(19) **United States**

(12) **Patent Application Publication**

ADHIKARI et al.

(10) **Pub. No.: US 2024/0030895 A1**

(43) **Pub. Date: Jan. 25, 2024**

(54) **TRANSVERSELY-EXCITED FILM BULK ACOUSTIC RESONATOR MATRIX FILTERS**

(71) Applicant: **Murata Manufacturing Co., Ltd.**, Nagaokakyo-shi (JP)

(72) Inventors: **Pintu ADHIKARI**, West Lafayette, IN (US); **Neal FENZI**, Santa Barbara, CA (US); **Andrew GUYETTE**, San Mateo, CA (US)

(21) Appl. No.: **18/478,193**

(22) Filed: **Sep. 29, 2023**

Related U.S. Application Data

(63) Continuation of application No. 17/830,219, filed on Jun. 1, 2022, now Pat. No. 11,811,377, which is a continuation of application No. 17/133,849, filed on Dec. 24, 2020, now Pat. No. 11,405,019, which is a continuation-in-part of application No. 17/121,724, filed on Dec. 14, 2020, now Pat. No. 11,405,017.

(60) Provisional application No. 63/087,789, filed on Oct. 5, 2020.

Publication Classification

(51) **Int. Cl.**

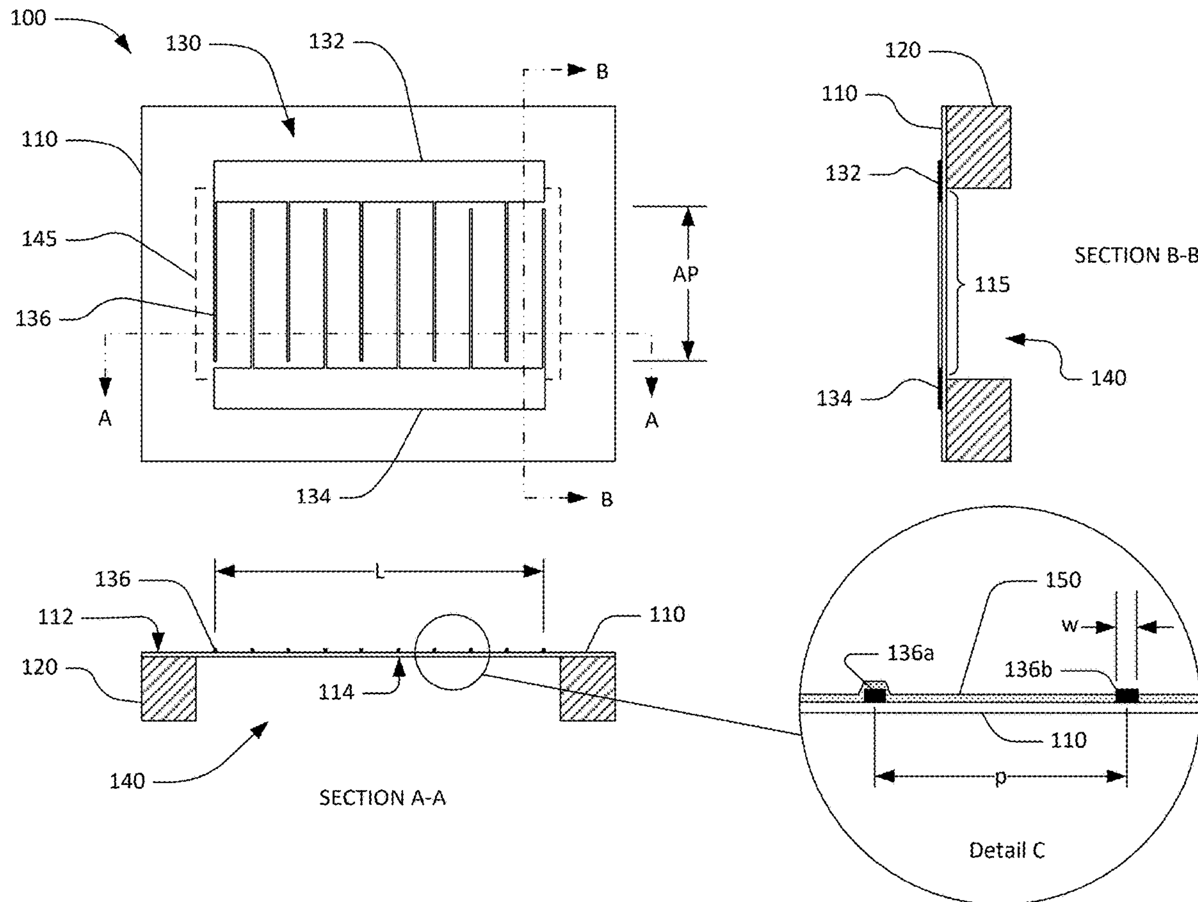
H03H 9/56	(2006.01)
H03H 3/02	(2006.01)
H03H 9/17	(2006.01)
H03H 9/54	(2006.01)
H03H 9/02	(2006.01)

(52) **U.S. Cl.**

CPC ***H03H 9/564*** (2013.01); ***H03H 3/02*** (2013.01); ***H03H 9/174*** (2013.01); ***H03H 9/542*** (2013.01); ***H03H 9/02228*** (2013.01); *H03H 2003/023* (2013.01)

(57) **ABSTRACT**

Radio frequency filters. A radio frequency filter includes a substrate attached to a piezoelectric plate, portions of the piezoelectric plate forming a plurality of diaphragms spanning respective cavities in the substrate. A conductor pattern formed on the piezoelectric plate includes a plurality of interdigital transducers (IDTs) of a respective plurality of resonators, interleaved fingers of each IDT disposed on a respective diaphragm of the plurality of diaphragms. The conductor pattern connects the plurality of resonators in a matrix filter circuit including a first sub-filter and a second sub-filter, each sub-filter comprising two or more resonators from the plurality of resonators.



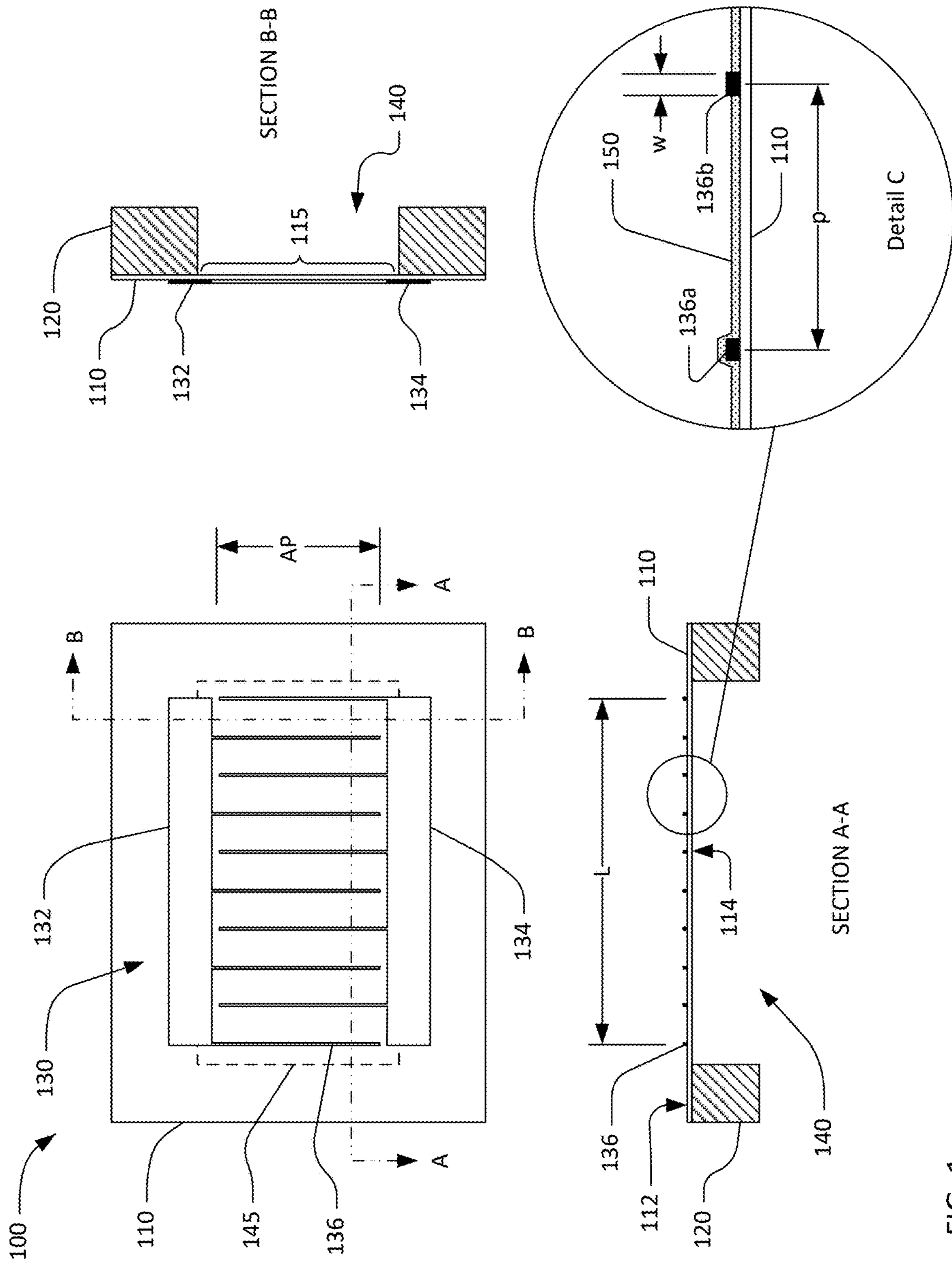


FIG. 1

200

|Admittance| (dB)

