United States Patent

[11] **3,562,563**

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[54] CIRCUMFERENTIALLY SLOTTED TUBULAR PIEZOELECTRIC TRANSFORMER

17 Claims, 6 Drawing Figs.

[52] **U.S. Cl.** **310/9.5,**
310/9.8, 310/8.1; 333/72
[51] **Int. Cl.** **H01v 7/00**
[50] **Field of Search** 310/9.5,
9.8, 8.5, 8.1, 8; 333/30, 72; 340/10

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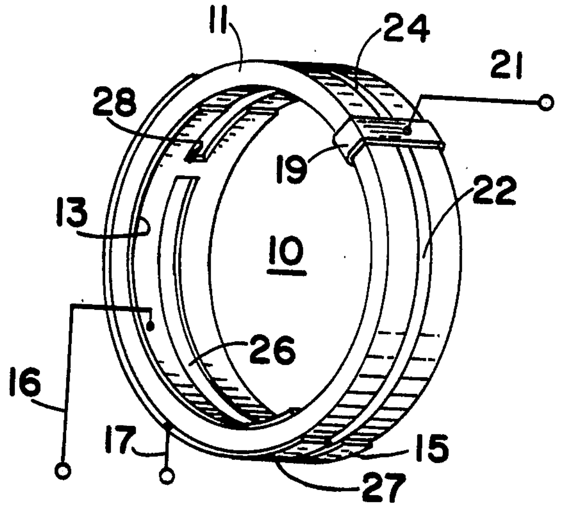
ABSTRACT: The output power limitations of a piezoelectric transformer operating in the hoop mode of vibration caused by dimensional ratio restrictions are overcome by forming the transformer out of a cylinder of piezoelectric material and cutting a plurality of circumferential slots into the cylinder to form a plurality of interconnected ring transformers, each having an optimal axial dimension.



