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(54) **PIEZOELECTRIC VIBRATION ENERGY HARVESTING DEVICE**

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(60) Provisional application No. 60/486,172, filed on Jul. 11, 2003.

Publication Classification

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(52) **U.S. Cl.** **310/339**

(57) **ABSTRACT**

A piezoelectric vibration energy harvesting device which is made up of a first mass, a second, a first spring coupled to the first mass, and a second spring coupled to the second mass. A piezoelectric element is bonded between the first mass and the second spring, so that a stress applied to the second spring is applied to the piezoelectric element

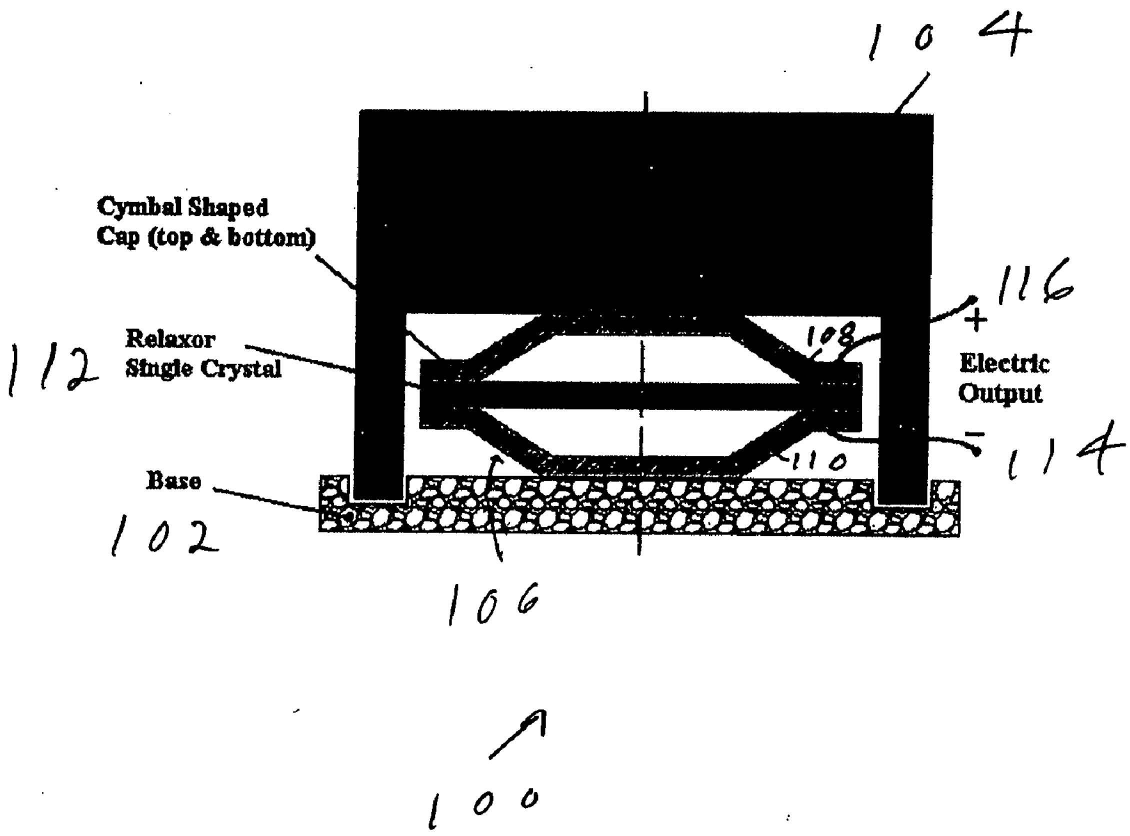
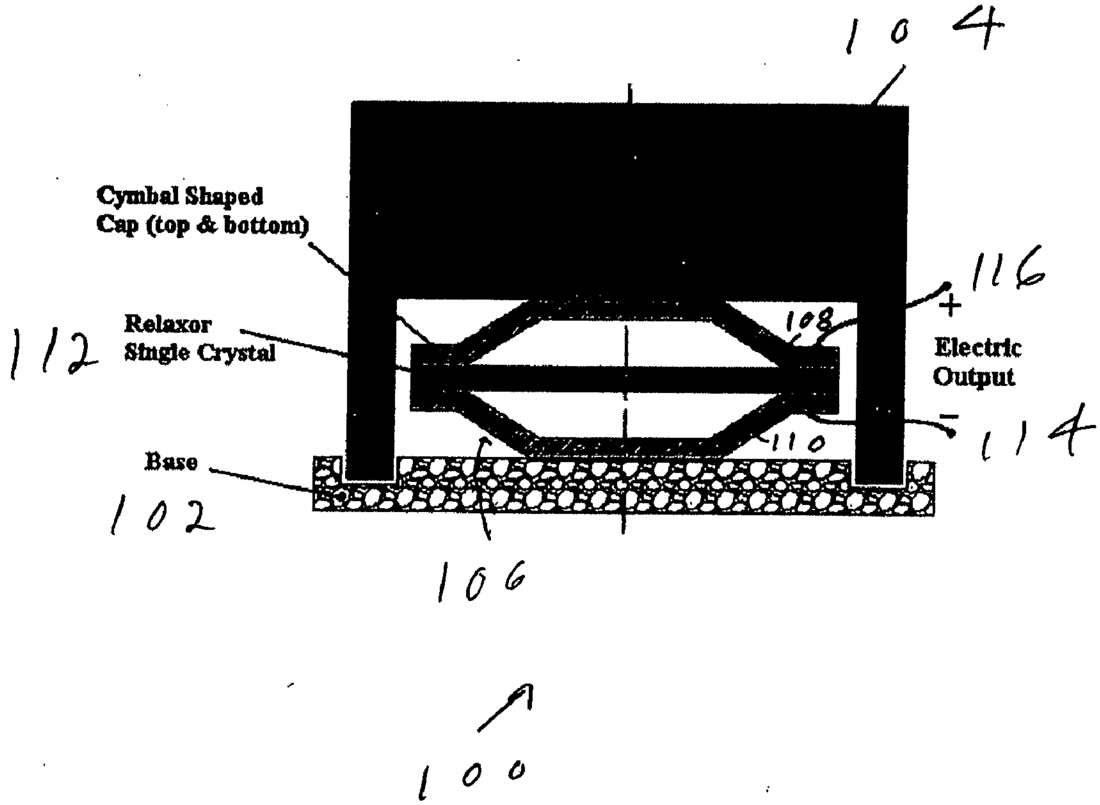