20
0
-30
-60
-90

212

214

3.2
3.6
4.0
4.4
4.8
5.2

Frequency (GHz)

FIG. 2B

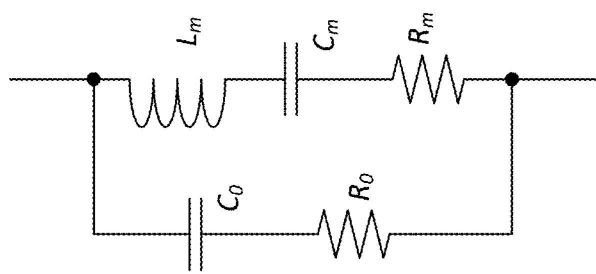


FIG. 2A

FIG. 2C

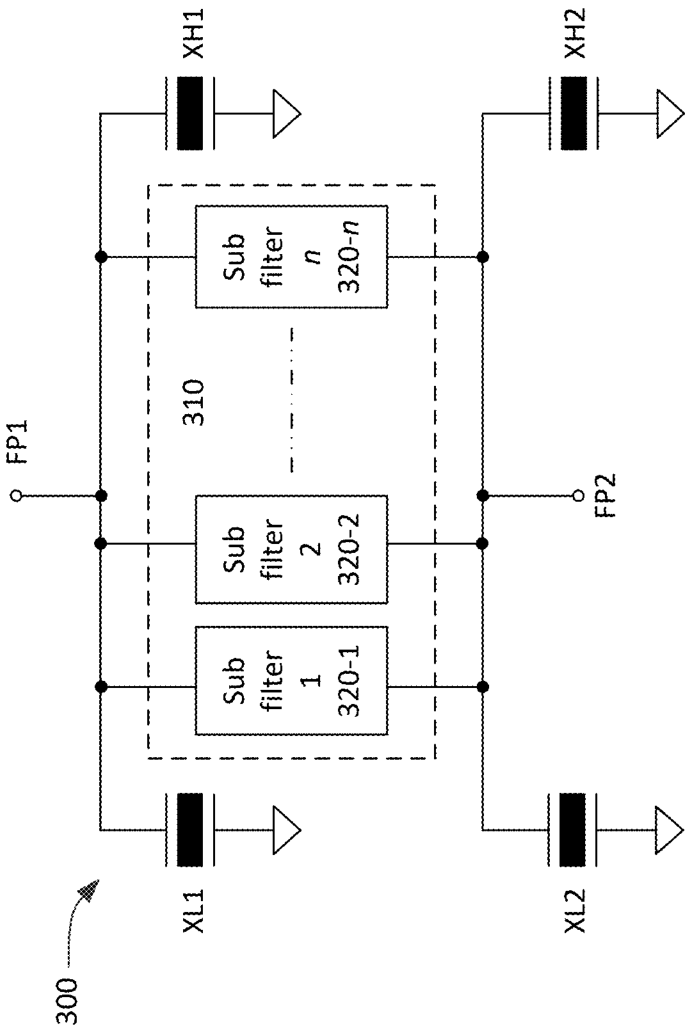


FIG. 3A

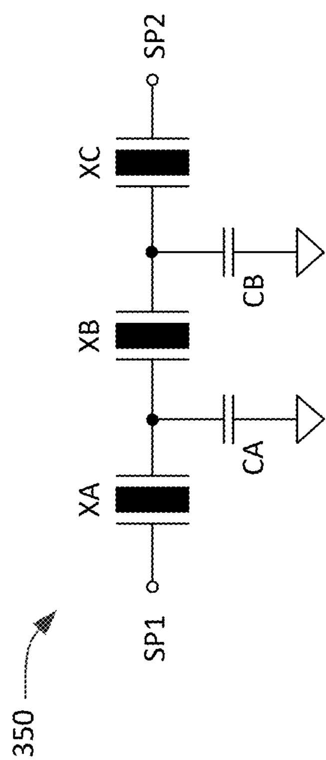


FIG. 3B

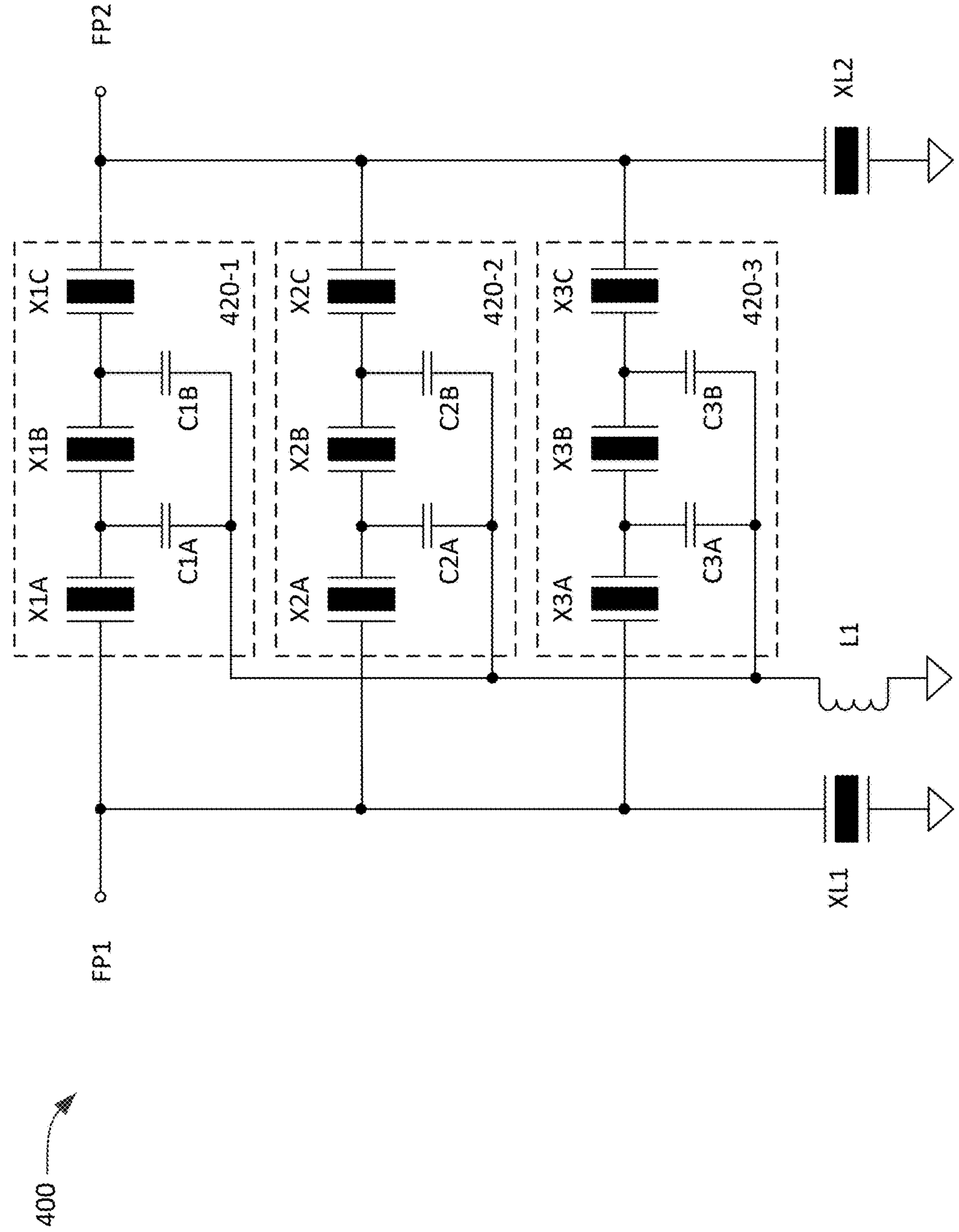


FIG. 4

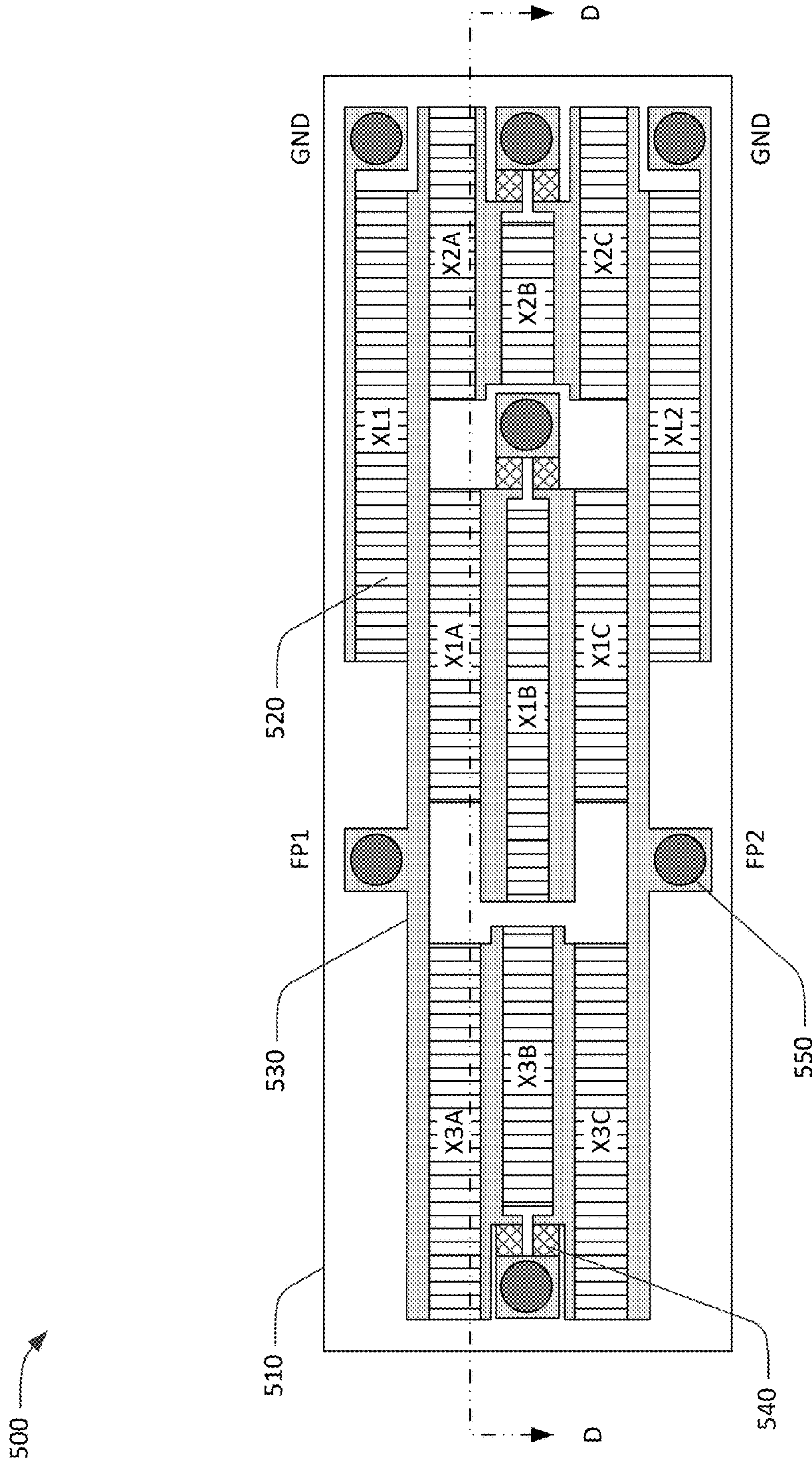


FIG. 5

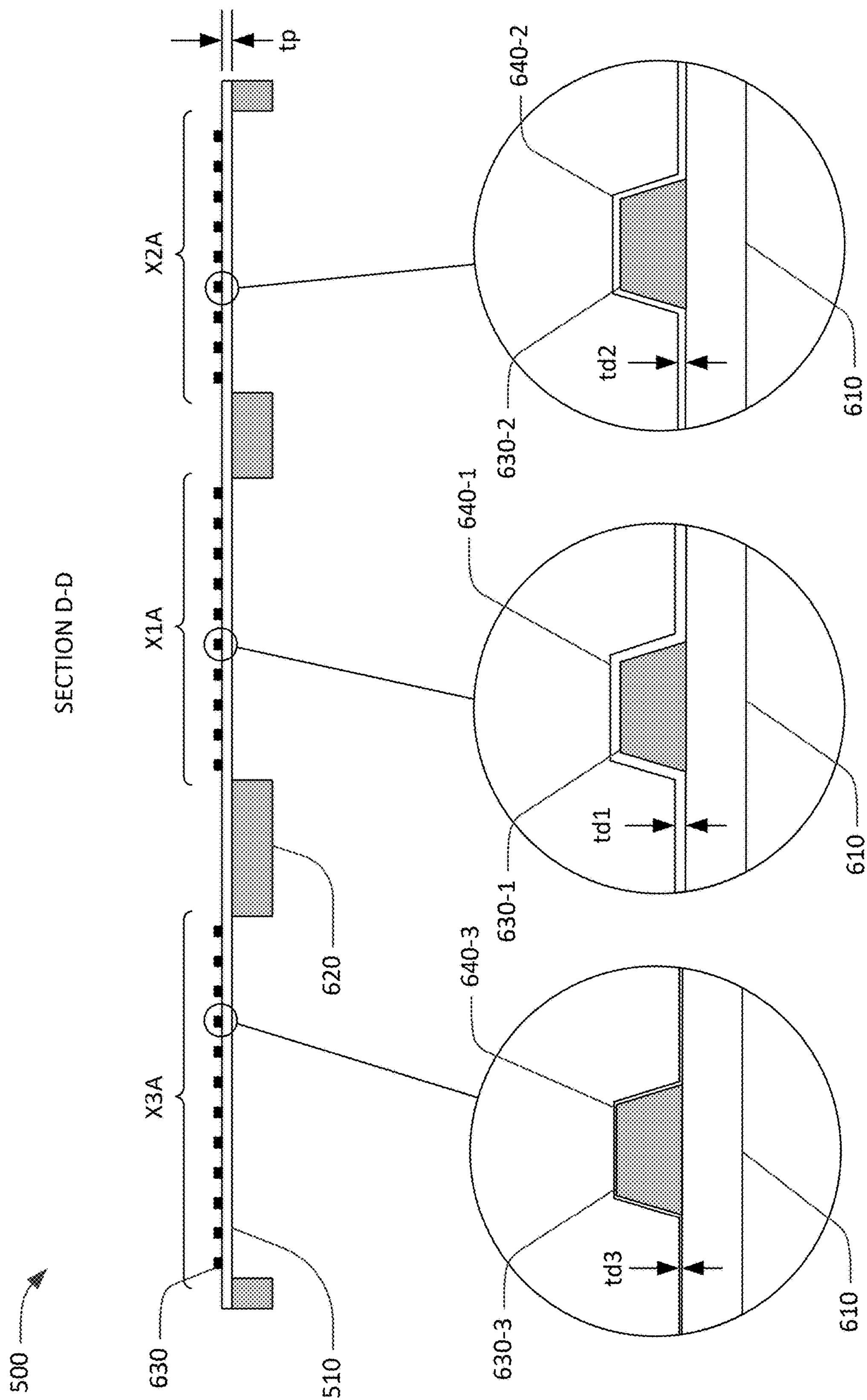


FIG. 6

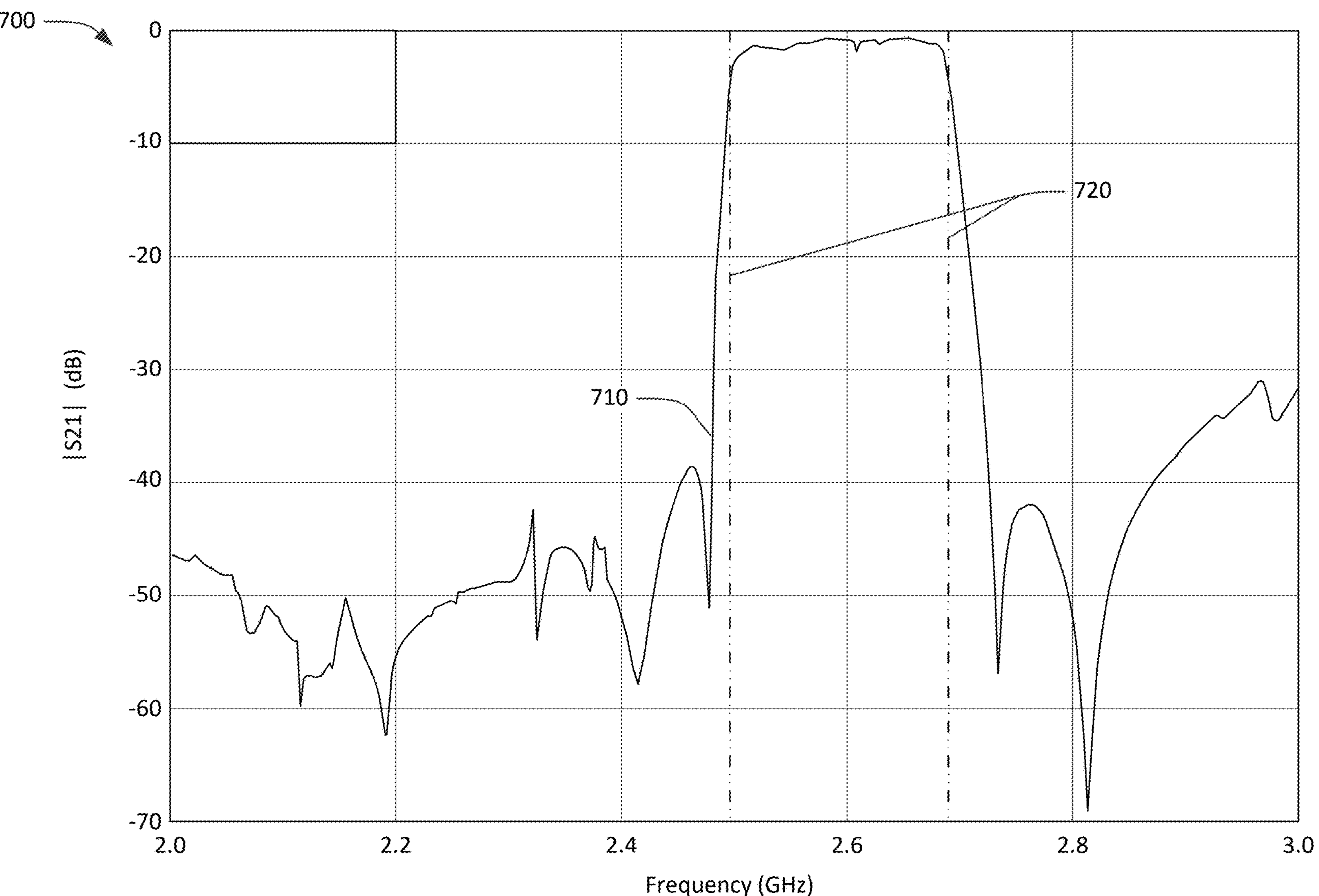


FIG. 7

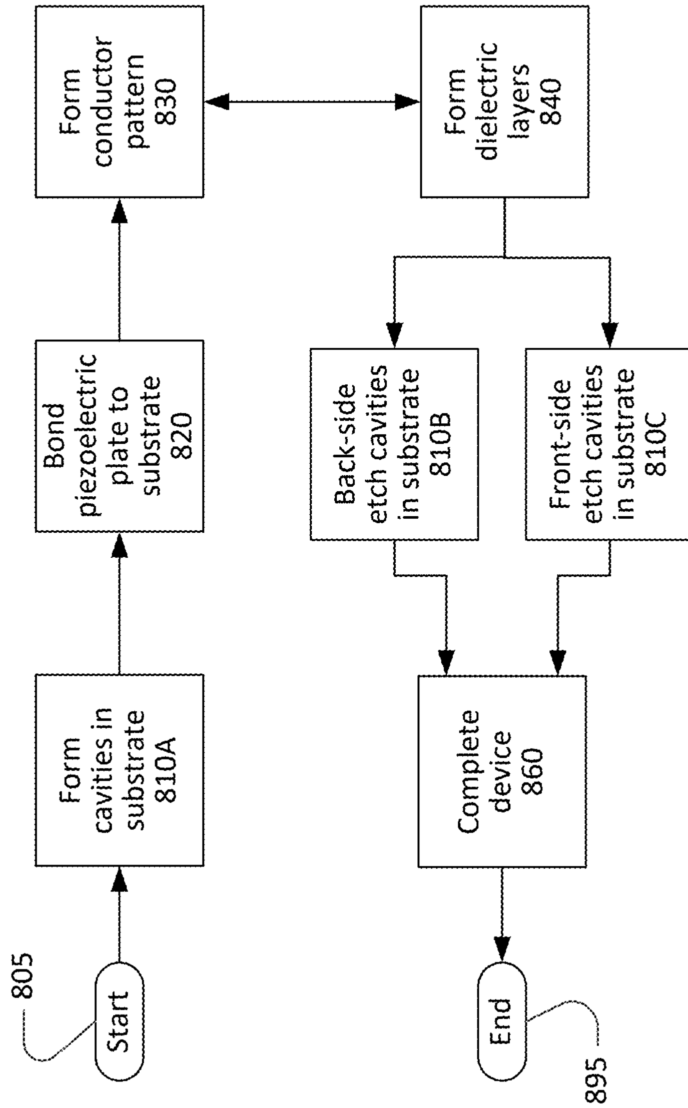


FIG. 8

TRANSVERSELY-EXCITED FILM BULK ACOUSTIC RESONATOR MATRIX FILTERS

CROSS REFERENCE TO RELATED APPLICATION

[0001] This patent is a continuation of U.S. patent application Ser. No. 17/830,219, filed Jun. 1, 2022, titled TRANSVERSELY-EXCITED FILM BULK ACOUSTIC RESONATOR MATRIX FILTERS, which is a continuation of U.S. patent application Ser. No. 17/133,849, filed Dec. 24, 2020, titled TRANSVERSELY-EXCITED FILM BULK ACOUSTIC RESONATOR MATRIX FILTERS, now U.S. Pat. No. 11,405,019, which is a continuation-in-part of U.S. patent application Ser. No. 17/121,724, filed Dec. 14, 2020, titled ACOUSTIC MATRIX FILTERS AND RADIOS USING ACOUSTIC MATRIX FILTERS, now U.S. Pat. No. 11,405,017, which claims priority from U.S. Provisional Patent application 63/087,789, filed Oct. 5, 2020, entitled MATRIX XBAR FILTER, all of which are incorporated herein by reference in their entirety.

TECHNICAL FIELD

[0002] This disclosure relates to radio frequency filters using acoustic wave resonators, and specifically to filters for use in communications equipment.

BACKGROUND

