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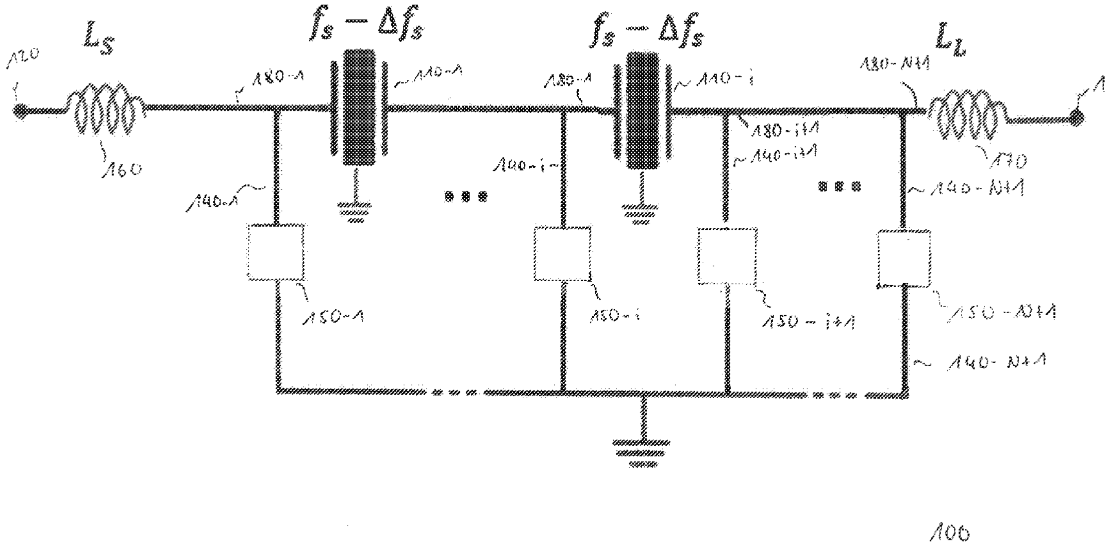


Fig. 1

(57) Abstract: A filter is provided. The filter (100) includes a cascade of coupled acoustic wave resonators (110-1,... 110-i) between an input terminal (120) and an output terminal (130) of the filter. The acoustic wave resonators are three terminal resonators and exhibit the same input impedance. Further, the filter includes a plurality of coupling structures (150-1,... 150-i, 150-i+1,... 150-N+1) each coupled to a respective one of a plurality of conductive paths (180-1,... 180- i, 180-i+1,... 180-N+1). Each of the plurality of coupling structures consists of a passive reactive element coupled between ground and the respective conductive path. The plurality of conductive paths couple pairs of consecutive acoustic wave resonators of the cascade of acoustic wave resonators, the input terminal and the first acoustic wave resonator of the cascade of acoustic wave resonators, and the output terminal and the last acoustic wave resonator of the cascade of acoustic wave resonators. Series inductors (160,170) may be added at the input and the output for impedance matching.

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WIDEBAND FILTER WITH CASCADED COUPLED ACOUSTIC RESONATORS AND SHUNT REACTIVE ELEMENTS

## Field

Examples relate to Acoustic Wave Resonator (AWR) based filters. In particular, examples relate to a filter and a mobile device comprising the filter.

## Background

Filtering at a Front-End Module (FEM) of a cellular user equipment is considered one of the bottle-neck technologies for manufacturing a cellular user equipment. Exploding demand for bandwidth, number of supported bands, and spectrum fidelity in the crowded sub-7GHz global frequency spectrum is presenting serious challenges for cellular user equipment technology.

Front-end filtering is the first line of defense in protecting the user equipment and network against the barrage of unwanted signals (interference) and ambient noise. AWRs based on MicroElectroMechanical Systems (MEMS) are basic building blocks and unrivalled in coming close to satisfying the stringent insertion loss, sharpness, and form-factor filtering requirements for cellular technology. Traditional AWR filters, however, are faced with a serious challenge in meeting, e.g., the 5$^{th}$ Generation New Radio (5G NR) bandwidth requirements. Unlike electrical resonators (e.g. LC, transmission line and microwave cavity resonators), MEMS resonators have an anti-resonance (parallel resonance at frequency $f_{pr}$) occurring at a frequency that closely follows the resonance frequency (series resonance frequency $f_{sr}$). Regarding the equivalent Butterworth-Van Dyke (BVD) model, the series $L_m C_m$ in the motional branch is responsible for the resonance and its combination with a parallel electro-static capacitance produces the anti-resonance.

The double resonance property limits the traditional bandpass operation by the small bandwidth between resonance and anti-resonance $\Delta f = f_{pr} - f_{sr}$. $\Delta f$ and thus the bandwidth ($BW$) of a conventional AWR ladder filter are determined by the resonator "electro-mechanical transduction" or "electro-mechanical coupling" coefficient $k_t^2$ as can be seen from the following mathematical expression:

$$k_t^2 = \frac{\pi^2}{8} \cdot \frac{f_{pr}^2 - f_{sr}^2}{f_{pr}^2} \approx \frac{\pi^2}{4} \cdot \frac{\Delta f}{f_{pr}} \qquad (1)$$

Accordingly, the fractional bandwidth $FBW$ of a conventional AWR ladder filter is determined by $k_t^2$ as can be seen from the following mathematical expression:

$$FBW = \frac{BW}{f_{sr}} \approx \frac{4}{\pi^2} \cdot k_{eff}^2 \approx 0.4 \cdot k_{eff}^2 \qquad (2)$$

The value of $k_t^2$ is highly dependent on the type of piezo-electric material, and ranges from $\sim 5 \times 10^{-3}$ or 0.5% to $\sim 7 \times 10^{-2}$ or 7% for industry standard materials such as PZT, AlN or ZnO. More recently, expensive exotic materials such as Lithium Niobate have been used with over 30% $k_t^2$.Other factors such as resonator type and physical structure, metal electrode shape and thickness, and filter structure can also play significant roles in the achievable filter bandwidth. $k_{eff}^2$ in mathematical expression (2) is the effective electro-acoustic coefficient, taking all such effects into account.

Hence, there may be a need for an improved AWR based filter.

## Brief description of the Figures

Some examples of apparatuses and/or methods will be described in the following by way of example only, and with reference to the accompanying figures, in which

Fig. 1 illustrates an example of an AWR based filter;

Fig. 2 illustrates another example of an AWR based filter;

Fig. 3 illustrates a further example of an AWR based filter;

Fig. 4 illustrates an example of a three-terminal resonator;

Fig. 5 illustrates an example of a BVD model for a three-terminal resonator;

Fig. 6 illustrates an example of a contour mode resonator; and

Fig. 7 illustrates an example of a mobile device comprising an AWR based filter.

## Detailed Description

Various examples will now be described more fully with reference to the accompanying drawings in which some examples are illustrated. In the figures, the thicknesses of lines, layers and/or regions may be exaggerated for clarity.

Accordingly, while further examples are capable of various modifications and alternative forms, some particular examples thereof are shown in the figures and will subsequently be described in detail. However, this detailed description does not limit further examples to the particular forms described. Further examples may cover all modifications, equivalents, and alternatives falling within the scope of the disclosure. Same or like numbers refer to like or similar elements throughout the description of the figures, which may be implemented identically or in modified form when compared to one another while providing for the same or a similar functionality.

It will be understood that when an element is referred to as being “connected” or “coupled” to another element, the elements may be directly connected or coupled via one or more intervening elements. If two elements A and B are combined using an “or”, this is to be understood to disclose all possible combinations, i.e. only A, only B as well as A and B, if not explicitly or implicitly defined otherwise. An alternative wording for the same combinations is “at least one of A and B” or “A and/or B”. The same applies, mutatis mutandis, for combinations of more than two Elements.

The terminology used herein for the purpose of describing particular examples is not intended to be limiting for further examples. Whenever a singular form such as “a”, “an” and “the” is used and using only a single element is neither explicitly or implicitly defined as being mandatory, further examples may also use plural elements to implement the same functionality. Likewise, when a functionality is subsequently described as being implemented using multiple elements, further examples may implement the same functionality using a single element or processing entity. It will be further understood that the terms “comprises”, “comprising”, "includes" and/or "including", when used, specify the presence of the stated features, integers, steps, operations, processes, acts, elements and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, processes, acts, elements, components and/or any group thereof.

