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Miller et al.

[11] **3,872,330**

[45] **Mar. 18, 1975**

[54] **HIGH POWER ACOUSTICAL TRANSDUCER WITH ELASTIC WAVE AMPLIFICATION**

[75] Inventors: **Darrow L. Miller,** Los Angeles; **William Y. Wells,** Torrance, both of Calif.

[73] Assignee: **Rockwell International Corporation,** El Segundo, Calif.

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[52] **U.S. Cl.** **310/8,** 310/8.2, 310/8.3, 310/8.6, 310/9.8, 310/8.1

[51] **Int. Cl.** **H01v 7/00**

[58] **Field of Search** ..... 310/8.1, 8.2, 8.3, 8.6, 310/9.8, 8; 73/67.5 R, 67.6, 67.8 R, 67.9; 181/.5 AG, .5 FS, .5 EM, .5 J; 318/116

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Primary Examiner—Mark O. Budd

Attorney, Agent, or Firm—Charles T. Silberberg

[57] **ABSTRACT**

A high power acoustic transducer is disclosed, comprised of a number of piezoelectric elements acoustically coupled together. To maximize the available energy in each element, the piezoelectric elements are simultaneously charged by a high voltage source through a high impedance path over a relatively long period. An electrical means is provided for discharging each in succession through a low impedance path. The stored energy is thereby released by each element in a very short time to provide an acoustical pulse of high peak power. Each element is discharged with an electrical phase delay such that the elastic wave of each element adds in phase to the elastic wave of the preceding element, resulting in an amplification of the acoustic wave as it progresses down the transmission path. The entire sequence is repeated at a desired rate to produce an acoustical beam of high-peak power.

13 Claims, 7 Drawing Figures

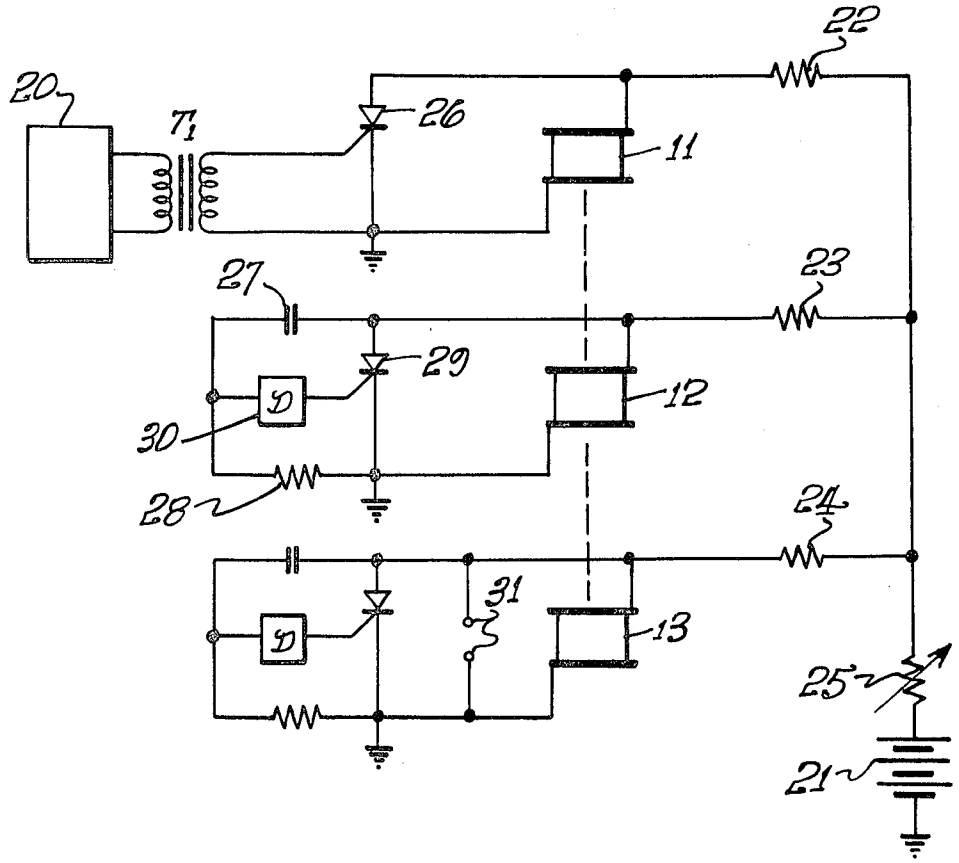


FIG. 1.

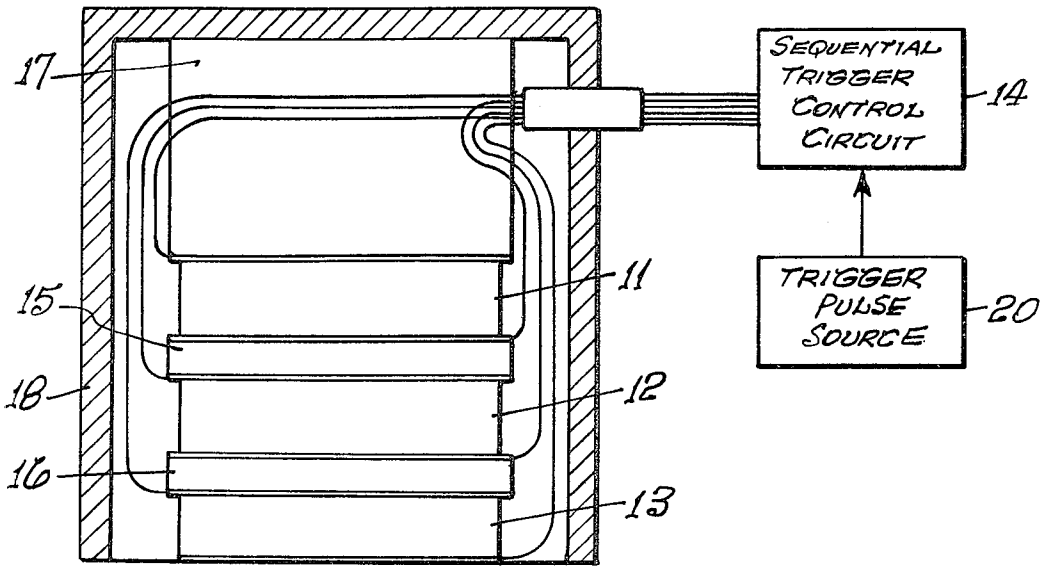

17
SEQUENTIAL TRIGGER CONTROL CIRCUIT
14
11
15
TRIGGER PULSE SOURCE
20
18
12
16
13

FIG. 2.