[0003] A radio frequency (RF) filter is a two-port device configured to pass some frequencies and to stop other frequencies, where “pass” means transmit with relatively low signal loss and “stop” means block or substantially attenuate. The range of frequencies passed by a filter is referred to as the “pass-band” of the filter. The range of frequencies stopped by such a filter is referred to as the “stop-band” of the filter. A typical RF filter has at least one pass-band and at least one stop-band. Specific requirements on a passband or stop-band depend on the specific application. For example, a “pass-band” may be defined as a frequency range where the insertion loss of a filter is better than a defined value such as 1 dB, 2 dB, or 3 dB. A “stop-band” may be defined as a frequency range where the rejection of a filter is greater than a defined value such as 20 dB, 30 dB, 40 dB, or greater depending on application.

[0004] RF filters are used in communications systems where information is transmitted over wireless links. For example, RF filters may be found in the RF front-ends of cellular base stations, mobile telephone and computing devices, satellite transceivers and ground stations, IoT (Internet of Things) devices, laptop computers and tablets, fixed point radio links, and other communications systems. RF filters are also used in radar and electronic and information warfare systems.

[0005] RF filters typically require many design trade-offs to achieve, for each specific application, the best compromise between performance parameters such as insertion loss, rejection, isolation, power handling, linearity, size and cost. Specific design and manufacturing methods and enhancements can benefit simultaneously one or several of these requirements.

[0006] Performance enhancements to the RF filters in a wireless system can have broad impact to system performance. Improvements in RF filters can be leveraged to provide system performance improvements such as larger cell size, longer battery life, higher data rates, greater network capacity, lower cost, enhanced security, higher reliability, etc. These improvements can be realized at many levels of the wireless system both separately and in combination, for example at the RF module, RF transceiver, mobile or fixed sub-system, or network levels.