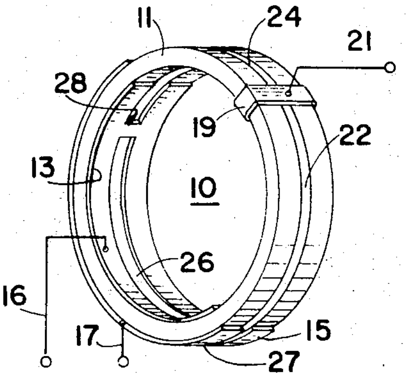


FIG 1

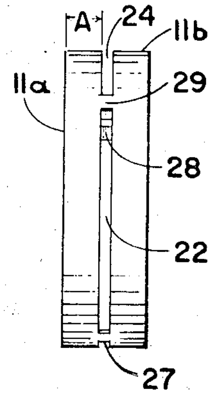


FIG. 2

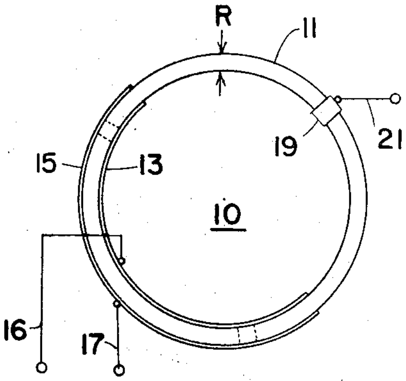


FIG. 3

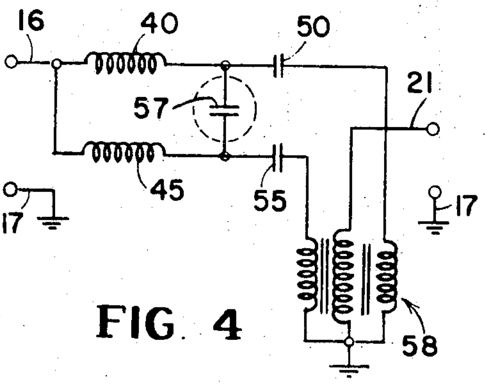


FIG. 4

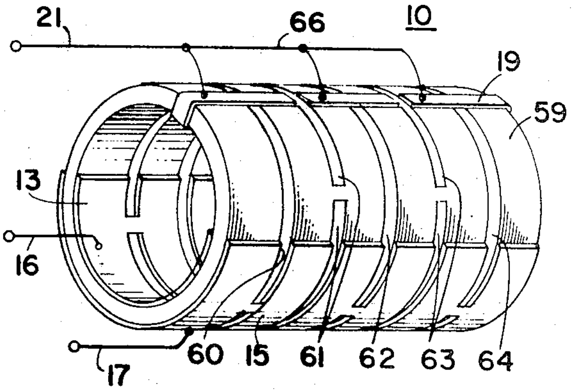


FIG. 5

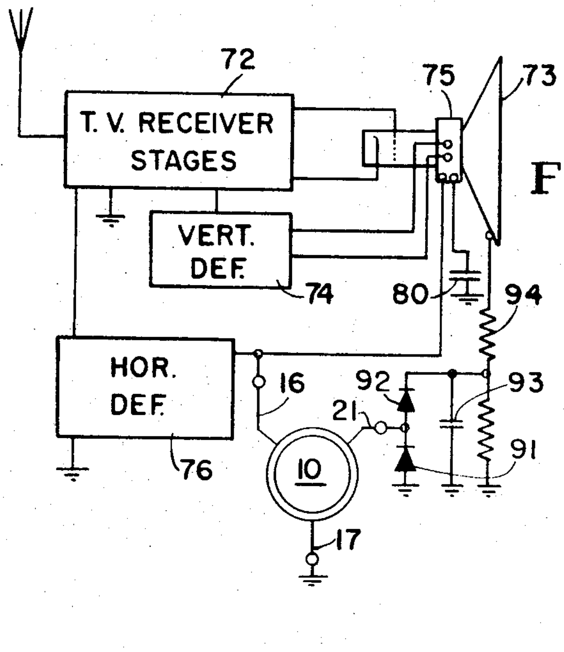


FIG. 6

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CIRCUMFERENTIALLY SLOTTED TUBULAR PIEZOELECTRIC TRANSFORMER

BACKGROUND OF THE INVENTION

Various applications exist for high voltage transformation devices in which a low voltage energizing wave is used to produce a very much higher voltage wave of modest current. For example, in a television receiver it is common to energize a voltage step-up system for the horizontal deflection signals in the receiver in order to develop a wave which can be rectified to produce 20,000 or more volts of direct current for the screen of the cathode ray picture tube. Such a high potential generally requires a costly transformer and special construction to prevent voltage breakdown or arcover within the receiver. Furthermore, after aging of the high voltage insulation for some time, the insulation may deteriorate, causing failure and reducing component life within the receiver.

In order to overcome the difficulties inherent in conventional high voltage transformers, a high voltage transformer in the form of a piezoelectric ceramic ring which resonantly vibrates in the hoop mode has been proposed. The power-handling capability of such ceramic ring transformers vibrating in the hoop mode, however, is limited by the active volume of the ceramic material used. The diameter of the ring is fixed by the resonant frequency at which the transformer is to operate, and the wall thickness is limited by the impedance ratios. As a consequence, the only dimension which can be increased in order to gain volume is the length or the longitudinal axial dimension of the ring. The length, however, cannot be increased indiscriminately without generating excessive internal losses caused by parasitic vibrations in the longitudinal direction. For example, it has been found that the length of the ring or the longitudinal dimension should, as a general rule, not exceed one-fifth of the mean diameter of the ring.

SUMMARY OF THE INVENTION

It is an object of this invention to provide an improved high voltage transformation device.

It is another object of this invention to increase the power handling capability of a ceramic ring transformer.

It is an additional object of this invention to increase the power handling capabilities of a ceramic ring transformer operating in the hoop mode of vibration.

In accordance with a preferred embodiment of this invention, a transformer device is formed from an annular member of material responsive to the stress of an electric field thereon to produce an electric potential, with the annular member being in the shape of a closed hoop and having a mean diameter to establish hoop mode of vibration at a given frequency. The member is slotted circumferentially, with at least one slot extending around a major portion of the circumference thereof with the cross-sectional area of each of the sections of the member formed on each side of the slot being such that the axial dimension thereof exceeds the radial thickness thereof. First and second electrodes then are positioned on arcuate portions of the member to embrace a driving region of the transformer, and the driving region is direct current polarized between the first and second electrodes. An output electrode is positioned on the annular member diametrically opposite the first and second electrodes to define driven sections of the member between the output electrode and the first and second electrodes. The polarization of the driven sections is along the circumference thereof, and the axial dimension and radial thickness of each of the sections of the closed hoop provide substantially uniform mechanical stress throughout the body of the annular material so that hoop mode of vibration of the member produces a transformed output voltage at the output electrode with minimized input and output impedances.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a perspective view of a preferred embodiment of the invention;

FIGS. 2 and 3 are an edge view and a front view, respectively, of the device shown in FIG. 1;

FIG. 4 is a schematic diagram of an equivalent circuit of the device shown in FIGS. 1, 2 and 3;

FIG. 5 is a perspective view of another embodiment of the transformer according to this invention; and

FIG. 6 is a schematic diagram of a television circuit incorporating a transformer according to a preferred embodiment of this invention.

