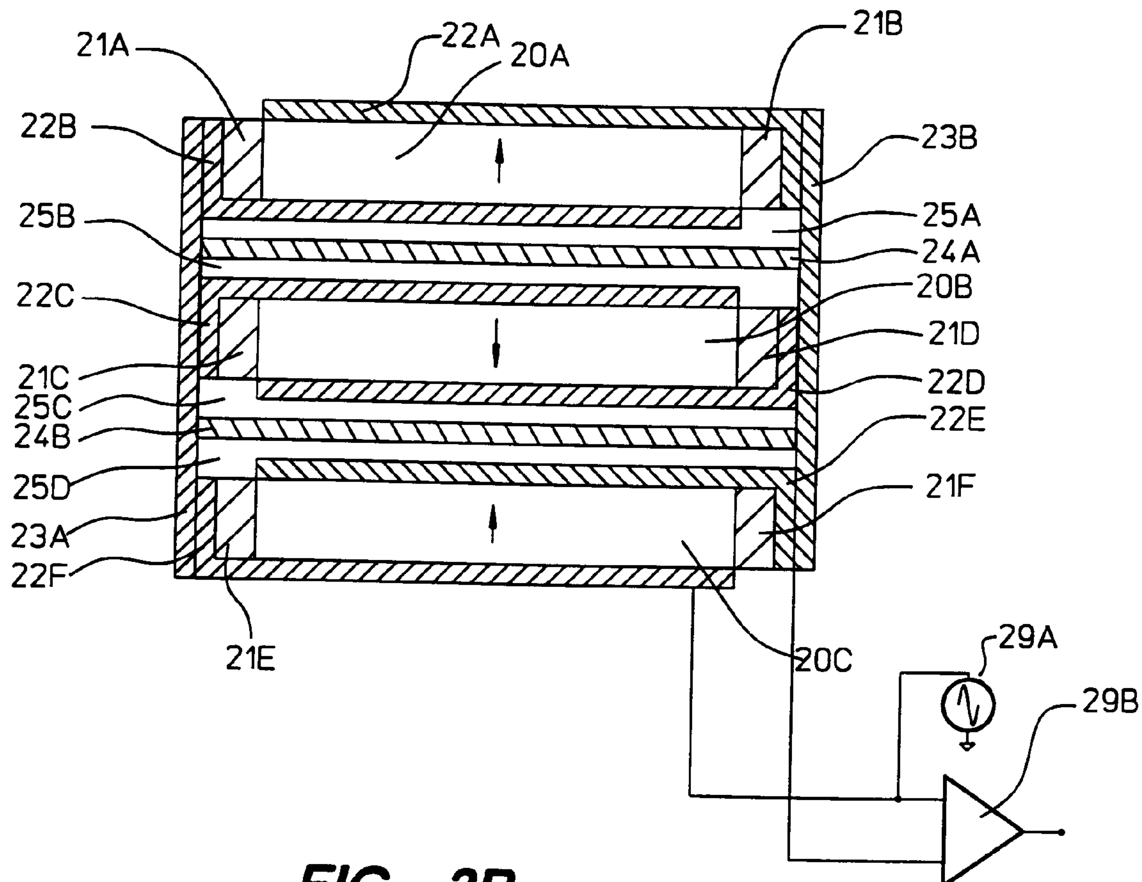
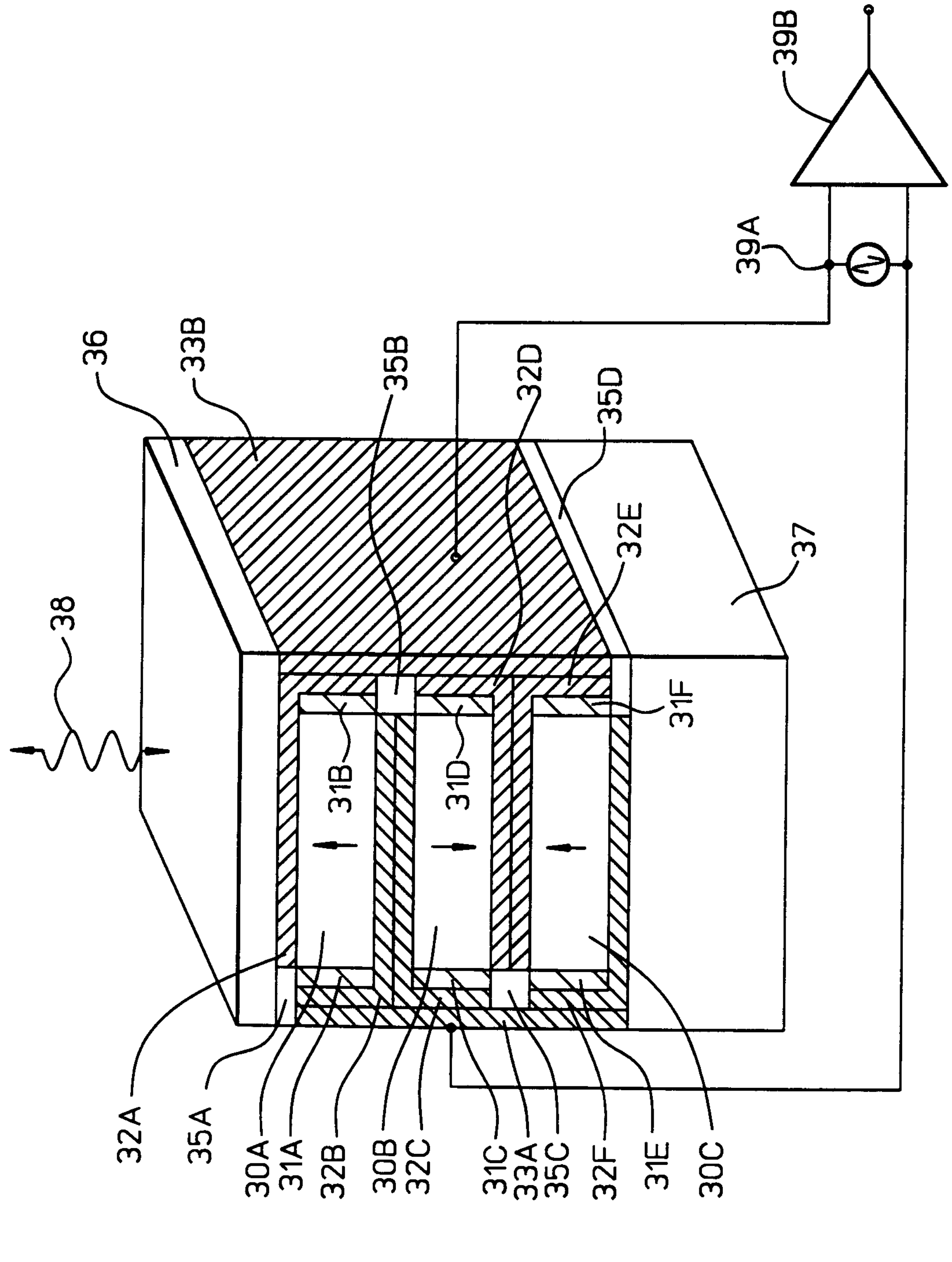

