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(54) Title: PIEZOELECTRIC TRANSFORMER AND OPERATING METHOD

(57) Abstract: A piezoelectric transformer has pairs of input/output electrodes located on a piezoelectric body corresponding to period locations on a standing sine wave superimposed on said body, and having a waveform corresponding to vibrational modes of the piezoelectric body at resonance. The transformer also has a grounded guard electrodes to reduce parasitic coupling between its input and output regions.

PIEZOELECTRIC TRANSFORMER AND OPERATING METHOD

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates generally to piezoelectric devices, and more particularly to a piezoelectric transformer supplied with an input a.c. current.

Description of the Related Art

Wound-type electromagnetic transformers have been used for generating high voltage in the internal power circuits of devices such as television deflectors or chargers for copiers which require high voltage. Such transformers consist of a conductor wound onto a magnetic core. Because a large number of turns are required to realize a high transformation ratio, transformers that are compact and slim in shape are extremely difficult to produce.

To remedy this problem, piezoelectric transformers utilizing the piezoelectric effect have been developed. FIG. 1 illustrates a Rosen-type piezoelectric transformer, according to Ohnishi, U.S. Patent 5,806,159, A plate of a piezoelectric material 102 has upper and lower input electrodes 104 and 106 which define a driving or input region 108 of the piezoelectric plate 102. The remainder of the plate 102 constitutes a generator or output region **110** with an output electrode **112** at its end. The input region **108** is polarized orthogonal to the electrodes 104 and 106, as indicated by arrow **114** in the figure, while the output region **110** is polarized orthogonal to electrode 112, as indicated by arrow **116**.

This piezoelectric transformer operates as follows: When a voltage is impressed across input electrodes **104** and **106** from external leads **118** and **120**, an electric field increases in the direction of polarization, and a longitudinal vibration in the transverse direction parallel to electrodes **104** and **106** is excited by the piezoelectric effect, displaced in a direction perpendicular to polarization, known as the piezoelectric transverse 31 effect, causing the entire transformer to vibrate. Moreover, in the output region **110**, due to the piezoelectric effect generating a potential difference in the polarization direction due to a mechanical strain in the polarization direction, a voltage is produced which has the same frequency as the input voltage from output electrode **112** to external lead **122**. At this time, if the voltage input frequency is made equal to the resonant frequency of the piezoelectric transformer, a high output voltage can be obtained.

This piezoelectric transformer is used in a resonant state. Compared with ordinary electromagnetic transformers it has numerous advantages, including: 1) a compact and slim shape that can be achieved because a wound-type construction is not required and energy density is high; 2) the potential for non-combustibility; and 3) a lack of electromagnetic induction noise. Furthermore, the Rosen piezoelectric transformer is monolithic, which gives it an advantage over multi-layer devices in that it does not suffer from bonding problems such as a reduction in efficiency due to softening of the bonding layer at high temperatures.

In Rosen and other types of conventional piezoelectric transformers, a rectangular waveform input, (having a harmonic content of a series of sine waves according to the Fourier transform $f_o + 3f_o + 5f_o \ldots +nf_o$), produces an output having a sine waveform of only the fundamental frequency. This can be a disadvantage because the rise and fall time of a sine wave is much slower than that of a rectangular wave, and fast rise and fall times are important for driving transistor switches OFF and ON (such as in DC-DC power converters), since significant power losses occur in the transistors during the transition between the OFF and ON states.

Moreover, in Rosen and other conventional piezoelectric transformers the input and output regions are not entirely electrically separated, due to a parasitic capacitance between the input and output regions.

SUMMARY OF THE INVENTION

This invention provides a piezoelectric transformer and operating method capable of passing the fundamental and third harmonic frequencies of a rectangular wave input and with a reduced parasitic capacitance.

The new piezoelectric transformer has a monolithic planar structure in the form of a thin rectangular piezoelectric plate having a uniform polarity orthogonal to its major surfaces. Pairs of input and output electrodes are formed on the top and bottom surfaces of the piezoelectric plate. Since the device is monolithic, it does not suffer from bonding problems (e.g. bond elasticity) inherent with multi-layer devices. However, it is also possible to stack transformer layers if a higher output current is desired.

A three electrode pair embodiment enables the device to pass the fundamental and third harmonic frequencies of a rectangular wave input, producing a pseudo-rectangular wave output. A pseudo-rectangular wave has a much faster rise and fall time then a sine wave, although somewhat slower then a true rectangular wave.

A piezoelectric transformer according to the present invention is further capable of producing multiple isolated outputs of either polarity. It is well suited for driving both capacitive loads such as the input gate of a MOSFET power transistor, and other loads such as resistive or resistive/capacitive circuits.

Parasitic capacitance is minimized by grounding leakage current between the input and output regions. This is accomplished by placing a grounding element such as a grounded guard electrode between the input and output regions. In a monolithic transformer the grounding element can be a thin electrode disposed in a continuous band around the surface of the piezoelectric body, between the input and output regions. This can reduce the stray capacitance by a factor of 10 to 20, and the effective input-output coupling capacitance can be reduced to 1-5% of the input capacitance, depending upon the dielectric constant of the piezoelectric material.

Moreover, in comparison to electromagnetic transformers, the new piezoelectric transformer is compact, simple to fabricate, low cost, and immune to magnetic interference.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of a prior Rosen-type piezoelectric transformer.

FIG. 2 is a perspective view of a basic piezoelectric transformer in accordance with the present invention.

FIG. 3 is a sectional view of the piezoelectric transformer of FIG. 2.

FIG. 4 is a top plan view of the piezoelectric transformer of FIG. 2.

FIG. 5 is a perspective view of a piezoelectric transformer in accordance with the present invention, with a three electrode pair geometry.

FIG. 6 is a sectional view of the piezoelectric transformer of FIG. 5.

FIG. 7 is a top plan view of the piezoelectric transformer of FIG. 5.

FIG. 8 is a plot of a pseudo-rectangular output waveform achievable with the invention, composed of the fundamental and third harmonic frequencies.

FIG. 9 is a plot comparing the pseudo-rectangular waveform of FIG. 8 to both a sine waveform and a pure rectangular waveform.

FIG. 10 is an illustration of a piezoelectric plate having three electrode pairs, with a superimposed sinusoidal standing wave.

FIG. 11 is an illustration of the piezoelectric plate of FIG. 10, with a superimposed third harmonic sinusoidal standing wave.

FIG. 12 is a sectional view of a piezoelectric transformer in accordance with the present invention, with n electrode pairs.

FIG. 13 is a sectional view of the piezoelectric transformer of FIG. 2, illustrating parasitic coupling.

FIG. 14 is a perspective view of the piezoelectric transformer of FIG. 2, with a guard electrode added.

FIG. 15 is a sectional view of the piezoelectric transformer of FIG. 14.

FIG. 16 is a top plan view of the piezoelectric transformer of FIG. 14.

FIG. 17 is a perspective view of the piezoelectric transformer of FIG. 5, with guard electrodes added.

FIG. 18 is a sectional view of the piezoelectric transformer of FIG. 17.

FIG. 19 is a top plan view of the piezoelectric transformer of FIG. 17.

FIG. 20 is a perspective view of the piezoelectric transformer of FIG. 14, with multiple isolated outputs.

FIG. 21 is a top plan view of the piezoelectric transformer of FIG. 20.

FIG. 22 is a bottom plan view of the piezoelectric transformer of FIG. 20.

FIG. 23 is a perspective view of the piezoelectric transformer of FIG. 17, with multiple isolated outputs.

FIG. 24 is a top plan view of the piezoelectric transformer of FIG. 23.

FIG. 25 is a bottom plan view of the piezoelectric transformer of FIG. 23.

FIG. 26 is a sectional view of a piezoelectric transformer in accordance with the present invention, with a three electrode pair geometry, and with a center input region.

FIG. 27 is a perspective view of the piezoelectric transformer having three regions with a continuous electrode connecting the outer input regions.

FIG. 28 is a top plan view of the piezoelectric transformer of FIG. 27.

FIG. 29 is a bottom plan view of the piezoelectric transformer of FIG. 27.

FIG. 30 is a perspective view of the piezoelectric transformer of FIG. 27 with a ground electrode added.

FIG. 31 is a top plan view of the piezoelectric transformer of FIG. 30.

FIG. 32 is a bottom plan view of the piezoelectric transformer of FIG. 30.

FIG. 33 is a sectional view of a multi-layer piezoelectric transformer, in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

FIGS. 2-4 illustrate a basic piezoelectric transformer 200 which is used here as a building block to illustrate various embodiments of the invention. It is noted that these and other figures illustrating various embodiments of a piezoelectric transformer are not to scale.

The piezoelectric transformer includes a body of piezoelectric material **202** which can be either a ceramic or a single crystal, and is in the form of a thin plate having a length **226**, a thickness **228** (typically 1mm or less), and a width **230**. The polarization of the piezoelectric plate **202** is oriented in the thickness direction, as indicated by the arrow **204** in FIGS. 2 and 3. A pair of input electrodes **206** and **208**, of equal areas, and a pair of output electrodes **212** and **214**, also of equal areas, are disposed on the top and bottom major surfaces of the plate **202**, using a technique such as sputtered deposition and photolithography. The input and output electrodes define input and output regions **210** and **216**, respectively, with similar electrode geometries on the plate's top and bottom surfaces. External leads **218**, **220**, **222** and **224**, are connected to the input and output electrodes **206**, **208**, **212**, and **214**, respectively.

The piezoelectric plate is poled to a uniform polarization direction by the application o f a high voltage(approximately 1000 to 3000 Volts for a 1mm thick material), See B. Jaffe, W.R. Cook, and H. Jaffe, "Piezoelectric Ceramics," (Academic Press, N.Y., 1971) Pg. 16.

The application of a voltage **232** across the input region through the input electrodes **206**, **208**, creates a transverse internal stress in the device by means of the transverse electromechanical coupling constant, k_{31}. This stress attains a maximum value at the resonant frequency of the device, determined by its length **226** and the velocity of sound in the piezoelectric material (See Jaffe, Cook, Jaffe, Pg. 30, 31). Hence, for example, the internal stress at the fundamental resonance frequency consists of an acoustic standing wave with a wavelength equal to twice the length of the device. This internal stress is then converted back to an electrical charge at the output electrodes, via the transverse coupling constant, k_{31}, resulting in an output voltage **234** across the output electrodes **212, 214**. (For an additional reference, see Encyclopedia of Electronics and Computers, S. Parker, McGraw-Hill 1984 p.625-630).

The open circuit voltage gain varies with the input/output electrode area ratio and the piezoelectric material constants according to:

$$|V_{out}| = \beta V_{in} k_{31}^2 Q/2$$

where V_{out} and V_{in} are the output and input voltages; β is a proportionality constant which depends upon the electrode geometry and the ratio of the input/output electrode areas, Q is the material's quality factor at resonance, and k_{31} is the transverse piezoelectric coupling constant for the material. Typically, β has a value close to one for equal area contacts. Q values can reach up to 1000, and $k_{31} \leq 0.4$ for most piezoelectric materials. Since the open circuit device is loaded by an internal output capacitance, the addition of an external load capacitance reduces the load impedance by a proportional amount, and therefore reduces the voltage gain of the device. The addition of a capacative load alters the resonant frequencies by a very small amount (typically 1-2%), but it does not significantly alter the device's Q.

Additionally, although the fundamental resonant frequency is determined by the length of the piezoelectric plate, its width can be any desired value. The width is typically greater then the length so as to minimize the output impedance of the device by maximizing the input and output electrode areas.

The basic piezoelectric transformer shown in FIGS. 2-4 and conventional piezoelectric transformers, such as the Rosen-type shown in FIG. 1, can pass only the fundamental frequency of a sine wave. However, harmonics of the fundamental frequency can be passed through the device by having multiple input and/or output regions forming a symmetry about the center of the piezoelectric plate. In theory, it is possible to have any number of input and output regions on a single piezoelectric plate. Each of these regions is defined by a pair of top and bottom electrodes, as in FIGS. 2-4.

FIGS. 5-7 illustrate a piezoelectric transformer **500** with a three-electrode pair geometry. This is similar to the piezoelectric transformer of FIGS. 2-4, except for the additional electrode pair. In FIGS. 5-7, a body of piezoelectric material **502**, similar to body 202 in FIGS. 2-4 has a length **526**, a thickness **528** (typically 1mm or less), and a width **530**. The polarization of the piezoelectric plate **502** is oriented in the thickness direction, as indicated by the arrow **504** in FIGS. 5 and 6. Two pairs of input electrodes **506**, **508** and **513**, **515**, of approximately equal areas, are disposed on the top and bottom surfaces at opposite ends of the plate **502** and define input regions **510** and **511**. A pair of output electrodes **512** and **514**, of approximately equal areas, are disposed on the top and bottom surfaces of the plate **502** between the input regions **510** and **511**, and define an output region **516**. The electrode geometries on the plate's top and bottom surfaces are similar. External leads **518**, **520**, **522**, **524**, **523** and **525** are connected to the input and output electrodes **506**, **508**, **513**, **515**, **512**, and **514**, respectively. The input regions are driven by impressing a voltage **532**, across the pair of input electrodes defining that region. The voltage across each of the regions has the same frequency, corresponding to the fundamental resonant frequency of the piezoelectric plate **502** to maximize the output, therefore a common voltage source for the two pairs of input electrodes **506**, **508** and **513**, **515** is preferable. This three electrode pair geometry enables the device to pass the fundamental frequency and the third harmonic of an input voltage **532** having a rectangular waveform to form an output voltage **534** having a pseudo-rectangular waveform.