DETAILED DESCRIPTION

Referring now to the drawings, wherein like reference numerals are used throughout the different views to designate the same or similar components, there are shown piezoelectric transformers in the form of annular members, the circumferences of which are selected to support resonant hoop mode vibration of the members at predetermined frequencies. The members may be driven by an electric field varying the resonant frequency of the members and produced by spaced electrodes on the members, so that the field is developed in the direction of polarization of driving areas of the members. Output voltage waves are derived between electrodes spaced to embrace regions of the members which are mechanically stressed by the resonant vibration and which regions are polarized in the direction of the vibration. In a highly efficient form of the devices shown in the drawing, the electrodes are arranged so that the electric driving field is in the direction of the resonant vibration and polarization of the entire piezoelectric member. Transforming devices of the type shown in the drawings are particularly adaptable for use in the high voltage system of a television receiver in which the energy can be used from the horizontal deflection system to develop an output wave which can be rectified to produce 20,000 volts or more for the screen of a cathode ray picture tube.

Referring now to FIGS. 1 to 3, there is shown a transforming device **10** comprising a slotted ring or annular member **11** which is of generally tubular configuration with an axial length less than the diameter thereof. A pair of input plate electrodes **13** and **15** which may be of fired silver or other suitable material are deposited on or otherwise fastened to the inner and outer surfaces of the annular member **11**. The plates **13** and **15** extend across the axial width of the member **11** and extend circumferentially around one-half or more of the inner and outer circumferences, respectively, of the annular member **11**.

In order to apply input signals to the inner and outer electrodes **13** and **15**, a pair of input leads **16** and **17** are connected to the electrodes and are adapted to be connected to a suitable source of input voltage (not shown) which is desired to be transformed by the transformer device **10**. An output electrode for the transformer is in the form of a band electrode **19** which surrounds a portion of the annular member **11** and is located at a point which is diametrically opposite the midpoints of the circumferential dimension of the inner and outer input electrodes **13** and **15**. All of the electrodes **13**, **15** and **19** may be deposited on the surface of the annular member **11** by electrolysis. Output signals are derived over an output lead **21** connected to the band electrode **19** with respect to one of the input terminals **16** or **17** which would be a common terminal for the transformer.

When a ring transformer is operated in a hoop mode vibration, there are a number of design considerations which have a bearing on the optimum proportions of the device. The input and output impedances are inversely proportional to the input and output capacities respectively. The input capacity is proportional to the axial dimension A divided by the radial dimension R, since the capacity is proportional to the area of the electrodes and inversely proportional to the distance between them. On the other hand, the output capacity is proportional to A times R, since it is directly proportional to the cross-sectional area between the input and output electrodes. The output voltage of the transformer is directly proportional to the ratio of input capacity to output capacity. From the above relationships it may be seen that the output voltage is also proportional to the inverse square of R. R, however, must be of a value substantial enough to handle the power requirements of the device since the power capability of the device is directly proportional to the dimension R. In addition, the power capability of the device is directly proportional to the dimension A, since both the dimensions A and R are necessary to determine the active cross-sectional area of the ceramic device.

From these above relationships, the design of ceramic ring transformers generally follows a pattern wherein the input and output impedances required are first determined. There should be a slight mismatch of impedances both at the input and at the output for optimum efficiency. The mean diameter of the ring is determined by the frequency at which it is desired to operate the transformer. The dimension R then is selected to be a minimum according to the power handling capabilities desired; and the values for the distance between the output electrodes, the area of the input and output electrodes, and the dimension A are selected according to the desired voltage output and impedance requirements.

In the design of solid ceramic ring transformers operating in the hoop mode of vibration, it has been found that for optimum efficiency, the dimension A should be at least equal to the dimension R and preferably should be substantially greater than R. The dimension A, however, is limited due to the fact that the more tubular the ring becomes, that is, the greater the dimension A becomes relative to the diameter of the ring, the greater the losses become due to the parasitic vibrations set up in the longitudinal mode, that is, the axial direction. As a general rule, it has been found that the dimension A probably should be no greater than one-fifth of the mean diameter of the ring, and it should be noted that the ring diameter is determined by the frequency at which the device is to be operated.