Unless otherwise defined, all terms (including technical and scientific terms) are used herein in their ordinary meaning of the art to which the examples belong.

**Fig. 1** illustrates an example of a filter 100 comprising a cascade of coupled AWRs 110-1, ..., 110-N which is coupled between an input terminal 120 and an output terminal 130 of the filter 100. The cascade of coupled AWRs 110-1, ..., 110-N may comprise any number $N \geq 2$ of AWRs 110-1, ..., 110-N. For reasons of simplicity, merely the AWRs 110-1 and 110-i ($i < N$) are illustrated in Fig. 1. The number of AWRs may, e.g., be equal to the desired order of the filter 100. For example, a third order filter may comprise a cascade of three coupled AWRs, whereas a fifth order filter may comprise a cascade of five coupled AWRs.

The AWRs 110-1, ..., 110-N are three-terminal resonators. Three-terminal resonators are also denoted as two-port resistors. An exemplary three-terminal AWR 110-i is illustrated in **Fig. 4**. The three-terminal AWR 110-i comprises an input terminal 111 for receiving an input signal for the resonator, an output terminal 112 for outputting an output signal of the resonator, and a ground terminal 113 for coupling to ground. The terminals 111 to 113 interact through a medium 114. For example, the medium 114 may be piezo-electric medium (material). The three-terminal AWR 110-i may be a MEMS resonator.

An equivalent BVD circuit 500 for modelling the behavior of the three-terminal AWR 110-i is illustrated in **Fig. 5**. The circuit 500 comprises a motional branch comprising an inductive element 501 exhibiting a motional inductance $L_M$, a capacitive element 502 exhibiting a motional capacitance $C_M$ and a resistive element 503 (for modelling the acoustic loss) exhibiting a motional resistance $R_M$ coupled in series between an input terminal 511 for receiving an input signal and an output terminal 512 for outputting an output signal of the resonator. The capacitive elements 504 and 505 exhibit a capacitance $C_0$ for modeling the static ground capacitance (i.e. the intrinsic capacitance of the resonator). The capacitive element 506 is coupled in parallel to the motional branch and exhibits a feedthrough capacitance $C_{ft}$ for modelling parasitic capacitances through the medium of the resonator.

Returning back to Fig. 1, one of the three terminals of each AWR 110-1, …, 110-N is coupled to ground similar to what is described above for three-terminal AWR 110-i illustrated in Fig. 4. The AWRs 110-1, …, 110-N may be any type of AWR. For example, the AWRs 110-1, …, 110-N may be acoustic wave MEMS resonators.

The cascaded AWRs 110-1, …, 110-N are of the same resonator type. The cascaded AWRs 110-1, …, 110-N may exhibit the same or different resonance frequencies $f_R$ and the same input impedance $Z_R$. In other words, the cascaded AWRs 110-1, …, 110-N may be identical. The resonance frequency (frequencies) $f_R$ of the AWRs 110-1, …, 110-N is/are different from a desired center frequency $f_S$ of the filter 100.

The filter 100 further comprises a plurality of coupling structures 140-1, …, 140-N+1 each coupled to a respective one of a plurality of conductive paths 180-1, …, 180-N+1. As can be seen from Fig. 1, the plurality of conductive paths 180-1, …, 180-N+1 couple pairs of consecutive (directly succeeding) AWRs of the cascade of AWRs 110-1, …, 110-N (e.g. AWRs 110-1 and 110-2), the input terminal 120 and the first AWR 110-1 of the cascade of AWRs 110-1, …, 110-N, and the output terminal 130 and the last AWR 110-N of the cascade of AWRs 110-1, …, 110-N.

In some examples, each of the plurality of coupling structures 140-1, …, 140-N+1 consists of (only, solely, exclusively) a single passive reactive element 150-1, …, 150-N+1 coupled between ground and the respective conductive path 180-1, …, 180-N+1. In alternative examples, the coupling structures may comprise more than one passive reactive element or zero passive reactive elements. The coupling structures 140-1, …, 140-N+1 are reactive inter-stage coupling components for coupling the AWRs 110-1, …, 110-N. The number of coupling structures is N+1, i.e. it depends on the number N of cascaded AWRs. The passive reactive element 150-1, …, 150-N+1 is a passive (i.e. not active) electric element that tries to resist a change in voltage or current in the filter (circuit) 100. For example, the passive reactive elements 150-1, …, 150-N+1 may be capacitive elements or inductive elements.

The filter 100 further comprises a first inductive element 160 coupled between the input terminal 120 and the first AWR 110-1 of the cascade of AWRs 110-1, …, 110-N. A second inductive element 170 is coupled between the output terminal 130 and the last AWR 110-N of the cascade of AWRs 110-1, …, 110-N. The first and second inductive elements 160 and 170 are for matching the input and output impedance of the filter 100.

Filter 100 may be understood as a cascaded three-terminal (two-port) resonator array with single shunt inter-stage reactive couplings (e.g. capacitive or inductive). The structure of the filter 100 may allow a $k_t^2$ agnostic passband characteristic of the filter 100. In this respect, $k_t^2$ agnostic passband characteristic of the filter 100 means that the passband characteristic of the filter 100 is not limited by the electro-mechanical coupling coefficient $k_t^2$ of the AWRs 110-1, …, 110-N. In other words, a desired bandwidth of the filter 100 is not limited by the electro-mechanical coupling coefficient $k_t^2$ of the AWRs 110-1, …, 110-N. By selecting respective AWRs 110-1, …, 110-N, a desired AWR grade sharpness may be achieved.

For a specific passband characteristic (band-pass performance, mask), a methodology is described in the following for determining the required number of AWRs, the resonance frequency (frequencies) $f_R$ of the (e.g. identical) AWRs, the input impedance $Z_R$ of the AWRs, and the passive reactive inter-stage coupling component (e.g. a capacitive element or an inductive element).

First, the desired classical canonical order N of the AWR based filter 100 is determined (selected). Further, respective polynomial coefficients $g_i$ for $i = 0, \dots, N + 1$ of a filter model determining the filter characteristic of the filter 100 are determined. The filter model determining the filter characteristic of the filter 100 is selected based on a desired insertion loss (e.g. passband or ripple) of the filter 100. For example, the filter model may be a Butterworth-filter, a Chebyshev-filter, an Elliptic-filter etc. The polynomial coefficients $g_i$ may, e.g., be taken from a look-up table or a polynomial of order N with the polynomial coefficients $g_i$ may be determined for the desired band-pass performance. The polynomial coefficients may, e.g., be $g_i = \{0.5176 \quad 1.4142 \quad 1.9318 \quad 1.9318 \quad 1.4142 \quad 0.5176 \quad 1.0000\}$ for a sixth order Butterworth-filter. In other examples, the polynomial coefficients may, e.g., be $g_i = \{1{,}7254 \quad 1.2479 \quad 2.6064 \quad 1.3137 \quad 2.4758 \quad 0.8696 \quad 1.9841\}$ for a sixth order Chebyshev-filter with a 0.5 dB ripple.

Then, normalized (inverter) coupling coefficients $\kappa_i$ for $i = 0, \dots, N + 1$ describing the coupling behavior of the coupling structures 140-1, …, 140-N+1 are determined using the following mathematical expression:

$$\kappa_i = \frac{1}{\sqrt{g_{i-1} \cdot g_i}} \qquad (3)$$

The coupling structures 140-1, …, 140-N+1 may be understood as coupling inverters since they effectively behave like inverters coupling the AWRs 110-1, …, 110-N.

Subsequently, the (inverter) coupling coefficients $\kappa_i$ are de-normalized for the desired fractional bandwidth $FBW$ of the filter 100 (i.e. the ratio of the desired bandwidth $\Delta f$ of the filter 100 to the desired center frequency $f_S$ of the filter 100). The de-normalization is done using the two following mathematical expressions:

$$K_i = \begin{cases} L_M^{lp} \cdot \kappa_i & for\ i = 2, \ldots, N \\ \sqrt{R_i \cdot L_M^{lp}} & for\ i = 1, N+1 \end{cases} \qquad (4),$$

and

$$L_M^{lp} = L_M \cdot 2\,\pi \cdot f_S \cdot FBW \qquad (5),$$

with $R_1 = R_S$ and $R_{N+1} = R_L$.