21A
22A
20A
21B
22B
23B
25B
25A
24A
20B
22C
21D
21C
22D
25C
24B
22E
25D
21F
23A
22F
21E
20C
29A
29B

FIG. 2B



36
33B
38
35B
32D
35D
32E
37
39A
39B
31B
31D
31F
32A
35A
30A
31A
32B
30B
32C
31C
33A
35C
32F
31E
30C

FIG. 3

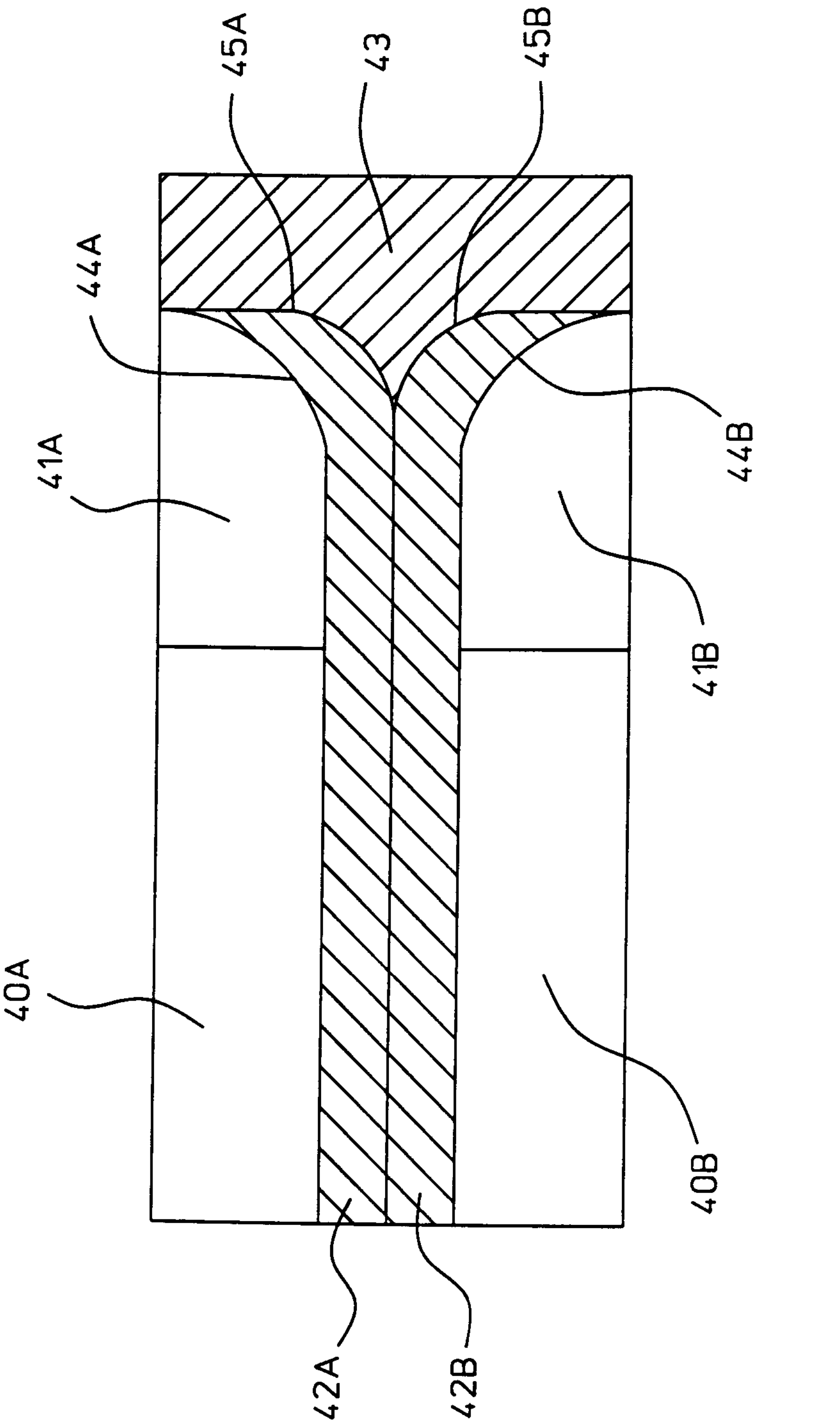
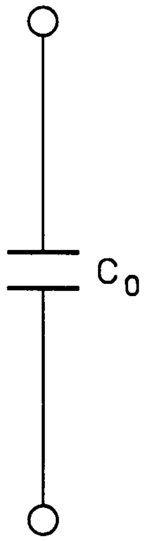