Thus, in the design of a conventional ceramic ring transformer operating in the hoop mode of vibration, there is a definite limit to the power which can be handled by the transformer, since the diameter of the transformer is fixed by the resonance frequency and the wall thickness is limited by the impedance ratios desired. Finally, the axial length A is limited by the parasitic losses due to vibrations set up in the longitudinal mode.

In order to utilize the desirable characteristics of the hoop mode vibration of a ceramic ring transformer, yet increasing substantially the power-handling capability of the ceramic ring transformer, it has been found that the dimension A may be increased beyond the limits which are practically feasible with a solid ring transformer to increase the cross-sectional area, while at the same time minimizing the internal losses, by interrupting the path of the longitudinal parasitic wave which otherwise is set up in the dimension A of the transformer. This interruption in the device shown in FIGS. 1, 2 and 3 is achieved by cutting three circumferential slots 22, 24 and 26 through the material 11 of the annular ring leaving a small bridge of material between the adjacent ends of the slots 22, 24 and 26. Two such bridges 27, 28 are shown in FIG. 1. A third bridge between the slots 22 and 24 also interconnects the two portions of the slotted ring transformer and underlies the ring electrode 19 shown in FIG. 1.

The inner and outer electrode plates 13 and 15 extend across the bridges 28 and 27, so that these plates each are electrically continuous. This bridging of the electrodes 13 and 15 is most clearly seen in FIG. 1, whereas in FIG. 2 the electrodes 13, 15 and 19 have been removed in order that the structure of the ceramic material itself may most clearly be seen.

In FIG. 2 the bridges 27, 28 and 29 are shown interconnecting the two halves of the slotted ring transformer thus formed, with the two portions or sections being designated as 11*a* and 11*b*. Thus, two ring devices, interconnected by the bridging portions 27, 28 and 29, are formed; and the length A in the axial direction of each of the sections 11*a* and 11*b* is chosen to be the optimum axial length which has been determined for a conventional solid ring type transformer operating in the hoop mode of vibration.

In the operation of the device shown in FIGS. 1, 2 and 3 it has been found that the unwanted, parasitic longitudinal mode vibrations are substantially eliminated due to the decoupling caused by the slots 22, 24 and 26. In addition, the power output of the transformer shown in FIGS. 1, 2 and 3 is found to be approximately double the power obtainable from a single slotted ring transformer having a maximum practical axial dimension A when each of the sections 11*a* and 11*b* has an axial dimension of a length A. In other words, the power obtainable from the transformer increases directly with the number of widths 11*a*, 11*b*, etc. used in the slotted ring configuration.

In the operation of the device shown in FIGS. 1, 2 and 3, no undesirable side effects were observed, and in addition, the transformer behaved in an entirely different mode from a conventional solid ring transformer. In the operation of a solid ring transformer vibrating in the hoop mode, the transformer exhibits an increasing input impedance with output load, but in the slotted transformer shown in FIGS. 1, 2 and 3, the reverse characteristics have been observed. The impedance of the slotted ring transformer decreases with increasing load at the output section. The reason for this phenomenon is not fully understood, but it appears to be due to the operation of the transformer in a manner which may best be explained in conjunction with reference to FIG. 4.

FIG. 4 there is illustrated what is believed to be the electrical equivalent of the transformer shown in FIGS. 1, 2 and 3. Apparently the split ring 11 behaves as if the slot actually produces two separate ring transformers which are coupled to one another through a compliance C. The electrical equivalents are the two series tuned circuits consisting of an inductor 40 and capacitor 50 and an inductor 45 and capacitor 55, respectively. The coupling between the tuned circuits is represented by the capacitor 57; and as the load increases, the Q decreases which results in a lower coupling between both of the tuned circuits. The outputs of the tuned circuits, as obtained from between the output lead 21 and the common input lead 17, is obtained by means of a transformer coupling which has been indicated in the drawing as a transformer 58, having primary windings exited from both of the tuned circuits 40, 50 and 45, 55 and having a secondary winding connected between the output terminals 17 and 21. Since the Q decreases with increasing load, the net result is a lower coupling between both of the tuned circuits and therefore is a reduction of input impedance with increasing load at the output section. It should be understood that the above analysis of the observed phenomenon merely constitutes what is believed to occur in the transformer shown but that it is possible that the phenomenon is due to some other theory unknown at this time.

