(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
28 March 2013 (28.03.2013)

(10) International Publication Number
WO 2013/044262 A1

(51) International Patent Classification:
H03H 9/56 (2006.01) *H03H 9/02* (2006.01)

(21) International Application Number:
PCT/US2012/056962

(22) International Filing Date:
24 September 2012 (24.09.2012)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
13/241,356 23 September 2011 (23.09.2011) US

(71) Applicant *(for all designated States except US)*: **QUALCOMM Incorporated** [US/US]; Attn: International Ip Administration, 5775 Morehouse Drive, San Diego, California 92121 (US).

(72) Inventors; and
(71) Applicants *(for US only)*: **ZUO, Chengjie** [CN/US]; 5775 Morehouse Drive, San Diego, California 92121 (US). **LO, Chi Shun** [GB/US]; 5775 Morehouse Drive, San Diego, California 92121 (US). **JOO, Sanghoon** [KR/US]; 5775 Morehouse Drive, San Diego, California 92121 (US). **YUN, Changhan** [KR/US]; 5775 Morehouse Drive, San Diego, California 92121 (US). **KIM, Jonghae** [KR/US]; 5775 Morehouse Drive, San Diego, California 92121 (US).

(74) Agent: **TALPALATSKY, Sam**; 5775 Morehouse Drive, San Diego, California 92121 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: PIEZOELECTRIC RESONATOR HAVING COMBINED THICKNESS AND WIDTH VIBRATIONAL MODES

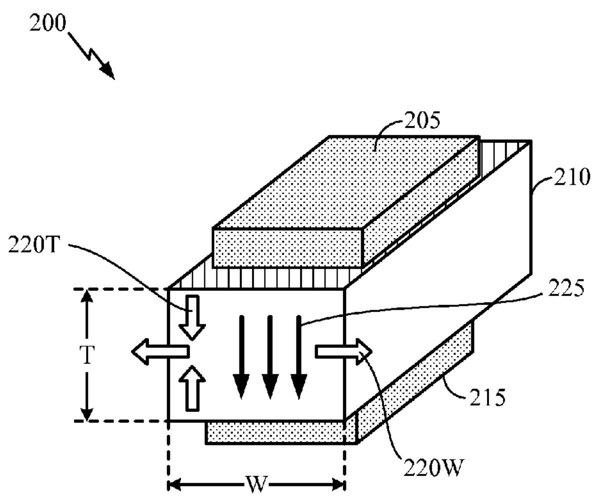

FIG. 2

(57) Abstract: A method and apparatus for a piezoelectric resonator (200) having combined thickness (220T) and width (220W) vibrational modes are disclosed. A piezoelectric resonator may include a piezoelectric substrate (210) and a first electrode (205) coupled to a first surface of the piezoelectric substrate. The piezoelectric resonator may further include a second electrode (215) coupled to a second surface of the piezoelectric substrate, where the first surface and the second surface are substantially parallel and define a thickness dimension of the piezoelectric substrate. Furthermore, the thickness dimension (T) and the width (W) dimension of the piezoelectric substrate are configured to produce a resonance from a coherent combination of a thickness vibrational mode and a width vibrational mode when an excitation signal is applied to the electrodes.

WO 2013/044262 A1

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

Published:

— *with international search report (Art. 21(3))*

PIEZOELECTRIC RESONATOR HAVING COMBINED THICKNESS AND WIDTH VIBRATIONAL MODES

Field of Disclosure

[0001] Disclosed embodiments are related to piezoelectric resonators, and more particularly, to piezoelectric resonators which combine thickness and width vibrational modes to improve electromechanical coupling.

Background

[0002] Piezoelectric resonators may be used in various components such as oscillators and filters over a wide range of frequency applications. These resonators may also be employed in generating clock signals in integrated circuits, where the frequency of vibration is directly related to a clock frequency.

[0003] Piezoelectric resonators may be thought of as solid state transducers which can convert mechanical energy into electrical energy and electrical energy back into mechanical energy, depending upon how the resonators are configured. The mechanical energy manifests itself as vibrations within the piezoelectric material of the resonator.

[0004] FIGS. 1A and 1B show different modes of resonance in conventional piezoelectric resonators. The various modes of resonance may be defined relative to the geometry of the piezoelectric material producing the vibrations. In FIG. 1A, piezoelectric resonator 100 may include a piezoelectric substrate 115 having a first electrode 105 coupled to its upper surface, and a second electrode 110 coupled to its lower surface. When an electric excitation signal is applied to the electrodes 105 and 110, an electric field 120 may be induced within the piezoelectric substrate 115. The electric field 120 may cause a width vibrational mode 125, where the frequency of vibration may depend upon the width of the piezoelectric substrate (W). The width vibrational mode may also be referred to as a "d31" vibration, where d31 is a piezoelectric coefficient related to the width dimension (i.e., lateral dimension as shown in FIG. 1A) of the piezoelectric substrate 115.

[0005] As shown in FIG. 1B, the same electric field 120 may also cause a thickness vibrational mode 130 in the piezoelectric substrate 115. Here the frequency of vibration may depend upon the thickness of the piezoelectric substrate (T). The thickness vibrational mode may also be referred to as a "d33" vibration, where d33 is a piezoelectric coefficient related to the thickness dimension (i.e., vertical dimension as shown in FIG. 1B) of the piezoelectric substrate 115.

[0006] A coefficient of electromechanical coupling, denoted by k_t^2, represents the efficiency of energy conversion, such that a higher coefficient of electromechanical coupling indicates that mechanical energy is more efficiently converted to electrical energy.

[0007] In practice, thickness vibrational modes are commonly exploited in piezoelectric resonators because this mode tends to exhibit a high coefficient of electromechanical coupling, k_t^2. However, resonators utilizing thickness-only vibrational modes suffer from the drawback that T may not provide the freedom to define the resonant frequency by layout design, which is an advantage of resonators having width-only vibrational modes. It should be noted that the layout design is a pre-fabrication process, which cannot be altered after fabrication. In other words, by doing only one fabrication run, the width vibrational modes may provide multiple frequencies of operation on a single wafer, but the thickness vibrational mode resonators only provide one frequency.