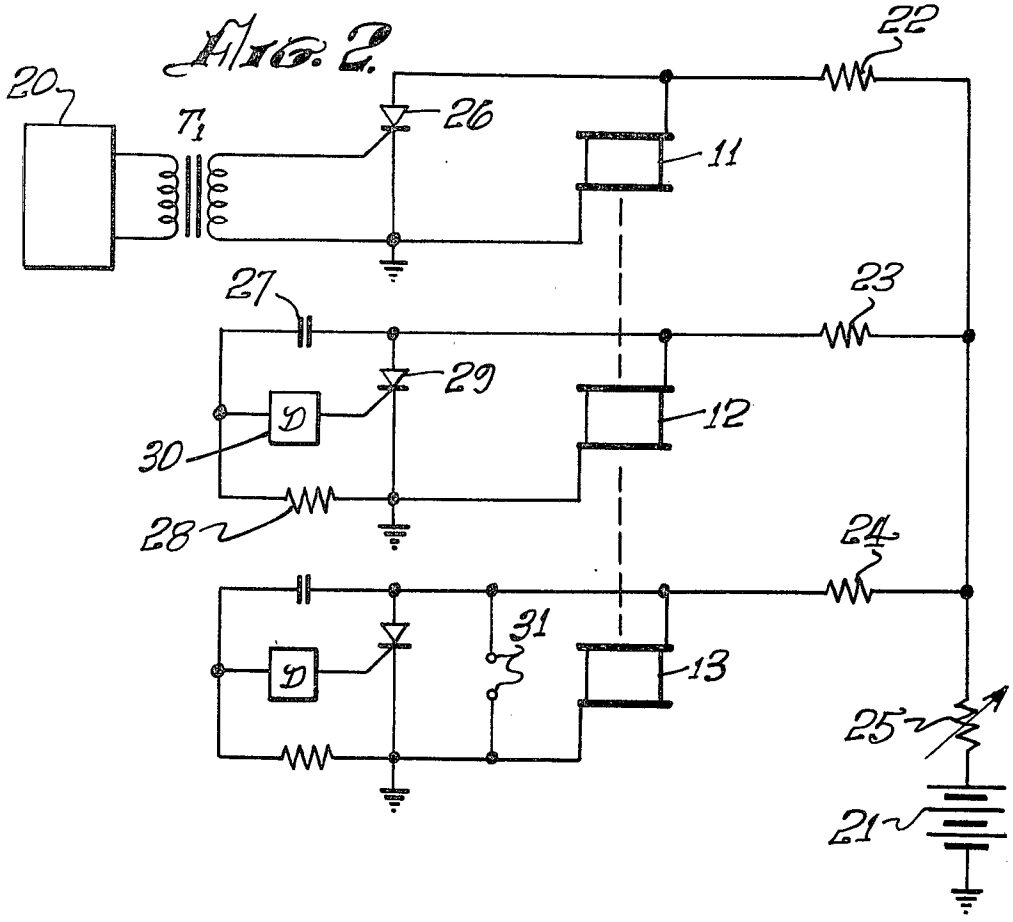
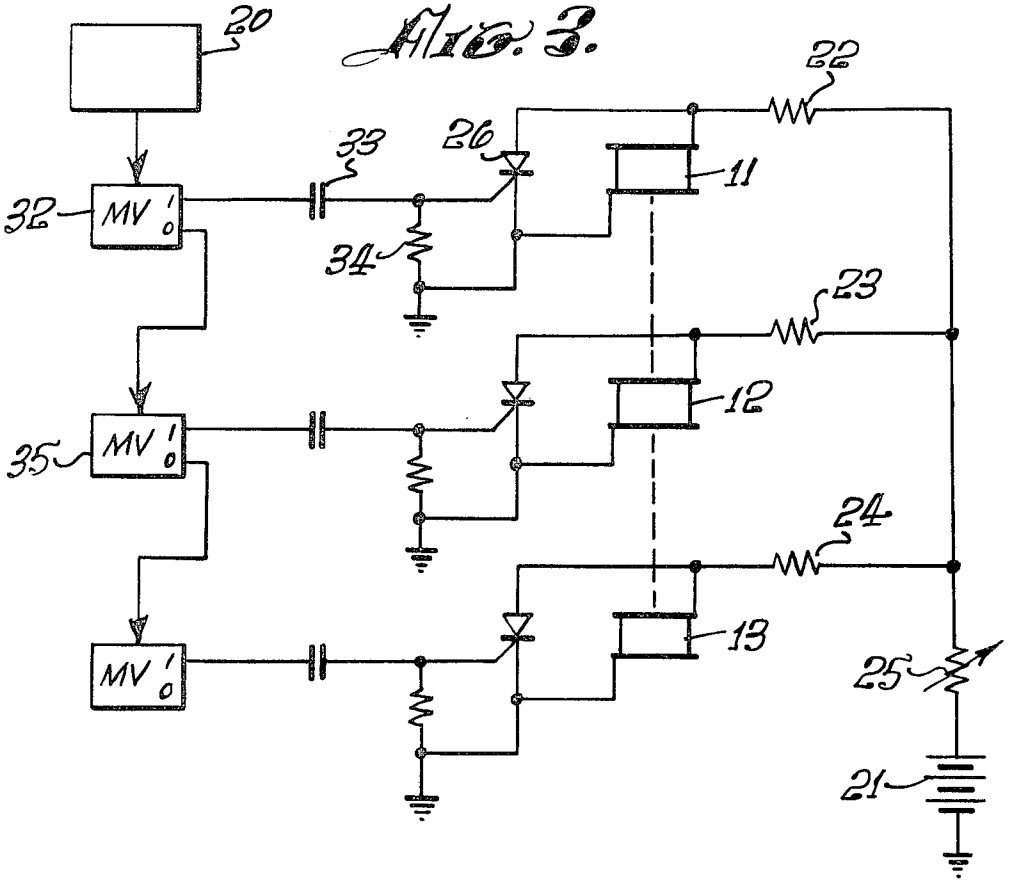

22
20
T1
26
11
27
23
29
D
12
30
28
24
31
D
13
25
21

FIG. 3.