It is also possible to have the center region be the input, and the two outer regions be two individual outputs, and obtain a pseudo-rectangular output. This device is illustrated in FIG. 26, where **512** and **514** are the input electrodes defining the input region **516**, and **506**, **508**, and **513**, **515** are the two output electrode pairs defining output regions **510** and **511**. External input leads **2602** and **2604** are connected to a voltage source **2606** for driving the device. Additionally, external output leads **2608**, **2610**, and **2612**, **2614** yield two separate outputs **2616** and **2618**, across each of the output regions 510, 511, respectively. These output regions can be connected together to enable a doubling of the available output current.

FIG. 8 is a plot of a pseudo-rectangular waveform output 800, composed of the fundamental and third harmonic frequencies, and FIG. 9 is a comparison of the pseudo-rectangular waveform with a corresponding sine waveform 900 and pure rectangular waveform 902. The pseudo-rectangular waveform produced has a much faster rise and fall time then a sine wave, although slower then the pure rectangular wave.

Thus, the new device which produces the pseudo-rectangular output can drive transistor switches off and on more rapidly and efficiently, since significant power losses occur in the transistors during the transitions between the off and on states. Additionally, the three-electrode pair device is ideally suited for driving a capacitive load, such as the input gate of a Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET). The input capacitance of MOSFETs decreases dramatically, and then rises again, as they transition from an OFF to an ON output conducting state. The net result is that, when a MOSFET gate is driven by the piezoelectric transformer, the voltage transition in the pseudo-rectangular wave output of the transformer is accelerated due to the decreased load capacitance of the MOSFET in the transition region between OFF and ON. Besides MOSFET transistors, the three electrode pair device can also drive other loads such as resistive or resistive/capacitive loads.

The third harmonic and fundamental frequencies are passed with the three-electrode pair device because the output waveform is affected by the symmetry of the input regions over the piezoelectric body. FIGS. 10 illustrates a three electrode pair piezoelectric plate **1000** with input regions **1002, 1004,** an output region **1006**, and a standing sine wave of half a period **1010** that corresponds to the vibrational mode of the piezoelectric plate at its fundamental resonant frequency, superimposed along the plate's length **1008**. FIG. 11 illustrates the same piezoelectric plate **1000** with a third harmonic sine wave of one-and-a-half periods, **1100** superimposed along its length. As can be seen from the figures, the symmetry of the input and output regions corresponds to the symmetry of the third harmonic and fundamental waves. Accordingly, it may be possible to produce other desired wave outputs by applying an input voltage to a piezoelectric body at symmetrical points corresponding to a superimposed waveform of the desired output.

FIG. 12 illustrates a piezoelectric transformer **1200**, similar to the piezoelectric transformer of FIGS. 5-7, but with n electrode pairs, where n is any number greater than 2. As in the three electrode pair embodiment, the input and output regions alternate. Additionally, the first electrode **1202** may define either an input or output region. Also, a voltage of the same frequency is applied to each of the input electrodes, and the outputs may either be combined or isolated.

Although in principle, the invention can be extended to any number of high order harmonics, experiments conducted with five electrode pairs on a ceramic PLZT piezoelectric (see U.S. Pat. No. 5,595,677) showed only faint but measurable fifth harmonics, and nearly undetectable fifth harmonics with a Strontium Barium Niobate (SBN) crystal piezoelectric.

Another feature of the new piezoelectric transformer is a reduction of the parasitic capacitive coupling between the input and output regions using a guard electrode. FIG. 13 illustrates the problem of parasitic coupling using the two electrode pair device **200** illustrated in FIGS. 2-4. Since the material used is a dielectric, there is capacitive coupling between the input and output regions **210** and **216**, illustrated by the dashed lines representing capacitor circuit branches **1300** and **1302**. This capacitive coupling causes current to leak between the input and output electrodes, as illustrated by the arrows **1304** in the figure, resulting in a lack of full electrical separation between the input and output.

To alleviate the parasitic coupling, the current leaking between the input and output regions **210** and **216** is grounded by a grounding element located between the two regions. This grounding element is preferably a grounded guard electrode located between the input and output regions. FIGS. 14-16 illustrate an example of the piezoelectric transformer of FIGS. 2 -4, with such a grounding electrode **1400**. The electrode **1400** can be of the same material as the input and output electrodes, and is disposed in a thin band preferably on the order of 1mm or less in width around the surface of the piezoelectric plate. The band can be deposited in the same deposition process used for the input and output electrodes, creating a division between the input and output regions

210 and 216. The electrode **1400** is grounded by connecting to an electrical ground (0 Volts) circuit. This grounding electrode typically lowers the effect of stray capacitance by a factor of 10 to 20, and reduces the effective coupling capacitance to 1-5% of the input capacitance as determined by the dielectric constant of the material used.

Having a guard electrode can greatly simplify electronic designs, because the parasitic capacitance coupling paths between the MOSFET inputs do not have to be worried about. In the case of driving active devices such as MOSFET transistors, the guard electrode can minimize potentially undesired interactions between the MOSFET and the input source to the transformer. Similarly, it can reduce coupling interaction between MOSFETs which are driven by multiple piezoelectric transformer outputs.

Additionally, it has been found that the grounding electrode improves the transformer gain and quality factor "Q".

A piezoelectric transformer having any number of input/output regions can have a guard electrode between each of the regions. Thus for a piezoelectric transformer having n electrode pairs, there are n-1 guard electrodes.

FIGS. 17-19 illustrate the three electrode pair device of FIGS. 5-7, with grounded guard electrodes **1700** and **1702** disposed in thin bands around the piezoelectric plate, between the input regions **510** and **511** and the output region **516**.

It is also possible to divide a single output region into multiple output regions, defined by multiple electrode pairs in each output region and isolated from each other. This can be done with any number of input/output regions. FIGS. 20-22 illustrate the device of FIGS. 14-16, with two isolated outputs **2000**, **2001** defined by two electrode pairs **2002**, **2006** and **2004** and **2008**, disposed on the top and bottom surfaces of output region **216**, and connected to the outputs **2000**, **2001** through external leads **2010**, **2012** and **2014**, **2016**. A guard electrode **2018**, extending from guard electrode **1400**, is located between the isolated output regions. Since this device has one input and one output region **210**, **216**, as discussed above, a pseudo-rectangular output is not attainable with this device, and the outputs will have a sine waveform.

FIGS. 23-25 illustrate the device in FIGS. 17-19, with two isolated outputs **2300**, **2301** defined by two electrode pairs **2302**, **2306** and **2304**, **2308**, disposed on the top and bottom surfaces of the output region **516**, and connected to the outputs **2300**, **2301** through external leads **2310**, **2312** and **2314**, **2316**. Guard electrodes **2318**, **2320** extending from guard electrodes **1700**, **1702** are located between the isolated output regions. Since this device has two input and one output regions, each of the isolated outputs **2300**, **2301** will have a pseudo-rectangular waveform.

Another multiple output configuration is illustrated in FIG. 26, where the center region is the input and the two outer regions are isolated outputs, as discussed above.

The output polarity is determined by the input polarity, phase shifted by 90° for a non loaded or capacitive loading condition. Such isolated outputs operate at the same frequency and can be connected to various parts of an electronic circuit. The outputs can be made to have opposite polarity by connecting them 180° out of phase from one another. This has a particular advantage for a two-output device, such as a DC-DC power converter, since the two outputs can be of opposite polarity. Such multiple isolated outputs are also useful for driving MOSFET switching transistors in an AC-to-DC or DC-DC conversion circuit. These devices are used in a bridge configuration, with one transistor off and the other on during each half of the AC input cycle. The piezoelectric transformer capable of multiple isolated outputs is well suited for this, since one output can be connected 180° out of phase from the other one, with both outputs operating at the exact same frequency. Additionally, a transformer capable of a pseudo-rectangular waveform output, and having the guard electrode, yields additional benefits as discussed above.

In theory, any number of isolated outputs can be obtained by further dividing each output region, as illustrated in FIGS. 20-25, and/or by increasing the number of input/output regions as illustrated in FIGS. 12 and 26. Many multiple output configurations are possible, although it is doubtful that more than two or three outputs would be of much interest. Although in FIGS. 20-25 the output regions are illustrated as being divided along the width, it may also be possible to divide the region along the length. Also, increasing the number of outputs decreases the individual output electrode areas, and hence the available current at each output, by a proportional amount. Other considerations for determining the specific set up include the desired voltage gain at the output, the given output load, the device dimensions, and voltage input.

Many variations in the electrode geometry are possible. FIGS. 27-29 illustrates one such variation, in which the two input regions **510** and **516** of FIGS. 5-7 are connected across the surface, forming continuous input electrodes **2700**, **2702** and output electrodes **2704**, **2706** on the top and bottom surfaces, which define the two input regions **510** and **511**. Hence only two external leads **2708**, **2710** are needed to connect to the input voltage **2712** for driving the input regions **510**, **511**.

FIGS. 30-32 illustrate the piezoelectric transformer of FIG. 27-29, with an added grounded guard electrode in the form of a "U" shaped thin electrode, located between the input and output electrodes. The guard electrode **3000** in this embodiment forms a loop that saddles around the output electrodes covering three sides of the plate, instead of forming a continuos band around the piezoelectric plate.

One example of a working model for a three electrode pair device, according to FIGS. 27-29, is as follows:

Material:	PLZT-9 (Rockwell, U.S. Pat. No. 5,595,677)
Length:	12 mm
Width:	40 mm
Thickness:	0.5 mm

Electrodes:	Gold (sputter deposited)
Resonant f_0:	155.0 kHz *
Output voltage gain (no load):	9.27
Input resistance:	18.9 ohms * (at resonant f_0)
Resonant Q:	64.6
Max output voltage:	120 volts (peak-to-peak) *

All electrical parameters depend upon the material used. Parameters marked with an asterisk are also determined by device dimensions

Although a single layer rectangular device is the preferred embodiment, the invention also includes other configurations such as a circular device with concentric electrode rings. However, this limits the amount of output current available (which is proportional to the input and output electrode areas), since the device diameter scales inversely with the fundamental operating frequency, f_0. With a rectangular device, only the device length scales inversely with f_0, while the width can be many times greater than the length, thus increasing the amount of output current. Another advantage of a rectangular device is that it is very easy to cut with great precision using common semiconductor processing equipment. Hence, processing can be fast and inexpensive.

The transformer can be implemented with multiple layers, preferably thin rectangular plates bonded together, instead of a long thin device, to increase the available output current. FIG. 33 shows such multi-layer device 3300. Although the figure illustrates the piezoelectric layers of the device in FIGS. 5-7, any of the other single layer devices according to this invention may be implemented in multiple layers. Any number of layers may be used, depending upon the desired output. An electrical connection is desired between the top and bottom electrodes of successive, adjacent layers, with the exception of the top electrode of the top layer and the bottom electrode of the bottom layer. This is illustrated in the figure where three bottom electrodes of the first piezoelectric layer **3302** are bonded to the three top electrodes of the second piezoelectric layer **3304**, and the bottom three electrodes of the second layer **3304** are bonded to the three top electrodes of the third layer **3306**, and so on, to the n^{th} layer **3310**, whose three top electrodes are bonded to the three bottom electrodes of the n^{th}-1 layer **3308**. Additionally, the layers are aligned with their polarizations in alternating directions, as illustrated by the arrows, **3322**, **3324**, **3326**, **3328**, **3330**, so that electrodes bonded to one another will have the same polarity.

The layers may be bonded together with a conducting epoxy layer, or a non conducting epoxy and then electrically connected by a conducting material. This can be done by bringing out electrodes to the edges of the piezoelectric layers, using very thin interconnection traces. The same metal used for the electrodes can be used for this.

The device is driven by applying a voltage **3312** to each of the input regions **510**, **511** through the top input electrodes and bottom input electrodes of each layer. All of the inputs and outputs may be connected in parallel to each other. Additionally, the layers may have guard electrodes.

The multi-layer device would be the preferred embodiment for high frequency devices operating in the range of 1 MHz, in which the length is only 1-2 mm.