[0007] High performance RF filters for present communication systems commonly incorporate acoustic wave resonators including surface acoustic wave (SAW) resonators, bulk acoustic wave (BAW) resonators, film bulk acoustic wave resonators (FBAR), and other types of acoustic resonators. However, these existing technologies are not well-suited for use at the higher frequencies and bandwidths proposed for future communications networks.

[0008] The desire for wider communication channel bandwidths will inevitably lead to the use of higher frequency communications bands. Radio access technology for mobile telephone networks has been standardized by the 3GPP (3rd Generation Partnership Project). Radio access technology for 5th generation mobile networks is defined in the 5G NR (new radio) standard. The 5G NR standard defines several new communications bands. Two of these new communications bands are N77, which uses the frequency range from 3300 MHz to 4200 MHz, and N79, which uses the frequency range from 4400 MHz to 5000 MHz. Both band N77 and band N79 use time-division duplexing (TDD), such that a communications device operating in band N77 and/or band N79 use the same frequencies for both uplink and downlink transmissions. Bandpass filters for bands N77 and N79 must be capable of handling the transmit power of the communications device. WiFi bands at 5 GHz and 6 GHz also require high frequency and wide bandwidth. The 5G NR standard also defines millimeter wave communication bands with frequencies between 24.25 GHz and 40 GHz.