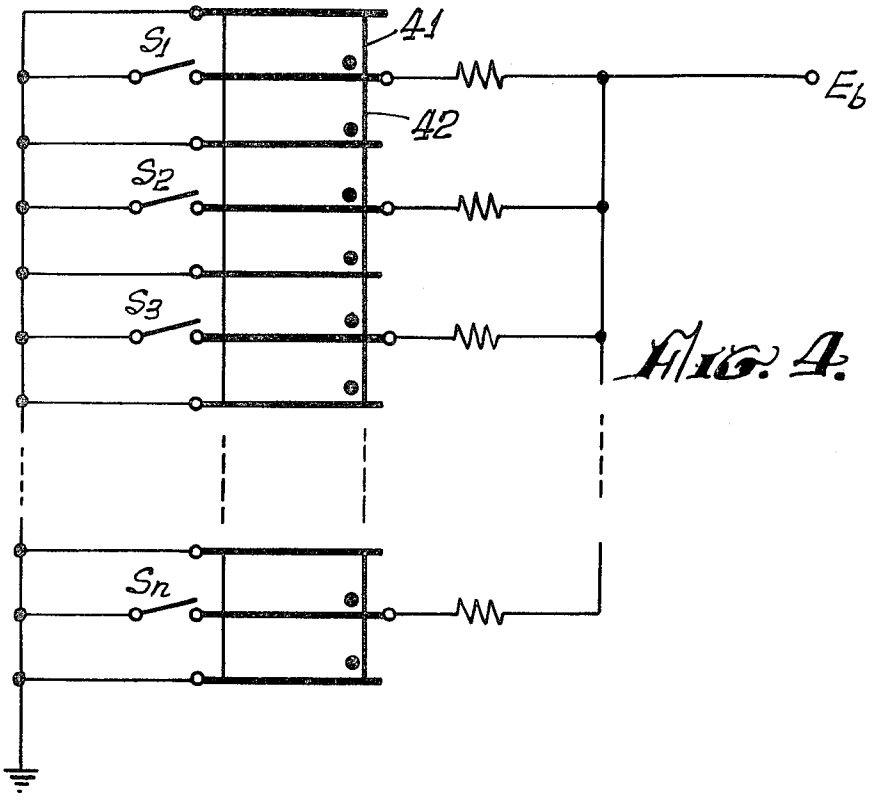


FIG. 4.

FIG. 5.

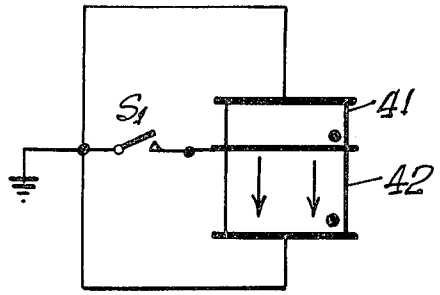
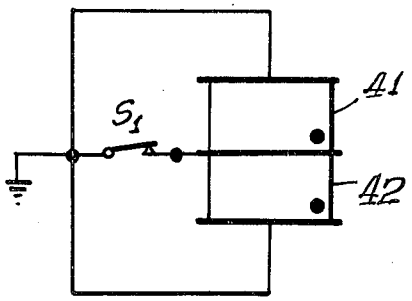


FIG. 6.



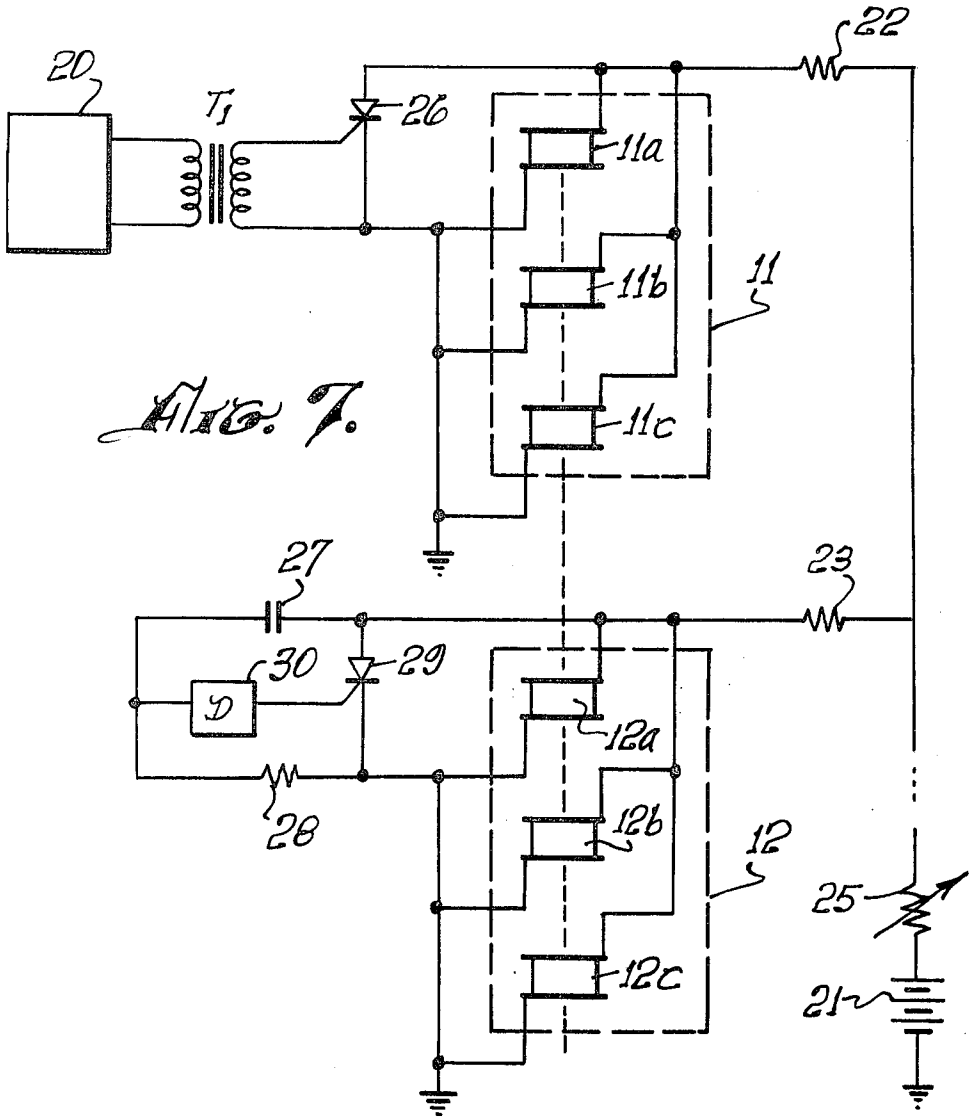


FIG. 7.