Figure 1


104
Cymbal Shaped
Cap (top & bottom)
116
+
108
112
Relaxor
Single Crystal
Electric
Output
-
114
110
Base
102
106
100

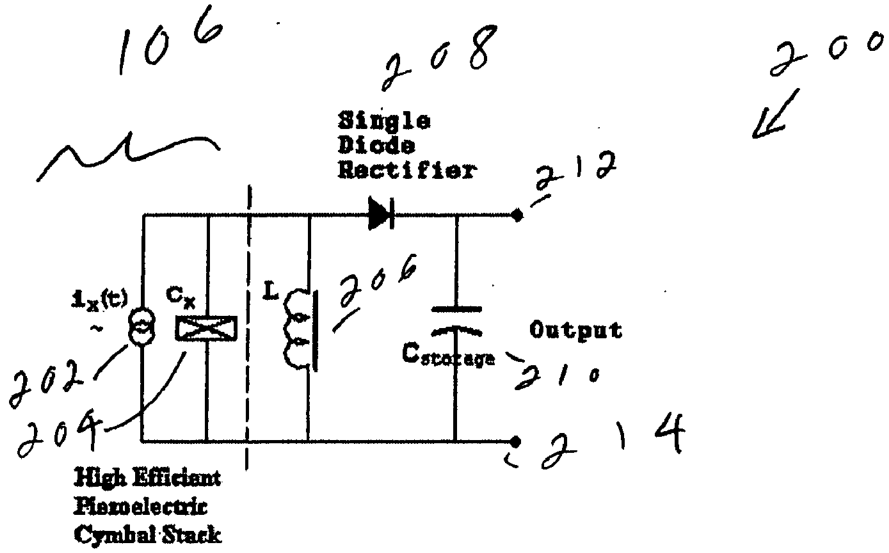
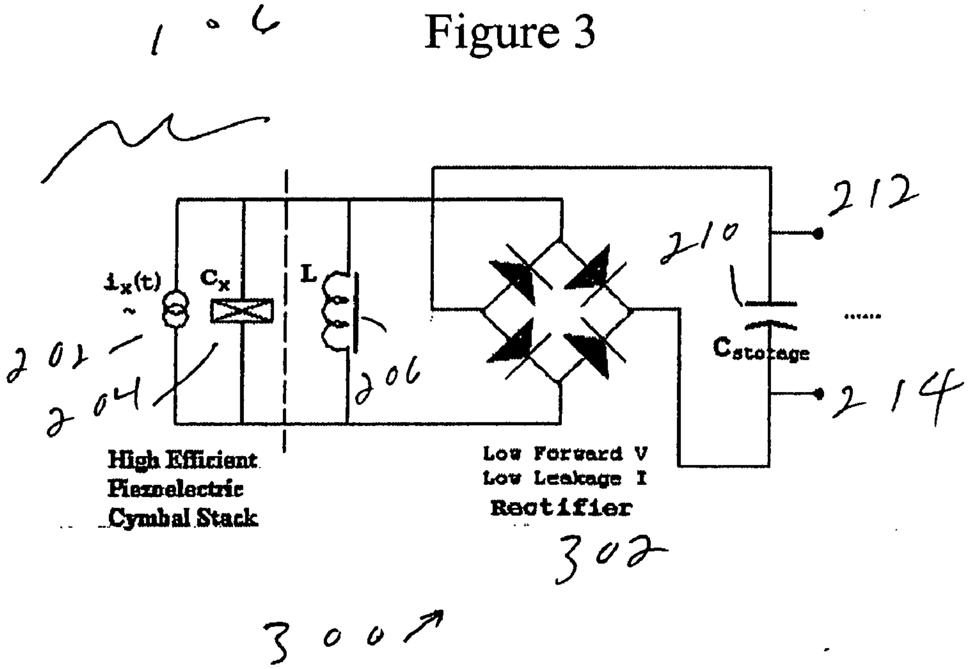