[0009] The Transversely-Excited Film Bulk Acoustic Resonator (XBAR) is an acoustic resonator structure for use in microwave filters. The XBAR is described in U.S. Pat. No. 10,491,291, titled TRANSVERSELY EXCITED FILM BULK ACOUSTIC RESONATOR, which is incorporated herein by reference. An XBAR resonator comprises an interdigital transducer (IDT) formed on a thin floating layer, or diaphragm, of a single-crystal piezoelectric material. The IDT includes a first set of parallel fingers, extending from a first busbar and a second set of parallel fingers extending from a second busbar. The first and second sets of parallel fingers are interleaved. A microwave signal applied to the IDT excites a shear primary acoustic wave in the piezoelectric diaphragm. XBAR resonators provide very high electromechanical coupling and high frequency capability. XBAR resonators may be used in a variety of RF filters including band-reject filters, band-pass filters, duplexers, and multiplexers. XBARs are well suited for use in filters for communications bands with frequencies above 3 GHz. Matrix XBAR filters are also suited for frequencies between 1 GHz and 3 GHz.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. **1** includes a schematic plan view, two schematic cross-sectional views, and a detailed cross-sectional view of a transversely-excited film bulk acoustic resonator (XBAR).

[0011] FIG. **2**A is an equivalent circuit model of an acoustic resonator.

[0012] FIG. **2**B is a graph of the admittance of an ideal acoustic resonator.

[0013] FIG. **2**C is a circuit symbol for an acoustic resonator.

[0014] FIG. **3**A is a schematic diagram of a matrix filter using acoustic resonators.

[0015] FIG. **3**B is a schematic diagram of a sub-filter of FIG. **3**A.

[0016] FIG. **4** is a schematic diagram of a matrix filter using transversely-excited film bulk acoustic resonators.

[0017] FIG. **5** is plan view of an embodiment of the matrix filter of FIG. **4**.

[0018] FIG. **6** is a schematic cross-sectional view of the matrix filter of FIG. **5**.

[0019] FIG. **7** is a graph of input-output transfer functions of an embodiment of the multiplexer of FIGS. **4**-**6**.

[0020] FIG. **8** is flow chart of a process for making a matrix filter using transversely-excited film bulk acoustic resonators.

[0021] Throughout this description, elements appearing in figures are assigned three-digit or four-digit reference designators, where the two least significant digits are specific to the element and the one or two most significant digit is the figure number where the element is first introduced. An element that is not described in conjunction with a figure may be presumed to have the same characteristics and function as a previously-described element having the same reference designator.

DETAILED DESCRIPTION

[0022] Description of Apparatus

[0023] FIG. **1** shows a simplified schematic top view, orthogonal cross-sectional views, and a detailed cross-sectional view of a transversely-excited film bulk acoustic resonator (XBAR) **100**. XBAR resonators such as the resonator **100** may be used in a variety of RF filters including band-reject filters, band-pass filters, duplexers, and multiplexers. XBARs are particularly suited for use in filters for communications bands with frequencies above 3 GHz. The matrix XBAR filters described in this patent are also suited for frequencies above 1 GHz.

[0024] The XBAR **100** is made up of a thin film conductor pattern formed on a surface of a piezoelectric plate **110** having parallel front and back surfaces **112**, **114**, respectively. The piezoelectric plate is a thin single-crystal layer of a piezoelectric material such as lithium niobate, lithium tantalate, lanthanum gallium silicate, gallium nitride, or aluminum nitride. The piezoelectric plate is cut such that the orientation of the X, Y, and Z crystalline axes with respect to the front and back surfaces is known and consistent. The piezoelectric plate may be Z-cut (which is to say the Z axis is normal to the front and back surfaces **112**, **114**), rotated Z-cut, or rotated YX cut. XBARs may be fabricated on piezoelectric plates with other crystallographic orientations.

[0025] The back surface **114** of the piezoelectric plate **110** is attached to a surface of the substrate **120** except for a portion of the piezoelectric plate **110** that forms a diaphragm **115** spanning a cavity **140** formed in the substrate. The portion of the piezoelectric plate that spans the cavity is referred to herein as the "diaphragm" **115** due to its physical resemblance to the diaphragm of a microphone. As shown in FIG. **1**, the diaphragm **115** is contiguous with the rest of the piezoelectric plate **110** around all of a perimeter **145** of the cavity **140**. In this context, "contiguous" means "continuously connected without any intervening item". In other configurations, the diaphragm **115** may be contiguous with the piezoelectric plate around at least 50% of the perimeter **145** of the cavity **140**.

[0026] The substrate **120** provides mechanical support to the piezoelectric plate **110**. The substrate **120** may be, for example, silicon, sapphire, quartz, or some other material or combination of materials. The back surface **114** of the piezoelectric plate **110** may be bonded to the substrate **120** using a wafer bonding process. Alternatively, the piezoelectric plate **110** may be grown on the substrate **120** or attached to the substrate in some other manner. The piezoelectric plate **110** may be attached directly to the substrate or may be attached to the substrate **120** via one or more intermediate material layers (not shown in FIG. **1**).

[0027] "Cavity" has its conventional meaning of "an empty space within a solid body." The cavity **140** may be a hole completely through the substrate **120** (as shown in Section A-A and Section B-B) or a recess in the substrate **120** under the diaphragm **115**. The cavity **140** may be formed, for example, by selective etching of the substrate **120** before or after the piezoelectric plate **110** and the substrate **120** are attached.

[0028] The conductor pattern of the XBAR **100** includes an interdigital transducer (IDT) **130**. The IDT **130** includes a first plurality of parallel fingers, such as finger **136**, extending from a first busbar **132** and a second plurality of fingers extending from a second busbar **134**. The first and second pluralities of parallel fingers are interleaved. The interleaved fingers overlap for a distance AP, commonly referred to as the "aperture" of the IDT. The center-to-center distance L between the outermost fingers of the IDT **130** is the "length" of the IDT.

[0029] The first and second busbars **132**, **134** serve as the terminals of the XBAR **100**. A radio frequency or microwave signal applied between the two busbars **132**, **134** of the IDT **130** excites a primary acoustic mode within the piezoelectric plate **110**. The primary acoustic mode of an XBAR is a bulk shear mode where acoustic energy propagates along a direction substantially orthogonal to the surface of the piezoelectric plate **110**, which is also normal, or transverse, to the direction of the electric field created by the IDT fingers. Thus, the XBAR is considered a transversely-excited film bulk wave resonator.

[0030] The IDT **130** is positioned on the piezoelectric plate **110** such that at least the fingers of the IDT **130** are disposed on the diaphragm **115** of the piezoelectric plate which spans, or is suspended over, the cavity **140**. As shown in FIG. **1**, the cavity **140** has a rectangular shape with an extent greater than the aperture AP and length L of the IDT **130**. A cavity of an XBAR may have a different shape, such as a regular or irregular polygon. The cavity of an XBAR may have more or fewer than four sides, which may be straight or curved.

[0031] The detailed cross-section view (Detail C) shows two IDT fingers **136*a***, **136*b*** on the surface of the piezoelectric plate **110**. The dimension p is the "pitch" of the IDT and the dimension w is the width or "mark" of the IDT fingers. A dielectric layer **150** may be formed between and optionally over (see IDT finger **136*a***) the IDT fingers. The dielectric layer **150** may be a non-piezoelectric dielectric material, such as silicon dioxide or silicon nitride. The dielectric layer **150** may be formed of multiple layers of two or more materials. The IDT fingers **136*a*** and **136*b*** may be alumi-

num, copper, beryllium, gold, tungsten, molybdenum, alloys and combinations thereof, or some other conductive material. Thin (relative to the total thickness of the conductors) layers of other metals, such as chromium or titanium, may be formed under and/or over and/or as layers within the fingers to improve adhesion between the fingers and the piezoelectric plate **110** and/or to passivate or encapsulate the fingers and/or to improve power handling. The busbars of the IDT **130** may be made of the same or different materials as the fingers.

[0032] For ease of presentation in FIG. **1**, the geometric pitch and width of the IDT fingers is greatly exaggerated with respect to the length (dimension L) and aperture (dimension AP) of the XBAR. A typical XBAR has more than ten parallel fingers in the IDT **110**. An XBAR may have hundreds of parallel fingers in the IDT **110**. Similarly, the thickness of the fingers in the cross-sectional views is greatly exaggerated.

[0033] An XBAR based on shear acoustic wave resonances can achieve better performance than current state-of-the art surface acoustic wave (SAW), film-bulk-acoustic-resonators (FBAR), and solidly-mounted-resonator bulk-acoustic-wave (SMR BAW) devices. In particular, the piezoelectric coupling for shear wave XBAR resonances can be high (>20%) compared to other acoustic resonators. High piezoelectric coupling enables the design and implementation of microwave and millimeter-wave filters of various types with appreciable bandwidth.