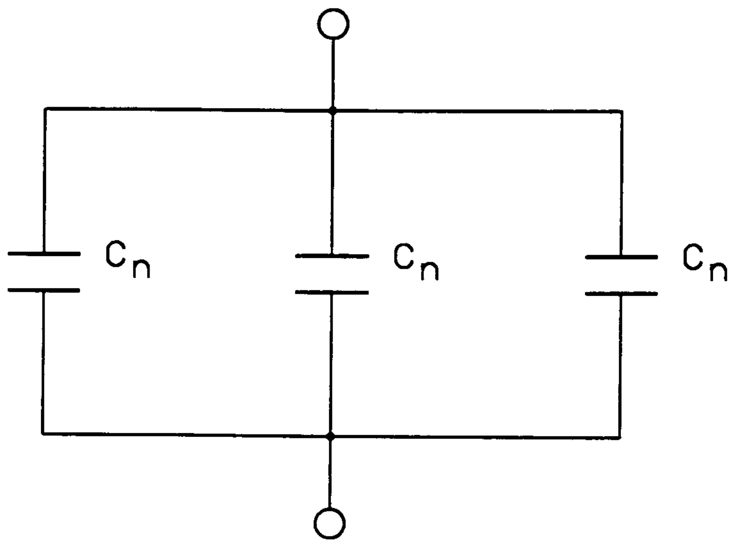
FIG. 4



$C_0 = \varepsilon A/t$

$Z_0 = 1/j\omega C_0$

FIG. 5A



$C_n = nC_0$ $\quad Z_n = (1/n)Z_0$

$Z_T = (1/n^2)Z_0$

FIG. 5B

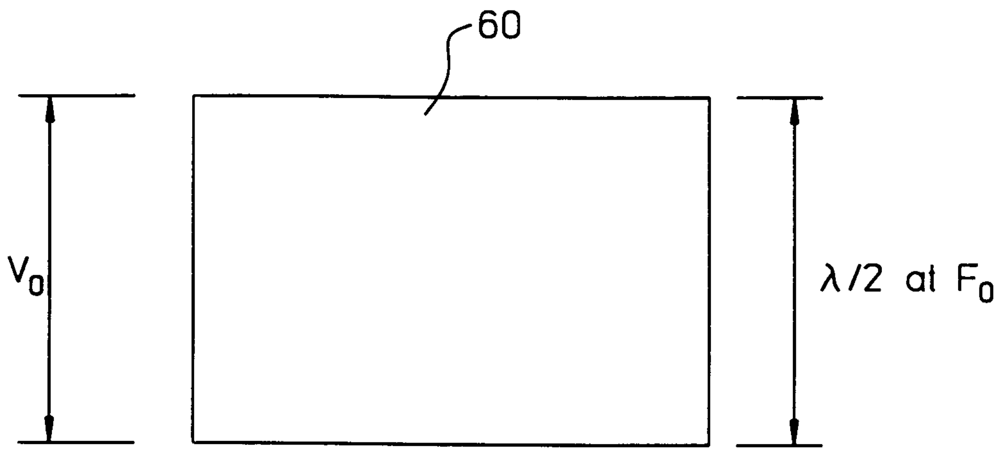

60
V_0
$\lambda/2$ at F_0

FIG. 6A

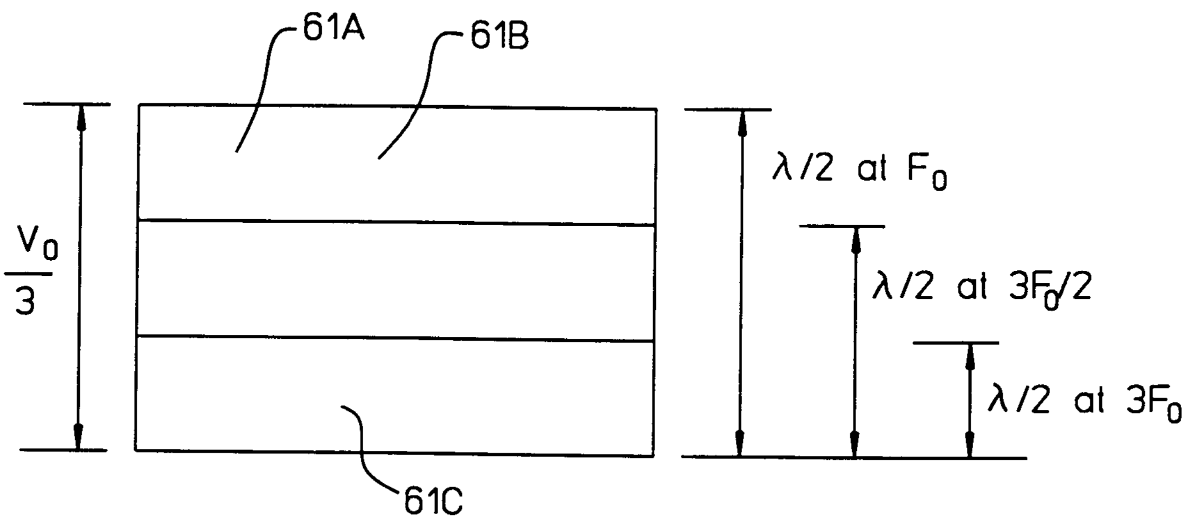

61A
61B
$\frac{V_0}{3}$
$\lambda/2$ at F_0
$\lambda/2$ at $3F_0/2$
$\lambda/2$ at $3F_0$
61C