Figure 2

Figure 3



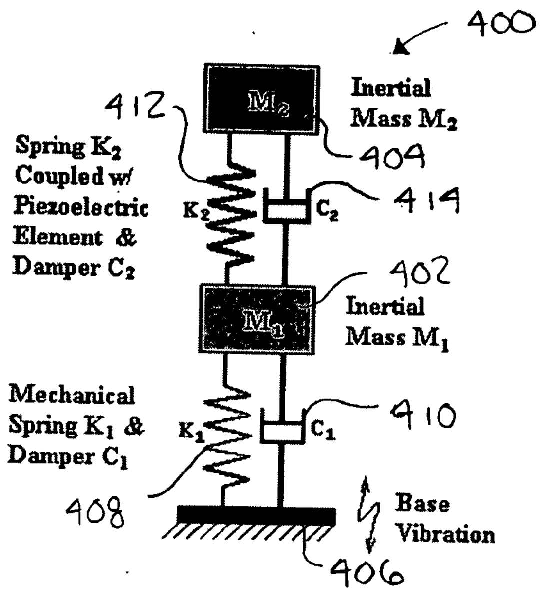


Figure 4

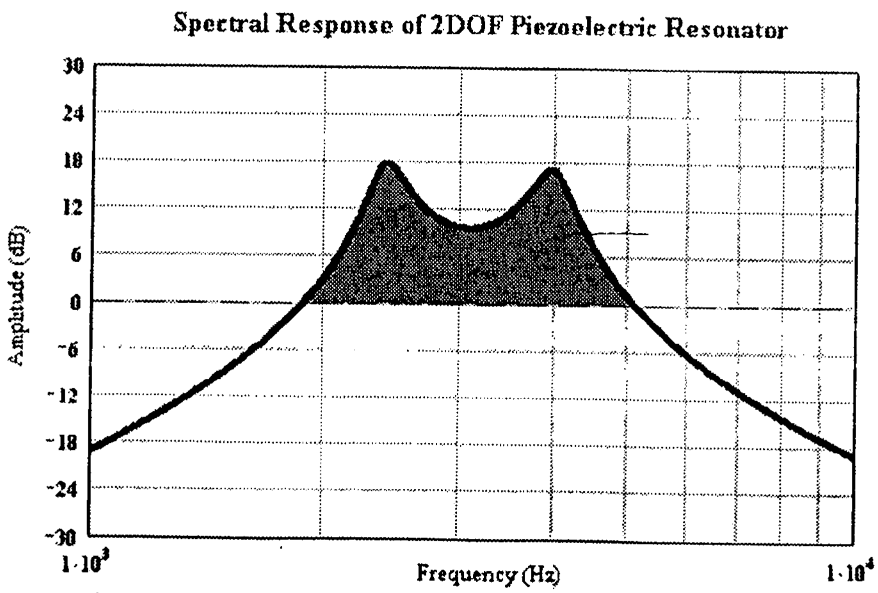


Figure 5

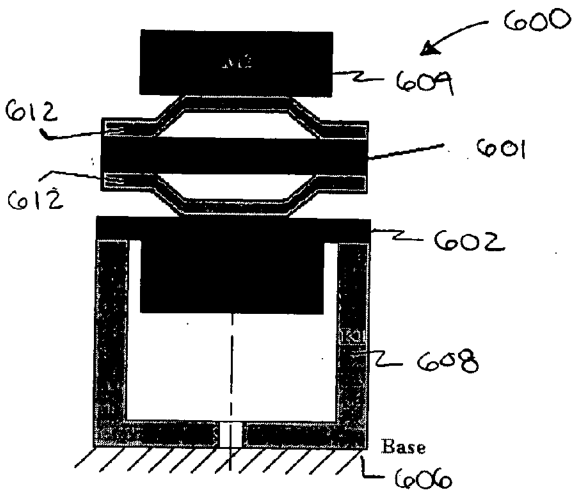


Figure 6

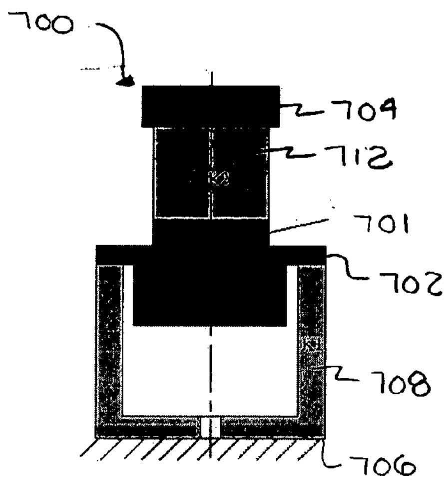


Figure 7

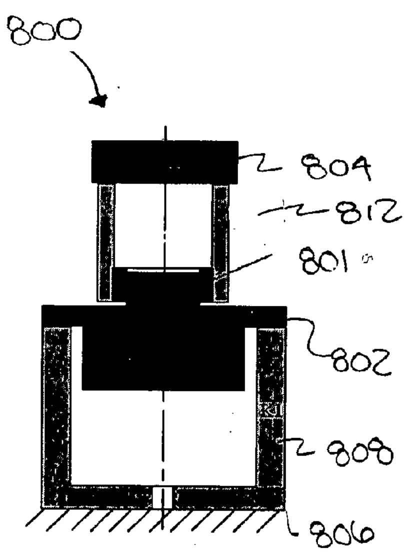


Figure 8

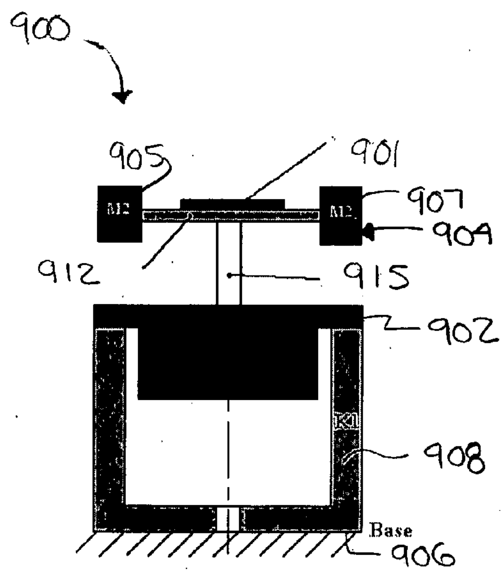


Figure 9

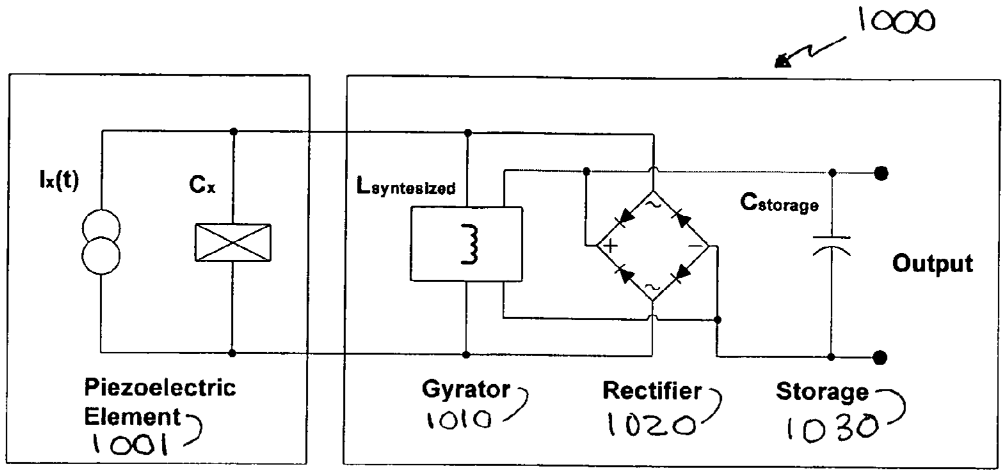


Figure 10

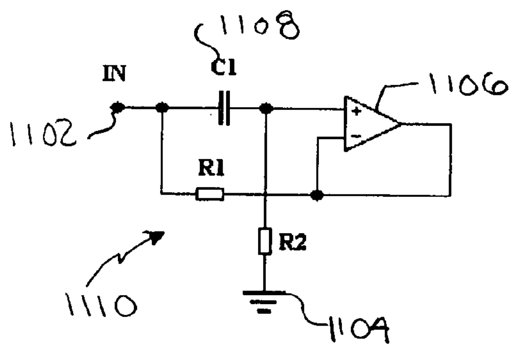
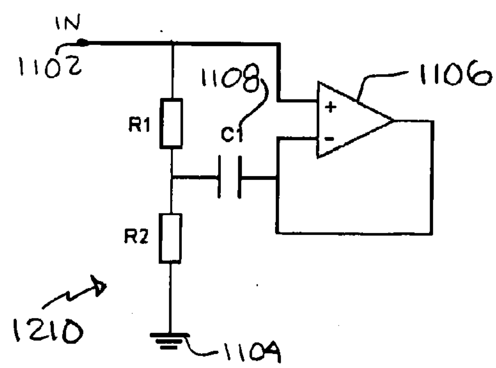


Figure 11

Figure 12



PIEZOELECTRIC VIBRATION ENERGY HARVESTING DEVICE

RELATED APPLICATIONS

[0001] This application is a continuation-in-part of co-pending U.S. patent application Ser. No. 10/887,216 to Ken K. Deng, filed Jul. 9, 2004, which claims the benefit of U.S. Provisional Patent Application Ser. No. 60/486,172, filed Jul. 11, 2003, the subject matter of both of which is incorporated by reference herein.

STATEMENT OF GOVERNMENT INTEREST

[0002] The work leading to the present invention was supported in part by Naval Surface Warfare Center Dahlgren Division (NSWCDD) Contract Number: N00178-03-C-3056. The government has certain rights in the invention.

FIELD OF THE INVENTION

[0003] The present invention is directed to a highly efficient, small size, vibration harvesting and electric energy storage device. The energy level is high enough to power a wireless sensor.

BACKGROUND OF THE INVENTION

[0004] Current technology for harvesting energy utilizes a flexural, piezoelectric composite bending structure as a vibration energy to electric energy transducer. Most conventional harvesting devices are single degree-of-freedom (SDOF) systems. The selected piezoelectric materials are PZT ceramics or PVDF polymer. The output of this device is connected to an AC-DC converter which is typically composed of a diode rectifier with a storage capacitor.