$L_M$ denotes the motional inductance in the equivalent BVD circuit for modelling the behavior of the AWRs 110-1, …, 110-N. $L_M^{lp}$ denotes the low-pass motional inductance. $R_S$ denotes the resistance of a signal source (not illustrated in Fig. 1) providing the input signal to the input node 120 of the filter 100. $R_L$ denotes the resistance of a load (not illustrated in Fig. 1) coupled to the output node 130 of the filter 100.

After, the coupling capacitances $C_i$ of the coupling structures 140-1, …, 140-N+1 for coupling the AWRs 110-1, …, 110-N are determined using the following mathematical expression:

$$C_i = \begin{cases} \frac{1}{K_i \cdot 2\,\pi \cdot f_S \cdot Z_0} - 2C_0 & for\ i = 2, \ldots, N \\ \frac{1}{K_i \cdot 2\,\pi \cdot f_S \cdot Z_0} - C_0 & for\ i = 1, N+1 \end{cases} \qquad (6),$$

with $C_0$ denoting the (input/output) electro-static capacitance of the AWRs 110-1, …, 110-N, and $Z_0$ denoting the desired characteristic impedance of the filter 100 (assuming a symmetric resonator structure; for a non-symmetric structure, e.g., an unequal of input/output fingers, the term $2C_0$ in mathematical expression (6) may be replaced by $C_{0\_input} + C_{0\_output}$).

As described above, the resonance frequency (frequencies) $f_R$ of the individual AWRs 110-1, …, 110-N may be different from (i.e. shifted w.r.t) the desired center frequency $f_S$ of the filter 100. The average shifted resonance frequency of the AWRs 110-1, …, 110-N is determined using the following mathematical expressions:

$$f_R = \frac{1}{2\pi(N+1)} \sum_i L_M C'_{Mi} \qquad (7)$$

and

$$C'_{Mi} = \begin{cases} \dfrac{1}{\frac{1}{C_M} + \frac{1}{C_i + 2C_0} + \frac{1}{C_{i+1} + 2C_0}} & for\ i = 2, \dots, N-1 \\ \dfrac{1}{\frac{1}{C_M} + \frac{1}{C_i + C_0} + \frac{1}{C_{i+1} + C_0}} & for\ i = 1, N \end{cases} \qquad (8)$$

If the determined coupling capacitances $C_i$ of the coupling structures 140-1, …, 140-N+1 for coupling the AWRs 110-1, …, 110-N are negative, they are converted to coupling inductances using the following mathematical expression:

$$L_i = -\frac{1}{(2\,\pi \cdot f_S)^2 \cdot C_i} \qquad (9)$$

In other words, if the determined coupling capacitances $C_i$ of the coupling structures 140-1, …, 140-N+1 are positive, the passive reactive elements 150-1, …, 150-N+1 are capacitive elements exhibiting the respective determined capacitance $C_i$. On the other hand, if the determined coupling capacitances $C_i$ of the coupling structures 140-1, …, 140-N+1 are negative, the passive reactive elements 150-1, …, 150-N+1 are inductive elements exhibiting the respective determined inductance $L_i$.

Additionally, the inductances $L_S$ and $L_L$ of the first and last inductive elements 160 and 170 are determined. In other words, the input/output matching inductances of the filter 100 are determined. The inductances $L_S$ and $L_L$ are determined using the following mathematical expression:

$$L_{S,L} = \frac{1}{(2\,\pi\, f_s)^2 (C_i + C_0)} \qquad (10),$$

wherein $i = 1$ and $N + 1$ since the first and last inductive elements 160 and 170 couple to the first AWR 110-1 and the last AWR 110-1 of the cascade of coupled AWRs 110-1, …, 110-N. Accordingly, $C_i$ denotes the capacitance of the passive reactive element 150-1 of the coupling structure 140-1 coupled to the conductive path 180-1 coupling the input terminal 120 and the first AWR 110-1 of the cascade of AWRs 110-1, …, 110-N or the capacitance of the passive reactive element 150-N+1 of the coupling structure 140-N+1 coupled to the conductive path 180-N+1 coupling the output terminal 130 and the last AWR 110-1 of the cascade of AWRs 110-1, …, 110-N.

In other words, the inductances $L_S$ and $L_L$ of the first inductive element 160 and the last inductive element 170 are proportional to an inverse of a square of the desired center frequency $f_s$ of the filter 100 and an inverse of the capacitance $C_i$ of the passive reactive element 150-1/150-N+1 of the coupling structure 140-1/140-N+1 coupled to the conductive path 180-1/180-N+1 coupling the input terminal 120 and the first AWR 110-1 of the cascade of AWRs 110-1, …, 110-N or coupling the output terminal 130 and the last AWR 110-1 of the cascade of AWRs 110-1, …, 110-N.

Subsequently, the determined values for the passive elements of filter 100 may be optimized (e.g. using a Minimum Mean Square Error, MMSE, estimation) to tweak the determined values for performance. For example, a computer-aided optimization of the determined values for the passive elements of filter 100 may be done.

The filter 100 is based on several approximations. For example, one assumption may be that $C_{ft} \ll C_0$ may be ignored in combining components such as three-terminal AWRs (e.g. made of piezo-electric material). Another assumption may be that the mathematical expression (3) used for determining the coupling coefficients $\kappa_i$ varies for less than the polynomial coefficients $g_i$ of the underlying filter model such as e.g. a Butterworth-filter, a Chebyshev-filter, etc. (for example, the polynomial coefficients $g_i$ may vary from $\sim 0.5$ to $\sim 3 - 4$ in common band-pass polynomials). Therefore, the individual angular resonance frequencies $\omega_{S,i}$ do not fluctuate much between the AWRs 110-1, …, 110-N. This allows for the uniform topology with a single AWR resonance frequency $f_R$ such that:

$$f_R = f_s - \Delta f_s \qquad (11),$$

wherein $\Delta f_s$ is defined as follows:

$$\Delta f_s = \frac{1}{N}\sum \Delta f_{S_i} \qquad (12),$$

with $\Delta f_{S_i}$ denoting the individual frequency deviation of each of the AWRs 110-1, …, 110-N from the desired center frequency $f_s$ of the filter 100. It is to be noted that though the AWRs 110-1, …, 110-N are described as identical such that they exhibit the same resonance frequency $f_R$, there may be slight differences between the individual AWRs 110-1, …, 110-N due to manufacturing tolerances etc.

By optimizing the determined values for the passive elements of filter 100, most errors resulting from the used approximations may be compensated.

In the following, further there is a given relationship between the values for the passive elements of the filter 100 and the input impedance $Z_R$ of the AWRs 110-1, …, 110-N as well as the electro-static capacitance $C_0$ of the AWRs 110-1, …, 110-N, the desired fractional bandwidth $FBW$ of the filter 100 and the electro-mechanical coupling coefficient $k_t^2$ of the AWRs 110-1, …, 110-N.

Given that

$$L = L_M^{lp} = L_M \cdot \omega_S \cdot FBW = \frac{FBW}{C_M \cdot \omega_S} = \frac{FBW}{p \cdot C_0 \cdot \omega_S} \qquad (13),$$

mathematical expression (13) may be rewritten as follows:

$$L = L^{lp} = \frac{1}{C_0 \cdot \omega_S} \cdot \frac{FBW}{0.4k_t^2} = |Z_R| \cdot \frac{FBW}{0.4k_t^2} \qquad (14)$$

Further, the angular resonance frequency $\omega_s$ of the AWRs 110-1, …, 110-N may be defined as follows:

$$\omega_S^2 = \frac{1}{L_M \cdot C_M} \qquad (15)$$

The input impedance of the AWRs 110-1, …, 110-N may be defined as follows:

$$Z_R = \frac{1}{j \cdot C_0 \cdot \omega_S} \qquad (16)$$

For example, for a 50Ω AWR, $|Z_R| = \frac{1}{C_0 \cdot \omega_S} = 50$.