While specific examples of the invention have been shown and described, numerous variations and alternate embodiments will occur to those skilled in the art. Accordingly, it is intended that the invention be limited only in terms of the appended claims.

I CLAIM:

1. A piezoelectric transformer, comprising:

a first piezoelectric body having at least one input region and at least one output region; and

a grounding element located between each pair of input and output regions and substantially preventing electrical charge from leaking between said regions.

2. The piezoelectric transformer of claim 1, further comprising input and output electrodes on said input and output regions, respectively.

3. The piezoelectric transformer of claim 2, wherein said piezoelectric body comprises a plate having major top and bottom surfaces.

4. The piezoelectric transformer of claim 3, wherein each of said input and output electrodes comprises a pair of electrode elements disposed respectively on the top and bottom major surfaces of the piezoelectric plate.

5. The piezoelectric transformer of claim 4, further comprising at least one additional piezoelectric plate, with aligned electrodes on plates bonded to each other.

6. The piezoelectric transformer of claim 4, wherein said piezoelectric body has a uniform polarization orthogonal to said top and bottom surfaces.

7. The piezoelectric transformer of claim 1, wherein said grounding element comprises a grounded electrode disposed in a continuous band around said piezoelectric body.

8. The piezoelectric transformer of claim 1, further comprising a plurality of output electrodes on at least one of said output regions.

9. A piezoelectric transformer, comprising a piezoelectric body having at least one input region and at least one output region;

said input and output regions alternating with each other and forming respective mirror symmetries about the center of said body.

10. A piezoelectric transformer, comprising a piezoelectric body having at least one input region and at least one output region;

said input and output regions are disposed at locations on said body corresponding to periodic locations on a standing sine wave superimposed on said body, said sine wave having a waveform corresponding to a vibrational mode of the piezoelectric body at a resonant frequency.

11. The piezoelectric transformer of claim 10, further comprising a plurality of electrical grounding elements located between respective pairs of input and output regions and substantially preventing electrical charge from leaking between said regions.

12. The piezoelectric transformer of claim 10, further comprising input and output electrodes on said input and output regions, respectively.

13. The piezoelectric transformer of claim 12, wherein said piezoelectric body comprises a plate having top and bottom major surfaces and a uniform polarity orthogonal to said surfaces.

14. The piezoelectric transformer of claim 13, wherein each of said input and output electrodes comprises a pair of electrode elements disposed respectively on the top and bottom major surfaces of the piezoelectric plate.

15. The piezoelectric transformer of claim 14, further comprising at least one additional piezoelectric

plate, with aligned electrodes on plates bonded to each other.

16. The piezoelectric transformer of claim 14, wherein adjacent input electrode elements disposed on a surface are electrically connected by a connecting surface electrode.

17. The piezoelectric transformer of claim 10, further comprising a plurality of output electrodes on at least one of said output regions.

18. The piezoelectric transformer of claim 10, said body having one output region between two input regions.

19. The piezoelectric transformer of claim 10, wherein said piezoelectric body having one input region between two output regions.

20. A method of operating a piezoelectric transformer having at least one input region and one output region, comprising:

applying an electrical input signal to said input region;

obtaining an output signal from said output region; and grounding leakage current that would otherwise flow between said input and output regions.

21. The method of claim 20, wherein said current is grounded between adjacent input and output regions of said transformer.

24. An electronic system, comprising

an electrically operated device, and

a piezoelectric transformer connected to provide current to the device, said piezoelectric transformer comprising a piezoelectric body having at least one input region and at least one output region;

said input and output regions are disposed at locations on said body corresponding to periodic locations on a standing sine wave superimposed on said body, said sine wave having a waveform corresponding to a vibrational mode of the piezoelectric body at a resonant frequency.

25. An electronic system comprising:

an electrically operated device, and

a piezoelectric transformer connecting to said device for providing current to the device, said piezoelectric transformer comprising:

a first piezoelectric body having at least one input region and at least one output region; and

a grounding element located between each pair of input and output regions and substantially preventing electrical charge from leaking between said regions.

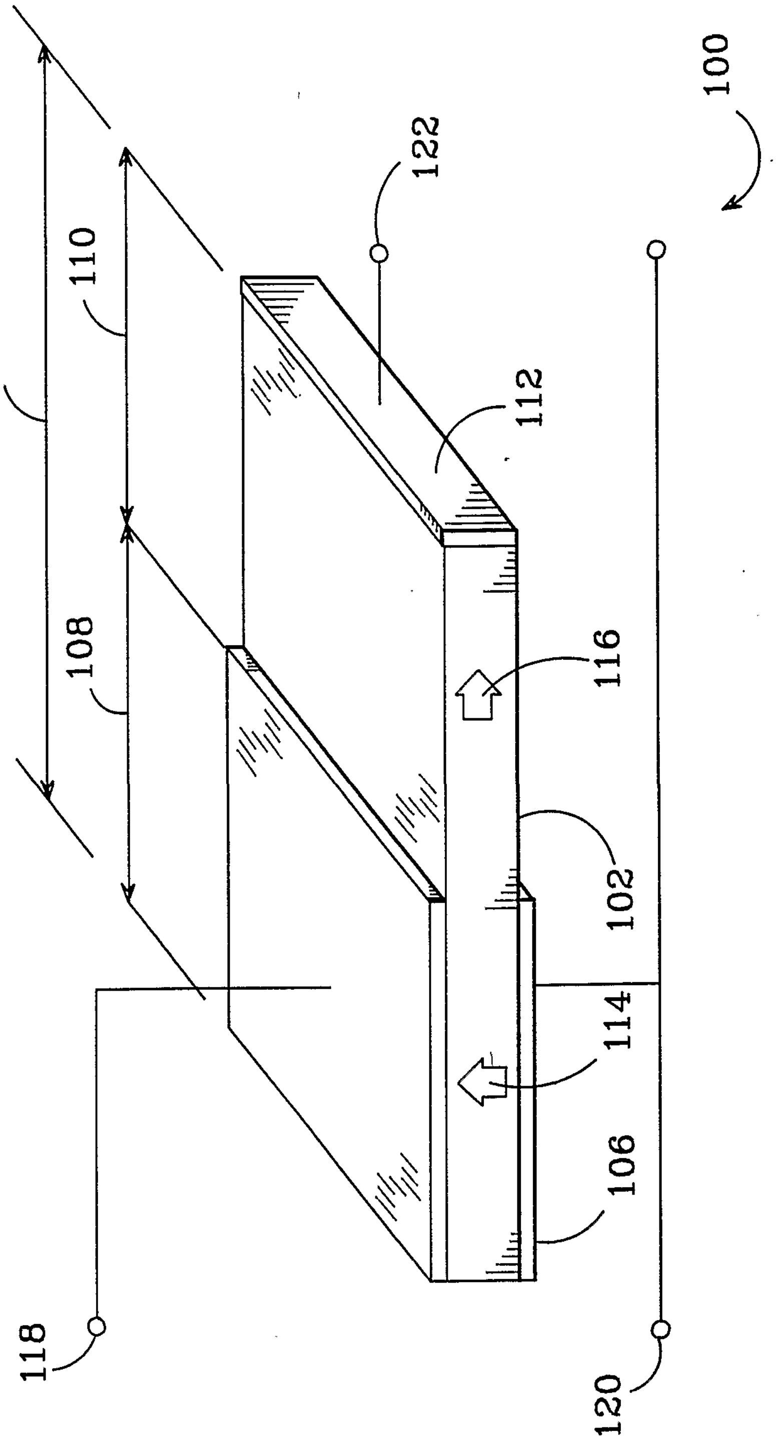


FIG.1
(Prior Art)