HIGH POWER ACOUSTICAL TRANSDUCER WITH ELASTIC WAVE AMPLIFICATION

BACKGROUND OF THE INVENTION

This invention relates to a high power acoustical transducer, and more particularly to an electro-acoustical transducer employing piezoelectric effects.

There is a need for high power ultrasonic transducers to detect small anomalies deep within metallic structures and other bodies. For example, to provide adequate resolution for detecting small (3/64 inch diameter) fractures, cavities or other defects in metal structures, bonded metals, filamentary composites and the like, the sound wavelength must be small relative to the mean diameter of the defect, preferably ¼ to 1/10 of the mean diameter. That requires an ultrasonic transducer of extremely high frequency (1 to 25MHz). Some materials exhibit high acoustical attenuation, particularly at higher frequencies. Consequently, for nondestructive inspection of critical parts, high-power high-frequency ultrasonic transducers are prerequisite to their reliable inspection.

There are other fields besides inspection of parts. For example, in the medical field X rays have been used extensively in examination of the human body for bone fractures, tumors, and other defects, and will continue to be used in those cases where a "quick look" will suffice. In other cases, when the required observation would be too long for the body to tolerate the effects of X rays, other examination techniques are required. Ultrasonics is a useful technology for that purpose, as well as for therapy and dentristry. However, the body tissues absorb a great amount of acoustic energy, particularly at high frequencies. Consequently, to find small defects, or otherwise observe small detail, ultrasonic transducers having higher transduction efficiencies at these high frequencies are necessary.

An improvement in the sound echo return from a defect interface, relative to the background spatial reflection noise, can be obtained by concentrating acoustical energy on the defect. This can be done by collimating or focusing the beam, but the round trip absorption loss in the material is a limiting factor. To overcome that limiting factor it is necessary to increase the energy content of the incident soundwave.

Some transducers, such as electromagnetic transducers do not permit operation at high frequencies because of their mass. Magnetostriction devices are restricted to frequencies below 50 KHz because of eddy current losses. Some piezoelectric devices are small and are capable of being operated at high frequencies up to 25 MHz, but are limited in power. The capacitance of a piezoelectric crystal (quartz, Rochelle or lithium sulphate) or thin layer of ferroelectric material (barium titanate, lead titanate zirconate, lead metaniobate and the like) increases in direct proportion to the area of electrodes on opposite sides and inversely in proportion to the distance between the electrodes. Consequently, for thin piezoelectric elements employed at high frequency, the capacitance is very high, particularly for the more efficient ceramic materials such as lead metaniobate or lead zirconate titanate, which have a high dielectric constant (250 to 1,700). High capacitance, in turn, means low capacitive impedance. For example, at a frequency of 10 MHz a ¼ × ⅝ inch lead metaniobate piezoelectric element with a dielectric constant of 250 typically has a capacitive impedance of approximately 10 ohms to a source of power applied to it. A lead zirconate titanate transducer of the same size would have an even lower impedance in proportion to its much higher dielectric constant.

Because of this low impedance, piezoelectric devices are very difficult to excite with a commercial 50 ohm power source. In commercial pulsing and display apparatus, the circuit usually consists of an electrical storage capacitor (typically 330 pf) which is charged through a high resistance (typically 220 K ohms) over a relatively long period of time and then connected across a single piezoelectric element. An electronic switch, such as a gas thyraton or silicon controlled rectifier (SCR) is employed to discharge the capacitor in a short period of time. However, this has not been entirely satisfactory because not all of the energy stored in the capacitor is transferred to the device; it is instead divided between the storage capacitor and the capacitance of the piezoelectric device. Pulsing a plurality of piezoelectric elements in sequence to increase the potential power output would require a complicated high-voltage low-impedance pulsing system capable of operating at a pulsing frequency determined approximately by the velocity of the elastic wave divided by the wavelength in the piezoelectric material. If each unit were to be pulsed simultaneously to avoid the high frequency pulsing system, the resulting behavior (as in the prior art) would be similar to a low-frequency device with a characteristic frequency and behavior determined by its length and mass.

SUMMARY OF THE INVENTION

An object of this invention is to produce soundwaves the magnitude of which can be selectively increased or decreased as they progress in time through acoustically coupled piezoelectric crystals.

Another object of this invention is to provide a high power acoustic transducer.

Ahother object is to increase the available electrical transduction energy in an acoustically coupled piezoelectric elements as compared to pulsing methods and apparatus of the prior art.

A further object is to provide a number of piezoelectric elements acoustically coupled and to actuate some or all of the elements such that the elastic wave of each element actuated adds in phase with any portion thereof of the elastic wave progressing through the element thereby resulting in an amplification of the wave.

A further object is to provide a number of piezoelectric elements acoustically coupled and to actuate some or all of the elements such that the elastic wave of each element so actuated is out of phase with an thereby subtracts from the elastic wave progressing through the elements.

Still another object is to provide a series of acoustically coupled piezoelectric elements with means for pulsing the first element and means for subsequently using the previously generated elastic wave itself to trigger the remaining elements in sequence such that the elastic wave of each element coupled to the next adds in phase to the elastic wave generated in the next element.

These and other objects of the invention are achieved by a method and apparatus for charging over a relatively long period a group of piezoelectric elements which are polarized in a thickness mode $d33$ parallel to

the sound transmission axis. (Alternatively they may be electrically polarized in another mode, such as a mode at a right angle to the transmission axis (d_{31}) and arranged in series for mechanical expansion and contraction along the axis of sound transmission). The piezoelectric elements are simultaneously charged through a high impedance means from a high voltage source. The electrical energy stored in the capacitance of the piezoelectric elements is released over a relatively short period through a low impedance means to develop a high peak power conversion in each element discharged starting with the first element at one end of the group and proceeding through the group. Each element is discharged at a rate that permits the elastic wave created by piezoelectric action during the extremely short discharge time of each preceding element to add in phase to (or subtract from if desired) the elastic wave produced by the piezoelectric element currently being discharged. The result is a high-power acoustic (sonic or ultrasonic) wave propagated off the end of the last element discharged.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates partially in section a first embodiment of the invention.

FIG. **2** illustrates the complete electrical circuit for driving the transducer of FIG. **1.**

FIG. **3** illustrates a second embodiment of the present invention.

FIG. **4** illustrates still another embodiment to eliminate the requirement for insulation between the elements.

FIGS. **5** and **6** illustrates respective charged and discharged states of piezoelectric elements in the embodiment of FIG. **4.**

FIG. **7** illustrates a third embodiment suitable for sonic frequency pulse operation.