As described above, normalized (inverter) coupling coefficients $\kappa_i$ for $i = 0, \ldots, N+1$ are determined by the following mathematical expression:

$$\kappa_i = \frac{1}{\sqrt{g_{i-1} \cdot g_i}} \qquad (17)$$

Further, the individual de-normalized (inverter) coupling coefficients $K_i$ summarized in above mathematical expression (4) are as follows:

$$K_1 = \kappa_1 \cdot \sqrt{L \cdot R_S} \qquad (18)$$

$$K_i = \kappa_i \cdot L \quad for\ i = 2, \ldots, N \qquad (19)$$

$$K_{N+1} = \kappa_{N+1} \cdot \sqrt{L \cdot R_L} \qquad (20)$$

Further, above mathematical expression (6) may be re-written as follows for $i = 2, \ldots, N$:

$$2C_0 + C_i = \frac{1}{\omega_S \cdot Z_0 \cdot K_i} = \frac{1}{\omega_S \cdot Z_0 \cdot L \cdot \kappa_i} = \frac{0.4 k_t^2}{Z_0 \cdot FBW \cdot \kappa_i} \qquad (21)$$

such that:

$$C_i = 2C_0\left[\frac{0.2k_t^2}{Z_0\cdot FBW\cdot\kappa_i} - 1\right] \qquad (22)$$

For $i = 1$ and $N + 1$, above mathematical expression (6) may be re-written as follows:

$$C_0 + C_i = \frac{1}{\omega_S\cdot Z_0\cdot K_i} = \frac{1}{\omega_S\cdot Z_0\cdot\sqrt{L\cdot R_i}} \qquad (23)$$

such that

$$C_i = C_0\left[\frac{\sqrt{\frac{0.4k_t^2}{FBW}}}{Z_0\cdot\kappa_i\cdot\sqrt{C_0\cdot\omega_S\cdot R_i}} - 1\right] \qquad (24)$$

If the filter 100 is matched such that $R_i = R_S = R_L = \frac{1}{C_0\cdot\omega_S}$, then mathematical expression (24) for $i = 1$ and $N + 1$ may be re-written as follows:

$$C_i = C_0\left[\frac{1}{Z_0\cdot\kappa_i}\cdot\sqrt{\frac{0.4k_t^2}{FBW}} - 1\right] \qquad (25)$$

That is, for $i = 2, \ldots, N$ the capacitance $C_i$ of the passive reactive elements is $C_i = 2\cdot C_0\cdot\left[\frac{1}{Z_0\cdot\kappa_i}\cdot\frac{0.2k_t^2}{FBW} - 1\right]$, whereas for $i = 1$ and $N + 1$ the capacitance $C_i$ of the passive reactive elements is $C_i = C_0\cdot\left[\frac{1}{Z_0\cdot\kappa_i}\cdot\sqrt{\frac{0.4k_t^2}{FBW}}\sqrt{\frac{|Z_R|}{R_i}} - 1\right]$.

It is evident from mathematical expressions (22) and (25) that the capacitances $C_i$ of the passive reactive elements is negative unless the desired fractional bandwidth $FBW$ is (very) small. For a wider desired fractional bandwidth $FBW$, the negative capacitances $C_i$ of the passive reactive elements are converted to inductances $L_i$ according to the following fundamental trade-off relationship:

$$X_{L_i} = L_i\cdot\omega_s = -\frac{1}{C_i\cdot\omega_s} = |Z_R|\cdot\frac{1}{2\cdot\left(1-\frac{1}{Z_0\cdot\kappa_i}\cdot\frac{0.2k_t^2}{FBW}\right)} \quad for\ i = 2, \ldots, N \qquad (26)$$

and

$$X_{L_i} = L_i \cdot \omega_s = -\frac{1}{C_i \cdot \omega_s} = |Z_R| \cdot \frac{1}{1 - \frac{1}{Z_0 \cdot \kappa_i} \cdot \sqrt{\frac{0.4k_t^2}{FBW}} \cdot \sqrt{\frac{|Z_R|}{R_i}}} \quad for\ i = 1\ and\ N+1 \tag{27}$$

Therefore, for $i = 2, \ldots, N$ the inductance $L_i$ of the passive reactive elements is $L_i = \frac{1}{\omega_s} \cdot |Z_R| \cdot \left[2 \cdot \left(1 - \frac{1}{Z_0 \cdot \kappa_i} \cdot \frac{0.2k_t^2}{FBW}\right)\right]^{-1}$, whereas for $i = 1$ and $N + 1$ the inductance $L_i$ of the passive reactive elements is $L_i = \frac{1}{\omega_s} \cdot |Z_R| \cdot \left[1 - \frac{1}{Z_0 \cdot \kappa_i} \cdot \sqrt{\frac{0.4k_t^2}{FBW}} \cdot \sqrt{\frac{|Z_R|}{R_i}}\right]^{-1}$.

As can be seen from the above mathematical expressions, the inductance of the passive reactive elements goes down for a larger fractional bandwidth $FBW$ and/or a smaller electro-mechanical coupling coefficient $k_t^2$ of the AWRs 110-1, ..., 110-N. On the contrary, the inductance of the first and second matching inductors 160 and 170 goes up for a larger fractional bandwidth $FBW$ and/or a smaller electro-mechanical coupling coefficient $k_t^2$ of the AWRs 110-1, ..., 110-N. This can be seen from the following mathematical expression:

$$-X_{L_{S,L}} = \frac{1}{C_{S,L} \cdot \omega_s} = Z_0 \cdot \kappa_{S,L} \cdot \sqrt{\frac{FBW}{0.4k_t^2} \cdot R_{S,L} \cdot |Z_R|} \tag{28},$$

with $C_{S,L}$ denoting the capacitance of the first and last inductive elements 160 and 170, and $\kappa_{S,L}$ denoting the coupling coefficient of the first and last inductive elements 160 and 170.

As can be seen from the above mathematical expressions, the desired bandwidth of the filter 100 is not limited by the electro-mechanical coupling coefficient $k_t^2$. The desired bandwidth of the filter 100 may be adjusted by selecting appropriate capacitance/inductance values for the passive reactive elements 150-1, ..., 150-N+1 and the first and second matching inductors 160 and 170.

The high-performance (broad-band) individual resonance frequency of an AWR is typically thickness dependent and multiple frequency operation cannot be integrated. AWR types that are not thickness dependent and can be integrated for multiple frequencies (e.g surface acoustic wave resonators, or contour mode resonators) are limited w.r.t electro-mechanical coupling coefficient $k_t^2$ (e.g. up to only 2%) and thus in filter bandwidth. The proposed filter architecture provides a topology and formal means to synthesize high-performance integrated AWR filters with substantially broad bandwidth independent of the resonators' electro-mechanical coupling coefficient $k_t^2$. Moreover, unlike traditional ladder filters with different series and shunt type resonators, the proposed topology may use only a single resonator type (same resonance frequency and input impedance). Further the used AWRs do not require costly trimming for a high precision resonance frequency. Further, unlike other proposed hybrid techniques, the proposed topology calls for only one passive reactive component per stage for inter-stage coupling.

In the following, two exemplary filters 200 and 300 comprising capacitive elements and inductive elements as passive reactive elements are described in connection with Figs. 2 and 3.

**Fig. 2** illustrates a filter 200 that is identical to above described filter 100, wherein the passive reactive elements 150-1, …, 150-N+1 are implemented as capacitive elements 250-1, …, 250-N+1.

The capacitive elements 250-1 and 250-N+1 may exhibit a capacitance as given in above mathematical expressions (6) and (25). Speaking more general, the capacitive elements 250-1 and 250-N+1 may exhibit a capacitance proportional to an expression which is mathematically correspondent to:

$$\frac{a_i}{\kappa_i} \cdot \sqrt{\frac{k_t^2}{FBW} - 1} \qquad (29),$$

with $a_i$ denoting a constant for the respective capacitive element.

As described above, the coupling coefficient $\kappa_i$ of the respective capacitive element 250-1 or 250-N+1 for coupling the first or the last AWR of the cascade of AWRs 110-1, …, 110-N is proportional to an inverse of a square root of a product of polynomial coefficients of a filter model determining the filter characteristic of the filter 200 (see above mathematical expression (3)), wherein one of the polynomial coefficients of the filter model is assigned to the first or the last AWR of the cascade of AWRs 110-1, …, 110-N.