FIG. 6B

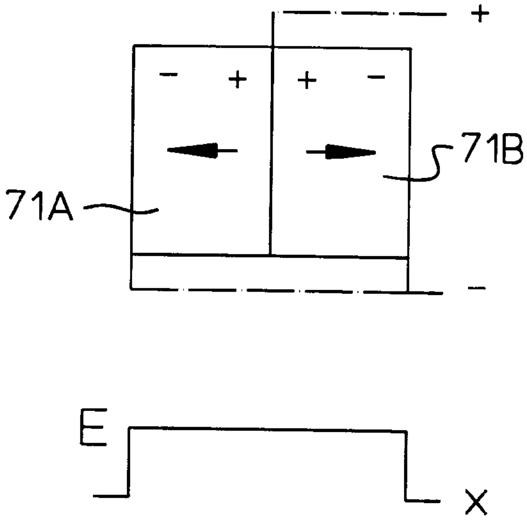


FIG. 7A

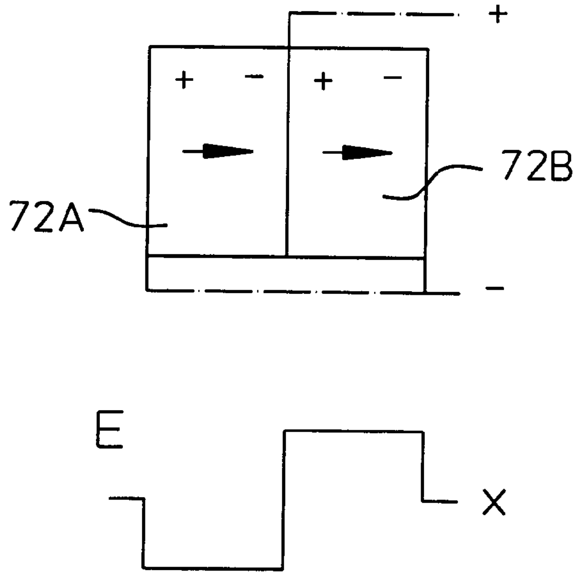


FIG. 7B

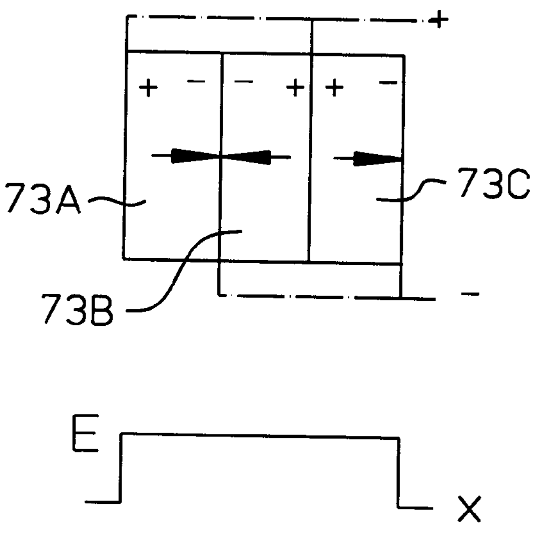


FIG. 7C