Since the use of the slots 22, 24 and 26 has removed the longitudinal restriction on the axial dimension A of the transformer, it is possible to obtain much higher power-handling capabilities by forming the transformer as a relatively long cylinder with a plurality of offset sets of slots, each set defining a separate ring transformer of optimum dimensions. The power-handling capability of the transformer then is determined by the power-handling capability of each of the separate ring sections multiplied by the number of sections formed by the number of different sets of slots.

Such a transformer is shown in FIG. 5 and is made out of a single tubular piece of ceramic material 59 having five sets of staggered slots 60, 61, 62, 63 and 64 interrupting the longitudinal path of the parasitic longitudinal wave which otherwise would be generated along the axial direction of the tube 59. These sets of slots 60 to 64 have been shown as each including three coplanar slots, with the ends of each of the slots in each of the sets, such as the set 60, being bridged by material of the cylinder 59 to provide a rigid unitary structure. The slots in the sets 60, 62 and 64 are arranged so that the bridging areas between the slots of each of these sets are in longitudinal alignment with one another, and the slots of the sets **61** and **63** are aligned with one another and offset by 60° with the slots **60, 62** and **64**. Thus, it is apparent that there is no direct longitudinal path through the body of the material **59** from end to end, so that the ceramic tube **59** is broken up into six substantially independent ring transformer members.

The axial dimensions A of each of the transformer members formed from the tube **59** are chosen to be the optimum dimensions which can be achieved for a single ring transformer operating in the hoop mode of vibration. It should be noted that the width of the slots **60, 61, 62, 63, 64** is chosen to be a minimum width sufficient to interrupt the longitudinal mode of vibration. By keeping the width of the slots to a minimum, maximum utilization of the ceramic material of the cylinder **59** may be achieved. The operation of the device shown in FIG. **5** is substantially the same as the operation of the device shown in FIG. **1** with input signals being applied to the electrodes **13** and **15** over the input leads **16** and **17**. The electrodes **13** and **15** each overlie bridging portions at the ends of at least one pair of slots in each of the sets of slots **60** to **64**, so that they are electrically continuous throughout the length of the cylinder **59**. If the output ring electrode **19** is formed by depositing it on the cylinder **59** prior to the cutting of the slots **60** through **64**, the electrode **19** would be severed in at least two places by the slots **61** and **63** as shown in FIG. **5** thereby providing an electrical discontinuity. As a consequence, it is necessary to complete the electrical connections bridging the cuts made by these slots, so that a single output terminal or lead **21** may suffice for coupling the outputs of all of the transformer members to a single output terminal. This has been shown by the use of a bridging conductor **66** on the outside of the tube **59**. It also should be noted that a similar bridging connector should be provided on the inside in order to complete the ring **19**. If the ring electrode **19** is not deposited prior to the cutting of the slots, but constitutes a foil electrode which is wound on the tube **59** after the slots have been formed, the bridging connector **66** is not necessary.

The annular ring transformer **11** shown in FIGS. **1, 2** and **3** and the transformer cylinder **59** shown in FIG. **5** are composed of a piezoelectric ceramic material such as berium titanate or lead titanate zirconate, the latter being preferable to the former and being presently available under the designation PZT–4 from the Clevite Corporation of Cleveland, Ohio. The mean circumference of the annular member **11** and the mean circumference of the cylinder **59** is selected to be one-half of the wave length of the exciting signal or a harmonic thereof, that is, one-half of the wave length of an integral multiple of the exciting signal. This permits resonant vibration of the ring **11**, or the rings formed out of the tube **59** by the slots **60** to **64**, in the hoop mode, with alternate expansion and contraction of the circumference.

By utilizing the piezoelectric effect in driving the ring in the hoop mode at its resonant frequency of vibration, the ceramic material is utilized most efficiently. In other modes of vibration, nodal points are set up such that there are points of maximum stress and points of zero stress on the transducer. Voltage is generated only where the stress is maximum; and, accordingly, if the nodal points or points of zero stress can be eliminated, the device will be more efficient. The hoop mode of vibration has no nodal points, and by utilizing slotted rings or a slotted tubular device, the power-handling limitations which are inherent in hoop mode transformers are substantially eliminated.