The capacitive elements 250-2 to 250-N may exhibit a capacitance as given in above mathematical expressions (6) and (22). Speaking more general, the capacitive elements 250-2 to 250-N may exhibit a capacitance proportional to an expression which is mathematically correspondent to:

$$\frac{a \cdot k_t^2}{\kappa_i \cdot FBW} - 1 \qquad (30),$$

with $a$ denoting a constant.

As described above, the coupling coefficient $\kappa_i$ of the respective capacitive element 250-2 to 250-N for coupling the pair of consecutive AWRs (e.g. AWRs 110-1 and 110-2) is proportional to an inverse of a square root of a product of polynomial coefficients of a filter model determining the filter characteristic of the filter (see above mathematical expression (3)), wherein the polynomial coefficients of the filter model are assigned to the pair of consecutive AWRs.

Further illustrated in Fig. 2 is a signal source 280 providing an input signal for the filter 200. The signal source 280 is coupled to the input terminal 120 of the filter 200. The signal source 280 is illustrated schematically in Fig. 2 by means of a resistive element 281 representing the resistance $R_S$ of the signal source 280 and a signal generator 282 generating the input signal for the filter 200. For example, the schematic signal source 280 may represent a transmitter, a transceiver or an antenna if the filter 200 is used in a wireless communication application.

Fig. 2 additionally illustrates a load 290 coupled to the output terminal 130 of the filter 200. The load 290 is illustrated schematically in Fig. 2 by means of a resistive element 291 representing the resistance $R_L$ of the load 290. For example, the schematic load 290 may represent an antenna, a transceiver or a receiver if the filter 200 is used in a wireless communication application.

The filter 200 may enable efficient narrowband filtering, wherein the passband of the filter 200 may be selected $k_t^2$ agnostic.

**Fig. 3** illustrates another filter 300 that is identical to above described filter 100, wherein the passive reactive elements 150-1, …, 150-N+1 are implemented as inductive elements 350-1, …, 350-N+1.

The inductive elements 350-1 and 350-N+1 may exhibit an inductance as given in above mathematical expressions (9) and (27). Speaking more general, the inductive elements 350-1 and 350-N+1 may exhibit an inductance proportional to an expression which is mathematically correspondent to:

$$\left(1-\frac{a_i}{\kappa_i}\cdot\sqrt{\frac{k_t^2}{FBW}}\right)^{-1} \quad (31),$$

with $a_i$ denoting a constant for the respective inductive element.

As described above, the coupling coefficient $\kappa_i$ of the respective inductive element 350-1 or 350-N+1 for coupling the first or the last AWR of the cascade of AWRs 110-1, …, 110-N is proportional to an inverse of a square root of a product of polynomial coefficients of a filter model determining the filter characteristic of the filter 300 (see above mathematical expression (3)), wherein one of the polynomial coefficients of the filter model is assigned to the first or the last AWR of the cascade of AWRs 110-1, …, 110-N.

The inductive elements 350-2 to 350-N may exhibit an inductance as given in above mathematical expressions (9) and (26). Speaking more general, the inductive elements 350-2 to 350-N may exhibit a capacitance proportional to an expression which is mathematically correspondent to:

$$\left(1-\frac{a\cdot k_t^2}{\kappa_i\cdot FBW}\right)^{-1} \quad (32),$$

with $a$ denoting a constant.

As described above, the coupling coefficient $\kappa_i$ of the respective inductive element 350-2 to 350-N for coupling the pair of consecutive AWRs (e.g. AWRs 110-1 and 110-2) is proportional to an inverse of a square root of a product of polynomial coefficients of a filter model determining the filter characteristic of the filter 300 (see above mathematical expression (3)), wherein the polynomial coefficients of the filter model are assigned to the pair of consecutive AWRs.

Similar to what is illustrated in Fig. 2, Fig. 3 further illustrates the signal source 280 coupled to the input terminal 120 of the filter 300 and the load 290 coupled to the output terminal 130 of the filter 300.

The filter 300 may enable efficient wideband filtering, wherein the passband of the filter 300 may be selected $k_t^2$ agnostic.

An exemplary AWR that may be used for an AWR based filter according to one or more aspects of the proposed technique or one or more examples described above is illustrated in **Fig. 6**. Fig. 6 illustrates a three-terminal (two-port) Contour Mode Resonator (CMR) 600 as an example for an AWR.

The CMR 600 comprises two interleaved interdigitated electrodes 610 and 620. The interdigitated electrode 610 is coupled to an input terminal 601 for receiving an input signal for the CMR 600. The other interdigitated electrode 610 is coupled to an output terminal 602 for outputting an output signal of the CMR 600. The two interleaved interdigitated electrodes 610 and 620 are arranged on the top (i.e. a first) surface of a suspended piezo-electric film 640. A third (e.g. metal) electrode 630 is arranged on the bottom (i.e. an opposite second) surface of the suspended piezo-electric film 640 as ground plane (i.e. the third electrode is coupled to ground).

The resonance frequency $f_R$ of the CMR 600 is determined by the pitch between consecutive fingers of the two interleaved interdigitated electrodes 610 and 620 as indicated in Fig. 6.

Therefore, in some examples, the cascaded AWRs of the proposed filter may be CMRs. However, it is to be noted that the proposed AWR based filter is not limited to using CMRs. In general, any type of three-terminal (two-port) AWR may be used. For example, a stacked (two-layer) Film Bulk Acoustic wave Resonator (FBAR) with middle metal layer connected to ground may be used for the cascaded AWRs of the proposed filter.

An example of an implementation using an AWR based filter according to one or more aspects of the proposed technique or one or more examples described above is illustrated in **Fig. 7**. Fig. 7 schematically illustrates an example of a mobile device 700 (e.g. mobile phone, smartphone, tablet-computer, or laptop) comprising a transceiver 710. The transceiver is coupled to at least one antenna element 720 of the mobile device. A filter 730 according to examples described herein is coupled between the transceiver 710 and the antenna element 720.

The characteristics of the filter 730 may be adapted to a frequency band supported by the transceiver 710 for transmission and/or reception of radio frequency signals. For example, a center frequency of the filter 730 may lie within the frequency band supported by the transceiver 710. Similarly, a passband of the filter 730 may at least partially cover the frequency band supported by the transceiver 710.

The mobile device 700 may comprise further elements such as, e.g., an application processor, memory, an audio driver, a camera driver, a touch screen, a display driver, sensors, removable memory, a power management integrated circuit or a smart battery.

To this end, a mobile device enabling broadband front-end filtering may be provided.

The above wireless communication circuits using an AWR based filter according to the proposed technique or one or more of the examples described above may be configured to operate according to one of the 3rd Generation Partnership Project (3GPP)-standardized mobile communication networks or systems. The mobile or wireless communication system may correspond to, for example, a 5G NR, a Long-Term Evolution (LTE), an LTE-Advanced (LTE-A), High Speed Packet Access (HSPA), a Universal Mobile Telecommunication System (UMTS) or a UMTS Terrestrial Radio Access Network (UTRAN), an evolved-UTRAN (e-UTRAN), a Global System for Mobile communication (GSM), an Enhanced Data rates for GSM Evolution (EDGE) network, or a GSM/EDGE Radio Access Network (GERAN). Alternatively, the wireless communication circuits may be configured to operate according to mobile communication networks with different standards, for example, a Worldwide Inter-operability for Microwave Access (WIMAX) network IEEE 802.16 or Wireless Local Area Network (WLAN) IEEE 802.11, generally an Orthogonal Frequency Division Multiple Access (OFDMA) network, a Time Division Multiple Access (TDMA) network, a Code Division Multiple Access (CDMA) network, a Wideband-CDMA (WCDMA) network, a Frequency

Division Multiple Access (FDMA) network, a Spatial Division Multiple Access (SDMA) network, etc.

The examples as described herein may be summarized as follows:

Example 1 is a filter, comprising: a cascade of coupled acoustic wave resonators between an input terminal and an output terminal of the filter, wherein the acoustic wave resonators are three-terminal resonators, and wherein the acoustic wave resonators exhibit the same input impedance; and a plurality of coupling structures each coupled to a respective one of a plurality of conductive paths, wherein each of the plurality of coupling structures consists of a passive reactive element coupled between ground and the respective conductive path, wherein the plurality of conductive paths couple: pairs of consecutive acoustic wave resonators of the cascade of acoustic wave resonators; the input terminal and the first acoustic wave resonator of the cascade of acoustic wave resonators; and the output terminal and the last acoustic wave resonator of the cascade of acoustic wave resonators.