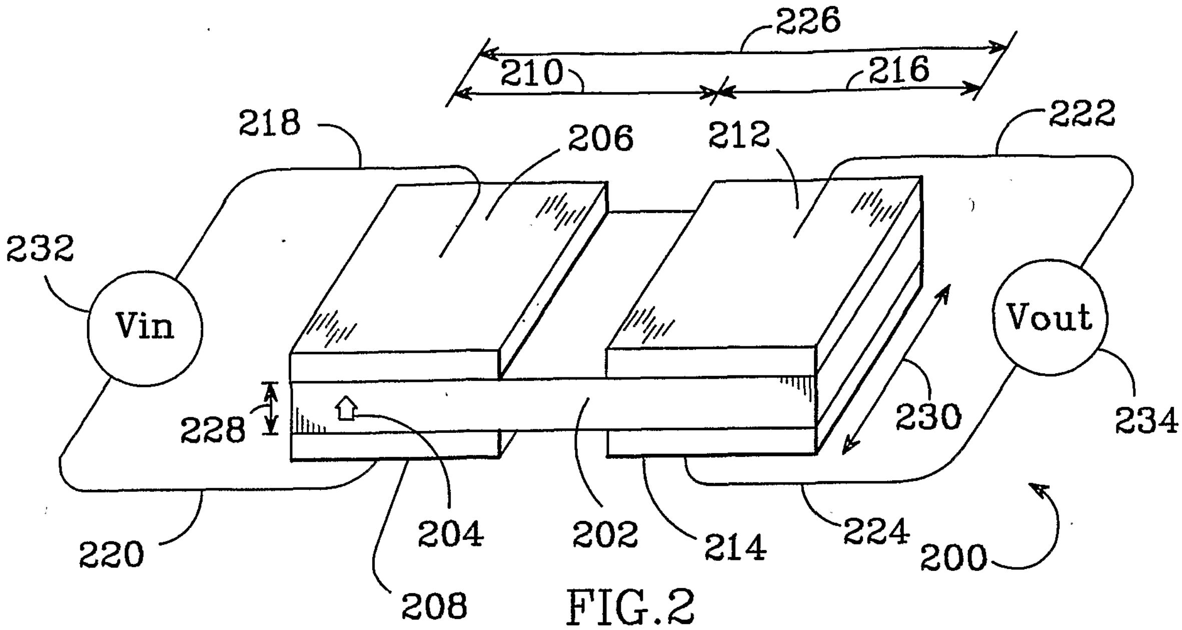


FIG.2

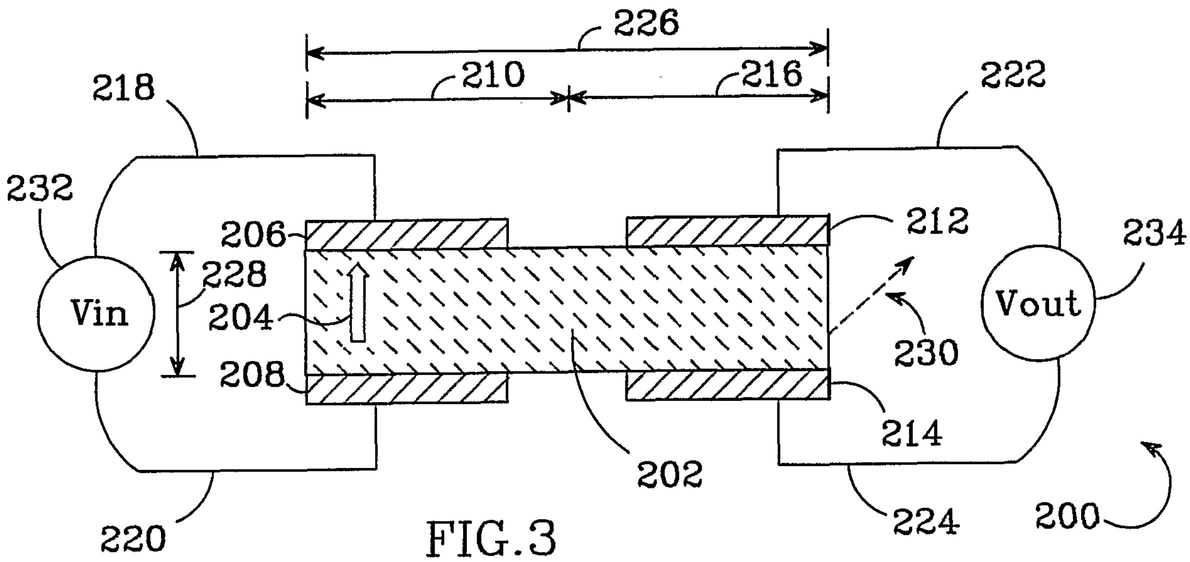


FIG.3

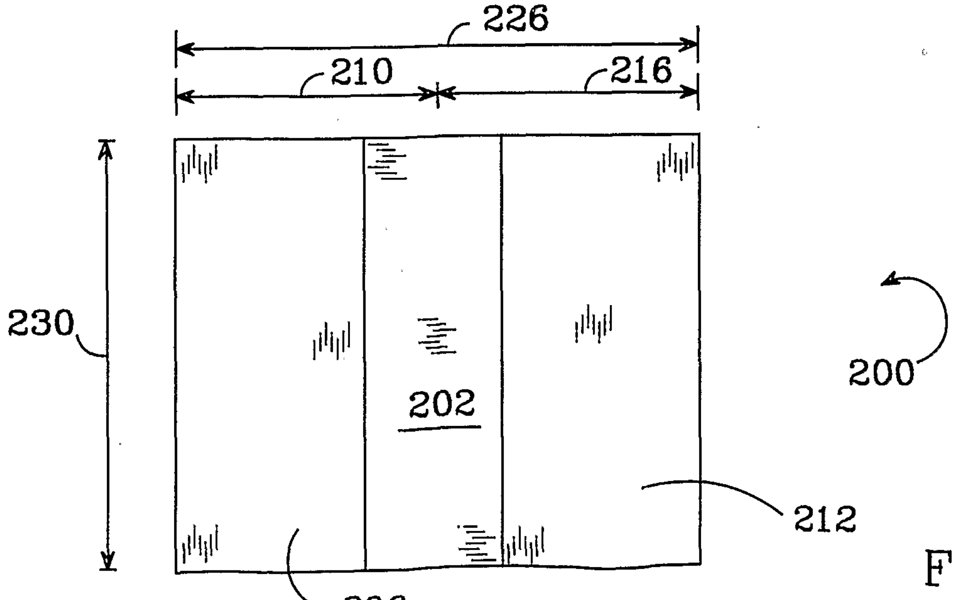


FIG.4

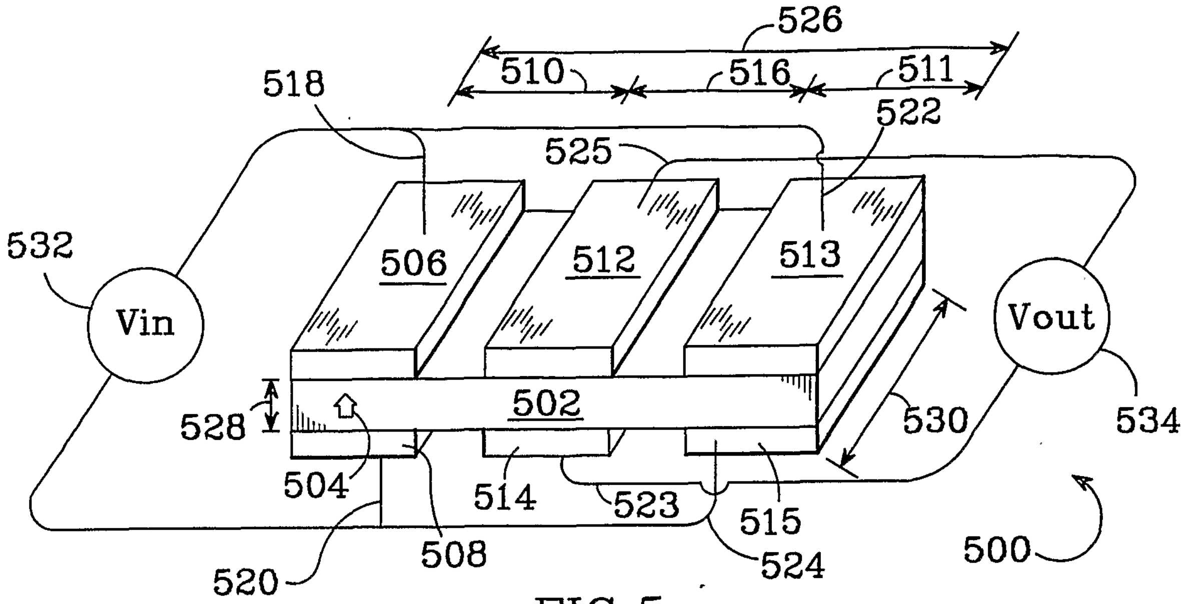


FIG.5

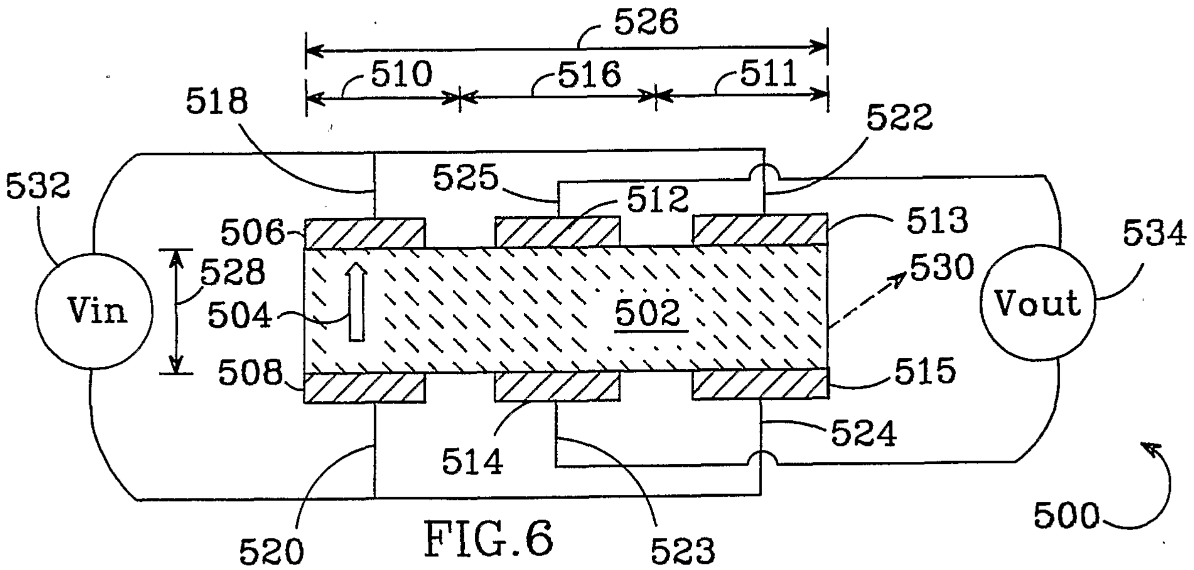


FIG.6

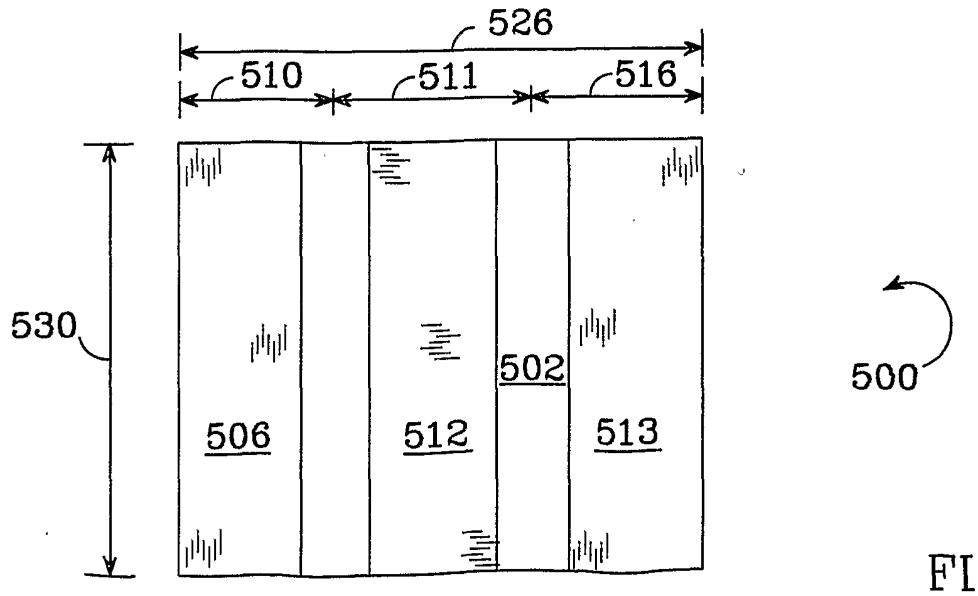


FIG.7

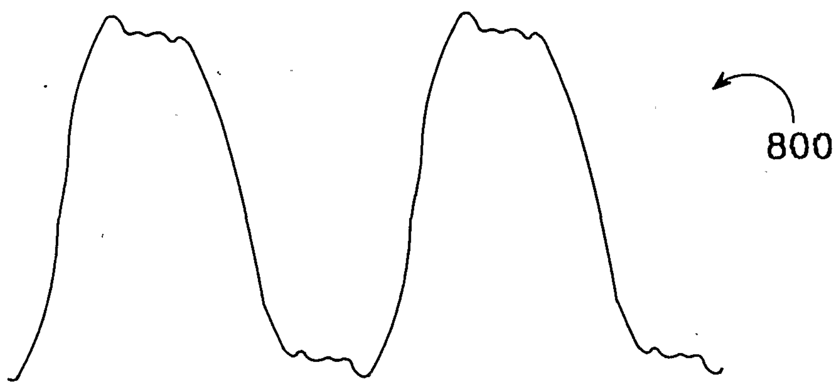


FIG.8

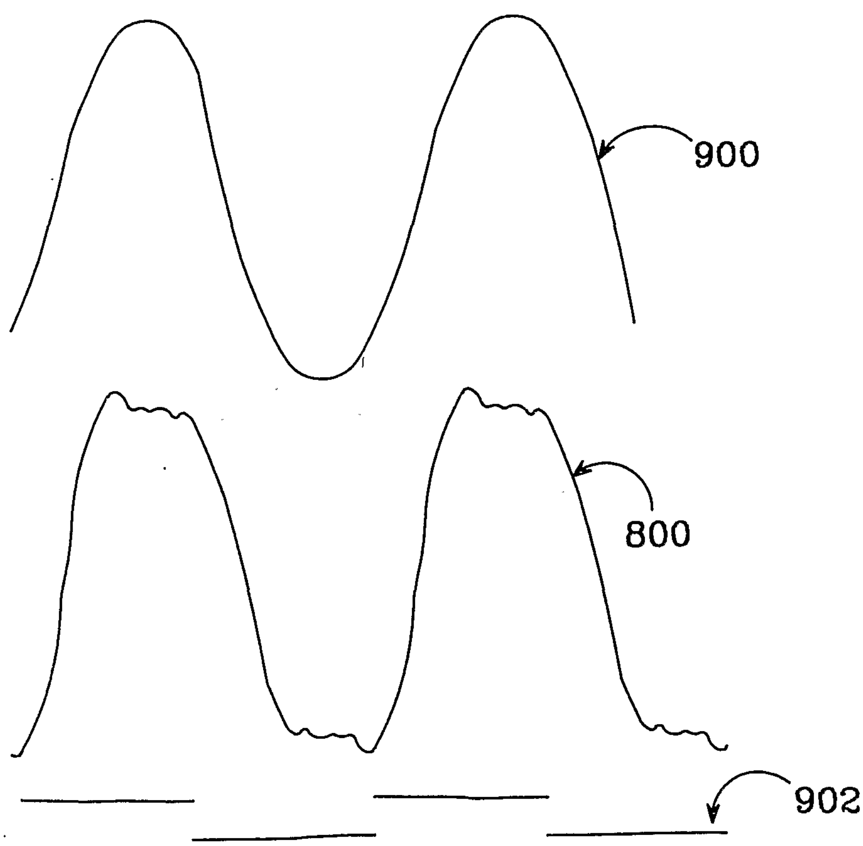