The input electrodes **13** and **15**, respectively, define a motor or driving section for the portion of the ring between the electrodes. The rings or annular members, formed between the slots or between an end one of the slots and the outside edge of either the slotted ring of FIG. **1** or the slotted tube **59** of FIG. **5**, each are polarized across the thickness or radial dimension R thereof throughout the portion between the input electrodes **13** and **15**, so that the applied driving field is in the same direction as the polarization. Changes in the radial dimension R of the portion between the input electrodes caused by the applied field result in corresponding changes in circumference due to Poisson coupling. The spacing between the input electrodes **13, 15** and the output electrode **19** defines generator or driven sections of the rings between the input electrodes and the output electrode which are electrically in parallel and mechanically in series. The ring is polarized circumferentially along this distance, so that this polarization is in the same direction as the resonant vibration in the hoop mode. Thus, there is a strain along the circumference of the sections of the ring **11** or the tube **59** throughout the driven sections due to the resonant excitation of the ring or tube to produce the output potential developed at the electrode **19**.

Since the sections of the ring **11*a*** and **11*b*** of the device shown in FIGS. **1, 2** and **3**, and the individual sections formed by the slots **60** to **64** cut in the tube **59** shown in FIG. **5**, each are integral pieces, the driven and output sections thereof are tightly coupled. There are no joints or other breaks in the ceramic material along the circumference of the rings formed between the slots, and the cross sections of these rings are rectangular for even field distribution. Even field distribution is desirable for efficient operation, because when the distribution is uneven, only that material between the closest portion of the electrodes is utilized and the rest is wasted. The same considerations make it desirable to keep the radial dimension R small with respect to the ring diameter. This minimizes variation in field distribution between the output electrodes. The output current of the device increases linearly with increase of the exciting frequency and also depends directly upon the area of the output electrode. The output voltage of the system is directly proportional to the distance between the input electrodes **13** and **15** and the output electrode **19** and to the Q of the member. For efficiency, however, it is desirable that the driving section be of greater length than the driven section (that the length of the ring between the electrodes **13** and **15** be greater than the length of the ring between the electrodes **13, 15** and the output electrode **19**) to make up for friction or conversion losses in the material. Thus the length of the electrodes **13, 15** is chosen to be equal to or greater than one-half the circumference of the ring **11** or tube **59**.

In FIG. **6** there is shown the use of the transforming device **10** of FIGS. **1, 2** and **3** or of FIG. **5** to provide the high voltage for the screen of the picture tube in a television receiver. The television receiver includes receiver stages **72**, which comprise a tuner, intermediate frequency amplifiers, a detector and a video amplifier for driving the cathode ray picture tube **73**. In addition, the stages **72** may include the usual sound detector and loud speaker system plus an automatic gain control system and a synchronizing signal separator to derive a vertical and horizontal synchronization signal from the received composite video signal. A vertical deflection system **74** is connected to a deflection yoke **75** on the neck of the cathode ray tube **73**. The horizontal deflection system **76** is also properly synchronized by means of the received synchronized pulses from the TV receiver stages **72**.

The deflection system **76** normally includes a horizontal or line deflection oscillator operative at a frequency of 15.75 kHz. From this oscillator, which is synchronized, a waveform is developed from which sawtooth deflection current is derived and applied to the horizontal deflection windings of the yoke **75**. This circuit is completed to ground through a capacitor **80**.

The output from the horizontal deflection system **76** to the deflection yoke **75** is also connected to the input terminal **16** of the ceramic transforming device **10**, and the common lead **17** is connected to ground. The voltage applied to the lead **16** is of pulse waveform having a repetition rate of 15,750 Hz. The voltage derived from the transformer device **10**, however, is of sinusoidal waveform. The output lead **21** is connected to a full wave rectifier comprised of a pair of series diodes **91** and **92** and a capacitor **93**. This rectifier is connected through an isolation resistor **94** to the screen of the cathode ray picture tube **73**.

In the television receiver of FIG. 6 it may be preferable to resonate the transforming device **10** at the second harmonic of the horizontal deflection frequency, namely, 31.5 kHz. With the device constructed in this manner, its energization signals are well above the highest audible frequency and the device can be constructed of relatively small size. For example, a mean diameter of between 1 ¼ and 1 ¾ inches probably is sufficient. There usually is a sufficient amount of the second harmonic available at the output of the horizontal deflection system in order to insure proper energization of the transformer device **10**. While much higher resonant frequencies can be used, such higher frequencies necessitate a smaller physical size of the device with the attendant problems of proper plating or other depositions of the electrodes and of voltage breakdown among closely spaced electrodes of the device. When it is considered that rectified potentials of the order of 20,000 volts or more are commonly applied to a picture tube the problem of voltage breakdown may be appreciated.