[0008] On the other hand, width vibrational mode piezoelectric resonators having substrates made from Aluminum Nitride exhibit a coefficient of electromechanical coupling that is nearly one third the value associated with thickness vibrational mode resonators. This means that efficiency of width vibration mode resonators may be low. However, the width may be easily alterable during a pre-fabrication design process by coupling multiple vibrational resonators to form a multi-finger resonator. The multiple fingers may be adjacently placed and mechanically coupled by their edges so that the entire structure, including multiple fingers, vibrates as a single body. The multiple fingers may be electrically connected in parallel so that the entire structure is electrically equivalent to a single resonator.

[0009] There are currently no piezoelectric resonators which can take advantage of the positive attributes of both the width and thickness vibrational modes. Accordingly, there is a need for piezoelectric resonators which can combine the advantages of width and thickness vibrational modes to improve efficiency, while still preserving the single-chip (i.e., single-fabrication) multiple frequency capability.

SUMMARY

[0010] The disclosed embodiments are directed to piezoelectric resonators having combined thickness and width vibrational modes.

[0011] One embodiment can comprise a piezoelectric resonator, which may include a piezoelectric substrate and a first electrode coupled to a first surface of the piezoelectric substrate. The piezoelectric resonator may further include a second electrode coupled to a second surface of the piezoelectric substrate, wherein the first surface and the second surface are substantially parallel and define a thickness dimension of the piezoelectric substrate, and further where the thickness dimension and a width dimension of the piezoelectric substrate are configured to produce a resonance from a coherent combination of a thickness vibrational mode and a width vibrational mode when an excitation signal is applied to the electrodes.

[0012] Another embodiment may include a method for generating an oscillating signal in a piezoelectric resonator. The method may include receiving an electric signal across a piezoelectric element, and establishing a first vibrational mode in a thickness dimension of the piezoelectric element. The method may further include establishing a second vibrational mode in a width dimension of the piezoelectric element, and combining coherently the first vibration mode and the second vibration mode to produce a resonant vibration which increases a coefficient of electromechanical coupling (k_t^2) beyond a width-only vibration mode while providing single-chip multiple frequency capability.

[0013] Another embodiment may include a piezoelectric resonator having resonations in a vertical direction, and resonations in a lateral direction. The resonations in the vertical direction and the resonations in the lateral direction may be combined to generate electrical signals.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The accompanying drawings are presented to aid in the description of embodiments and are provided solely for illustration of the embodiments and not limitation thereof.

[0015] FIGS. 1A and 1B show diagrams of conventional piezoelectric resonators showing different vibrational modes.

[0016] FIG. 2 illustrates a diagram of an exemplary single piezoelectric resonator having combined width and thickness vibrational modes.

[0017] FIG. 3 is a diagram showing an exemplary multi-finger piezoelectric resonator having combined width and thickness vibrational modes.

[0018] FIG. 4 is a diagram showing an exemplary piezoelectric resonator having a hollow disk shape.

[0019] FIG. 5 is a diagram showing an exemplary piezoelectric resonator having a cylindrical shape.

[0020] FIG. 6 shows a plot of the relationship between the electromagnetic coupling k_t^2 and the thickness to width ratio (T/W).

[0021] FIG. 7 is a diagram which depicts an embodiment where a piezoelectric resonator is incorporated into a remote unit.

DETAILED DESCRIPTION

[0022] Aspects of the embodiments are disclosed in the following description and related drawings directed to such embodiments. Alternate embodiments may be devised without departing from the scope of the invention. Additionally, well-known elements used and applied in the embodiments will not be described in detail or will be omitted so as not to obscure the relevant details.

[0023] The word “exemplary” is used herein to mean “serving as an example, instance, or illustration.” Any embodiment described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other embodiments. Likewise, the term “embodiments” does not require that all embodiments include the discussed feature, advantage or mode of operation. The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises", "comprising,", "includes" and/or "including", when used herein, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0024] Further, many embodiments are described in terms of sequences of actions to be performed by, for example, elements of a computing device. It will be recognized that various actions described herein can be performed by specific circuits (e.g., application specific integrated circuits (ASICs)), by program instructions being executed by one or more processors, or by a combination of both. Additionally, these sequence of actions described herein can be considered to be embodied entirely within any form of computer readable storage medium having stored therein a corresponding set of computer instructions that upon execution would cause an associated processor to perform the functionality described herein. Thus, the various aspects of the invention may be embodied in a number of different forms, all of which have been contemplated to be within the scope of the claimed subject matter. In addition, for each of the embodiments described herein, the corresponding form of any such embodiments may be described herein as, for example, “logic configured to” perform the described action.

[0025] Embodiments provided herein discuss piezoelectric resonators having combined width and thickness vibrational modes using a common excitation signal. As used herein, width vibrational modes, which may also be referred to as lateral vibration modes, may be defined as the dimension of vibration which is perpendicular to the applied electric field. The thickness vibrational mode, which may also be referred to as the vertical vibration mode, may be defined as the dimension of vibration which is parallel to the applied electric field. Electrical energy generated from the vibrations in both width and thickness may be harnessed to increase efficiency and maximize the electromechanical coupling. It is observed through experimentation that a thickness to width ratio (T/W) of approximately 1 (i.e. width is approximately equal to thickness) provide improved efficiency, as will be discussed in more detail below. The piezoelectric resonators may be fabricated using known techniques and embodied in at least one semiconductor die.

[0026] FIG. 2 illustrates a diagram of an exemplary single piezoelectric resonator 200 having combined width and thickness vibrational modes. The piezoelectric resonator 200 may have a first electrode 205 and a second electrode 215, both of which may be coupled to a piezoelectric substrate 210 on the opposing side thereof. However, in some embodiments, the electrical signal may be applied directly to the piezoelectric substrate without the use of fabricated electrodes 205, 215.

[0027] The piezoelectric substrate 210 may typically be formed using Aluminum Nitride (AlN), Zinc Oxide (ZnO), or any other suitable material having piezoelectric properties. The ratio of the width to the thickness (T/W) may lie in the range between .75 and 1.25, and may be, for example, one. When T/W is equal to one, the thickness and width extents are the same and the piezoelectric substrate 210 has a square cross-section. When T/W = 1, the combined frequency of vibration inversely depends upon the dimensions. That is, $T = W = \lambda/2$, where λ corresponds to the wavelength of the resonant vibration. The frequency may be determined by f = ν/λ, where ν is the velocity of propagation of the vibrational wave through the piezoelectric substrate 210. The velocity of propagation ν is the acoustic velocity of the wave which travels in the piezoelectric substrate 210.