Example 2 is the filter of example 1, wherein the acoustic wave resonators are acoustic wave MEMS resonators.

Example 3 is the filter of example 1 or example 2, wherein the acoustic wave resonators are contour mode resonators.

Example 4 is the filter of any of examples 1 to 3, wherein one of the three-terminals of each acoustic wave resonator is coupled to ground.

Example 5 is the filter of any of examples 1 to 4, wherein the acoustic wave resonators exhibit the same or different resonance frequencies, and wherein the resonance frequency or the resonance frequencies of the acoustic wave resonators is/are different from a desired center frequency of the filter.

Example 6 is the filter of any of examples 1 to 5, wherein the passive reactive element is a capacitive element.

Example 7 is the filter of example 6, wherein the capacitive element of one of the plurality of coupling structures that is coupled to a conductive path coupling a pair of consecutive acoustic wave resonators of the cascade of acoustic wave resonators exhibits a capacitance proportional to an expression which is mathematically correspondent to:

$$\frac{a \cdot k_t^2}{\kappa_i \cdot FBW} - 1,$$

with $a$ denoting a constant, $\kappa_i$ denoting the coupling coefficient of the capacitive element for coupling the pair of consecutive acoustic wave resonators, $k_t^2$ denoting an electro-mechanical coupling coefficient of the acoustic wave resonators, and $FBW$ denoting a desired fractional bandwidth of the filter.

Example 8 is the filter of example 7, wherein the coupling coefficient of the capacitive element for coupling the pair of consecutive acoustic wave resonators is proportional to an inverse of a square root of a product of polynomial coefficients of a filter model determining the filter characteristic of the filter, wherein the polynomial coefficients of the filter model are assigned to the pair of consecutive acoustic wave resonators.

Example 9 is the filter of example 8, wherein the capacitance of the capacitive element is determined by an expression which is mathematically correspondent to:

$$C_i = 2 \cdot C_0 \cdot \left[\frac{1}{Z_0 \cdot \kappa_i} \cdot \frac{0.2 k_t^2}{FBW} - 1\right],$$

with $C_i$ denoting the capacitance of the capacitive element, $C_0$ denoting the electro-static capacitance of the acoustic wave resonators, $Z_0$ denoting the desired characteristic impedance of the filter, $\kappa_i$ denoting the coupling coefficient of the capacitive element for coupling the pair of consecutive acoustic wave resonators, $k_t^2$ denoting the electro-mechanical coupling coefficient of the acoustic wave resonators, and $FBW$ denoting the desired fractional bandwidth of the filter.

Example 10 is the filter of any of examples 6 to 9, wherein the capacitive element of one of the plurality of coupling structures that is coupled to a conductive path coupling the input terminal and the first acoustic wave resonator of the cascade of acoustic wave resonators or coupling the output terminal and the last acoustic wave resonator of the cascade of acoustic wave resonators exhibits a capacitance proportional to an expression which is mathematically correspondent to:

$$\frac{a_i}{\kappa_i} \cdot \sqrt{\frac{k_t^2}{FBW}} - 1,$$

with $a_i$ denoting a constant for the capacitive element, $\kappa_i$ denoting the coupling coefficient of the capacitive element for coupling the pair of consecutive acoustic wave resonators, $k_t^2$ denoting an electro-mechanical coupling coefficient of the acoustic wave resonators, and $FBW$ denoting a desired fractional bandwidth of the filter.

Example 11 is the filter of example 10, wherein the coupling coefficient of the capacitive element for coupling the first or the last acoustic wave resonator of the cascade of acoustic wave resonators is proportional to an inverse of a square root of a product of polynomial coefficients of a filter model determining the filter characteristic of the filter, wherein one of the polynomial coefficients of the filter model is assigned to the first or the last acoustic wave resonator of the cascade of acoustic wave resonators.

Example 12 is the filter of example 11, wherein the capacitance of the capacitive element is determined by an expression which is mathematically correspondent to:

$$C_i = C_0 \cdot \left[\frac{1}{Z_0 \cdot \kappa_i} \cdot \sqrt{\frac{0.4 k_t^2}{FBW}} \sqrt{\frac{|Z_R|}{R_i}} - 1\right],$$

with $C_i$ denoting the capacitance of the capacitive element, $C_0$ denoting the electro-static capacitance of the acoustic wave resonators, $Z_0$ denoting the desired characteristic impedance of the filter, $\kappa_i$ denoting the coupling coefficient of the capacitive element for coupling the first or the last acoustic wave resonator of the cascade of acoustic wave resonators, $k_t^2$ denoting the electro-mechanical coupling coefficient of the acoustic wave resonators, $FBW$ denoting the desired fractional bandwidth of the filter, $Z_R$ denoting the input impedance of the acoustic wave resonators, and $R_i$ denoting a resistance presented to the input node or the output node of the filter by an electric element coupled to the input node or the output node of the filter.

Example 13 is the filter of any of examples 1 to 5, wherein the passive reactive element is an inductive element.

Example 14 is the filter of example 13, wherein the inductive element of one of the plurality of coupling structures that is coupled to a conductive path coupling a pair of consecutive acoustic wave resonators of the cascade of acoustic wave resonators exhibits an inductance proportional to an expression which is mathematically correspondent to:

$$\left(1 - \frac{a \cdot k_t^2}{\kappa_i \cdot FBW}\right)^{-1},$$

with $a$ denoting a constant, $\kappa_i$ denoting the coupling coefficient of the capacitive element for coupling the pair of consecutive acoustic wave resonators, $k_t^2$ denoting an electro-mechanical coupling coefficient of the acoustic wave resonators, and $FBW$ denoting a desired fractional bandwidth of the filter.

Example 15 is the filter of example 14, wherein the coupling coefficient of the inductive element for coupling the pair of consecutive acoustic wave resonators is proportional to an inverse of a square root of a product of polynomial coefficients of a filter model determining the filter characteristic of the filter, wherein the polynomial coefficients of the filter model are assigned to the pair of consecutive acoustic wave resonators.

Example 16 is the filter of example 15, wherein the inductance of the inductive element is determined by an expression which is mathematically correspondent to:

$$L_i = \frac{1}{\omega_S} \cdot |Z_R| \cdot \left[2 \cdot \left(1 - \frac{1}{Z_0 \cdot \kappa_i} \cdot \frac{0.2 k_t^2}{FBW}\right)\right]^{-1},$$

with $L_i$ denoting the inductance of the inductive element, $\omega_S$ denoting the angular resonance frequency of the acoustic wave resonators, $|Z_R|$ denoting the input impedance of the acoustic wave resonators, $Z_0$ denoting the desired characteristic impedance of the filter, $\kappa_i$ denoting the coupling coefficient of the capacitive element for coupling the pair of consecutive acoustic wave resonators, $k_t^2$ denoting the electro-mechanical coupling coefficient of the acoustic wave resonators, and $FBW$ denoting the desired fractional bandwidth of the filter.

Example 17 is the filter of any of examples 13 to 16, wherein the inductive element of one of the plurality of coupling structures that is coupled to a conductive path coupling the input terminal and the first acoustic wave resonator of the cascade of acoustic wave resonators or coupling the output terminal and the last acoustic wave resonator of the cascade of acoustic wave resonators exhibits an inductance proportional to an expression which is mathematically correspondent to:

$$\left(1-\frac{a_i}{\kappa_i}\cdot\sqrt{\frac{k_t^2}{FBW}}\right)^{-1},$$

with $a_i$ denoting a constant for the capacitive element, $\kappa_i$ denoting the coupling coefficient of the capacitive element for coupling the pair of consecutive acoustic wave resonators, $k_t^2$ denoting an electro-mechanical coupling coefficient of the acoustic wave resonators, and $FBW$ denoting a desired fractional bandwidth of the filter.

Example 18 is the filter of example 17, wherein the coupling coefficient of the inductive element for coupling the first or the last acoustic wave resonator of the cascade of acoustic wave resonators is proportional to an inverse of a square root of a product of polynomial coefficients of a filter model determining the filter characteristic of the filter, wherein one of the polynomial coefficients of the filter model is assigned to the first or the last acoustic wave resonator of the cascade of acoustic wave resonators.