It also is possible to construct the transformer device **10** to be resonant at the horizontal deflection frequency of 15.75 kHz, but this requires a relatively large physical size and may result in some audible vibration from the device. While it has been stated that the ceramic transformer device **10** should be constructed to be resonant at an exact integral multiple of the energizing frequencies, it should be understood that a resistive and/or capacitive load for the high voltage energization system will lower the resonant frequency of the device by a slight amount. Accordingly, it may be desirable that the resonance of the device **10** be a few percent higher than the frequency at which mechanical resonance occurs in order to compensate for this effect of the load.

Either the transformer shown in FIGS. 1 to 3 or shown in FIG. 5 may be utilized in the system of FIG. 6, and in either of these devices a piezoelectric ceramic member is utilized as a "motor" to resonantly drive a "generator" through electrorestrictive action within the member. With the device operated in this manner, it is possible to obtain a maximum voltage step-up with great efficiency and with no difficulty in matching materials and maintaining the match during utilization of the device. In addition, the power-handling capabilities of the transformer are quite flexible because merely by increasing the number of sections separated by the slots shown in FIGS. 1 to 3 or shown in FIG. 5, a multiplication of the power-handling capabilities based directly on the number of sections utilized is possible. For example, a single ring ceramic transformer utilizing a predetermined axial length A considered to be optimum for the operation of that transformer may produce 50 watts of output power. If the power output of the transformer needs to be doubled, the configuration of FIGS. 1, 2 and 3 may be employed, with each of the sections **11***a* and **11***b* having the axial dimension A of the single ring which produces 50 watts of output. The double ring configuration formed in accordance with FIGS. 1 to 3 then produces 100 watts of output power. Further increases in the output power may be realized by increasing the number of sections in accordance with the teachings of FIG. 5 so that the limitations of power previously inherent in the use of a ceramic ring transformer are overcome. It should be noted that not all of the sections of the slotted transformer need to have the same axial dimension, nor is it necessary that this dimension be the maximum feasible for each section. By employing coupled sections having different axial dimensions, varying power handling capacities can be realized.

It may be seen that the device which has been described is an electromechanical device for producing a high voltage waveform upon energization from a relatively low potential resonating drive signal. The device is of relatively simple and sturdy construction and it may be formed in a manner to remain in reliable service over a long period of time. The device is an impedance transformer, whereas a conventional transformer is an inductive device; and the device is basically an electromechanical transducer which is highly efficient and has particular application for energizing the screen of a cathode ray tube, since suitable periodic energizing signals are available in a cathode ray tube system for scanning of the cathode ray beam. By utilizing the described design, it is possible to produce a voltage step-up greatly in excess of 100 times while still maintaining very desirable efficiency in voltage transforming of the type required in television and similar applications. Merely by increasing the number of sections in the slotted ring transformer, the power-handling capabilities of the device may be increased manyfold over those which can be realized from the use of a single solid ceramic ring transformer.

I claim:

1. A transformer device including in combination:
   - an annular member formed of material responsive to the stress of an electric field thereon to produce an electric potential, the annular member being formed in the shape of a closed hoop and having a mean diameter to establish hoop mode vibration therein at a given frequency, the annular member having a cross-sectional area such that the axial dimension thereof exceeds the radial thickness thereof, the annular member having at least one circumferential slot through said member and extending around the major portion of the circumference of said member effectively to form at least two separate sections therefrom;
   - first and second electrodes positioned on opposite sides of arcuate portions of the annular member forming therebetween a driving region of the transformer; and
   - a further electrode positioned on the member diametrically opposite the first and second electrodes forming driven regions of the member between the further electrode and the first and second electrodes, the axial dimension and radial thickness of the closed hoop providing substantially uniform mechanical stress throughout the body thereof, and the slot minimizing internal losses caused by parasitic vibrations in the axial dimension of said hoop, so that hoop mode vibration of the annular member produces a transformed output voltage at the further electrode with minimized input and output impedances.

2. The combination according to claim **1** wherein the axial dimension of the annular member from an outer edge thereof to the slot is at least as great as the radial thickness thereof.