[0005] A conventional flexural mode piezoelectric effect (d_{31} mode) is very inefficient resulting in a low conversion efficiency from vibrational energy to electrical energy (less than 10%). Additionally, flexural mode piezoelectric structures are bulky and not suitable for a high frequency vibration condition. SDOF devices have a single resonance peak, at which the harvested energy reaches the highest conversion efficiency. However, the bandwidth of a SDOF system is narrow, thereby limiting its applications. Additionally, most conventional harvesting devices use bulky discrete inductors for impedance matching with the capacitive piezoelectric element of the device. These drawbacks make the conventional devices impractical for many applications.

SUMMARY OF THE INVENTION

[0006] It is therefore an object of the invention to efficiently harvest vibrational kinetic energy from the ambient environment or machinery and store it in the form of electrical energy, which later is used to power an electronic device. A highly efficient, small size vibration harvesting device will enable a self-powered, truly wireless transducer system.

[0007] In accordance with an embodiment of the present invention, by using the state-of-the-art relaxor single crystal, which exhibits the highest piezoelectric coupling coefficient, and a compression-tension piezoelectric composite, cymbal structure, a compact, highly efficient vibration energy extracting device is accomplished. Moreover, before connecting a stack including a piezoelectric element disposed between two cymbal-shaped caps, with a rectifier/storage circuit, an inductor L is introduced which is parallel with the piezoelectric stack. The resonance of the LC loop is tuned around the resonance of the stack. This inductor will greatly improve the electrical energy transferring efficiency.

[0008] A major difference between the prior art and the above design is in the piezoelectric transduction structure. Instead of using a flexural plate or beam, the new vibration energy harvesting device uses a composite cymbal stack with a proof mass on top. During vibration, the inertial force is transmitted to the piezoelectric disk through the circular cymbal caps. Then the piezoelectric disk is under both compression and tension stresses ($d_{33}+d_{31}$ mode). The present invention is therefore more efficient than the prior art where the piezoelectric layer is only subject to in-plane stress (d_{31} mode). Another major change is the transduction material; a relaxor crystal, which has the highest piezoelectric property, is incorporated in the device. In addition, the electric output from the cymbal stack is connected to an inductor before it is linked to a rectifier. The resonance frequency of the inductor L and piezoelectric crystal C_x is tuned to be approximately the same as the mechanical resonance of the cymbal stack. Doing so, the electrical energy flows much efficiently from the harvesting device to the storage capacitor.

[0009] The invention allows for a much more efficient vibrational energy harvesting device. It also allows for a very small size.

[0010] In accordance with another embodiment of the present invention a multiple degree of freedom dynamic system is provided that has a wide band peak. The wider band of resonating frequency range combined with a more efficient compression mode of piezoelectric material and impedance matching electronics, creates a more versatile and efficient energy harvesting device. In addition, the utilization of a gyrator to synthesize an inductor allows maximum power to be stored into the storage element. A gyrator simulates large coils electronically. A gyrator converts an impedance into its inverse. This allows for replacement of an inductor with a capacitor, two or more amplifiers, and some resistors. The synthesized inductor or gyrator also allows an electronically tunable harvester, in which the harvester can automatically tune itself around the bandwidth where vibrational energy is mostly concentrated by changing the value of the synthesized inductor.

[0011] Other objects, advantages and salient features of the invention will become apparent from the following detailed description, which, taken in conjunction with the annexed drawings, discloses preferred embodiments of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] A more complete appreciation of the invention and many of the attendant advantages thereof will be readily obtained as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings, wherein:

[0013] **FIG. 1** shows an elevational view of a device with a cymbal stack in accordance with a first embodiment of the present invention;

[0014] **FIGS. 2 and 3** show circuit diagrams of the device of **FIG. 1** connected to different rectifiers, with the device of **FIG. 1** being represented by an equivalent circuit to the left of the dashed line;

[0015] **FIG. 4** is a diagram of a device in accordance with a second embodiment of the present invention, showing a two degree of freedom system;

[0016] **FIG. 5** is a graph showing the frequency response of the electric output from a device utilizing the two degree of freedom system illustrated in **FIG. 4**;

[0017] **FIGS. 6-9** are elevational views of different devices incorporating the two degree of freedom system illustrated in **FIG. 4**;

[0018] **FIG. 10** is a circuit diagram of a device in accordance with a third embodiment of the present invention showing the addition of a gyrator; and

[0019] **FIGS. 11 and 12** are exemplary circuit diagrams of the gyrator of the circuit diagram illustrated in **FIG. 10**.