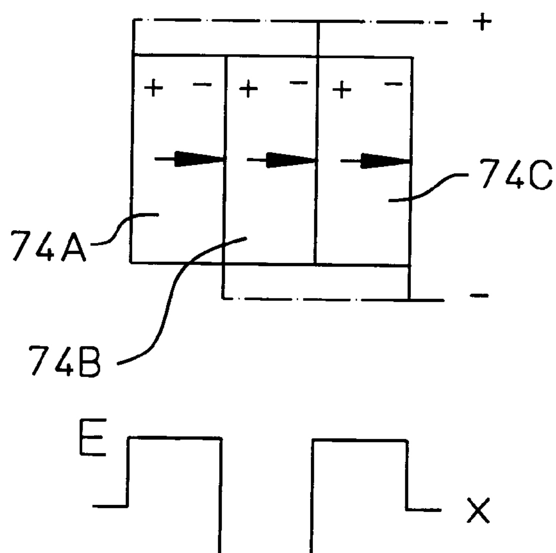


FIG. 7D

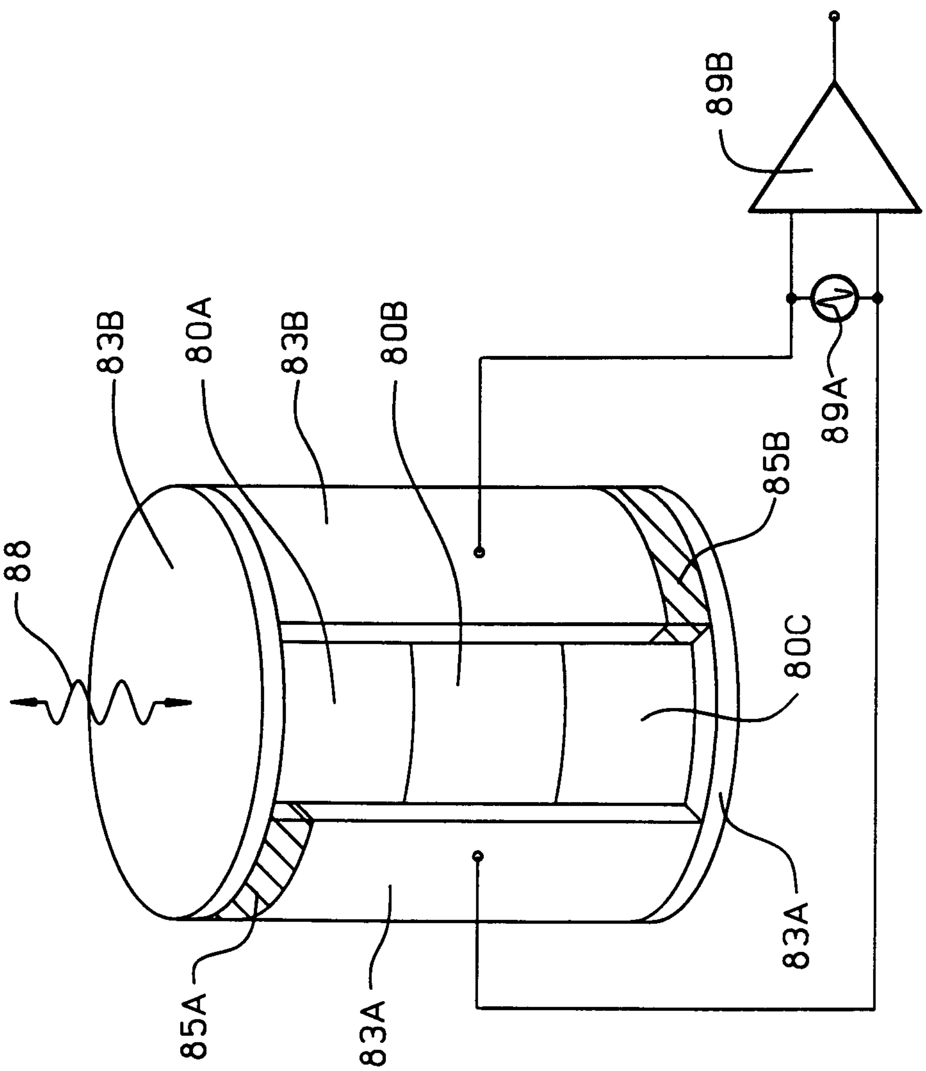


FIG. 8

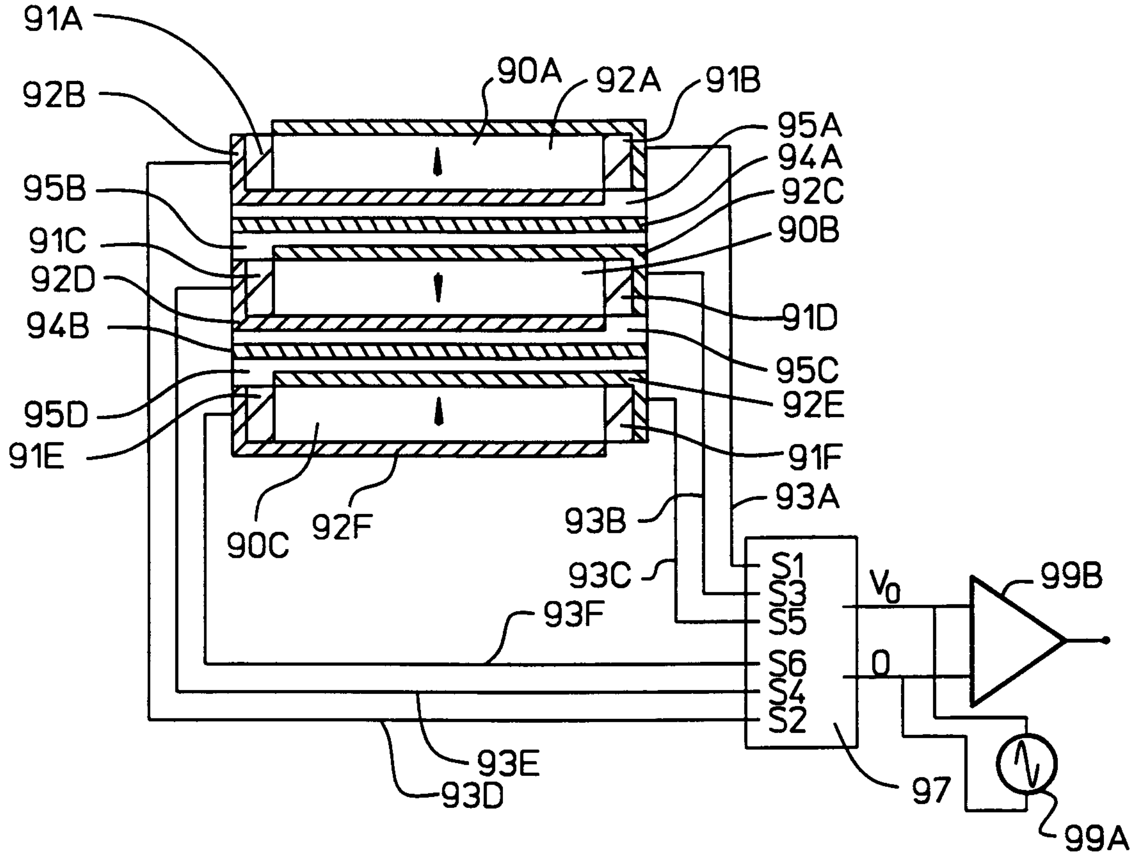


FIG. 9A

	S_1	S_2	S_3	S_4	S_5	S_6