[0028] When an electric excitation signal is applied to electrodes 205 and 215, an electric field 225 may be formed in the piezoelectric substrate 210. The electric field 225 excites the piezoelectric substrate 210 and induces vibrations in the width (W) extent (i.e., excites a width vibrational mode 220W) and induces vibrations in the thickness (T) extent (i.e., excites a thickness vibrational mode 220T). The two vibrational modes occur simultaneously and can combine in a coherent manner within the piezoelectric substrate 210, thus producing a combined vibrational mode which is more efficient than a width-only vibrational mode component. The two vibrational modes manifest mechanical energy which may be converted back into an electrical signal.

[0029] The coherent combination of the two modes of vibration may result in a higher effective electromechanical coupling k_t^2 (wherein k_t^2 is the ratio of the mechanical energy to the electrical energy) than the width-only vibrational mode. Accordingly, this technique provides a way to optimize the k_t^2 of laterally vibrating (width vibrational mode) resonators by engineering the piezoelectric thin film thickness, so that both high k_t^2 and single-chip multiple frequency capability can be achieved simultaneously in a single device technology. One should appreciate that the T/W ratio doesn't have to be exactly equal to 1 to achieve this goal, but should be close to 1 for improved k_t^2 results.

[0030] Piezoelectric resonator 200 as shown in FIG. 2 is a finger resonator, where the first electrode 205 may serve as the input, and the second electrode 215 may serve as the output electrode or as ground. For example, if the second electrode 215 is grounded, the resonator is a one-port resonator, which is a two-terminal device. If the second electrode is output, the resonator is a two-port resonator, which is a four-terminal device.

[0031] According to one embodiment, the piezoelectric resonator 200 may include a means (205, 215) for receiving an electric signal across a piezoelectric element, a means (210) for establishing a first vibrational mode in a width direction, a means (210) for establishing a second vibrational mode a thickness direction, and a means (210) for combining the first vibration mode and the second vibration mode to produce a resonant vibration which increases a coefficient of electromechanical coupling (k_t^2) beyond a width-only vibration mode.

[0032] Accordingly, another embodiment may include a piezoelectric resonator 200 having resonations in a vertical direction, and resonations in a lateral direction. The resonations in the vertical direction and the resonations in the lateral direction may be combined in the piezoelectric substrate 210 to generate electrical signals.

[0033] FIG. 3 is a diagram showing an exemplary multi-finger piezoelectric resonator 300 having combined width and thickness vibrational modes. The piezoelectric resonator 300 includes an extended piezoelectric substrate 310. A first set of electrodes 305A-305D are coupled to a first surface of the extended piezoelectric substrate 310, and a second set of electrodes 315A-315D are coupled to second side of the extended piezoelectric substrate 310. The second side may be opposite and/or parallel to the first side.

[0034] The multi-finger piezoelectric resonator 300 includes an integer number (N) of sub-resonators. Each sub-resonator may have a width dimension of W and a thickness dimension of T. The ratio T/W may lie in the range of .75 to 1.25, and, for example, may be equal to 1. Accordingly, the entire extent in the width dimension of the piezoelectric substrate 310 is approximately N x W. The opposing pairs of electrodes (e.g., 305A, 315A) disposed across each sub-resonator. Both sets of electrodes 305, 315 may be equally spaced in the width dimension along the extended piezoelectric substrate 310, separated by a pitch value proportional to W.

[0035] The multi-finger piezoelectric resonator 300 may be a multi-port resonator. Each port may include two terminals. Generally one of the two terminals is typically ground; however, this does not necessarily have to be the case. In one example, where the resonator 300 may utilize a two-port electrode configuration, the electrodes 305A and 305C can form the input terminal, while 315B and 315D may form the output terminal. The remaining electrodes may form the ground terminal and be shared by both the input and output ports. The input terminal and ground terminal (two terminals) form the input port. The output terminal and ground terminal form the output port.

[0036] In another example, the multi-finger piezoelectric resonator 300 may utilize a four-port electrode configuration which can be used to support differential input and differential output. The ground terminal can be shared by the four terminals to form the four ports: port1: input+ and ground; port 2: input- and ground; port 3: output+ and ground; port 4: output- and ground.

[0037] Because the adjacent sub-resonators generally vibrate out-of-phase with respect to each other, the electrical field lines have an alternating pattern for different sub-resonators. This phasing arrangement permits the design of the equivalent impedance of the entire multi-finger piezoelectric resonator. The k_t^2 is improved by engineering the W/T ratio, but may have little to do with the multiple finger arrangement, having some electrodes dedicated to input signals, others dedicated to output signals, and some other dedicated to ground. For example, electrodes 305A and 315B may be designated to receive input signals, electrodes 305C and 315D designated to provide output signals, and 315A, 305B, 315C and 305D tied to ground. Because the signals associated with adjacent sub-resonators have opposite polarity, the direction of the electric field lines is opposite in adjacent sub-resonators as shown in FIG. 3. Different electrode configurations may create different coupling between the sub-resonators. The sub-resonator coupling may also enhance the overall equivalent k_t^2 of the entire resonator.

[0038] FIG. 4 is a diagram showing an exemplary piezoelectric resonator 400 having a hollow disk shape. In this embodiment, piezoelectric resonator 400 may include a piezoelectric substrate 410 which is a hollow disk. The width of each of the circular sub-resonator (formed by circular electrodes on the piezoelectric substrate) may be W, so the entire thickness of the solid portion would approximately be N x W, where N is the number of sub-resonators (e.g., in FIG. 4, the number of sub-resonators N is 2). The thickness of the disk is T as seen in FIG. 4. A first set of electrodes 405 may be coupled to a first side of the piezoelectric substrate. A second set of electrodes 415 may be coupled to a second side, which is parallel to the first side. The operation of piezoelectric resonator 400 is similar to the piezoelectric resonator 200 shown in FIG. 2, as the length dimension of the piezoelectric resonator 200 is essentially “wrapped into a circle” in the embodiment shown in FIG. 4. The width and thickness dimensions are essentially the same in that the ratio T/W may lie in the range between .75 and 1.25, and, for example, may be equal to one (1).