Example 19 is the filter of example 18, wherein the inductance of the inductive element is determined by an expression which is mathematically correspondent to:

$$L_i=\frac{1}{\omega_S}\cdot|Z_R|\cdot\left[1-\frac{1}{Z_0\cdot\kappa_i}\cdot\sqrt{\frac{0.4k_t^2}{FBW}}\cdot\sqrt{\frac{|Z_R|}{R_i}}\right]^{-1},$$

with $L_i$ denoting the inductance of the inductive element, $\omega_S$ denoting the angular resonance frequency of the acoustic wave resonators, $|Z_R|$ denoting the input impedance of the acoustic wave resonators, $Z_0$ denoting the desired characteristic impedance of the filter, $\kappa_i$ denoting the coupling coefficient of the capacitive element for coupling the first or the last acoustic wave resonator of the cascade of acoustic wave resonators, $k_t^2$ denoting the electro-mechanical coupling coefficient of the acoustic wave resonators, $FBW$ denoting the desired fractional bandwidth of the filter, $Z_R$ denoting the input impedance of the acoustic wave resonators, and $R_i$ denoting a resistance presented to the input node or the output node of the filter by electric elements coupled to the input node or the output node of the filter.

Example 20 is the filter of any of examples 1 to 19, further comprising: a first inductive element coupled between the input terminal and the first acoustic wave resonator of the cascade of acoustic wave resonators; and a second inductive element coupled between the output terminal and a last acoustic wave resonator of the cascade of acoustic wave resonators.

Example 21 is the filter of example 20, wherein inductances of the first inductive element and the second inductive element are proportional to an inverse of a square of the desired center frequency of the filter and an inverse of a capacitance of the passive reactive element of the coupling structure coupled to the conductive path coupling the input terminal and the first acoustic wave resonator of the cascade of acoustic wave resonators or coupling the output terminal and a last acoustic wave resonator of the cascade of acoustic wave resonators.

Example 22 is the filter of example 21, wherein the inductances of the first inductive element and the second inductive element are determined by an expression which is mathematically correspondent to:

$$L_{S,L} = [(2\pi \cdot f_S)^2 \cdot (C_i + C_0)]^{-1},$$

with $L_{S,L}$ determining the inductances of the first inductive element and the second inductive, $f_S$ denoting the desired center frequency of the filter, $C_i$ denoting the capacitance of the passive reactive element of the coupling structure coupled to the conductive path coupling the input terminal and the first acoustic wave resonator of the cascade of acoustic wave resonators or coupling the output terminal and a last acoustic wave resonator of the cascade of acoustic wave resonators, and $C_0$ denoting the electro-static capacitance of the acoustic wave resonators.

Example 23 is the filter of any of examples 1 to 22, wherein the number of acoustic wave resonators is equal to the desired order of the filter.

Example 24 is a mobile device comprising a transceiver coupled to an antenna element, wherein a filter according to any of examples 1 to 23 is coupled between the transceiver and the antenna element.

Example 25 is the mobile device of example 24, wherein a center frequency of the filter lies within a frequency band supported by the transceiver.

The aspects and features mentioned and described together with one or more of the previously detailed examples and figures, may as well be combined with one or more of the other examples in order to replace a like feature of the other example or in order to additionally introduce the feature to the other example.

The description and drawings merely illustrate the principles of the disclosure. Furthermore, all examples recited herein are principally intended expressly to be only for illustrative purposes to aid the reader in understanding the principles of the disclosure and the concepts contributed by the inventor(s) to furthering the art. All statements herein reciting principles, aspects, and examples of the disclosure, as well as specific examples thereof, are intended to encompass equivalents thereof.

A block diagram may, for instance, illustrate a high-level circuit diagram implementing the principles of the disclosure.

It is to be understood that the disclosure of multiple acts, processes, operations, steps or functions disclosed in the specification or claims may not be construed as to be within the specific order, unless explicitly or implicitly stated otherwise, for instance for technical reasons. Therefore, the disclosure of multiple acts or functions will not limit these to a particular order unless such acts or functions are not interchangeable for technical reasons. Furthermore, in some examples a single act, function, process, operation or step may include or may be broken into multiple sub–acts, -functions, -processes, -operations or –steps, respectively. Such sub acts may be included and part of the disclosure of this single act unless explicitly excluded.

Furthermore, the following claims are hereby incorporated into the detailed description, where each claim may stand on its own as a separate example. While each claim may stand on its own as a separate example, it is to be noted that - although a dependent claim may refer in the claims to a specific combination with one or more other claims - other examples may also include a combination of the dependent claim with the subject matter of each other dependent or independent claim. Such combinations are explicitly proposed herein unless it is stated that a specific combination is not intended. Furthermore, it is intended to include also features of a claim to any other independent claim even if this claim is not directly made dependent to the independent claim.

## Claims

What is claimed is:

1. A filter, comprising:

a cascade of coupled acoustic wave resonators between an input terminal and an output terminal of the filter, wherein the acoustic wave resonators are three-terminal resonators, and wherein the acoustic wave resonators exhibit the same input impedance; and

a plurality of coupling structures each coupled to a respective one of a plurality of conductive paths, wherein each of the plurality of coupling structures consists of a passive reactive element coupled between ground and the respective conductive path, wherein the plurality of conductive paths couple:

pairs of consecutive acoustic wave resonators of the cascade of acoustic wave resonators;

the input terminal and the first acoustic wave resonator of the cascade of acoustic wave resonators; and

the output terminal and the last acoustic wave resonator of the cascade of acoustic wave resonators.

2. The filter of claim 1, wherein the acoustic wave resonators are acoustic wave MEMS resonators.

3. The filter of claim 1, wherein the acoustic wave resonators are contour mode resonators.

4. The filter of claim 1, wherein one of the three-terminals of each acoustic wave resonator is coupled to ground.

5. The filter of claim 1, wherein the acoustic wave resonators exhibit the same or different resonance frequencies, and wherein the resonance frequency or the resonance frequencies of the acoustic wave resonators is/are different from a desired center frequency of the filter.

6. The filter of claim 1, wherein the passive reactive element is a capacitive element.

7. The filter of claim 6, wherein the capacitive element of one of the plurality of coupling structures that is coupled to a conductive path coupling a pair of consecutive acoustic wave resonators of the cascade of acoustic wave resonators exhibits a capacitance proportional to an expression which is mathematically correspondent to:

$$\frac{a \cdot k_t^2}{\kappa_i \cdot FBW} - 1,$$

with $a$ denoting a constant, $\kappa_i$ denoting the coupling coefficient of the capacitive element for coupling the pair of consecutive acoustic wave resonators, $k_t^2$ denoting an electro-mechanical coupling coefficient of the acoustic wave resonators, and $FBW$ denoting a desired fractional bandwidth of the filter.

8. The filter of claim 7, wherein the coupling coefficient of the capacitive element for coupling the pair of consecutive acoustic wave resonators is proportional to an inverse of a square root of a product of polynomial coefficients of a filter model determining the filter characteristic of the filter, wherein the polynomial coefficients of the filter model are assigned to the pair of consecutive acoustic wave resonators.

9. The filter of claim 8, wherein the capacitance of the capacitive element is determined by an expression which is mathematically correspondent to:

$$C_i = 2 \cdot C_0 \cdot \left[\frac{1}{Z_0 \cdot \kappa_i} \cdot \frac{0.2 k_t^2}{FBW} - 1\right],$$

with $C_i$ denoting the capacitance of the capacitive element, $C_0$ denoting the electro-static capacitance of the acoustic wave resonators, $Z_0$ denoting the desired characteristic impedance of the filter, $\kappa_i$ denoting the coupling coefficient of the capacitive element for coupling the pair of consecutive acoustic wave resonators, $k_t^2$ denoting the electro-mechanical coupling coefficient of the acoustic wave resonators, and $FBW$ denoting the desired fractional bandwidth of the filter.