[0034] The basic behavior of acoustic resonators, including XBARs, is commonly described using the Butterworth Van Dyke (BVD) circuit model as shown in FIG. **2**A. The BVD circuit model consists of a motional arm and a static arm. The motional arm includes a motional inductance L_m, a motional capacitance C_m, and a resistance R_m. The static arm includes a static capacitance C_0 and a resistance R_0. While the BVD model does not fully describe the behavior of an acoustic resonator, it does a good job of modeling the two primary resonances that are used to design band-pass filters, duplexers, and multiplexers (multiplexers are filters with more than 2 input or output ports with multiple passbands).

[0035] The first primary resonance of the BVD model is the motional resonance caused by the series combination of the motional inductance L_m and the motional capacitance C_m. The second primary resonance of the BVD model is the anti-resonance caused by the combination of the motional inductance L_m, the motional capacitance C_m, and the static capacitance C_0. In a lossless resonator (R_m=R_0=0), the frequency F_r of the motional resonance is given by

$$F_r = \frac{1}{2\pi\sqrt{L_m C_m}} \tag{1}$$

The frequency F_a of the anti-resonance is given by

$$F_a = F_r\sqrt{1+\frac{1}{\gamma}} \tag{2}$$

where $\gamma = C_0/C_m$ is dependent on the resonator structure and the type and the orientation of the crystalline axes of the piezoelectric material.

[0036] FIG. **2**B is a graph **200** of the magnitude of admittance of a theoretical lossless acoustic resonator. The acoustic resonator has a resonance **212** at a resonance frequency where the admittance of the resonator approaches infinity. The resonance is due to the series combination of the motional inductance L_m and the motional capacitance C_m in the BVD model of FIG. **2**A. The acoustic resonator also exhibits an anti-resonance **214** where the admittance of the resonator approaches zero. The anti-resonance is caused by the combination of the motional inductance L_m, the motional capacitance C_m, and the static capacitance C_0. In a lossless resonator (R_m=R_0=0), the frequency F_r of the resonance is given by

$$F_r = \frac{1}{2\pi\sqrt{L_m C_m}} \tag{1}$$

The frequency F_a of the anti-resonance is given by

$$F_a = F_r\sqrt{1+\frac{1}{\gamma}} \tag{2}$$

[0037] In over-simplified terms, the lossless acoustic resonator can be considered a short circuit at the resonance frequency **212** and an open circuit at the anti-resonance frequency **214**. The resonance and anti-resonance frequencies in FIG. **2**B are representative, and an acoustic resonator may be designed for other frequencies.

[0038] FIG. **2**C shows the circuit symbol for an acoustic resonator such as an XBAR. This symbol will be used to designate each acoustic resonator in schematic diagrams of filters in subsequent figures.

[0039] FIG. **3**A is a schematic diagram of a matrix filter **300** using acoustic resonators. The matrix filter **300** includes an array **310** of n sub-filters **320-1**, **320-2**, **320-*n*** connected in parallel between a first filter port (FP**1**) and a second filter port (FP**2**), where n is an integer greater than one. Each of the n sub-filters **320-1**, **320-2**, **320-*n*** is a bandpass filter having a bandwidth about 1/n times the bandwidth of the matrix filter **300**. The sub-filters **320-1**, **320-2**, **320-*n*** have contiguous passbands such that the bandwidth of the matrix filter **300** is equal to the sum of the bandwidths of the constituent sub-filters. In the subsequent examples in this patent n=3. n can be less than or greater than 3 as necessary to provide the desired bandwidth for the matrix filter **300**.

[0040] The array **310** of sub-filters is terminated at both ends by acoustic resonators XL**1**, XL**2**, XH**1**, and XH**2**, which are preferably but not necessarily XBARs. The acoustic resonators XL**1**, XL**2**, XH**1**, and XH**2** create "transmission zeros" at their respective resonance frequencies. A "transmission zero" is a frequency where the input-output transfer function of the filter is very low (and would be zero if the acoustic resonators XL**1**, XL**2**, XH**1**, and XH**2** were lossless). Typically, but not necessarily, the resonance frequencies of XL**1** and XL**2** are equal, and the resonance frequencies of XH**1** and XH**2** are equal. The resonant frequencies of the acoustic resonators XL**1**, XL**2** are selected to provide transmission zeros adjacent to the lower edge of the filter passband. XL**1** and XL**2** may be referred to as "low-edge resonators" since their resonant frequencies are proximate the lower edge of the filter passband. The acoustic

resonators XL1 and XL2 also act as shunt inductances to help match the impedance at the ports of the filter to a desired impedance value. In the subsequent examples in this patent, the impedance at all ports of the filters is matched to 50 ohms. The resonant frequencies of acoustic resonators XH1, XH2 are selected to provide transmission zeros at or above the higher edge of the filter passband. XH1 and XH2 may be referred to as "high-edge resonators" since their resonant frequencies are proximate the higher edge of the filter passband. High-edge resonators XH1 and XH2 may not be required in all matrix filters.

[0041] FIG. **3**B is a schematic diagram of a sub-filter **350** suitable for sub-filters **320-1**, **320-2**, and **320-*n***. The sub-filter **350** includes three acoustic resonators XA, XB, XC connected in series between a first sub-filter port (SP**1**) and a second sub-filter port (SP**2**). The acoustic resonators X**1**, X**2**, X**3** are preferably but not necessarily XBARs. The sub-filter **350** includes two coupling capacitors CA, CB, each of which is connected between ground and a respective node between two of the acoustic resonators. The inclusion of three acoustic resonators in the sub-filter **350** is exemplary. A sub-filter may have m acoustic resonators, where m is an integer greater than one. A sub-filter with m acoustic resonators includes m−1 coupling capacitors. The m acoustic resonators of a sub-filter are connected in series between the two ports SP**1** and SP**2** of a sub-filter and each of the m−1 coupling capacitors is connected between ground and a node between a respective pair of acoustic resonators from the m acoustic resonators.

[0042] Compared to other types of acoustic resonators, XBARs have very high electromechanical coupling (which results in a large difference between the resonance and anti-resonance frequencies), but low capacitance per unit area. The matrix filter architecture, as shown in FIG. **3**A and FIG. **3**B, takes advantage of the high electromechanical coupling of XBARs without requiring high resonator capacitance.

[0043] FIG. **4** is a schematic circuit diagram of an exemplary matrix filter **400** implemented with XBARs. The matrix filter **400** includes three sub-filters **420-1**, **420-2**, **420-3** connected in parallel between a first filter port (FP**1**) and a second filter port (FP**2**). The sub-filters **420-1**, **420-2**, **420-3** have contiguous passbands such that the bandwidth of the matrix filter **300** is equal to the sum of the bandwidths of the constituent sub-filters. Each sub-filter includes three XBARs connected in series and two capacitors. For example, sub-filter **420-1** includes XBARs X**1**A, X**1**B, X**1**C and capacitors CIA, CiB. Components of the other sub-filters **420-2** and **420-3** are similarly identified. Low-edge XBARs XL**1** and XL**2** are connected between FP**1** and FP**2**, respectively, and ground. All of the capacitors within the sub-filters are connected to ground through a common inductor L**1**. The inclusion of the inductor L**1** improves the out-of-band rejection of the matrix filter **400**. The matrix filter **400** does not include high-edge resonators.

[0044] The exemplary matrix filter **400** is symmetrical in that the impedances at FP**1** and FP**2** are both equal to 50 ohms. The internal circuitry of the filter is also symmetrical, with XBARs X_A and X_C within each sub-filter being the same and low-edge resonators XL**1** and XL**2** being the same. Other matrix filters may be designed to have significantly different impedances at FP**1** and FP**2**, in which event the internal circuitry will not be symmetrical.

[0045] FIG. **5** is a plan view of an exemplary matrix filter **500** which has the same schematic circuit diagram as the matrix filter **400** of FIG. **4**. The exemplary matrix filter is an LTE band **41** bandpass filter with a passband from 2496 to 2690 MHz.

[0046] The matrix filter **500** includes a Z-cut lithium tantalate piezoelectric plate **510** which is bonded to a substrate (not visible). The thickness of the piezoelectric plate is 730 nm. Other matrix filters may use lithium niobate piezoelectric plates and other crystal orientations including rotated Z-cut and rotated Y-cut.

[0047] The matrix filter **500** includes eleven XBARs, such as the XBAR **520**. A cavity (not visible) is formed in the substrate under each XBAR. Each XBAR is shown as a rectangle with vertical hatching and is identified by the designator (XL**1**, X**1**A, . . .) used in the schematic diagram of FIG. **4**. The vertical hatching is representative of the direction of the IDT fingers of each XBAR but not to scale. Each XBAR has between 65 and 130 IDT fingers. The IDT fingers are aluminum 925 nm thick. The apertures (vertical direction as shown in FIG. **5**) of the XBARs range from 40 microns to 58 microns, and the lengths (left-right direction as shown in FIG. **5**) range from 500 to 1000 microns. In other embodiments of XBAR matrix filters, the XBARs may be divided into sections to limit the length of the diaphragm within each XBAR. The pitch of the IDTs of each XBAR is between 7.5 and 8.6 microns and the mark/pitch ratio of each XBAR is between 0.22 and 0.31.