[0039] FIG. 5 is a diagram showing an exemplary piezoelectric resonator 500 having a cylindrical shape. In this embodiment, piezoelectric resonator 500 may include a piezoelectric substrate 510 which is a solid cylinder. The thickness of the cylinder is T, and the width of the cylinder is W and is also the radius of the circular surface as shown in FIG. 5. A first electrode 505, which may be shaped as a disk, may be coupled to a first circular side of the piezoelectric substrate 510. A second electrode 515, may also be shaped as a disk, and may be coupled to a second circular side of the piezoelectric substrate 510, which is parallel to the first circular side. In this case, the radius (W) of the top (bottom) circular surface determines the frequency of lateral vibration. The thickness (T) determines the frequency of vertical vibration. The width and thickness dimensions may be configured so that the ratio T/W lies in the range between .75 and 1.25, and, for example, may be equal to one. When the T/W ratio is approximately equal to 1, the effective electromagnetic coupling k_t^2 may be improved as described above in the description of the embodiment shown in FIG. 2.

[0040] FIG. 6 shows a plot of an exemplary relationship between the electromechanical coupling k_t^2 and the thickness to width ratio (T/W). FIG. 6 illustrates the results of a simulation, which predicts that the maximum electromechanical coupling k_t^2 may occur when T/W = 1. In this case, the width vibrational mode and the thickness vibrational mode may coherently combine to produce the peak shown in Fig. 6. However, gains may be made in electromechanical coupling k_t^2 when the T/W ratio lies in the range .75 to 1.25.

[0041] FIG. 7 is a diagram showing an exemplary wireless communication system 700 in which embodiments of the disclosure may be employed. For purposes of illustration, FIG. 7 shows three remote units 720, 730, and 750 and two base stations 740. It is noted that conventional wireless communications systems can have many more remote units and base stations. The remote units 720, 730 and 750 may include piezoelectric resonators 725A, 725B and 725C, which may be an embodiment of the disclosure as discussed above. FIG. 7 further shows forward link signals 780 from the base stations 740 to the remote units 720, 730, and 750 and reverse link signals 790 from the remote units 720, 730 and 750 to the base stations 740.

[0042] In FIG. 7, remote unit 720 is shown as a mobile telephone, remote unit 730 is shown as a portable computer, and remote unit 750 is shown as a fixed location remote unit in a wireless local loop system. For example, the remote units may be mobile phones, hand-held personal communication systems (PCS) units, portable data units such as personal data assistants, GPS enabled devices, navigation devices, set top boxes, music players, video players, entertainment units, fixed location data units such as meter reading equipment, or any other device that stores or retrieves data or computer instructions, or any combination thereof. Although FIG. 7 illustrates remote units according to the teachings of the disclosure, the disclosure is not limited to these exemplary illustrated units. Embodiments of the disclosure may be suitably employed in any device which includes active integrated circuitry including memory and on-chip circuitry for test and characterization. Embodiments of the disclosure may be suitably employed in any device which includes active integrated circuitry including memory and on-chip circuitry for test and characterization. The piezoelectric resonators described herein may be used as in a variety of applications, such as, for example, frequency sources for clocks, local oscillators, resonator filters, resonant sensors, duplexers, etc.

[0043] The foregoing disclosed devices and methods may be designed and configured into GDSII and GERBER computer files, which can be stored on a computer readable media. These files are in turn provided to fabrication handlers who fabricate devices based on these files. The resulting products are semiconductor wafers that are then cut into semiconductor die and packaged into a semiconductor chip. The chips are then employed in devices described above.

[0044] Those of skill in the art will appreciate that information and signals may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof.

[0045] While the foregoing disclosure shows illustrative embodiments, it should be noted that various changes and modifications could be made herein without departing from the scope of the invention as defined by the appended claims. The functions, steps and/or actions of the method claims in accordance with the embodiments described herein need not be performed in any particular order. Furthermore, although elements of the embodiments may be described or claimed in the singular, the plural is contemplated unless limitation to the singular is explicitly stated.

CLAIMS

WHAT IS CLAIMED IS:

1. A piezoelectric resonator, comprising:

a piezoelectric substrate;

a first electrode coupled to a first surface of the piezoelectric substrate; and

a second electrode coupled to a second surface of the piezoelectric substrate, wherein the first surface and the second surface are substantially parallel and define a thickness dimension of the piezoelectric substrate, and

further wherein the thickness dimension and a width dimension of the piezoelectric substrate are configured to produce a resonance from a coherent combination of a thickness vibrational mode and a width vibrational mode, when an excitation signal is applied to the electrodes.

2. The piezoelectric resonator according to claim 1, wherein a ratio of the thickness dimension to the width dimension lies within a range between .75 and 1.25.

3. The piezoelectric resonator according to claim 2, wherein the ratio of the thickness dimension to the width dimension is approximately equal to one.

4. The piezoelectric resonator according to claim 1, wherein the first electrode is an input terminal, and the second electrode is an output terminal or a ground terminal.

5. The piezoelectric resonator according to claim 1, wherein the piezoelectric substrate is extended in width over multiples of the width dimension to form a plurality of sub-resonators, further comprising:

a plurality of first electrodes coupled to a first surface of an extended piezoelectric substrate and equally spaced along an extended width dimension, wherein each of the plurality of first electrodes is substantially centered over each sub-resonator; and

a plurality of second electrodes coupled to a second extended surface of the extended piezoelectric substrate and equally spaced along the extended width dimension, wherein each of the plurality of second electrodes is substantially centered over each sub-resonator, and the first extended surface and the second extended surface are substantially parallel; and

wherein the thickness dimension and width dimension of the each of the sub-resonators are configured to produce a resonance from a coherent combination of a thickness vibrational mode and a width vibrational mode when excitation signals are applied to each of the electrodes.

6. The piezoelectric resonator according to claim 5, further comprising:

an input port, further comprising:

a set of input electrodes selected from non-adjacent electrodes from the plurality of first electrodes, and

a first set of ground electrodes, selected from non-adjacent electrodes from the plurality of second electrodes, wherein the set of input electrodes and the first set of ground electrodes are diametrically opposed; and

an output port, further comprising:

a set of output electrodes selected from non-adjacent electrodes from the plurality of second electrodes, and

a second set of ground electrodes, selected from non-adjacent electrodes from the plurality of first electrodes, wherein the set of output electrodes and the second set of ground electrodes are diametrically opposed.