F_0	0	V_0	V_0	0	0	V_0
$1.5F_0$	0	0	0	V_0	V_0	0
$3F_0$	0	0	0	0	0	V_0

96

FIG. 9B

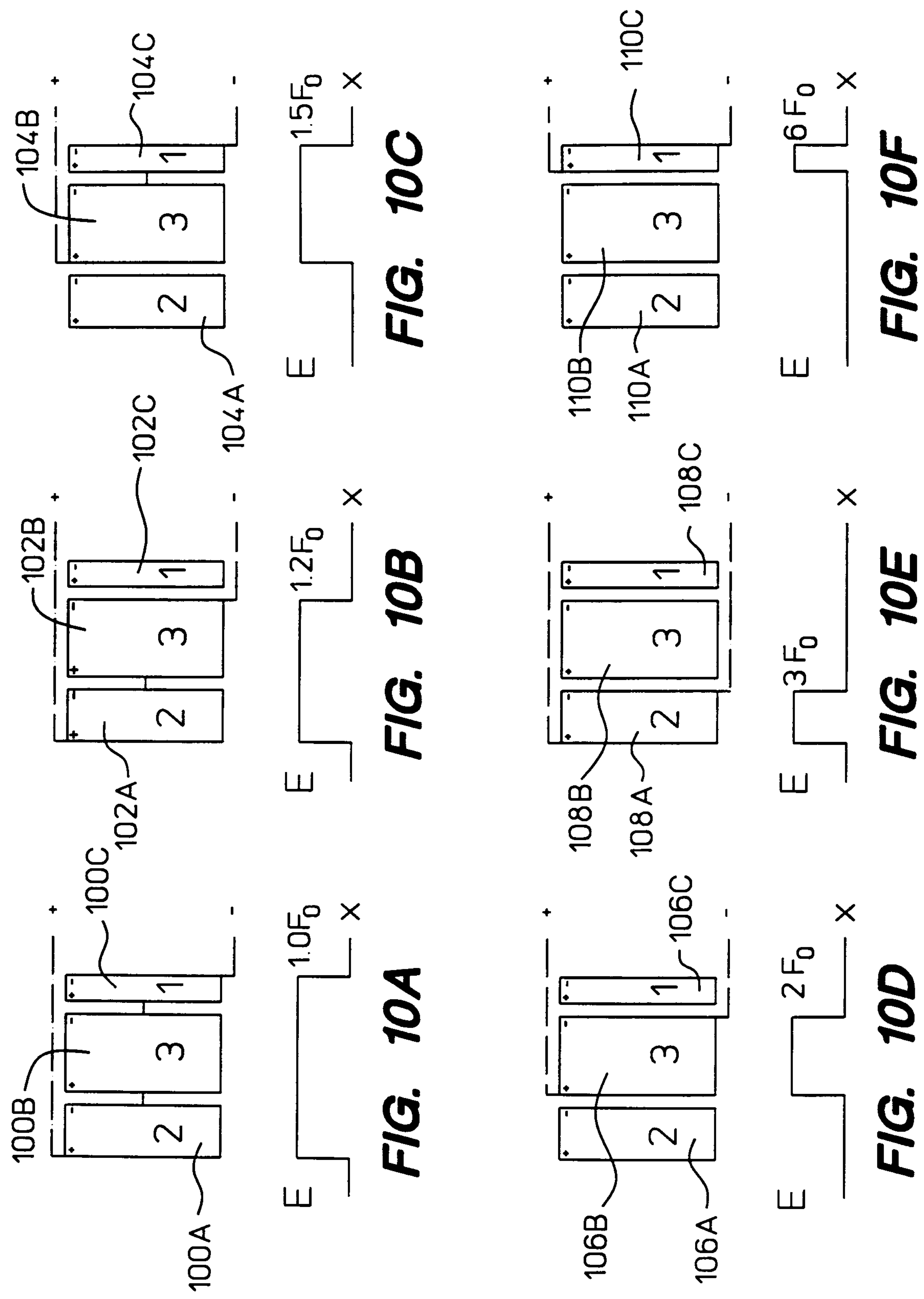


FIG. 10A

FIG. 10B

FIG. 10C

FIG. 10D

FIG. 10E

FIG. 10F