FIG.9

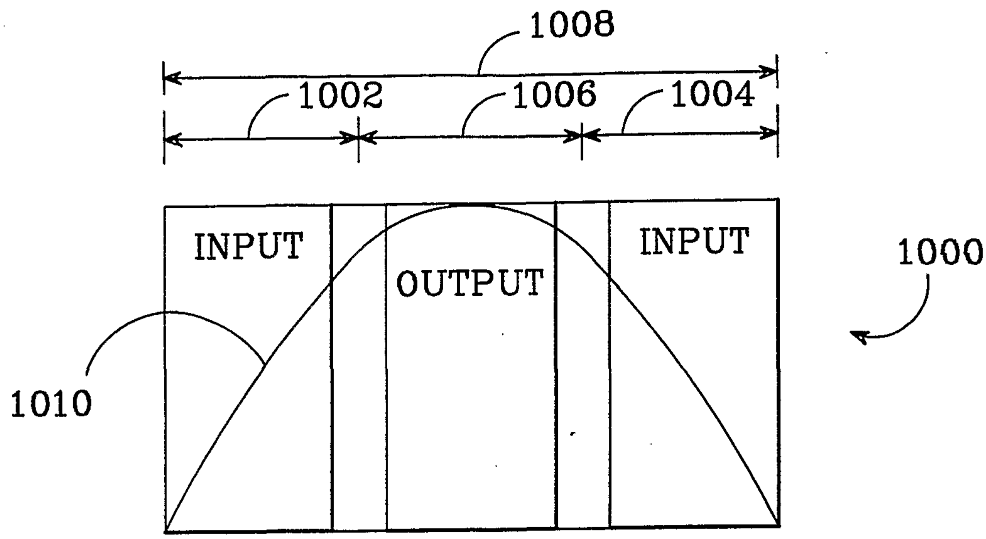

1008
1002
1006
1004
INPUT
OUTPUT
INPUT
1000
1010

FIG.10

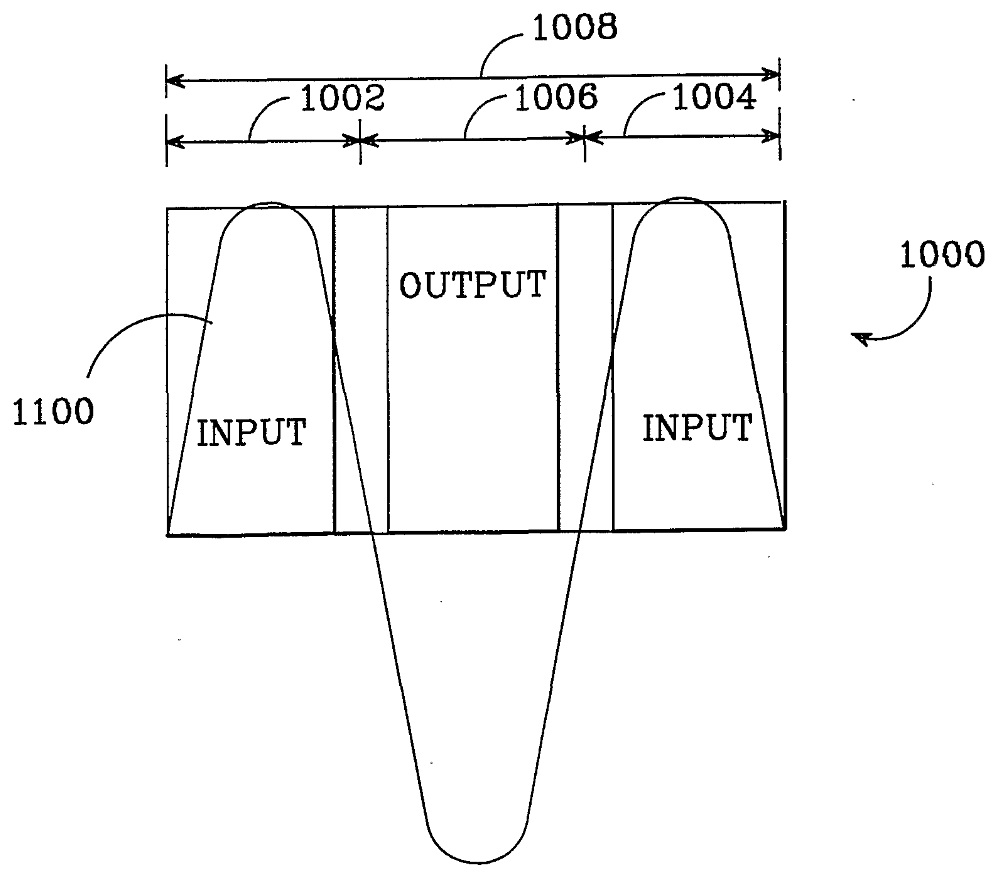

1008
1002
1006
1004
OUTPUT
1000
1100
INPUT
INPUT

FIG.11

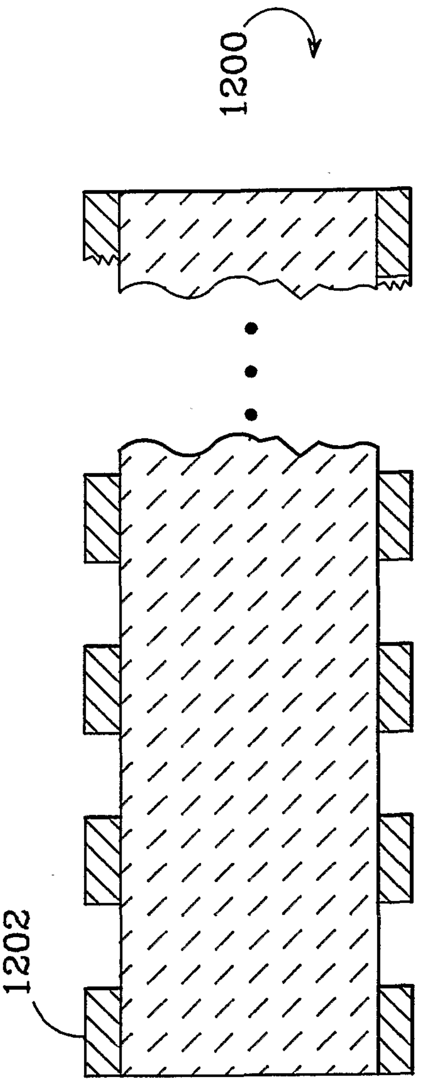

1200
1202

FIG.12

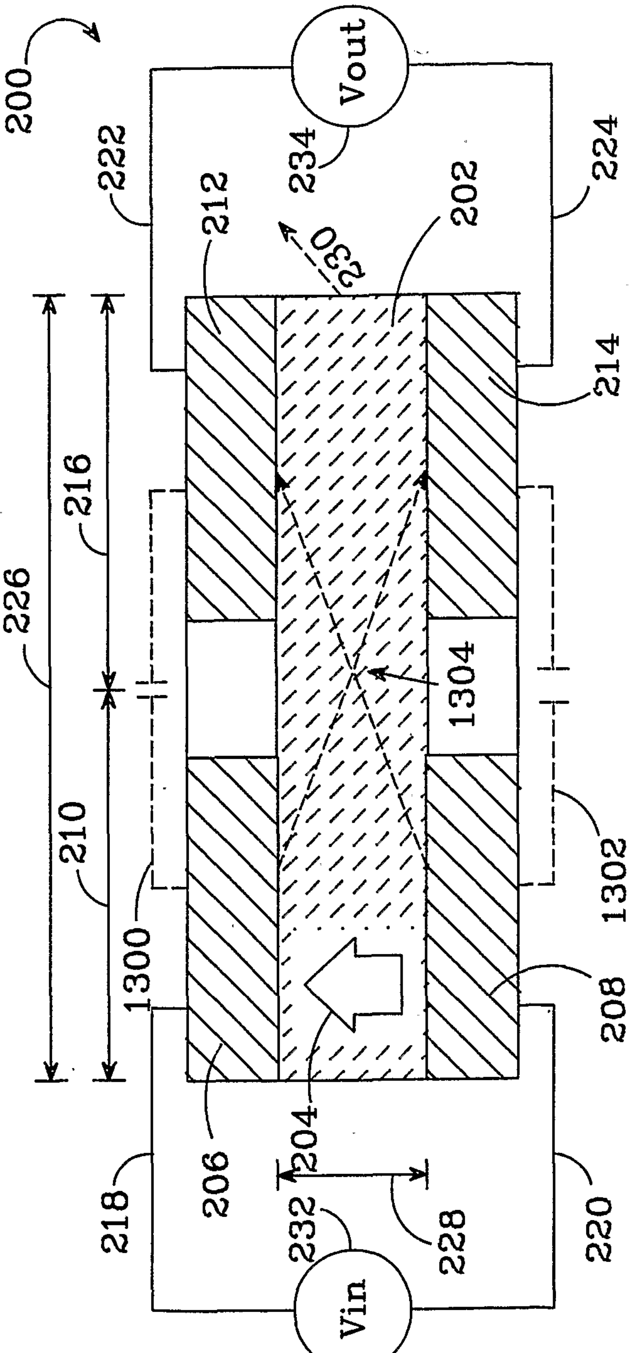

200
Vout
222
234
212
230
202
224
214
216
226
1304
210
1302
1300