7. The piezoelectric resonator according to claim 5, further comprising:

a first port, further comprising a positive input terminal selected from the plurality of first electrodes and a first ground terminal selected from the plurality of second electrodes, wherein the positive input terminal and the first ground terminal are diametrically opposed;

a second port, further comprising a negative input terminal selected from the plurality of first electrodes and a second ground terminal selected from the plurality of second electrodes, wherein the negative input terminal and the second ground terminal are diametrically opposed;

a third port, further comprising a positive output terminal selected from the plurality of first electrodes and a third ground terminal selected from the plurality of second electrodes, wherein the positive output terminal and the third ground terminal are diametrically opposed; and

a fourth port, further comprising a negative output terminal selected from the plurality of first electrodes and a fourth ground terminal selected from the plurality of second electrodes, wherein the negative output terminal and the fourth ground terminal are diametrically opposed.

8. The piezoelectric resonator according to claim 5, further wherein the excitation signals applied to adjacent sub-resonators have opposite polarity.

9. The piezoelectric resonator according to claim 1 is one of a rectangular prism, a hollow cylinder, or a disk.

10. The piezoelectric resonator according to claim 1, wherein the substrate is formed from one of Aluminum Nitride, PZT, Lithium Niobate, Lithium Tantalate, or Zinc Oxide.

11. The piezoelectric resonator according to claim 1 integrated in at least one semiconductor die.

12. The piezoelectric resonator according to claim 1, further comprising an electronic device, selected from the group consisting of a set top box, music player, video player, entertainment unit, navigation device, communications device, personal digital assistant (PDA), fixed location data unit, and a computer, into which the piezoelectric resonator is integrated.

13. A method for generating an oscillating signal in a piezoelectric resonator, comprising:

receiving an electric signal across a piezoelectric element;

establishing a first vibrational mode in a thickness dimension of the piezoelectric element;

establishing a second vibrational mode in a width dimension of the piezoelectric element; and

combining coherently the first vibration mode and the second vibration mode to produce a resonant vibration which increases a coefficient of electromechanical coupling (k_t^2) beyond a width-only vibration mode while providing single-chip multiple frequency capability.

14. The method according to claim 13, wherein the piezoelectric resonator is applied in an electronic device, selected from the group consisting of a set top box, music player, video player, entertainment unit, navigation device, communications device, personal digital assistant (PDA), fixed location data unit, and a computer, into which the piezoelectric resonator is integrated.

15. A method for generating an oscillating signal in a piezoelectric resonator, comprising

step for receiving an electric signal across a piezoelectric element;

step for establishing a first vibrational mode in a thickness dimension of the piezoelectric element;

step for establishing a second vibrational mode in a width dimension of the piezoelectric element; and

step for combining coherently the first vibration mode and the second vibration mode to produce a resonant vibration which increases a coefficient of electromechanical coupling (k_t^2) beyond a width-only vibration mode while providing single-chip multiple frequency capability.

16. A piezoelectric resonator, comprising:

means for receiving an electric signal across a piezoelectric element;

means for establishing a first vibrational mode in a width direction;

means for establishing a second vibrational mode in a thickness direction; and

means for combining the first vibration mode and the second vibration mode to produce a resonant vibration which increases a coefficient of electromechanical coupling (k_t^2) beyond a width-only vibration mode.

17. A piezoelectric resonator, comprising:

resonations in a vertical direction; and

resonations in a lateral direction, wherein the resonations in the vertical direction and the resonations in the lateral direction are combined to generate electrical signals.

18. The piezoelectric resonator of claim 17, wherein a frequency of resonations in the vertical direction are based on a thickness dimension, and a frequency of resonations in the lateral direction are based on a width dimension.

19. The piezoelectric resonator of claim 18, wherein a ratio of the thickness dimension and the width dimension is approximately equal to 1.

20. The piezoelectric resonator of claim 17, wherein an effective coefficient of electromechanical coupling is based on a sum of electromechanical couplings of resonations in the vertical direction and the lateral direction.

21. The piezoelectric resonator of claim 17, further comprising a top electrode and bottom electrode, such that current flow is in the vertical direction.

22. The piezoelectric resonator of claim 17 further comprising multiple top electrodes and bottom electrodes, such that current flow is in the vertical direction.

23. The piezoelectric resonator of claim 17, wherein a frequency of the electrical signal can be altered by altering the width dimension.