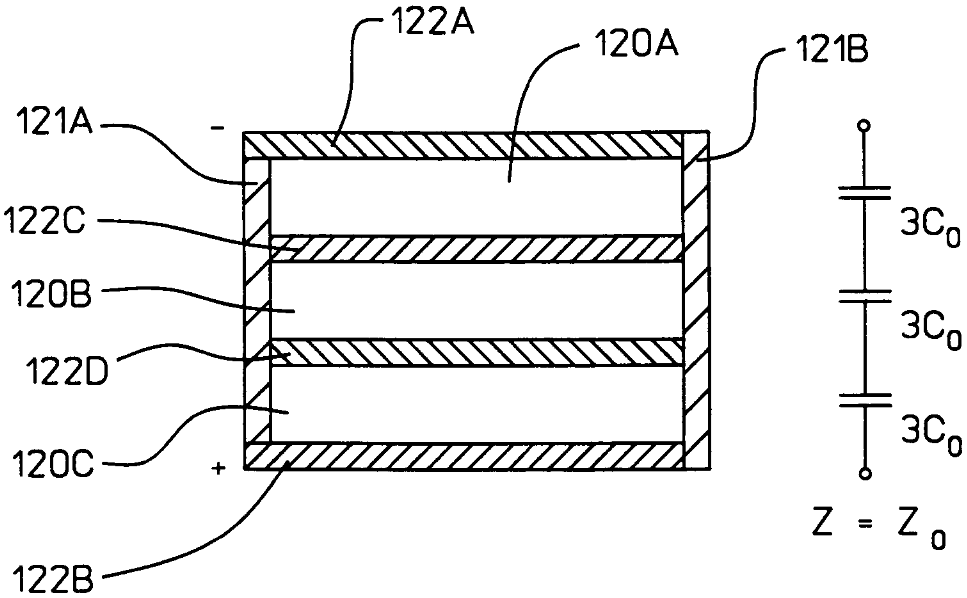


FIG. 11A

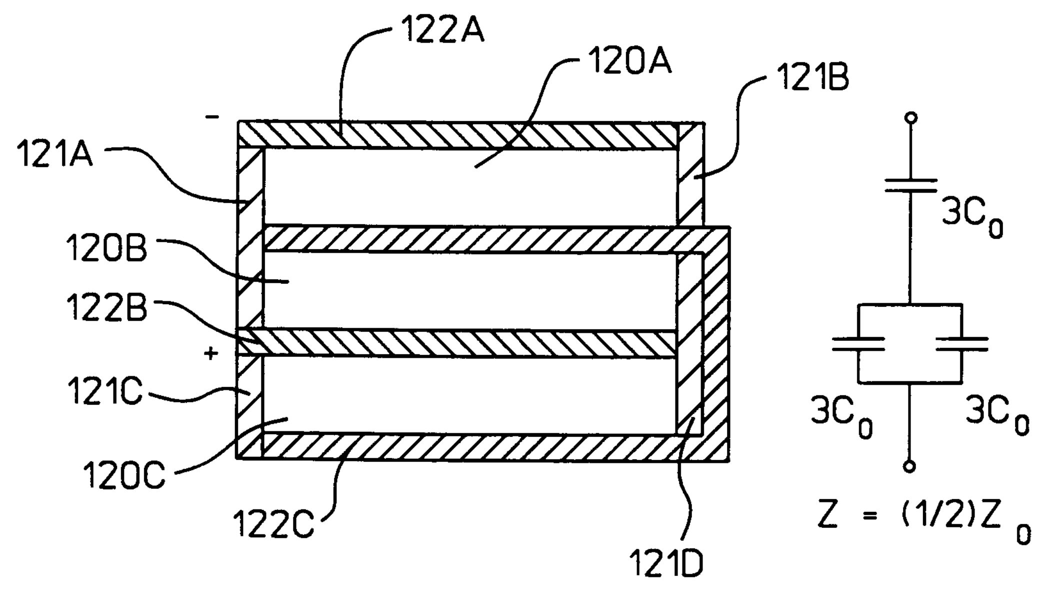


FIG. 11B

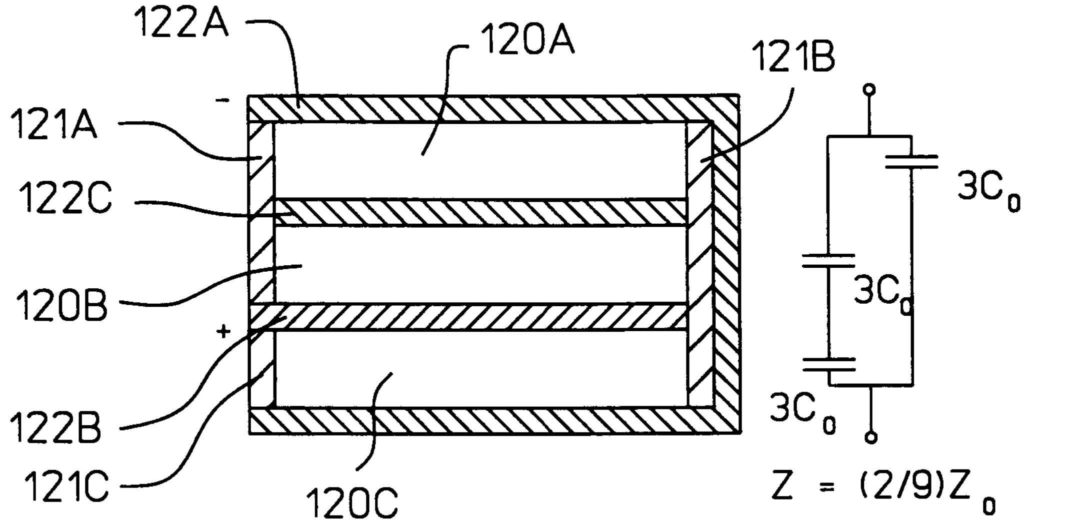


FIG. 11C