DETAILED DESCRIPTION OF THE INVENTION

[0020] Referring to **FIGS. 1-3**, **FIG. 1** shows an energy harvesting device **100**. The device **100** includes a base **102** and a proof mass **104**. Disposed between the base **102** and the proof mass **104** is a cymbal stack **106** including top and bottom cymbal-shaped caps **108, 110** sandwiching a relaxor single crystal **112**. The cymbal-shaped caps **108, 110** are connected to electrodes **114, 116** forming an electric output.

[0021] **FIG. 2** shows a first circuit **200** incorporating the energy harvesting device **100**. In the circuit diagram of **FIG. 2**, the cymbal stack **106** is represented by an electrical circuit comprising a current source **202** and a capacitor **204**. Connected in parallel across the output of the cymbal stack **106** is an inductor **206**. A single diode rectifier **208**, a storage capacitor **210** and output electrodes **212, 214** complete the circ **200**.

[0022] **FIG. 3** shows a second circuit **300** incorporating the energy harvesting device **100**. The single diode rectifier **208** is replaced with a low forward voltage, low leakage current rectifier **302**.

[0023] Referring to **FIGS. 4-5**, a multiple degree of freedom dynamic harvesting system, such as a two degree of freedom system (2DOF) piezoelectric resonator or device **400**, is shown that has a wide band peak. As seen in **FIG. 4**, the system **400** includes a first inertial mass **402** and a second inertial mass **404**. Between a base **406** of the device **400** and the first mass **402** is a first spring element **408** and a first damper **410**. Between the first mass **402** and the second mass **404** is a second spring element **412** and a second damper **414**, so that the piezoelectric element (described below) is stressed whenever the second spring element **412** is stressed. The first and second masses **402** and **404** are attached to the first and second spring elements **408** and **412**, respectively. As seen in **FIG. 5**, there are two resonance peaks **502** and **504** created by the 2DOF system **400**. Once the two resonance peaks **502** and **504** are tuned close to each other, the resulting response from the piezoelectric element of the harvester is a much wider resonant range or band of high efficiency compared to a SDOF system. The solid curve of **FIG. 5** is the projected spectral response from the piezoelectric element which is coupled with the second spring element **412**. The bandwidth of the 2DOF system **400** could be as wide was 2-3 kHz.

[0024] **FIGS. 6-9** are examples of harvesting devices that use the 2DOF system **400** of **FIGS. 4 and 5**. Referring to **FIG. 6**, a harvesting device **600** is a tension-compression mode cymbal design similar to the harvesting device **100** of the first embodiment, except the harvesting device **600** incorporates the 2DOF system **400**. Specifically, a piezoelectric element or plate **601** of the harvesting device **600** is disposed between cymbal-shaped caps or spring elements **612**. Another spring element **608** is connected to the base **606** of the device **600**. A first mass **602** is located below the cymbal-shaped spring element **612** such that the piezoelectric element **601** is bonded between the first mass **602** and the second spring element **612**. A second mass **604** is disposed on top of the cymbal-shaped spring elements **612**.

[0025] Referring to **FIG. 7**, a harvesting device **700** is a compression mode piezoelectric plate design that has a first spring element **708** connected to a base **706** of the device **700**. A piezoelectric element **701** is bonded between a first mass **702** and a second compression spring element **712**. A second mass **704** is disposed on top of the second spring element **712**.

[0026] Referring to **FIG. 8**, a harvesting device **800** is a shear mode piezoelectric ring design that includes a first spring element **808** disposed on a base **806** of the device **800**. A first mass **802** is disposed on top of the first spring element **808**. A piezoelectric ring element **801** is disposed around a portion of the first mass **802** inside of a second spring element **812**, such that piezoelectric ring element **801** is bonded between the first mass **802** and the second spring **812**. A second mass **804** is disposed on top of the second spring element **812**.