208
204
206
218
232
228
220
Vin

FIG.13

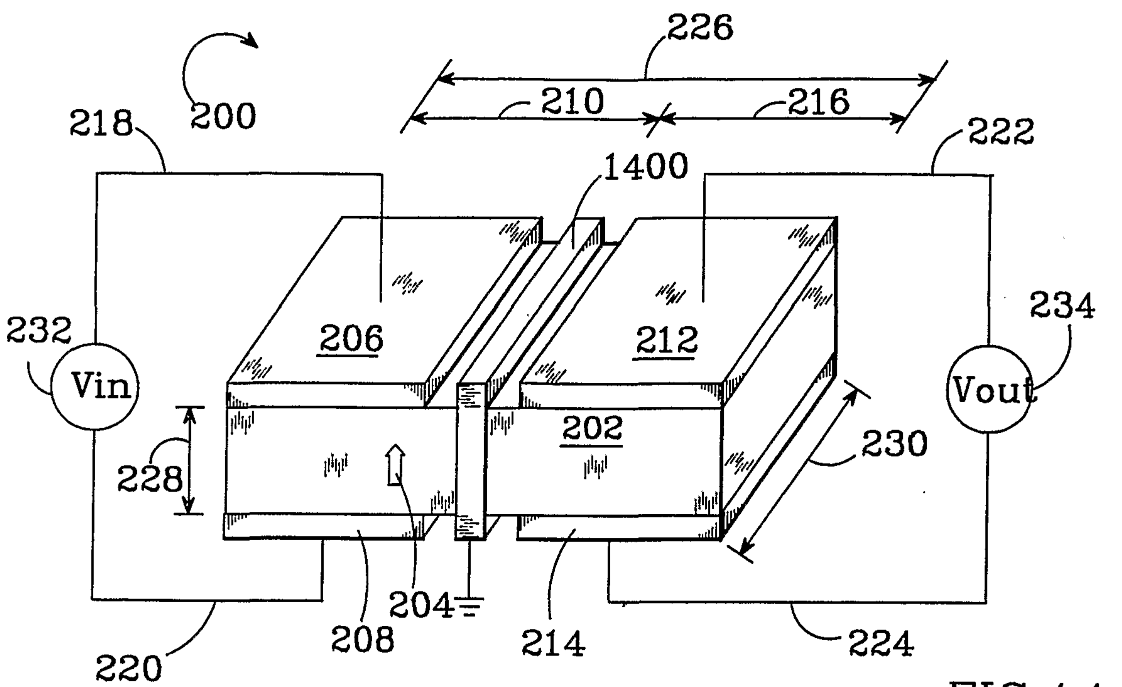


FIG.14

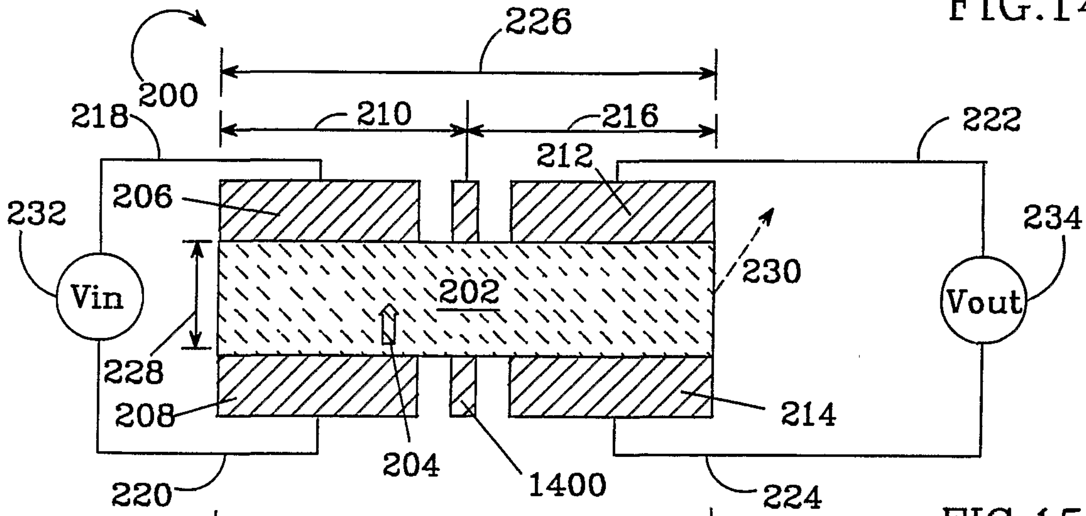


FIG.15

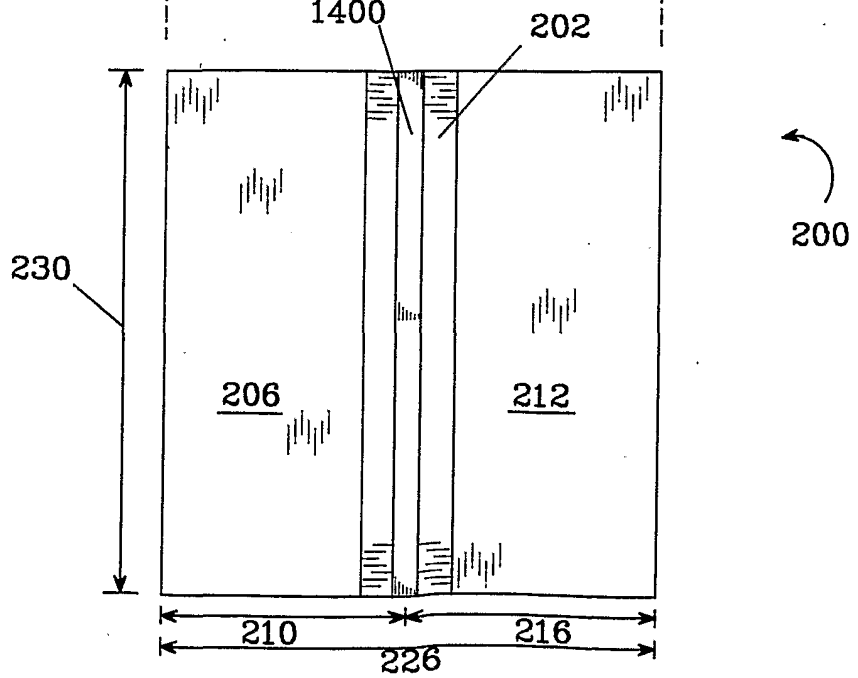


FIG.16

8/14

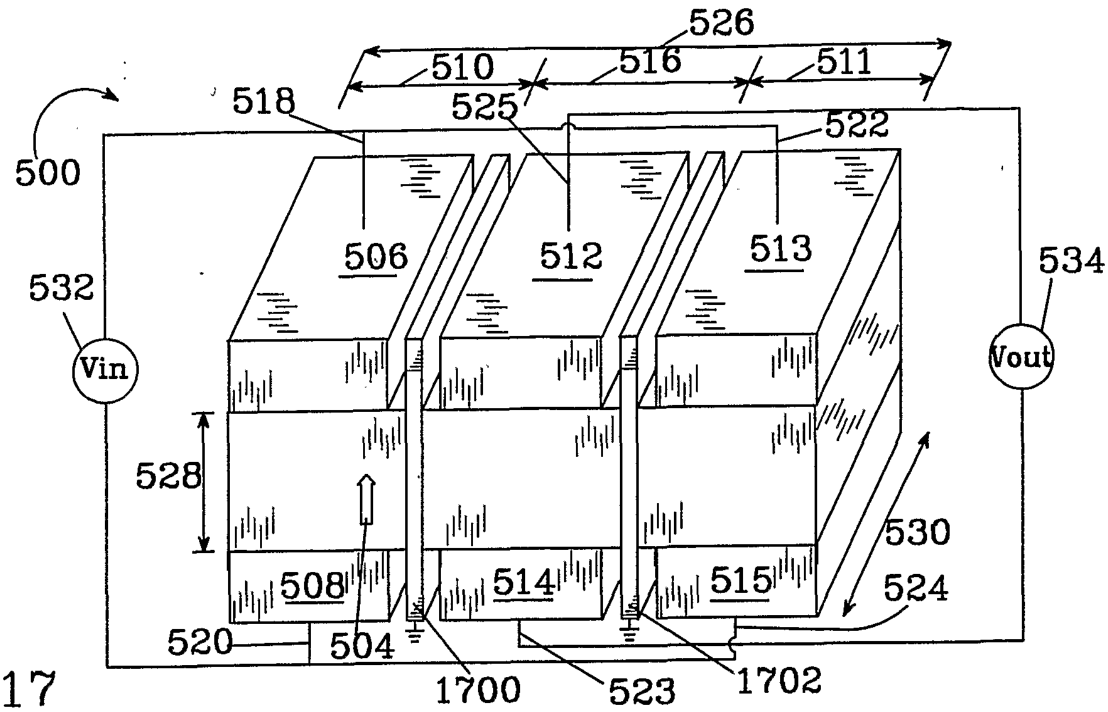


FIG.17

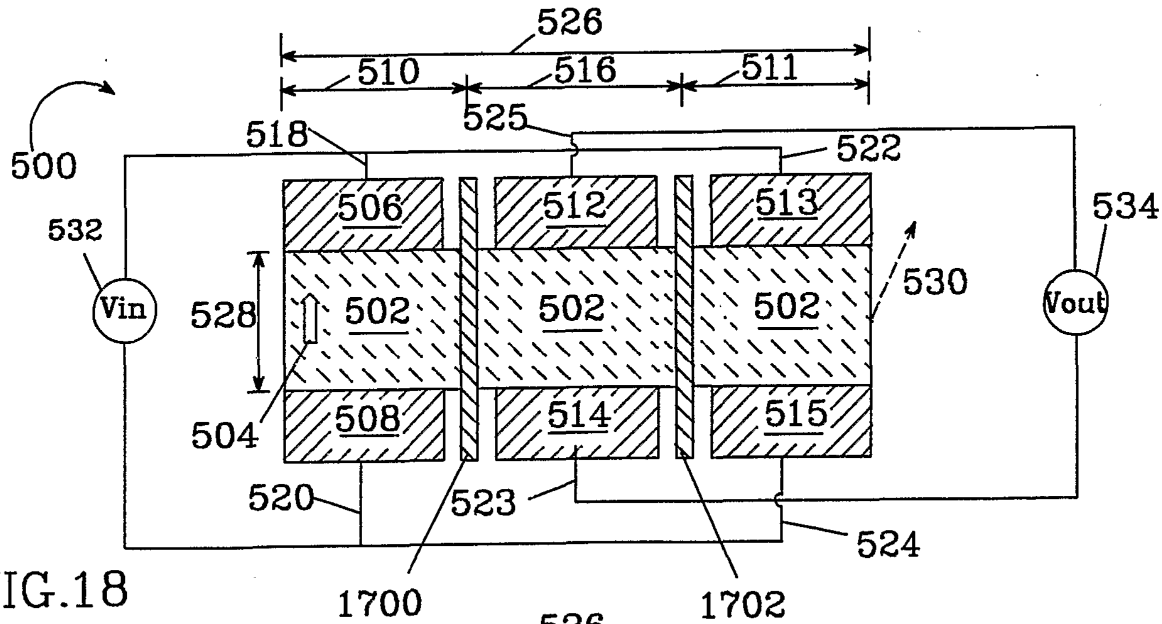


FIG.18

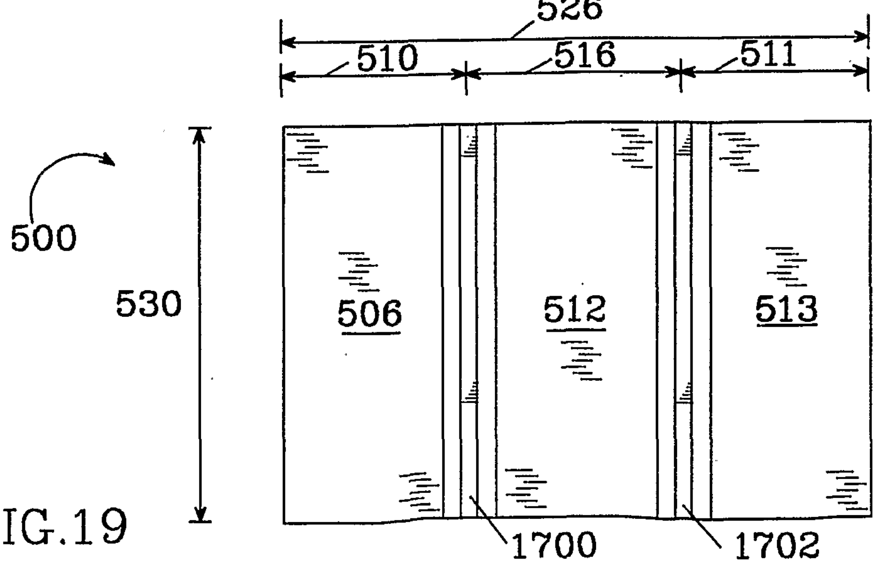
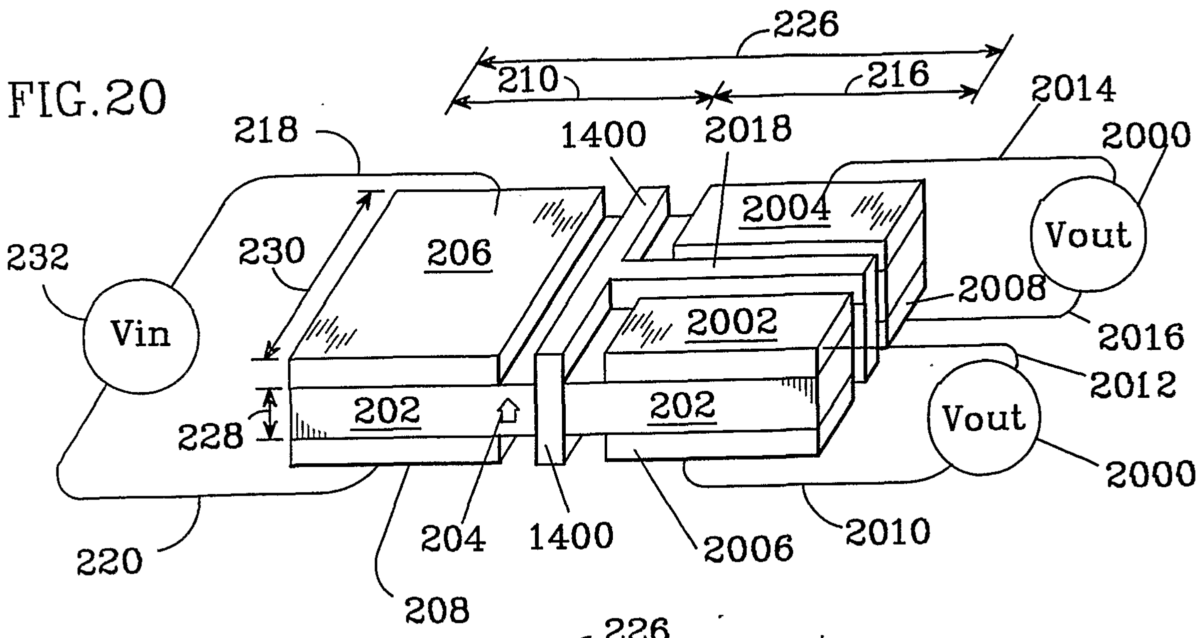