[0048] The XBARs are connected by conductors such as conductor **530**. Cross-hatched rectangles are metal-insulator-metal capacitors, of which only capacitor **540** is identified. The identified capacitor **540** is C**3**B in the schematic diagram of FIG. **4**.

[0049] Connections from the filter **510** and circuitry external to the filter are made by means of conductive pads indicated by shaded circles, such as conductive pad **550**. The conductive pads for Filter Port **1** (FP**1**), Filter Port **2** (FP**2**), and ground (GND) are labeled. The three other conductive pads connect to ground through inductor L**1** (in FIG. **4**), which is located external to the filter **510**.

[0050] As previously described, the sub-filters of a matrix filter have contiguous passbands that span the passband of the matrix filter. Within a matrix filter, the center frequency of the passband of each sub-filter is different from the center frequency of any other sub-filter. Consequentially, the resonance frequencies of the XBARs in the sub-filter are different from the resonance frequencies of the XBARs within any other sub-filter.

[0051] The resonance frequency of an XBAR is primarily determined by the thickness of the diaphragm within the XBAR. The resonance frequency has a smaller dependence on IDT pitch and mark or finger width. U.S. Pat. No. 10,491,291 describes the use of a dielectric layer formed between the IDT fingers to adjust the resonance frequency of an XBAR.

[0052] FIG. **6** is a schematic cross-section view of the matrix filter **500** at a section plane D-D defined in FIG. **5**. The section plane D-D passes through one XBAR (X**1**A, X**2**A, X**3**A) from each of the three sub-filters in the matrix filter **500**. Each XBAR includes IDT fingers (of which only IDT finger **630** is identified) formed on a respective diaphragm spanning a respective cavity in a substrate **620**. Each diaphragm includes a portion of a piezoelectric plate **510**. As in previous figures, the thickness of the piezoelectric plate

510 and the thickness, pitch, and finger width of the IDTs are greatly exaggerated for visibility. Drawn to scale, the thickness of the piezoelectric plate **610** and the IDT fingers would be less than one-half percent of the thickness of the substrate **620** and each IDT would have 65 to 130 IDT fingers.

[0053] The three detail views illustrate the use of dielectric thickness to set the resonance frequencies of the XBARs within each sub-filter. Consider first the detail view of an IDT finger of XBAR X**1**A (the middle view of the three detail views), which shows an IDT finger **630-1** formed on a portion of the piezoelectric plate **510**. The IDT finger **630-1** is shown with a trapezoidal cross-section. The trapezoidal shape is exemplary and IDT fingers may have other cross-sectional shapes. The IDT finger **630-1** and the space between IDT finger **630-1** and adjacent IDT fingers is covered by a dielectric layer **640-1** having a thickness td**1**.

[0054] Similarly, the right-hand detail shows IDT finger **630-2** from XBAR X**2**A, which is covered by a dielectric layer **640-2** having a thickness td**2**. The left-hand detail shows IDT finger **630-3** from XBAR X**3**A, which is covered by a dielectric layer **640-3** having a thickness td**3**. The dielectric layers **640-1**, **640-2**, **640-3** may be silicon dioxide, silicon nitride, aluminum oxide or some other dielectric material or combination of materials. The dielectric layers **640-1**, **640-2**, **640-3** may be the same or different materials.

[0055] In this example, XBAR X**1**A is an element of the sub-filter with the lowest passband frequency and XBAR X**3**A is an element of the sub-filter with the highest passband frequency. In this case td**1**>td**2**>td**3**≥0.

[0056] In a more general case where a matrix filter has n sub-filters, which are numbered in order of increasing passband frequency, td**1**>td**2**> . . . >tdn, where tdi is the dielectric thickness over the XBARs of sub-filter i.

[0057] An XBAR filter device typically includes a passivation dielectric layer applied over the entire surface of the device, other than contact pads, to seal and passivate the conductor patterns and other elements of the device. The thickness t_{pass} of the passivation layer sets the minimum dielectric thickness over the IDTs of the XBARs. Further, a practical maximum dielectric thickness over the IDTs of the XBARs is about 0.35 times the thickness tp of the piezoelectric plate. Above this dielectric thickness, substantial energy may be coupled into spurious acoustic modes that degrade the performance of a matrix filter. With these constraints, 0.35tp≥td**1**>td**2**> . . . >tdn≥tpass.

[0058] FIG. **7** is graph **700** of the simulated performance of a matrix filter similar to the matrix filter **500**. The curve **710** is a plot of S**21**, the input-output transfer function, of the filter determined by simulation of a physical model of the filter using finite element techniques. The broken lines **720** mark the band edges of 5G NR communication band n41. The matrix filter architecture extends the application of XBARs to lower frequency communications bands that are impractical using a conventional ladder filter architecture.

[0059] Description of Methods

[0060] FIG. **8** is a simplified flow chart showing a process **800** for making an XBAR or a filter incorporating XBARs. The process **800** starts at **805** with a substrate and a plate of piezoelectric material and ends at **895** with a completed XBAR or filter. The flow chart of FIG. **8** includes only major process steps. Various conventional process steps (e.g. surface preparation, cleaning, inspection, baking, annealing, monitoring, testing, etc.) may be performed before, between, after, and during the steps shown in FIG. **8**.

[0061] The flow chart of FIG. **8** captures three variations of the process **800** for making an XBAR which differ in when and how cavities are formed in the substrate. The cavities may be formed at steps **810**A, **810**B, or **810**C. Only one of these steps is performed in each of the three variations of the process **800**.

[0062] The piezoelectric plate may be, for example, Z-cut lithium niobate or lithium tantalate with Euler angles 0, 0, 90°. The piezoelectric plate may be rotated Z-cut lithium niobate with Euler angles 0, β, 90°, where β is in the range from −15° to +5°. The piezoelectric plate may be rotated Y-cut lithium niobate or lithium tantalate with Euler angles 0, β, 0, where β is in the range from 0 to 60°. The piezoelectric plate may be some other material or crystallographic orientation. The substrate may preferably be silicon. The substrate may be some other material that allows formation of deep cavities by etching or other processing.

[0063] In one variation of the process **800**, one or more cavities are formed in the substrate at **810**A, before the piezoelectric plate is bonded to the substrate at **820**. A separate cavity may be formed for each resonator in a filter device. The one or more cavities may be formed using conventional photolithographic and etching techniques. Typically, the cavities formed at **810**A will not penetrate through the substrate.

[0064] At **820**, the piezoelectric plate is bonded to the substrate. The piezoelectric plate and the substrate may be bonded by a wafer bonding process. Typically, the mating surfaces of the substrate and the piezoelectric plate are highly polished. One or more layers of intermediate materials, such as an oxide or metal, may be formed or deposited on the mating surface of one or both of the piezoelectric plate and the substrate. One or both mating surfaces may be activated using, for example, a plasma process. The mating surfaces may then be pressed together with considerable force to establish molecular bonds between the piezoelectric plate and the substrate or intermediate material layers.

[0065] A conductor pattern, including IDTs of each XBAR, is formed at **830** by depositing and patterning two or more conductor levels on the front side of the piezoelectric plate. The conductor levels typically include a first conductor level that includes the IDT fingers, and a second conductor level formed over the IDT busbars and other conductors except the IDT fingers. In some devices, a third conductor levels may be formed on the contact pads. Each conductor level may be one or more layers of, for example, aluminum, an aluminum alloy, copper, a copper alloy, or some other conductive metal. Optionally, one or more layers of other materials may be disposed below (i.e. between each conductor layer and the piezoelectric plate) and/or on top of each conductor layer. For example, a thin film of titanium, chrome, or other metal may be used to improve the adhesion between the first conductor level and the piezoelectric plate. The second conductor level may be conduction enhancement layer of gold, aluminum, copper or other higher conductivity metal may be formed over portions of the first conductor level (for example the IDT bus bars and interconnections between the IDTs).

[0066] Each conductor level may be formed at **830** by depositing the appropriate conductor layers in sequence over the surface of the piezoelectric plate. The excess metal may then be removed by etching through patterned photoresist.

The conductor level can be etched, for example, by plasma etching, reactive ion etching, wet chemical etching, and other etching techniques.

[0067] Alternatively, each conductor level may be formed at **830** using a lift-off process. Photoresist may be deposited over the piezoelectric plate. and patterned to define the conductor level. The appropriate conductor layers may be deposited in sequence over the surface of the piezoelectric plate. The photoresist may then be removed, which removes the excess material, leaving the conductor level.

[0068] When a conductor level has multiple layers, the layers may be deposited and patterned separately. In particular, different patterning processes (i.e. etching or lift-off) may be used on different layers and/or levels and different masks are required where two or more layers of the same conductor level have different widths or shapes.