DESCRIPTION OF PREFERRED EMBODIMENTS

Referring now to FIG. **1,** a first embodiment of the invention is shown using only three piezoelectric elements **11, 12,** and **13.** In practice, any number of elements may be used. Each element is made of piezoelectric material, such as lead metaniobate, lead titanate zirconate, barium titanate, and the like, prepared in a known way by ceramic methods and made to have piezoelectric properties better than those of some natural crystals, such as quartz, by putting them through a cycle of polarization with a high electrostatic field.

Prepared and polarized piezoelectric ceramics are commercially available in a wide range of electromechanical transduction properties with dielectric constants ranging from 5 to 1,700 and in various sizes, shapes and thicknesses (half or full wavelength). The material is usually selected with a dielectric constant, frequency constant, and electromechanical conversion parameters to provide an optimum length or thickness (measured along the axis of sound propagation, i.e., along the axis of desired piezoelectric mechanical strain), capacitance, and transduction performance for a specific design frequency. For high frequency operation, the piezoelectric material is usually made in a slab configuration for polarization in the thickness mode. (A bar configuration is advantageously used for long wavelength elements. The bar shaped piezoelectric elements are polarized in a right angle mode (d_{31}) for mechanical expansion and contraction at each end). The slabs are usually ½ wavelength thick. The exact thickness will depend on the frequency constant of the material. The following table sets forth electromechanical properties of lead metaniobate available as Kezite K **81** from Keremos, Inc., Lizton, Indiana.

Table I

ELECTROMECHANICAL PROPERTIES OF LEAD METANIOBATE

K_3	relative dielectric constant	250
d_{33}	piezoelectric strain constant ($X10^{-12}$ coulomb/newton)	85
g_{33}	piezoelectric voltage constant ($X10^{-3}$ volt meter/newton)	40
d_{31}	piezoelectric strain constant ($X10^{-12}$ coulomb/newton)	−15
g_{31}	piezoelectric voltage constant ($X10^{-3}$ volt meter/newton)	−7
Dissipation factor at 1 KHz		<1.0
Resistivity (ohm-cm)		10^{13}
Qm mechanical Q (thickness mode)		<10
Frequency constant (thickness mode) (KC in./sec)		58
Curie temperature (° C)		>400
dh hydrostatic constant ($X10^{-12}$ coulomb/newton)		55
Density	(gm/cm^3)	5.8

For an operating frequency of 2.25 MHz, and using material having the properties set forth in Table I, the halfwave thickness for the slab configuration would be about 0.025 inches and the capacitance about 1,000 pf for a ¾ inch diameter slab. The piezoelectric slabs (or bars if the elements are polarized in a right angle mode) are arranged (stacked) along the axis of sound transmission and electrically insulated from each other with a low acoustical loss material as in the first embodiment of FIG. **1.** A second full-wave embodiment illustrated in FIG. **4** requires no insulation between elements. Before stacking the slabs, they are prepared with electrodes in the form of thin films of conductive material, such as vapor deposited silver, on both sides, with a small tab extending from the edge of each face through which electrical connections are made to a sequential trigger control circuit **14.**

In assembling the electroded slabs into sequentially operative piezoelectric elements, wafers **15** and **16** made of electrical insulating material, such as mica, are cemented between the piezoelectric elements. The cement successfully used was an epoxy type EC 1469 made by Minnesota Mining and Manufacturing Corporation. However, any epoxy or other cement may be used which can be applied in a liquid state and which sets in a solid state for form a good adhesive bond with a low interfacial acoustical loss. An epoxy is preferred for the additional insulating qualities of that material, but other types of cement may be used. As will be more fully appreciated hereinafter, the material serves not only to hold the elements together with their electrical connecting tabs but also provides a low reflection, low loss acoustical transmission media between each element. The scope of the present invention also includes other insulating materials such as oil or liquids which may be employed in a thin film to provide a low acoustical loss between elements.

After the elements have been cemented to the insulating wafers, an acoustical back wave damper **17** is cemented to the back of the first element. A satisfactory acoustical damper for 2 ¼ MHz operation consists of the metal loaded matrix material delineated in the following table.

Table II

	ACOUSTICAL DAMPING MATERIAL
1.	Epoxy Matrix 10 grams epoxy (3-M type EC1469) mixed with 4 grams catalyst (U)
2.	Damping Filler 2 grams toluene mixed with 0.3 gram Alon (alumina) and 32 grams tungsten powder (−325 mesh)
3.	Combine mixtures, pour into mold, and cure in oven 120° F for 20 to 30 minutes.

The thickness of the damper is approximately ½ inch and comprises the bulk of the transducer height shown in FIG. **1.** It should therefore be understood that the dimensions shown in that drawing are not proportional. The dampened stack of piezoelectric elements is then placed in a housing open at one end with the third element flush with the opening. To secure the elements in place with the electrical leads passing through the housing as shown, the housing is filled with a plastic material. Alternatively, the stack of piezoelectric elements may be "potted" in plastic such that the plastic itself constitutes the housing, or they may be placed in a housing filled with oil to provide a thin insulating film between each element. In either case, quick-disconnect receptacles may be provided for connecting the electrical leads to the outside so that the connections to the circuit **14** can be easily changed. The completed three-element high-power ultrasonic transducer is then ready to be placed on the object to be inspected. A liquid, paste or other acoustical coupling media is employed to acoustically couple the transducer to the test article. A suitable dry acoustical coupling matrix material is described in U.S. Pat. No. 3,663,842.

The sequential trigger control circuit for driving the transducer of FIG. **1** is shown in FIG. **2.** For ease in understanding the circuit, the piezoelectric elements are shown separated from each other although it is understood that they are acoustically coupled by an insulating medium. That coupling is represented by a dotted line from one element to the next.

A trigger pulse source **20** transmits a single pulse for each time the transducer is to be actuated. Between trigger pulses, the elements are charged to a high voltage 250 V or greater from a source **21** through separate resistors **22, 23** and **24.** These resistors are selected to be large (typically 150 K ohms) and the charge time is controlled (by varying a series resistor **25**) to be shorter than the reciprocal of the trigger pulse rate. This assures maximum storage of energy for release in response to each trigger pulse.