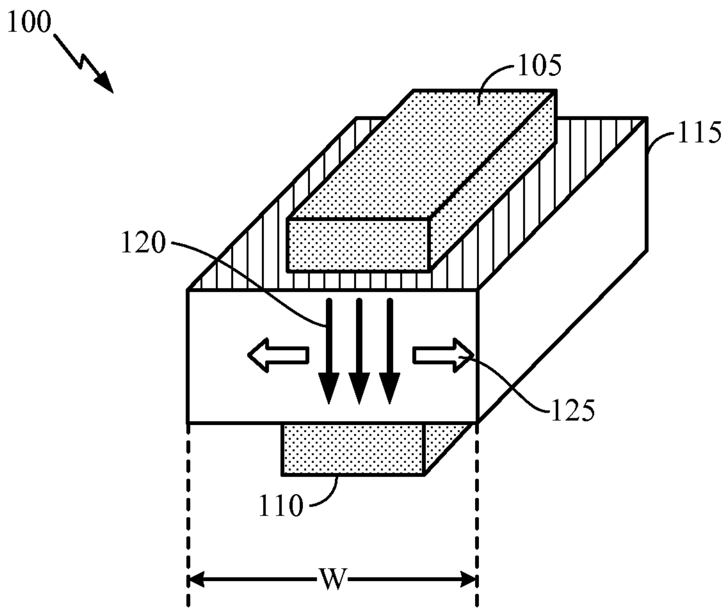

FIG. 1A
BACKGROUND ART

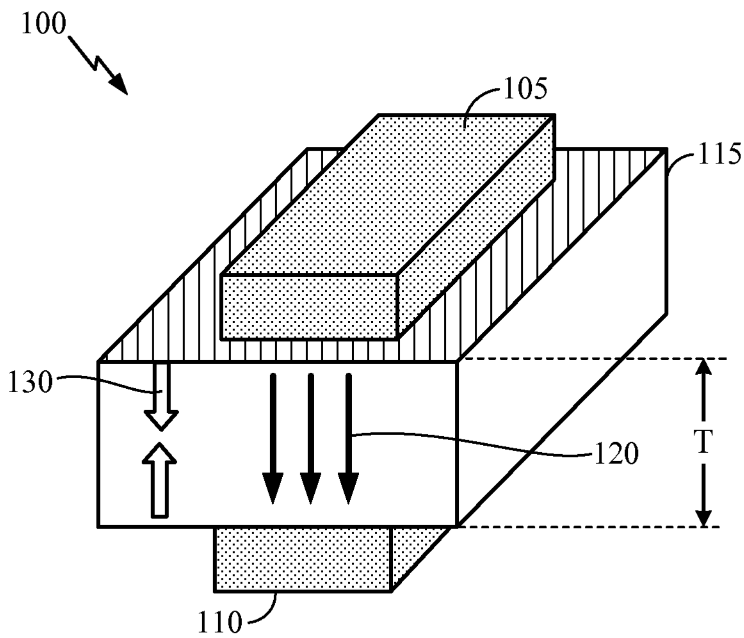

FIG. 1B
BACKGROUND ART

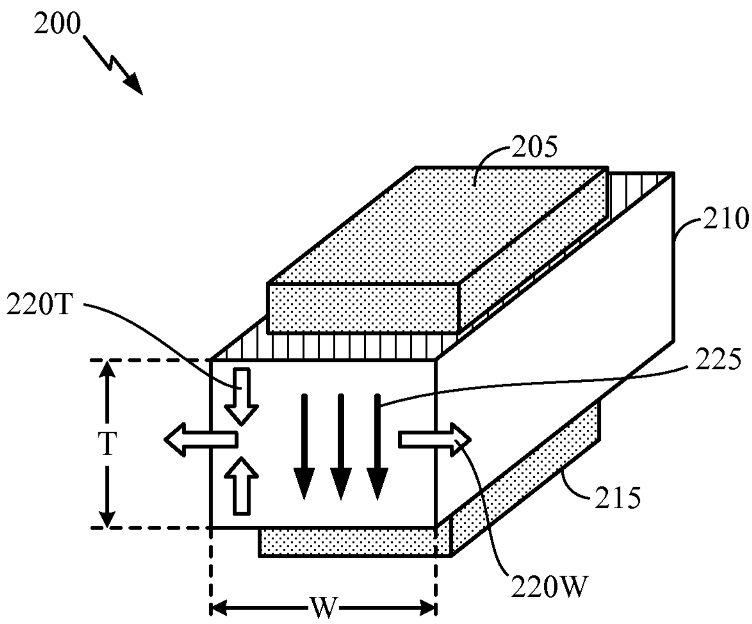
200
205
210
220T
225
T
215
220W
W

FIG. 2

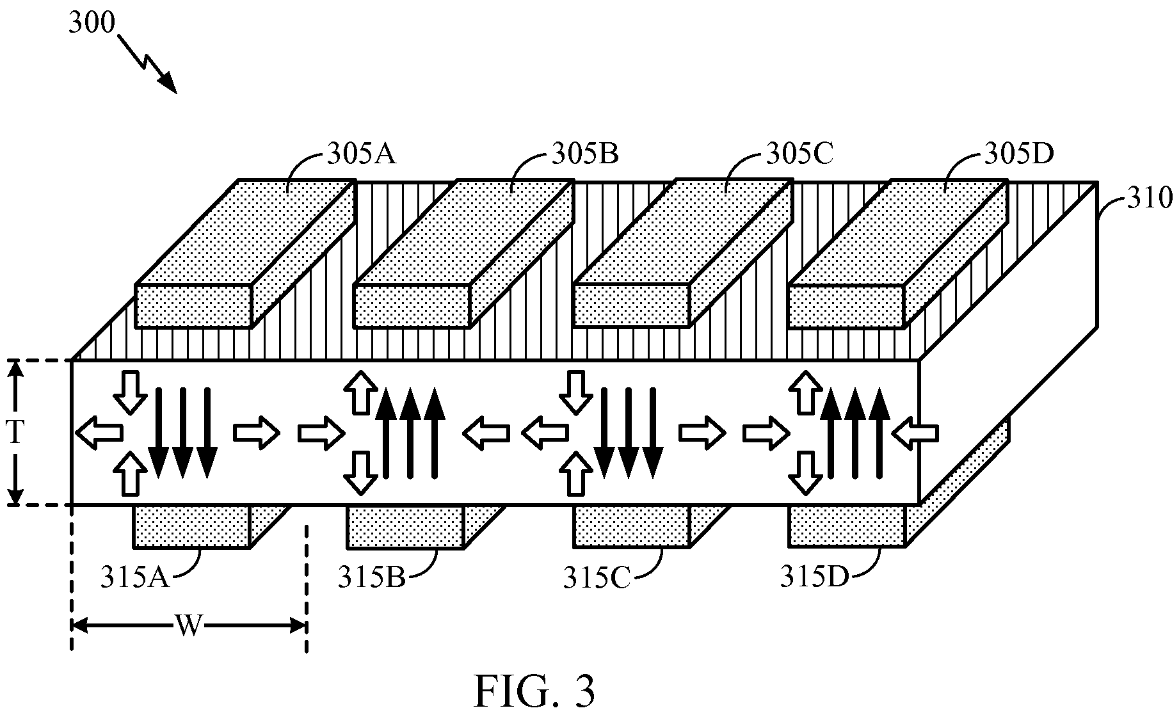
300
305A
305B
305C
305D
310
T
315A
315B
315C
315D
W