FIG.19

FIG.20



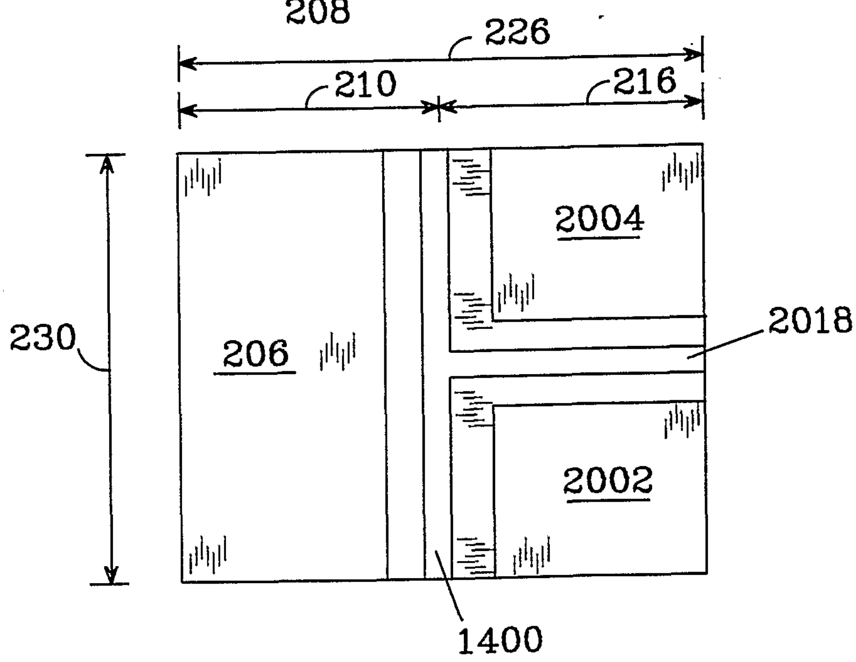


FIG.21

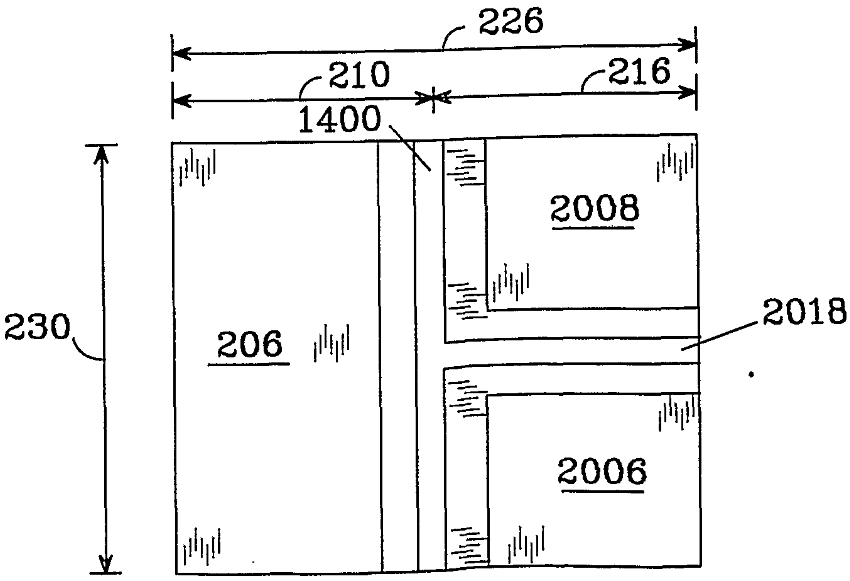


FIG.22

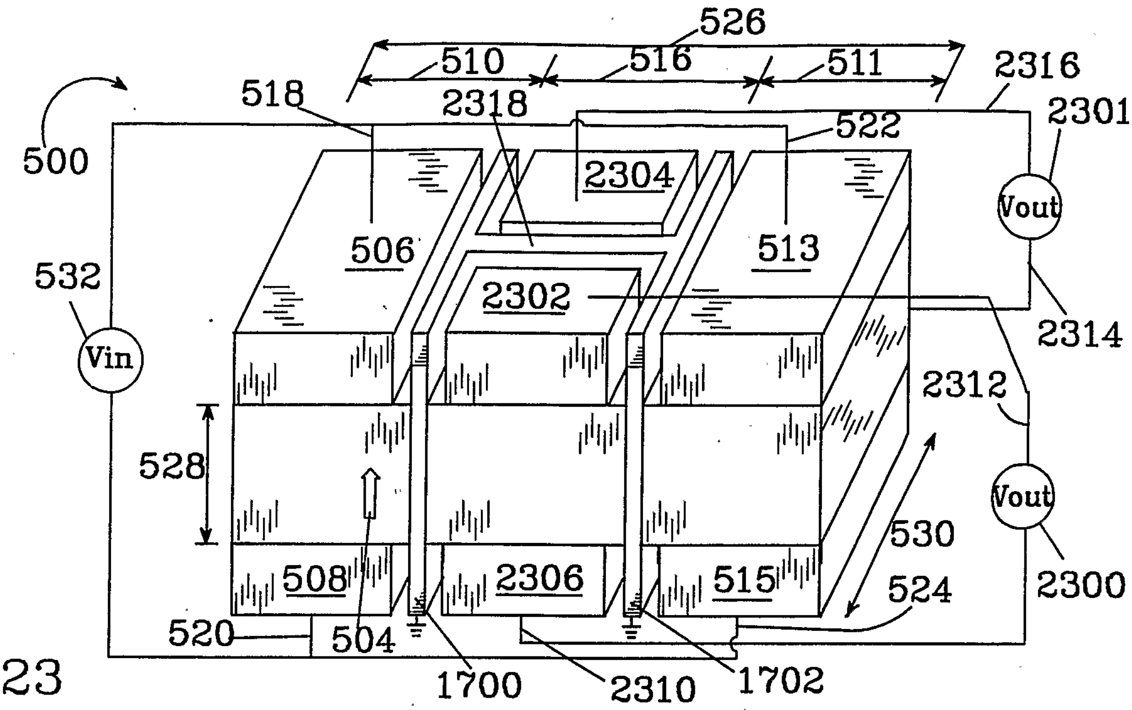


FIG.23

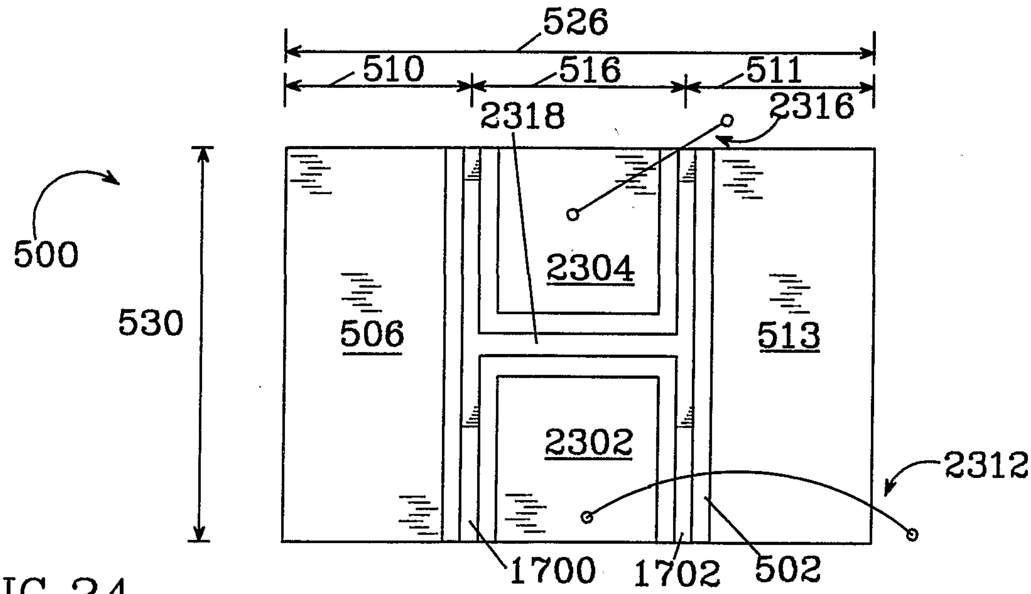


FIG.24

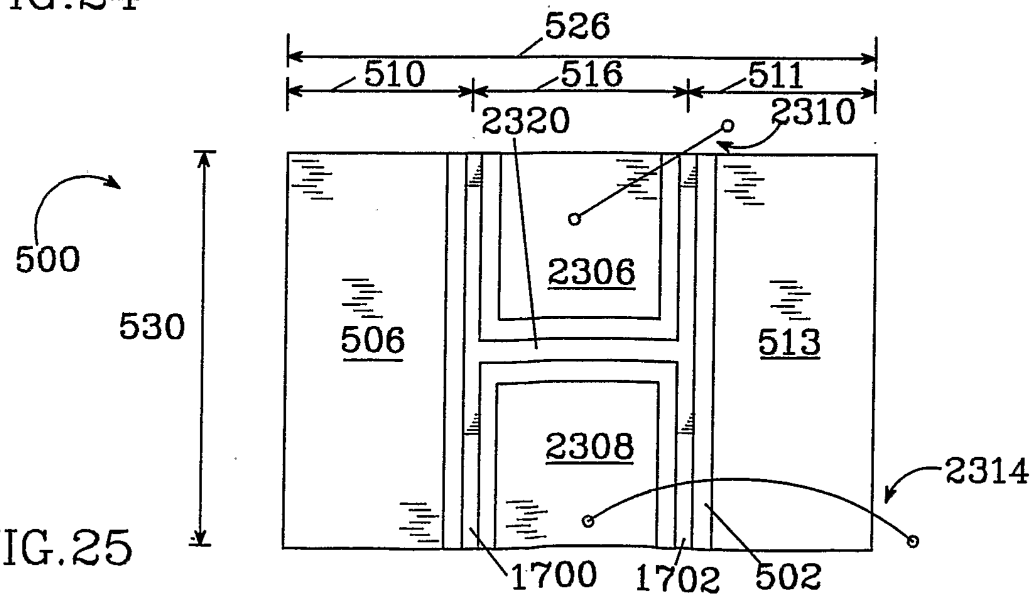


FIG.25

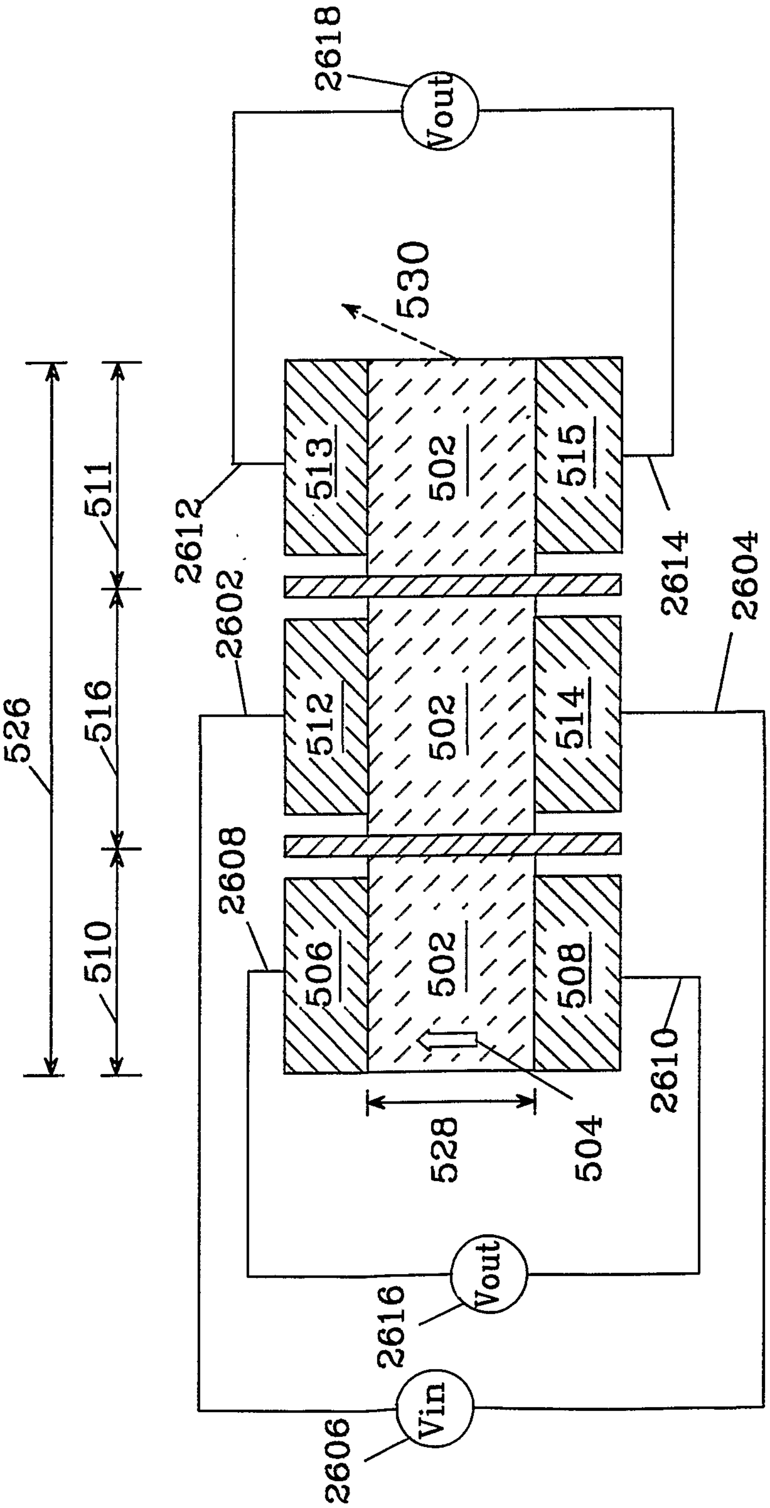

2618
Vout
530
526
511
516
510
513
502
515
512
514
506
508
2612
2614
2602
2604
2608
2610
504
528
Vout
2616
Vin
2606

FIG.26

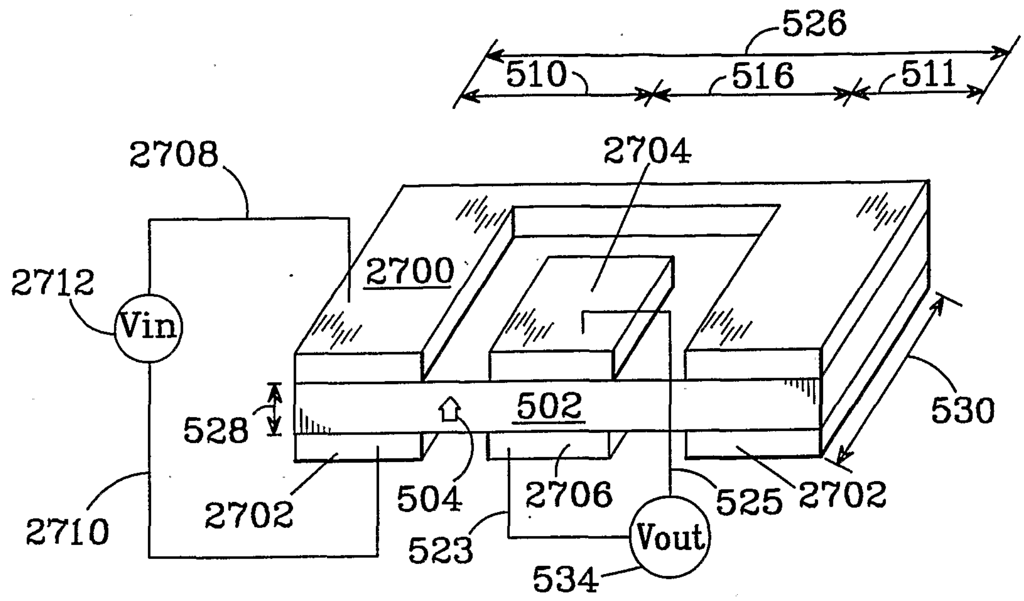