A trigger pulse is coupled by a pulse transformer T_1 to the gate electrode of a silicon controlled rectifier (SCR) **26** which then fires to provide a low impedance discharge path for the first element **11.** The electric wave produced by the sudden change in voltage across the element **11** causes a change in pressure across the next element **12.** For example, when the polarization of the elements is such that the emf from the source **25** causes the piezoelectric material to contract in the vertical axis, the elastic wave resulting from the sudden discharge of element **11** will initially cause the next element **12** to be contracted even more in the vertical axis. This produces a transient increase in the voltage across element **12.** That transient is coupled by a capacitor **27** across a resistor **28** connected between the gate and cathode of an SCR **29** to trigger it, thus causing the next element to discharge and thereby produce an elastic wave or a portion thereof which adds in phase with the elastic wave from the first element. To assure that phase relationship, a delay element **30** may be included as shown or the RC time constant of the capacitor **27** and resistor **28** can be adjusted such that the second element does not discharge until the elastic wave from the first element has traveled a sufficient distance to combine in phase with that from the second element. The third element then discharges in sequence in a similar manner to complete one cycle of operation. Before the next trigger pulse from the source **20** occurs, all elements will be recharged in parallel for the next cycle. The result is one acoustical energy burst for each trigger pulse, each element independently discharging in sequence with a traveling elastic wave initially generated by the electrical discharge of the first element. This process is repeated sequentially in time at a search pulse rate of 800 to 1,000 pps.

The scope of the present invention also includes having piezoelectric elements in the device which are not charged and/or discharged. Further, each piezoelectric element need not always be discharged in sequence (as to make a wider duration high energy pulse).

When required for a particular design criteria, delay element **30** or RC time constant of capacitor **27** and resistor **28** can be adjusted such that the discharge of the second element combines out of phase with the elastic wave of the second element resulting in a net decrease in the magnitude of the traveling elastic wave at this position.

Transducers used in the ultrasonic frequency range have in the past been limited in power by their small physical size, half wave thickness and heat dissipation capabilities. Single high frequency elements have been actuated by applying a short duration voltage pulse (about one microsecond) from a low impedance (50 ohm) source to the piezoelectric material. This technique is not very efficient and poor power transfer at ultrasonic frequencies results.

Stacked piezoelectric elements with electrical power inputs of 1 to 15 KW have been used as transducers to generate high acoustical power but only in the lower sonic frequency region (500 to 20 KHz). Some transducers consist of a group of transverse expander (45° Z cut) plates with interleaved foil electrodes electrically connected in parallel. The ends and not the faces of the plates of the stacked crystals act together simultaneously to form a single lateral expansion entirely different from this invention. Other combined arrangements of the prior art employ, in certain instances, thin parallel connected slabs of Y-cut lithium sulphate to form a cube or rod in which again the plates all expand and contract in unison to provide a single strong piezoelectric volume expansion effect which is in no way representative of the principle and apparatus employed in this invention. Thick slabs, long rods, large tubes, rings and other shapes are also used in this manner, but in general, such transducers are employed only in the sonic frequency region and when combined arrangements are employed, all the sections operate simultaneously, each individual slab, ring, or other geometric configuration changing dimensions in unison in the same direction and at the same time.

Another invention, U.S. Pat. No. 3,693,415, employs multiple piezoelectric elements uniformly spaced in a row relative to the workpiece with successive units or

groups energized in a manner so that successive foci are on a path on the outer surface of the workpiece. The angles are such that the pulses arrive substantially at the same time at a point within the workpiece. Several transducers are employed and cover a substantial portion of the workpiece. This principle involves a number of transducers each acting independently at predetermined fixed angles. The amplitude output of one is not added to the next and to the next as a function of time as in the present invention. Conventional pulsing techniques are used. The longer acoustical path in the sample makes this possible. Similar techniques to the above are used in the prior art for scanning a large area with surface waves using sequentially operated multiple transducers. Another similar invention employs a liquid with multiple electrodes. These and other inventions of the prior art do not involve the principles disclosed in this invention.

The present invention is based upon simultaneously charging a number of elements through a high impedance from a common voltage source and then discharging the stored charges in the elements, each over a short period (less than one microsecond) through a low impedance path ($<<0.1$ ohm). To recharge the elements for the next cycle, the same common high impedanace source is used, and each element charges independently over a relatively long period. Thus, all of the piezoelectric elements are simultaneously recharged during the interval between acoustical search pulses from the source **20.** The charge time is relatively long (0.08 to 0.001 second) as compared to the envelope of the acoustical energy burst (0.2 to 1 microsecond). The energy stored in the elements is transformed to mechanical energy which deforms the elements making them thicker or thinner, depending upon the polarization of the elements and the polarity of the power source. The total energy stored in each unit is proportional to the square of the battery or power supply voltage and can be exceedingly high compared to conventional pulsing techniques where only a portion of the pulsing voltage is applied across the transducer. Since all of the stored energy can be released in about a microsecond or less, the result is a high peak acoustical power burst from each element in the stack: viz., watt seconds $= \frac{1}{2} CE^2$ where C is the capacitance of an element and E is the voltage of the source **21.**

Assuming that 8×10^{-4} watt seconds of energy is stored in each piezoelectric element if this energy is dissipated in 1 microsecond, the peak electrical power available for conversion to mechanical energy would be approximately 800 watts per element. If the energy were dissipated in about 200 nanoseconds, the peak conversion power would be 4 kilowatts per element. Assuming no interface or other losses and a 100 percent electromechanical conversion, the power-time behavior indicted by the energy equation would theoretically be multiplied by the number of elements in the stack. Such an example is obviously unrealistic. Electromechanical conversion factors range between 0.5 to 0.8, and there are interface, spatial and absorption losses. The example, however, serves to illustrate that a peak power gain of substantial magnitude can be obtained by these techniques. If *n* elements are in the stack and each is shorted by an SCR switch at a period in time substantially in phase with the elastic wave from the preceding element, the amplitude of the elastic wave traveling down the stack is increased. The battery voltage is thus effectively multiplied *n* times, and an elastic wave power gain will be obtained.

In the embodiment described with reference to FIG. **2,** the sonic energy induced voltage in each piezoelectric element is used to trigger the SCR of the next element and the receiving element. Recepticals **31** are provided to connect suitable recording or display apparatus. Both the transmitted signal and the echo return signal can be observed by using the last element **13** as a receiving as well as a transmitting piezoelectric transducer. With adjustable delay element in the gate circuits of the SCRs, it is possible to maximize the transmitted acoustic signal adjusting the delay elements **30** until maximum echo return from the defect is achieved in a standard environment.