FIG. 3

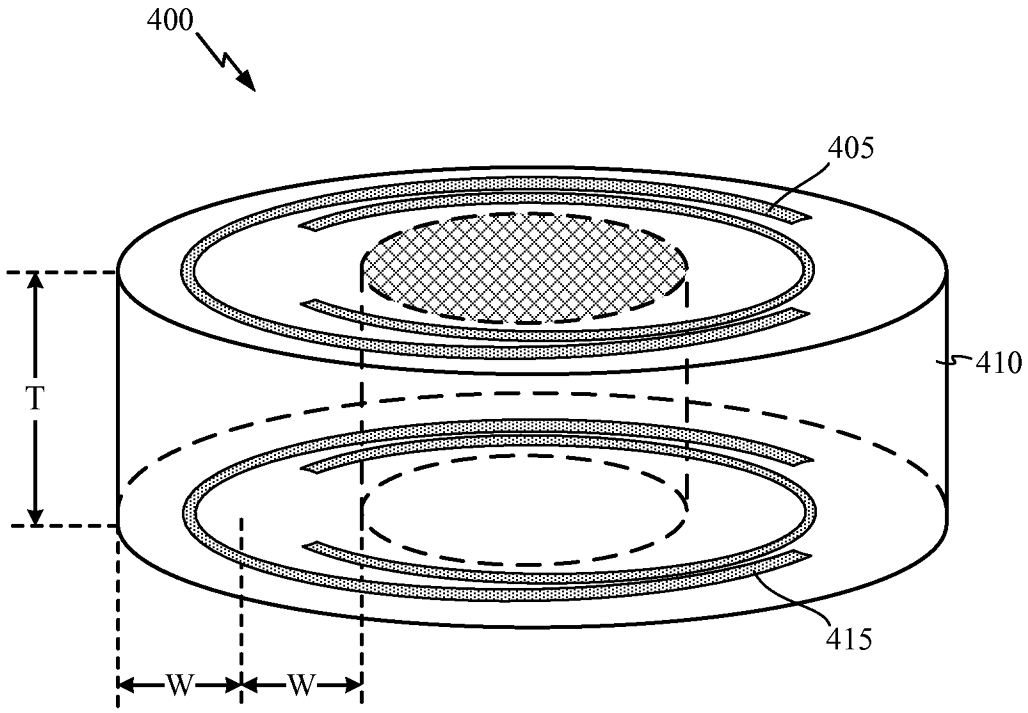

FIG. 4

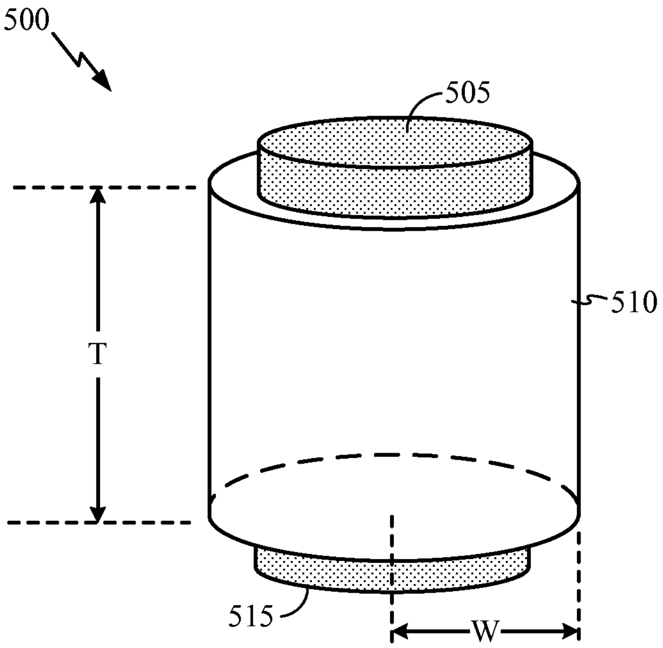

FIG. 5

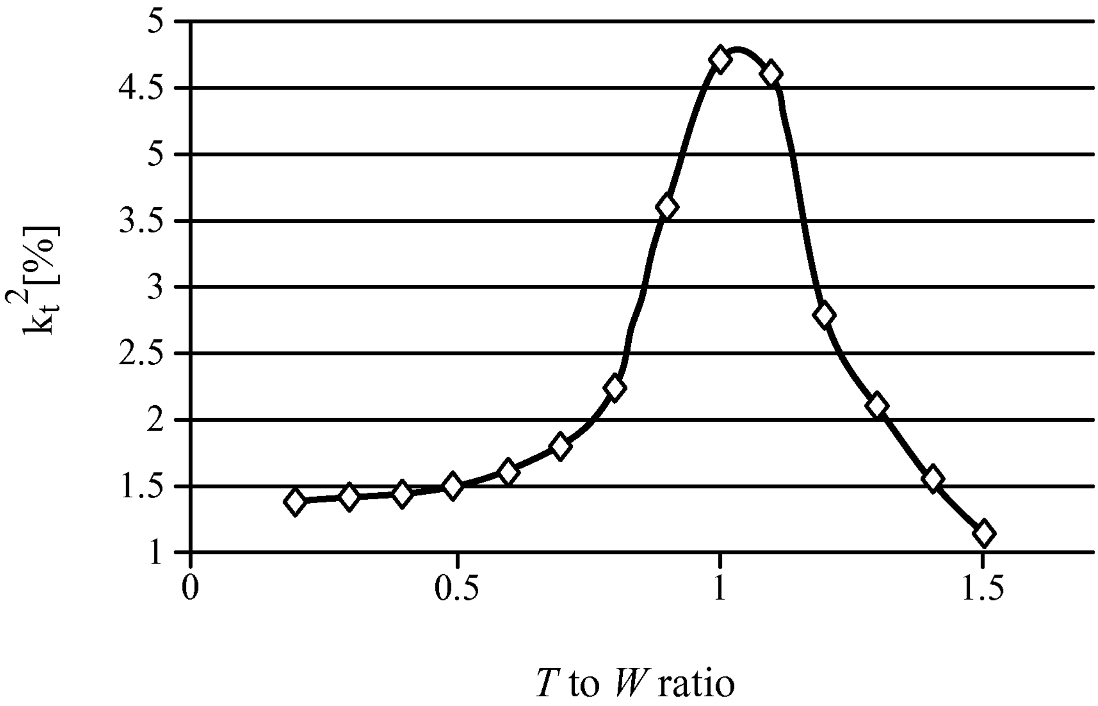

FIG. 6

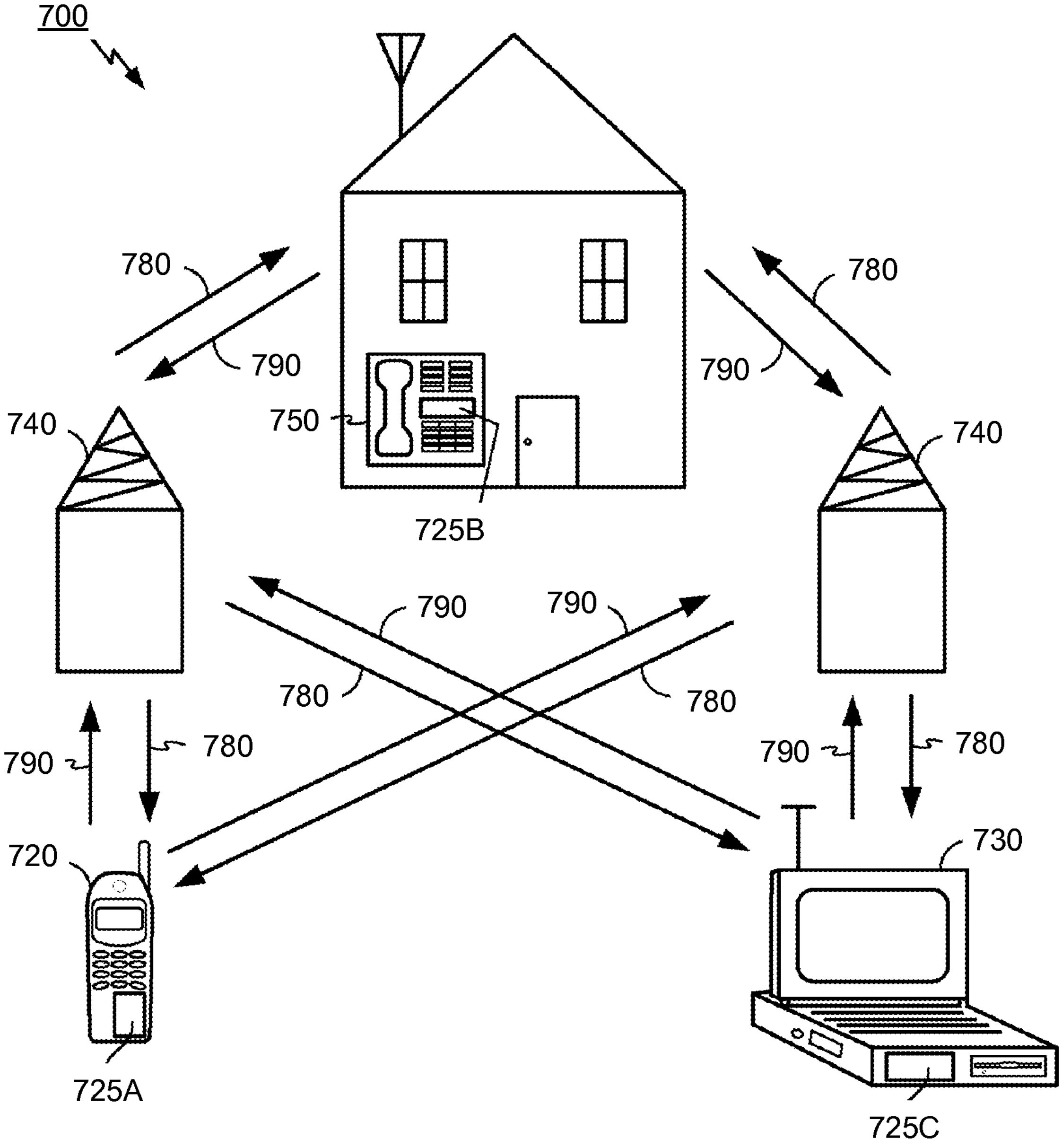
700
780
790
780
790
740
750
725B
740
790
790
780
780
790
780
790
780
720
730
725A
725C

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2012/056962

A. CLASSIFICATION OF SUBJECT MATTER
INV. H03H9/56 H03H9/02
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H03H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data, COMPENDEX, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1 887 690 A2 (EPSON TOYOCOM CORP [JP] SEIKO EPSON CORP [JP]) 13 February 2008 (2008-02-13)	1,4,9-16
Y	paragraph [0049] - paragraph [0051];	2,3
A	figures 2A,2B,2C	5-8
Y	US 6 054 797 A (WAJIMA MASAYA [JP] ET AL) 25 April 2000 (2000-04-25) column 6, line 29 - line 39; figure 8	2,3

-/--

[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 December 2012	21/12/2012

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Lecoutre, Renaud

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PIAZZA ET AL: "One and two port piezoelectric higher order contour-mode MEMS resonators for mechanical signal processing", SOLID STATE ELECTRONICS, ELSEVIER SCIENCE PUBLISHERS, BARKING, GB, vol. 51, no. 11-12, 19 November 2007 (2007-11-19), pages 1596-1608, XP022360463, ISSN: 0038-1101, DOI: 10.1016/J.SSE.2007.09.037 paragraph [02.1]; figure 4 -----	5-8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2012/056962

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 17-23
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
see FURTHER INFORMATION sheet PCT/ISA/210

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box II.2

Claims Nos.: 17-23