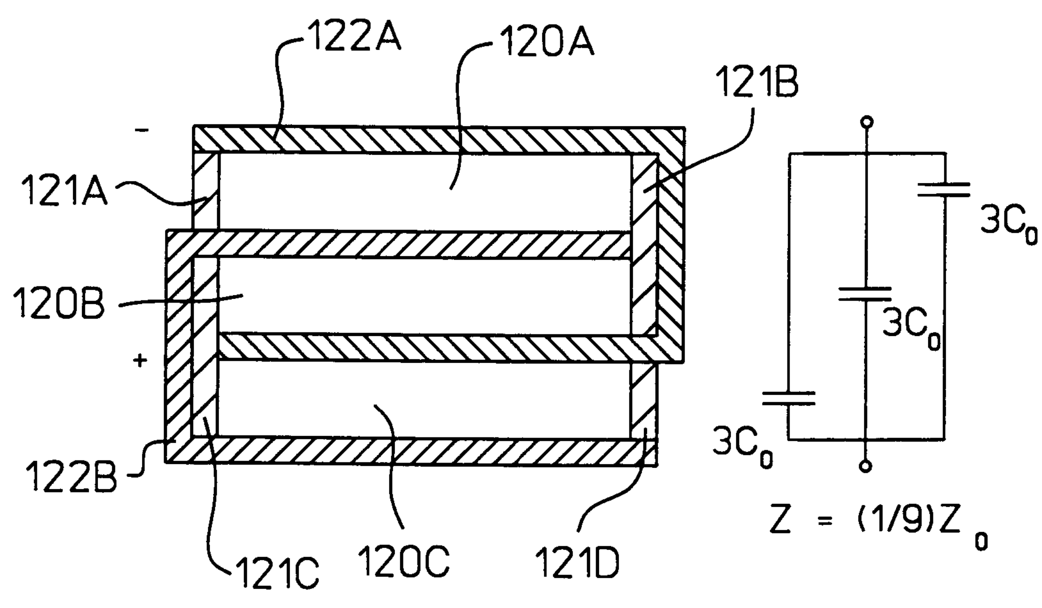


FIG. 11D

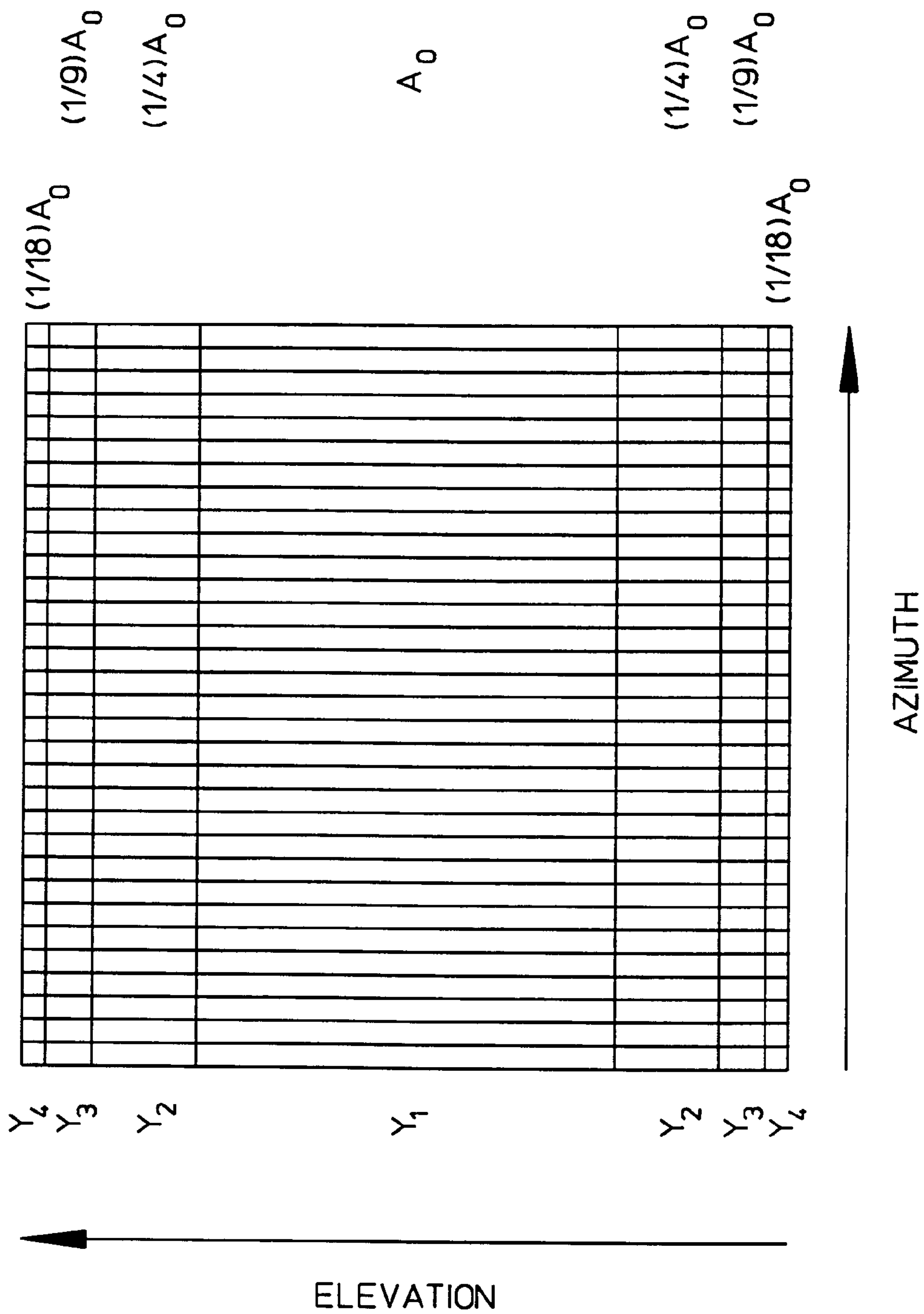

(1/18)A0
(1/9)A0
(1/4)A0
A0
(1/4)A0
(1/9)A0
(1/18)A0
Y4
Y3
Y2
Y1
Y2
Y3
Y4
AZIMUTH
ELEVATION

FIG. 12