In a second embodiment to be described with reference to FIG. **3,** the SCRs are triggered in sequence through separate multivibrators. For convenience, all circuit components which are the same as in the embodiment of FIG. **2** are identified by the same reference numerals. A pulse from the source **20** triggers a first multivibrator **32.** The leading edge of the positive going output from the true (**1**) output terminal is coupled by a differentiating circuit to the gate of the SCR **26.** The differentiating circuit is comprised of a capacitor **33** and a resistor **34** that actuates the first element **11.** When the multivibrator **32** resets after a predetermined period, its false (**0**) output goes positive and triggers a multivibrator **35** to trigger the second element **12.** After a predetermined period, the multivibrator **35** resets and triggers a multivibrator **36** to activate the third element **13.** The periods of the multivibrators are set to cause the elements to be discharged sequentially and inphase with the traveling elastic wave generated by the first element.

Still other techniques may be devised for providing sequential trigger control. For example, a delay line with taps to each SCR may be used in place of a chain of multivibrator circuits. Alternatively, digital techniques may be used employing a clock pulse source and a counter to time the periods between the activation of elements. Analog techniques would provide as an advantage a static control signal for each element, rather than a sharp triggering pulse. An advantage of a static control signal is that other electronic switching devices may then be used to discharge the element, such as a transistor switch which is turned on during the presence of the control signal. For higher discharge voltages, two transistor switches can be connected in series and turned on simultaneously by the same control signal. Still other possibilities will occur to those skilled in the art. All that is essential is that the elements be charged over a relatively long period from a common high impedance voltage source, and discharged in phase sequence through very low impedance switches. The shorter the discharge period, the greater the peak electrical power available for conversion to mechanical energy.

Any number of elements can be used to further increase the power gain achieved upon actuating the elements in phase with the elastic wave from the first element. However, there is a maximum number of elements over which there would be no practical advantage due to the losses between the elements. This occurs when the nth element contributes only about 10 percent increase to the transmitted signal. Power out

(P_o) contributed by the nth element will then be $(10/100)^2$ of the input power P_i.

The reduction in power due to the attenuation, a, of the insulating wafers between elements for the nth element will be

$$P_o = \frac{P_i}{\log^{-1}\frac{(n-1)a}{10}} \quad \text{(assuming } a_1=a_2=a_3=a_n\text{)}$$

substituting

$$(10/100)^2 P_i = P_i \left(\frac{1}{\log^{-1}\frac{(n-1)a}{10}}\right)$$

$\log^{-1}(n-1)a/10 = 100$
$(n-1)a = 10 \log 1{,}000$
$(n-1)a = 30$
$a = 30/n-1$

For example, the practical limit to the number of elements should not exceed 50 if a is 0.6 db. However, only a few elements may be necessary because of the energy stored in each element. The gain in db for n elements over a single element can be derived as follows, where $n>1$:

power from one element = P
power from two elements) = $P + (KP)$
power from three elements = $P + (KP) + (K^2P)$
power from four elements = $P + KP + K^2P + K^3P$
power from n elements = $P + (K+K^2+K^3+ \ldots K^{n-1})P$

$$\text{db gain} = 10 \log_{10} \frac{P + \sum_{2}^{n} K^{(n-1)}P}{P}$$

$$\text{db gain} = 10 \log_{10} (1 + \sum_{2}^{n} K^{n-1})$$

where K is the transmissibility of the interface expressed in percent.

Other possibilities within this concept of simultaneously charging and sequentially discharging stacked piezoelectric elements will occur to those skilled in the art in respect to how the elements are stacked for close acoustical coupling with minimum coupling losses. The optimum would be to stack the elements back to back without any intervening insulating material. One arrangement, illustrated in FIG. **4**, allows adjacent elements to be cemented directly without insulators and permits the top and bottom surfaces of the stack to be at ground potential.

In this arrangement, elements are discharged in pairs. The elements of a pair are connected to the power supply E_b oppositely. All elements in the stack are arranged with the same ferroelectric polarization as indicated by dots. Consequently, in a given pair, such as the first pair of elements **41** and **42**, charging the elements will cause the element **41** to contract and the element **42** to expand longitudinally, i.e., along the axis of the stack, as shown in FIG. **5**. When a switch S_1 is closed, the element **41** will expand and the element **42** will contract simultaneously. The quiescent state of the first pair after the switch S_1 is closed and the stored charge has been fully discharged is illustrated in FIG. **6**. The net effect is an elastic wave from the pair coupled to the next pair which is then actuated in phase sequence upon closing a switch S_2. The switches are here represented as mechanical switches, but it is understood that in practice they will be implemented with electronic devices, such as with SCRs.

Since elements operate in pairs in this alternative arrangement for the stack, it should be understood that, in the accompanying claims, "piezoelectric elements" said to be charged simultaneously and discharged in phase sequence can mean paired piezoelectric wafers, each pair constituting an element. The principles and circuit techniques for sequential in phase discharge of elements is the same as for other embodiments.

It is desirable to use a high charge potential as previously described. Consequently, when constructing a transducer for use in the ultrasonic region, as the design frequency is increased flashover can occur across the edges of the elements. This occurs because the half or full wavelength thickness decreases as the frequency is increased. The problem can be obviated by proper selection of the piezoelectric and surrounding materials. Piezoelectric materials are available in a wide range of dielectric constants (4.5 to 1,700).

The bottom piezoelectric element employed as a receiving transducer can be made from a high-voltage constant (G_{33}) material to provide optimum receiving characteristics. The other elements in the stack can be manufactured from a high-strain constant (D_{33}) material to provide good electromechanical transduction. The receiving element may conceivably be geometrically or ultrasonically phase isolated to provide excellent near surface resolution. It is practical for the solid-state switching circuitry to be integrated with the piezoelectric stack to form a composite transducer within one housing. This technique provides pulsing leads of minimum length, a prerequisite for ultra-high frequency performance. State-of-the-art microelectronic integrated circuit techniques are now developed sufficiently for this purpose.

At low (sonic) frequencies, the thickness of each element is necessarily greater than at high frequencies due to the greater half or full wavelength. Consequently, the capacitance of each element would be too small to store the sufficient energy due to the greater distance between electrodes. However, the present invention can still be practiced at low frequencies by effectively increasing the capacitance of each element. That is accomplished by dividing the thickness of each element into subelements, and constructing the subelements in the same manner as in the previously described embodiments, but electrically connecting the subelements in parallel. The paralleled subelements are then simultaneously triggered as a single element in phase with the elastic wave traveling down the stack from the adjacent paralleled subelements. The combined length of the stacked subelements provides longer wavelengths (low frequencies) while the combined capacitance of the electrically paralleled subelements provides greater capacity for storing energy. FIG. **7** illustrates this technique for the embodiment of FIGS. **1** to **3**. For convenience, the same reference numerals are employed for corresponding elements with subscripts, a, b, c . . . for components of subelements. The same technique may

be employed in an analogous manner to adapt the embodiment of FIGS. 4 to 6 to low frequencies.