1. Independent claim 17 is drafted in such an obscure way that no meaningful search can be carried out. (1) The characteristic "resonations in vertical direction" has no clear meaning. It is impossible to figure out what is a resonation in vertical direction. (2) The characteristic "resonations in lateral direction" has no clear meaning. It is impossible to figure out what is a resonation in lateral direction. (3) The characteristic "the resonations .... are combined to generate electrical signals" has no clear meaning. It is impossible to figure out what are these resonations and should they be vibrational mode, then it is also impossible to figure out how a combination of them could lead to the generation of electrical signals. 2. Claims 18 to 23 are dependent on claim 17 and therefore no meaningful search can be carried out for the same reasons as given above. There being no reasonable basis in the application that clearly indicates the subject matter which might be expected to form the subject of the claims later in the procedure, no search was deemed possible for claims 17 to 23.

The applicant's attention is drawn to the fact that claims relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure. If the application proceeds into the regional phase before the EPO, the applicant is reminded that a search may be carried out during examination before the EPO (see EPO Guideline C-VI, 8.2), should the problems which led to the Article 17(2) declaration be overcome.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2012/056962

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
EP 1887690	A2	13-02-2008	CN	101123423	A	13-02-2008
			EP	1887690	A2	13-02-2008
			EP	2372908	A1	05-10-2011
			JP	4305542	B2	29-07-2009
			JP	2008067345	A	21-03-2008
			KR	20080013811	A	13-02-2008
			US	2008036335	A1	14-02-2008
			US	2009300894	A1	10-12-2009
			US	2011068660	A1	24-03-2011
US 6054797	A	25-04-2000	CN	1196607	A	21-10-1998
			DE	19816488	A1	15-10-1998
			US	6054797	A	25-04-2000