3. The combination according to claim **1** wherein the first and second electrodes extend around said hoop-shaped annular member at least one-half the circumference thereof.

4. The combination according to claim **1** wherein the material of the annular member is a piezoelectric material.

5. The combination according to claim **1** wherein the first electrode extends along the inner surface of the annular member and the second electrode extends along the outer surface of the annular member.

6. The combination according to claim **5** wherein the two separate sections are interconnected by a bridge of material at the end of said slot and wherein the first and second electrodes overlie both of the separate sections and are interconnected across the bridge.

7. The combination according to claim **5** wherein first and second conductors are connected to the first and second electrodes, respectively, for applying an input voltage across the first and second electrodes to strain the annular member at the radial dimension thereof, the annular member being vibrated in the hoop mode due to Poisson coupling.

8. A piezoelectric transformer device including in combination:
   - a piezoelectric annular member responsive to the stress of an electric field thereon to produce an electric potential, the annular member being formed in the shape of a closed hoop having a mean diameter to establish hoop mode vibration therein at a given frequency, the annular member having at least one slot formed therethrough and extending around a major portion of the circumference thereof to form at least first and second sections of the annular member, the sections each having a cross-sectional

configuration such that the axial dimension thereof exceeds the radial thickness thereof, first and second electrodes positioned opposite one another respectively on part of the inside and outside surfaces of the sections, with the electrodes overlying each of the sections being interconnected to form common first and second electrodes;

a further electrode positioned on the annular member diametrically opposite the first and second electrodes to define driven portions of the member between the further electrode and the first and second electrodes, the driven portions of the member being direct current polarized along the circumference thereof, the axial dimension and radial thickness of each of the sections of the annular member providing substantially uniform mechanical stress throughout the body thereof, whereby hoop mode vibration of the sections of said member produces a transformed output voltage at the further electrode with minimized input and output impedances.

9. The combination according to claim **8** wherein each of the sections of the annular member has a generally rectangular cross-sectional shape of which the axial dimension is at least as great as the radial dimension.

10. The combination according to claim **9** wherein the first and second electrodes extend around the sections at least one-half the circumference thereof and wherein the further electrode is positioned on the annular member symmetrically with respect to the first and second electrodes.

11. A transformer device including in combination:

a cylindrical member formed of a material responsive to the stress of an electric field thereon to produce an electric potential, the cylindrical member having a plurality of circumferential slots extending therethrough and extending around a major portion of the circumference of the cylindrical member to produce a plurality of annular members joined together by bridging material at the end of each of the slots each of the annular members thereby being formed in the shape of a closed hoop and having a mean diameter to establish hoop mode vibration therein at a given frequency, each of the annular members having a cross-sectional configuration such that the axial dimension thereof is at least as great as the radial thickness thereof;

first and second electrodes positioned on opposite sides of arcuate portions of the annular members and bridging the annular members to form therebetween driving regions on each of the annular members of the transformer, the driving regions being direct current polarized between the first and second electrodes; and

a further electrode positioned on the annular members diametrically opposite the first and second electrodes and bridging the annular members to form similar driven regions of each of the annular members between the further electrode and the first and second electrodes, the driven regions of the members being direct current polarized along the circumference thereof, the axial dimension and radial thickness of each of the closed hoops formed by the annular members providing substantially uniform mechanical stress throughout the body thereof, and the output step-up voltage of the transformer being proportional to the number of annular members, whereby hoop mode vibration of the annular members produces a transformed output voltage at the further electrode with minimized input and output impedances.

12. The combination according to claim **11** wherein said slots are longitudinally offset from one another so that the bridging material at the end of the slots is offset from slot to slot longitudinally along the cylindrical member to minimize parasitic longitudinal vibrations.

13. The combination according to claim **11** wherein the cylindrical member is formed from piezoelectric material.

14. The combination according to claim **11** wherein each of said slots defining the annular members is formed of at least two parts lying in the same plane, with bridging material separating each end of the parts to form a rigid support for interconnecting each of the annular sections formed out of the cylindrical member.

15. The combination according to claim **14** wherein the slots are offset, so that the bridging material in adjacent slots is longitudinally offset along the surface of the cylindrical member.

16. The combination according to claim **11** wherein the first and second electrodes extend around the annular members at least one-half the circumference thereof.

17. The combination according to claim **16** wherein the first electrode extends along the inner surface of the annular members and the second electrode extends along the outer surface of the annular members.