[0027] Referring to **FIG. 9**, a harvesting device **900** is a bending mode flexural beam design that includes a base **906** with a first spring element **908** disposed thereon. A first mass **902** is disposed on the first spring element **908**. Between the first mass **902** and a cantilever beam second spring element **912** is a supporting post **915**. First and second parts **905** and **907** of a second mass **904** are disposed on opposite ends of the second spring element **912**. A piezoelectric element or plate **901** is bonded to the second spring element **912**.

[0028] The piezoelectric elements **601, 701, 801** and **901** can be made of any piezoelectric material, including a single crystalline, such as a diamond, or a multi-crystalline, such as a ceramic.

[0029] Referring to **FIGS. 10-12**, a harvesting device **1000** is similar to the device **100** of **FIGS. 2 and 3**, except the device **1000** uses a synthesized inductor or gyrator **1010** instead of a conventional metal coil inductor. The gyrator **1010** is placed in parallel with the piezoelectric element (represented by circuit **1001**) prior to the rectifier **1020** and **1030** storage circuitry. Because of the very high value inductor (in the hundreds of Henry) required to resonate at low frequencies, the use of a conventional metal inductor can be impractical. The gyrator **1010** is an electronic circuit that simulates an inductor. Therefore, the conventional heavy and bulky inductor can be replaced with a smaller lighter weight synthesized inductor.

[0030] **FIGS. 11 and 12** represent two alternative circuits **1110** and **1210** for the gyrator **1010**. The gyrator **1010** can synthesize very large inductors at very low power, which is preferably taken from the storage element. The input **1102** (IN) and the ground **1104** of both circuits **1110** and **1210** simulate the two ends of a conventional metal inductor. The gyrator **1010** is made of a ultra low power, low voltage operation amplifier **1106** along with a capacitor **1108** (C1) and uses the gyration effects to convert the capacitor into an inductor. The inductance at the input **1102** of both circuits **1110** and **1210** is $L_{synthesized}=C1*R1*R2$.

[**0031**] While particular embodiments have been chosen to illustrate the invention, it will be understood by those skilled in the art that various changes and modification can be made therein without departing from the scope of the invention as defined in the appended claims.

What is claimed is:

1. A piezoelectric vibration energy harvesting device, comprising:

a base;

a mass; and

a cymbal stack disposed between the base and the proof mass, the cymbal stack comprising:

a piezoelectric element disposed between the base and the proof mass;

a first cymbal-shaped cap disposed between the mass and the piezoelectric crystal; and

a second cymbal-shaped cap disposed between the piezoelectric crystal and the base.

2. A device of claim 1, wherein

the piezoelectric element is a relaxor crystal.

3. A device of claim 1, wherein

the first and second cymbal-shaped caps also function as electrodes and are connected to an electric output of the device.

4. A device of claim 1, wherein

the electrical output is connected to an inductor.

5. A device of claim 4, wherein

the piezoelectric element and the inductor have a resonance frequency which is tuned to be approximately equal to a mechanical resonance of the cymbal stack.

6. A device of claim 4, wherein

the inductor is a metal coil.

7. A device of claim 4, wherein

the inductor is a gyrator, said gyrator simulating an inductor coil by converting impedance into its inverse.

8. A piezoelectric vibration energy harvesting device, comprising:

a first mass;

a second mass;

a first spring element coupled to said first mass;

a second spring element coupled to said second mass; and

a piezoelectric element bonded between the first mass and the second spring,

whereby a stress applied to said second spring is applied to said piezoelectric element.

9. A device according to claim 8, wherein

said piezoelectric element is connected in parallel with an inductor.

10. A device according to claim 9, wherein

said inductor is a gyrator, said gyrator simulating an inductor coil by converting impedance into its inverse.

11. A device according to claim 8, wherein

said second spring element is a compression spring, and

said piezoelectric element being disposed on an end of said spring.

12. A device according to claim 8, wherein

said piezoelectric element is a ring disposed around a portion of said first mass and disposed inside of said second spring element.

13. A device according to claim 8, wherein

said second spring element includes a cantilever beam;

said piezoelectric element being disposed on said beam; and

said second mass being connected to an end of said beam.

14. A device according to claim 8, wherein

said second spring element includes first and second cymbal-shaped caps, and

said piezoelectric element being disposed between said first and second caps.

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