FIG.27

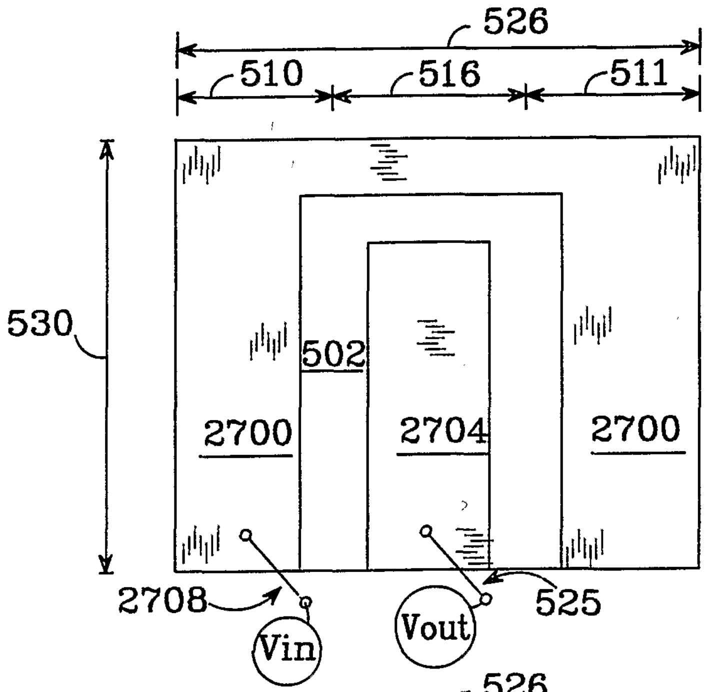


FIG.28

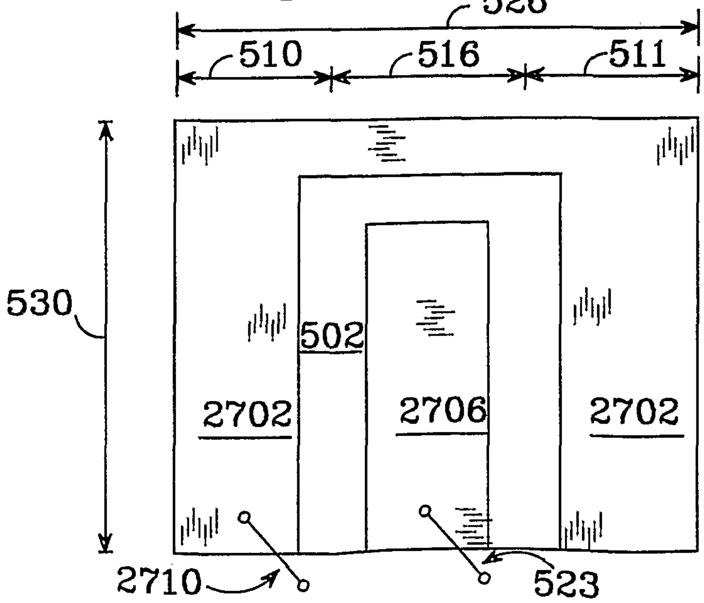


FIG.29

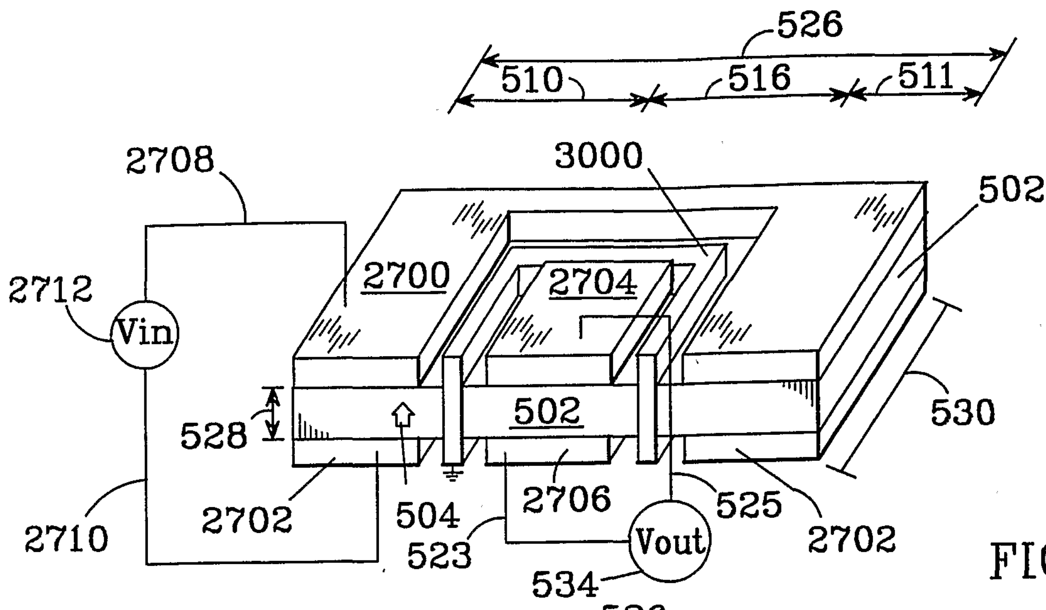


FIG.30

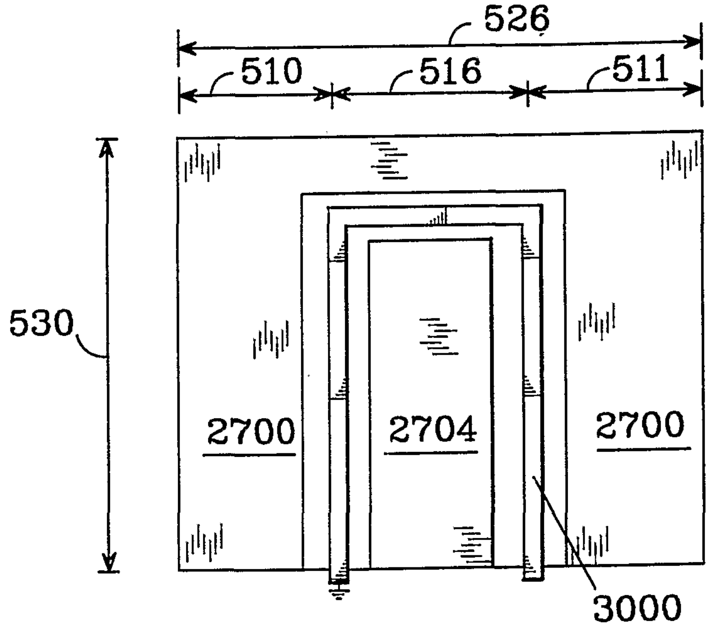


FIG.31

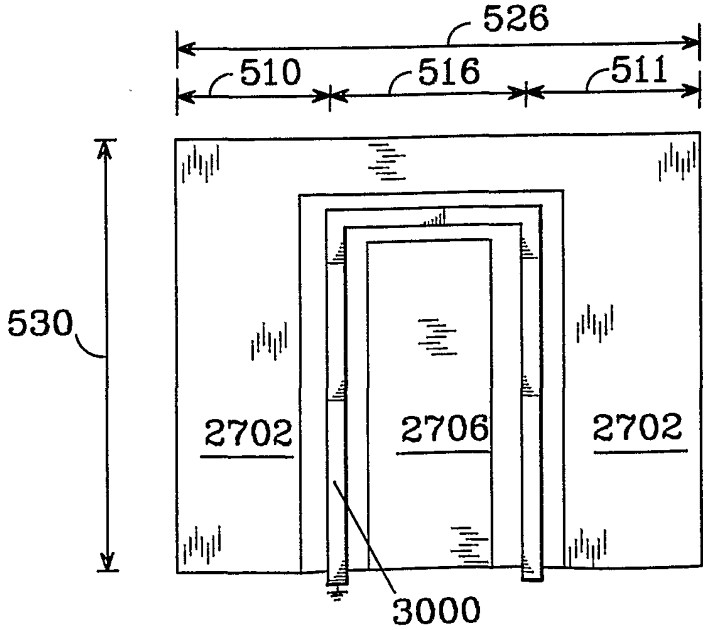


FIG.32

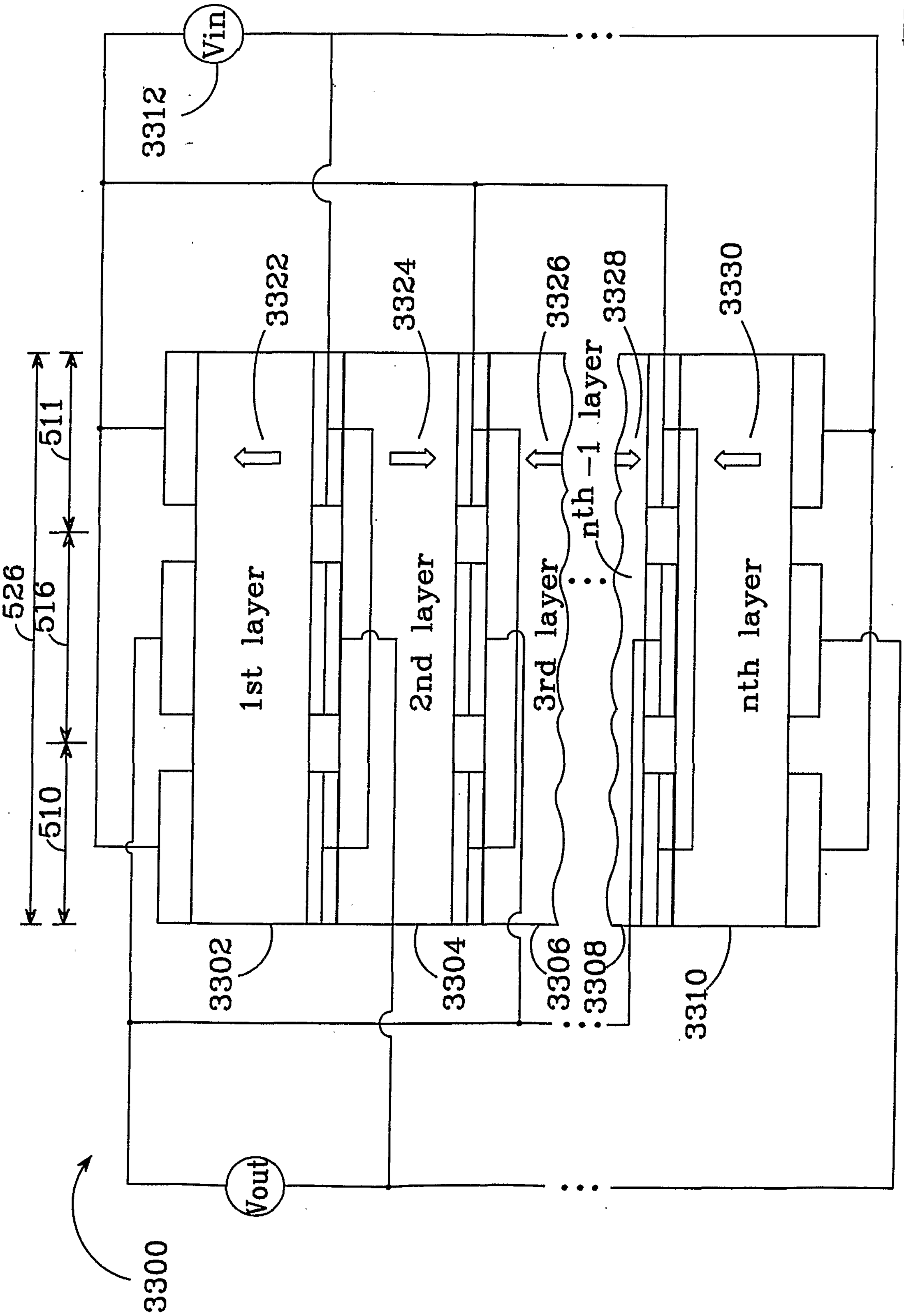

Vin
3312
3322
3324
3326
3328
3330
1st layer
2nd layer
3rd layer
nth -1 layer
nth layer
526
516
511
510
3302
3304
3306
3308
3310
Vout
3300

FIG.33