Although particular embodiments of the invention have been described and illustrated, it is recognized that modifications and variations may readily occur to those skilled in the art. Consequently, it is intended that the claims be interpreted to cover such modifications and variations.

What is claimed is:

1. A method of producing sonic or ultrasonic waves from a number of piezoelectric elements acoustically coupled, said elements being polarized for expansion and contraction along the axis of soundwave transmission comprising the steps of

charging said elements simultaneously through a high impedance from a voltage source,

discharging said elements in sequence, each element being discharged through a low impedance path, and

timing the discharge of each succeeding element after the first element has been discharged by detecting the sonic energy induced voltage produced in each element by the elastic wave progressing through said element and triggering a switch to discharge the element in which the induced voltage is detected whereby the discharge occurs in phase sequence with the elastic wave passing through it from the preceding element.

2. A method as defined in claim 1 wherein the timing of the discharge of each succeeding element after the first is predetermined to occur in phase sequence such that the elastic wave or any portion thereof produced by each succeeding element is in phase with, and adds to, the elastic wave progressing through the group of elements.

3. A method as defined in claim 1 wherein the timing of the discharge of each succeeding element after the first is predetermined to occur in phase sequence that the elastic wave or any portion thereof produced by each succeeding element is out of phase with, and subtracts from, the elastic wave progressing through said group of elements.

4. A method as defined in claim 1 wherein the timing of the discharge in each succeeding element after the first is predetermined to occur in phase sequence such that the elastic wave or any portion thereof produced by one or more of the succeeding elements is in phase with and adds to the elastic wave progressing through said group of elements and the elastic wave produced by one or more of the succeeding elements is out of phase with and subtracts from the elastic wave progressing through said group of elements.

5. A method as defined in claim 1 wherein each element is comprised of a plurality of piezoelectric subelements acoustically coupled, and wherein subelements of each element are discharged simultaneously, thus providing a longer element for low frequency sonic waves of high energy.

6. Apparatus for producing an acoustical energy burst of high power ultrasonic soundwaves comprising

a stack of piezoelectric elements acoustically coupled, each element comprising a slab of piezoelectric material polarized for operation in the thickness mode in a direction along an axis of said stack, said axis being perpendicular to flat sides of said stacked elements, and a separate conductive film on each side of each slab,

high impedance means for simultaneously charging the capacitance of said elements with an electrical charge across each of said elements, and

means for discharging each element sequentially through a separate low impedance discharge path in phase relationship with the traveling elastic wave progressing along the sound axis, said discharging means comprising

a separate low impedance electronic switch connected to each element, each switch having an anode connected to said conductive film on one side of an element, a cathode connected to said conductive film on the other side of said element, and a control electrode,

a capacitor between the anode and control electrode of each switch except the first at one end of said stack,

a resistor connected between the control electrode and cathode of each switch except said first one, and

means for inducing a voltage pulse between said control electrode and cathode of said first one of said switches, said voltage pulse being of a predetermined polarity to cause said first one of said switches to conduct, thereby discharging the end one of said elements to which said first one of said switches is connected, each of said elements after said end one being polarized to produce an induced voltage pulse of said predetermined polarity in response to an elastic wave from a preceding element in said stack.

7. The combination as defined in claim 6 wherein at least one of said low impedance electronic switches is a controlled rectifier.

8. Apparatus for producing soundwaves comprising:

a plurality of piezoelectric elements acoustically coupled, each of said elements being polarized for expansion and contraction along the axis of sound transmission,

means for charging said elements simultaneously from a voltage source,

means for discharging said charged elements in sequence, each element being discharged through a low impedance path, and

means for timing the discharge by detecting the sonic energy induced voltage produced in each element by the elastic wave progressing through said element and triggering a switch to discharge the element in which the induced voltage is detected.

9. Apparatus for producing an acoustical energy burst of high power ultrasonic soundwaves comprising

a plurality of piezoelectric elements acoustically coupled, each element comprising a slab of piezoelectric material polarized for operation in the thickness mode in a direction along an axis of said stack, said axis being perpendicular to flat sides of said stacked elements, and a separate conductive film on each side of each slab,

high impedance means for simultaneously charging the capacitance of said elements with an electrical charge across each of said elements, and

means comprising a controlled rectifier for discharging each element sequentially through a separate low impedance discharge path in phase relationship with the traveling elastic wave progressing along the sound axis, each controlled rectifier having an anode connected directly to a conductive

film on one side of a unique one of said slabs, a cathode connected directly to a conductive film on the other side of said unique one of said slabs, and a control electrode connected to receive a triggering signal.

10. The combination as defined in claim **9** wherein said means for discharging comprises

a capacitor connected between the anode and control electrode of each controlled rectifier except the first at one end,

a resistor connected between the control electrode and cathode of each controlled rectifier except said first one, and

means for inducing a voltage pulse between said control electrode and cathode of said first one of said controlled rectifier, said voltage pulse being of a predetermined polarity to cause said first one of said controlled rectifiers to conduct, thereby discharging the end one of said elements to which said first one of said controlled rectifiers is connected, each of said elements after said first one being polarized to produce an induced voltage pulse of said predetermined polarity in response to an elastic wave from a preceding element.

11. The combination of claim **9** wherein said means for discharging comprises

a separate resistor between said cathode and control electrode of each silicon controlled rectifier,

a separate capacitor having two terminals, one terminal connected to said control electrode of each silicon controlled rectifier, and

means for distributing a trigger pulse to second terminal of each of said capacitors in sequence.

12. The combination of claim **9** wherein each of said elements includes a plurality of piezoelectric subelements, each with separate conductive film on each side, said subelements of an element acoustically coupled with a polarization for operation in said thickness mode along said axis, all of said subelements of an element being electrically connected in parallel for simultaneous charging, and electrically connected in parallel for simultaneous discharging by said means for discharging.

13. The combination of claim **12** wherein said means for discharging comprises

a capacitor connected between the anode and control electrode of each controlled rectifier except the first at one end,

a resistor connected between the control electrode and cathode of each controlled rectifier except said first one, and

means for inducing a voltage pulse between said control electrode and cathode of said first one of said controlled rectifier, said voltage pulse being of a predetermined polarity to cause said first one of said controlled rectifiers to conduct, thereby discharging the end one of said elements to which said first one of said controlled rectifiers is connected, each of said elements after said first one being polarized to produce an induced voltage pulse of said predetermined polarity in response to an elastic wave from a preceding element.

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