[0069] At **840**, dielectric layers may be formed by depositing one or more layers of dielectric material on the front side of the piezoelectric plate. As previously described, the dielectric layers may include a different dielectric thickness over the IDT fingers of the XBARs within each sub-filter. Each dielectric layer may be deposited using a conventional deposition technique such as sputtering, evaporation, or chemical vapor deposition. Each dielectric layer may be deposited over the entire surface of the piezoelectric plate, including on top of the conductor pattern. Alternatively, one or more lithography processes (using photomasks) may be used to limit the deposition of the dielectric layers to selected areas of the piezoelectric plate, such as only between the interleaved fingers of the IDTs. Masks may also be used to allow deposition of different thicknesses of dielectric materials on different portions of the piezoelectric plate.

[0070] The matrix filter shown in FIG. **5** and FIG. **6** includes metal-insulator-metal (MIM) capacitors. A MIM capacitor consists of a first metal level and a second metal level separated by a dielectric layer. When a matrix filter includes MIM capacitor, the steps of forming the conductor patterns at **830** and forming the dielectric layers at **840** must overlap. At least one dielectric layer has to be formed at **840** after a first metal level is formed at **830** and before a final metal level is formed at **830**.

[0071] In a second variation of the process **800**, one or more cavities are formed in the back side of the substrate at **810**B. A separate cavity may be formed for each resonator in a filter device. The one or more cavities may be formed using an anisotropic or orientation-dependent dry or wet etch to open holes through the back side of the substrate to the piezoelectric plate. In this case, the resulting resonator devices will have a cross-section as shown in FIG. **1**.

[0072] In the second variation of the process **800**, a back-side dielectric layer may be formed at **850**. In the case where the cavities are formed at **810**B as holes through the substrate, the back-side dielectric layer may be deposited through the cavities using a conventional deposition technique such as sputtering, evaporation, or chemical vapor deposition.

[0073] In a third variation of the process **800**, one or more cavities in the form of recesses in the substrate may be formed at **810**C by etching the substrate using an etchant introduced through openings in the piezoelectric plate. A separate cavity may be formed for each resonator in a filter device.

[0074] In all variations of the process **800**, the filter device is completed at **860**. Actions that may occur at **860** include depositing an encapsulation/passivation layer such as SiO_2 or Si_3O_4 over all or a portion of the device; forming bonding pads or solder bumps or other means for making connection between the device and external circuitry; excising individual devices from a wafer containing multiple devices; other packaging steps; and testing. Another action that may occur at **860** is to tune the resonant frequencies of the resonators within the device by adding or removing metal or dielectric material from the front side of the device. After the filter device is completed, the process ends at **895**.

[0075] Closing Comments

[0076] Throughout this description, the embodiments and examples shown should be considered as exemplars, rather than limitations on the apparatus and procedures disclosed or claimed. Although many of the examples presented herein involve specific combinations of method acts or system elements, it should be understood that those acts and those elements may be combined in other ways to accomplish the same objectives. With regard to flowcharts, additional and fewer steps may be taken, and the steps as shown may be combined or further refined to achieve the methods described herein. Acts, elements and features discussed only in connection with one embodiment are not intended to be excluded from a similar role in other embodiments.

[0077] As used herein, "plurality" means two or more. As used herein, a "set" of items may include one or more of such items. As used herein, whether in the written description or the claims, the terms "comprising", "including", "carrying", "having", "containing", "involving", and the like are to be understood to be open-ended, i.e., to mean including but not limited to. Only the transitional phrases "consisting of" and "consisting essentially of", respectively, are closed or semi-closed transitional phrases with respect to claims. Use of ordinal terms such as "first", "second", "third", etc., in the claims to modify a claim element does not by itself connote any priority, precedence, or order of one claim element over another or the temporal order in which acts of a method are performed, but are used merely as labels to distinguish one claim element having a certain name from another element having a same name (but for use of the ordinal term) to distinguish the claim elements. As used herein, "and/or" means that the listed items are alternatives, but the alternatives also include any combination of the listed items.

It is claimed:

1. A radio frequency filter, comprising:

a substrate;

at least one piezoelectric layer above the substrate, portions of the at least one piezoelectric layer over respective cavities of the radio frequency filter; and

a conductor pattern at the at least one piezoelectric layer, the conductor pattern including a plurality of interdigital transducers (IDTs) of a respective plurality of resonators, interleaved fingers of each IDT disposed on respective portions of the at least one piezoelectric layer over the respective cavities,

wherein the conductor pattern connects the plurality of resonators in a matrix filter circuit comprising a first sub-filter and a second sub-filter, each sub-filter comprising two or more resonators from the plurality of resonators.

2. The radio frequency filter of claim **1**, further comprising:
a first port and a second port,
wherein the two or more resonators of the first sub-filter are connected in series between the first port and the second port, and
wherein the two or more resonators of the second sub-filter are connected in series between the first port and the second port.

3. The radio frequency filter of claim **2**, further comprising:
a first low-edge resonator, from the plurality of resonators, connected between the first port and ground; and
a second low-edge resonator, from the plurality of resonators, connected between the second port and ground,
wherein respective resonance frequencies of the first and second low-edge resonators are adjacent to a lower edge of a passband of the radio frequency filter.

4. The radio frequency filter of claim **3**, wherein all of the first and second low-edge resonators have a common substrate material and a common piezoelectric material.

5. The radio frequency filter of claim **2**, further comprising:
a first high-edge resonator, from the plurality of resonators, connected between the first port and ground; and
a second high-edge resonator, from the plurality of resonators, connected between the second port and ground,
wherein respective resonance frequencies of the first and second high-edge resonators are adjacent to a higher edge of the passband of the filter.

6. The radio frequency filter of claim **1**, wherein the at least one piezoelectric layer and the plurality of IDTs are configured such that respective radio frequency signals applied to the IDTs excite respective primary shear acoustic modes in the respective portions of the at least one piezoelectric layer over the respective cavities.

7. The radio frequency filter of claim **1**, further comprising:
a first dielectric layer having a first thickness and that is formed over the IDTs of the two or more resonators of the first sub-filter; and
a second dielectric layer having a second thickness and that is formed over the IDTs of the two or more resonators of the second sub-filter, the first thickness being different than the second thickness.

8. The radio frequency filter of claim **7**,
wherein either the first or second dielectric layer has a thickness t_{dn}, and
wherein the radiofrequency filter further comprises a passivation layer of dielectric having a thickness t_{pass} at the at least one piezoelectric layer, wherein t_{dn} t_{pass}.

9. The radio frequency filter of claim **1**, wherein each of the first and second sub-filters comprises:
m resonators connected in series, where m is an integer greater than one; and
m−1 capacitors, each capacitor connected from a junction between two of the m resonators and a common terminal.

10. The radio frequency filter of claim **9**, wherein each of the m−1 capacitors of each sub-filter are metal-insulator-metal capacitors.

11. The radio frequency filter of claim **9**, wherein each of the m−1 capacitors of each sub-filter are interdigitated capacitors.

12. The radio frequency filter of claim **1**, wherein the first and second sub-filters are one of a plurality of n sub-filters, each of the n sub-filters further comprising m−1 capacitors that are each connected from a junction between two of the plurality of resonators and a common terminal.

13. The radio frequency filter of claim **12**, wherein each of the m−1 capacitors of each of the n sub-filters are metal-insulator-metal capacitors.

14. The radio frequency filter of claim **12**, further comprising an inductor connected from the common terminal to ground.

15. A radio frequency filter, comprising:
a substrate;
at least one piezoelectric layer above the substrate; and
a conductor pattern at the at least one piezoelectric layer, the conductor pattern including a plurality of interdigital transducers (IDTs) of a respective plurality of resonators, each IDT including a plurality of interleaved fingers,
wherein the conductor pattern connects the plurality of resonators in a matrix filter circuit comprising a first sub-filter and a second sub-filter, and
wherein each sub-filter comprises two or more resonators from the plurality of resonators.

16. The radio frequency filter of claim **15**,
wherein the at least one piezoelectric layer comprises a plurality of portions that are disposed over respective cavities of the radio frequency filter, and
wherein the interleaved fingers of each IDT are disposed on respective portions of the at least one piezoelectric layer over the respective cavities.

17. The radio frequency filter of claim **15**, further comprising:
a first port and a second port,
wherein the two or more resonators of the first sub-filter are connected in series between the first port and the second port, and
wherein the two or more resonators of the second sub-filter are connected in series between the first port and the second port.

18. The radio frequency filter of claim **17**, further comprising:
a first low-edge resonator, from the plurality of resonators, connected between the first port and ground; and
a second low-edge resonator, from the plurality of resonators, connected between the second port and ground,
wherein respective resonance frequencies of the first and second low-edge resonators are adjacent to a lower edge of a passband of the radio frequency filter.

19. The radio frequency filter of claim **18**, wherein all of the first and second low-edge resonators have a common substrate material and a common piezoelectric material.

20. The radio frequency filter of claim **15**, further comprising:
a first high-edge resonator, from the plurality of resonators, connected between the first port and ground; and
a second high-edge resonator, from the plurality of resonators, connected between the second port and ground,
wherein respective resonance frequencies of the first and second high-edge resonators are adjacent to a higher edge of the passband of the filter.

* * * * *