10. The filter of claim 6, wherein the capacitive element of one of the plurality of coupling structures that is coupled to a conductive path coupling the input terminal and the first acoustic wave resonator of the cascade of acoustic wave resonators or coupling the output terminal and the last acoustic wave resonator of the cascade of acoustic wave resonators exhibits a capacitance proportional to an expression which is mathematically correspondent to:

$$\frac{a_i}{\kappa_i} \cdot \sqrt{\frac{k_t^2}{FBW}} - 1,$$

with $a_i$ denoting a constant for the capacitive element, $\kappa_i$ denoting the coupling coefficient of the capacitive element for coupling the pair of consecutive acoustic wave resonators, $k_t^2$ denoting an electro-mechanical coupling coefficient of the acoustic wave resonators, and $FBW$ denoting a desired fractional bandwidth of the filter.

11. The filter of claim 10, wherein the coupling coefficient of the capacitive element for coupling the first or the last acoustic wave resonator of the cascade of acoustic wave resonators is proportional to an inverse of a square root of a product of polynomial coefficients of a filter model determining the filter characteristic of the filter, wherein one of the polynomial coefficients of the filter model is assigned to the first or the last acoustic wave resonator of the cascade of acoustic wave resonators.

12. The filter of claim 11, wherein the capacitance of the capacitive element is determined by an expression which is mathematically correspondent to:

$$C_i = C_0 \cdot \left[\frac{1}{Z_0 \cdot \kappa_i} \cdot \sqrt{\frac{0.4 k_t^2}{FBW}} \sqrt{\frac{|Z_R|}{R_i}} - 1\right],$$

with $C_i$ denoting the capacitance of the capacitive element, $C_0$ denoting the electro-static capacitance of the acoustic wave resonators, $Z_0$ denoting the desired characteristic impedance of the filter, $\kappa_i$ denoting the coupling coefficient of the capacitive element for coupling the first or the last acoustic wave resonator of the cascade of acoustic wave resonators, $k_t^2$ denoting the electro-mechanical coupling coefficient of the acoustic wave resonators, $FBW$ denoting the desired fractional bandwidth of the filter, $Z_R$ denoting the input impedance of the acoustic wave resonators, and $R_i$ denoting a resistance presented to the input node or the output node of the filter by an electric element coupled to the input node or the output node of the filter.

13. The filter of claim 1, wherein the passive reactive element is an inductive element.

14. The filter of claim 13, wherein the inductive element of one of the plurality of coupling structures that is coupled to a conductive path coupling a pair of consecutive acoustic wave resonators of the cascade of acoustic wave resonators exhibits an inductance proportional to an expression which is mathematically correspondent to:

$$\left(1 - \frac{a \cdot k_t^2}{\kappa_i \cdot FBW}\right)^{-1},$$

with $a$ denoting a constant, $\kappa_i$ denoting the coupling coefficient of the capacitive element for coupling the pair of consecutive acoustic wave resonators, $k_t^2$ denoting an electro-mechanical coupling coefficient of the acoustic wave resonators, and $FBW$ denoting a desired fractional bandwidth of the filter.

15. The filter of claim 14, wherein the coupling coefficient of the inductive element for coupling the pair of consecutive acoustic wave resonators is proportional to an inverse of a square root of a product of polynomial coefficients of a filter model determining the filter characteristic of the filter, wherein the polynomial coefficients of the filter model are assigned to the pair of consecutive acoustic wave resonators.

16. The filter of claim 15, wherein the inductance of the inductive element is determined by an expression which is mathematically correspondent to:

$$L_i = \frac{1}{\omega_S} \cdot |Z_R| \cdot \left[2 \cdot \left(1 - \frac{1}{Z_0 \cdot \kappa_i} \cdot \frac{0.2k_t^2}{FBW}\right)\right]^{-1},$$

with $L_i$ denoting the inductance of the inductive element, $\omega_S$ denoting the angular resonance frequency of the acoustic wave resonators, $|Z_R|$ denoting the input impedance of the acoustic wave resonators, $Z_0$ denoting the desired characteristic impedance of the filter, $\kappa_i$ denoting the coupling coefficient of the capacitive element for coupling the pair of consecutive acoustic wave resonators, $k_t^2$ denoting the electro-mechanical coupling coefficient of the acoustic wave resonators, and $FBW$ denoting the desired fractional bandwidth of the filter.

17. The filter of claim 13, wherein the inductive element of one of the plurality of coupling structures that is coupled to a conductive path coupling the input terminal and the first acoustic wave resonator of the cascade of acoustic wave resonators or coupling the output terminal and the last acoustic wave resonator of the cascade of acoustic wave resonators exhibits an inductance proportional to an expression which is mathematically correspondent to:

$$\left(1 - \frac{a_i}{\kappa_i} \cdot \sqrt{\frac{k_t^2}{FBW}}\right)^{-1},$$

with $a_i$ denoting a constant for the capacitive element, $\kappa_i$ denoting the coupling coefficient of the capacitive element for coupling the pair of consecutive acoustic wave resonators, $k_t^2$ denoting an electro-mechanical coupling coefficient of the acoustic wave resonators, and $FBW$ denoting a desired fractional bandwidth of the filter.

18. The filter of claim 17, wherein the coupling coefficient of the inductive element for coupling the first or the last acoustic wave resonator of the cascade of acoustic wave resonators is proportional to an inverse of a square root of a product of polynomial coefficients of a filter model determining the filter characteristic of the filter, wherein one of the polynomial coefficients of the filter model is assigned to the first or the last acoustic wave resonator of the cascade of acoustic wave resonators.

19. The filter of claim 18, wherein the inductance of the inductive element is determined by an expression which is mathematically correspondent to:

$$L_i = \frac{1}{\omega_S} \cdot |Z_R| \cdot \left[1 - \frac{1}{Z_0 \cdot \kappa_i} \cdot \sqrt{\frac{0.4 k_t^2}{FBW}} \cdot \sqrt{\frac{|Z_R|}{R_i}}\right]^{-1},$$

with $L_i$ denoting the inductance of the inductive element, $\omega_S$ denoting the angular resonance frequency of the acoustic wave resonators, $|Z_R|$ denoting the input impedance of the acoustic wave resonators, $Z_0$ denoting the desired characteristic impedance of the filter, $\kappa_i$ denoting the coupling coefficient of the capacitive element for coupling the first or the last acoustic wave resonator of the cascade of acoustic wave resonators, $k_t^2$ denoting the electro-mechanical coupling coefficient of the acoustic wave resonators, $FBW$ denoting the desired fractional bandwidth of the filter, $Z_R$ denoting the input impedance of the acoustic wave resonators, and $R_i$ denoting a resistance presented to the input node or the output node of the filter by electric elements coupled to the input node or the output node of the filter.

20. The filter of claim 1, further comprising:

a first inductive element coupled between the input terminal and the first acoustic wave resonator of the cascade of acoustic wave resonators; and

a second inductive element coupled between the output terminal and a last acoustic wave resonator of the cascade of acoustic wave resonators.

21. The filter of claim 20, wherein inductances of the first inductive element and the second inductive element are proportional to an inverse of a square of the desired center frequency of the filter and an inverse of a capacitance of the passive reactive element of the coupling structure coupled to the conductive path coupling the input terminal and the first acoustic wave resonator of the cascade of acoustic wave resonators or coupling the output terminal and a last acoustic wave resonator of the cascade of acoustic wave resonators.

22. The filter of claim 21, wherein the inductances of the first inductive element and the second inductive element are determined by an expression which is mathematically correspondent to:

$$L_{S,L} = [(2\pi \cdot f_S)^2 \cdot (C_i + C_0)]^{-1},$$

with $L_{S,L}$ determining the inductances of the first inductive element and the second inductive, $f_S$ denoting the desired center frequency of the filter, $C_i$ denoting the capacitance of the passive reactive element of the coupling structure coupled to the conductive path coupling the input terminal and the first acoustic wave resonator of the cascade of acoustic wave resonators or coupling the output terminal and a last acoustic wave resonator of the cascade of acoustic wave resonators, and $C_0$ denoting the electro-static capacitance of the acoustic wave resonators.

23. The filter of claim 1, wherein the number of acoustic wave resonators is equal to the desired order of the filter.

24. A mobile device comprising a transceiver coupled to an antenna element, wherein a filter according to claim 1 is coupled between the transceiver and the antenna element.

25. The mobile device of claim 24, wherein a center frequency of the filter lies within a frequency band supported by the transceiver.

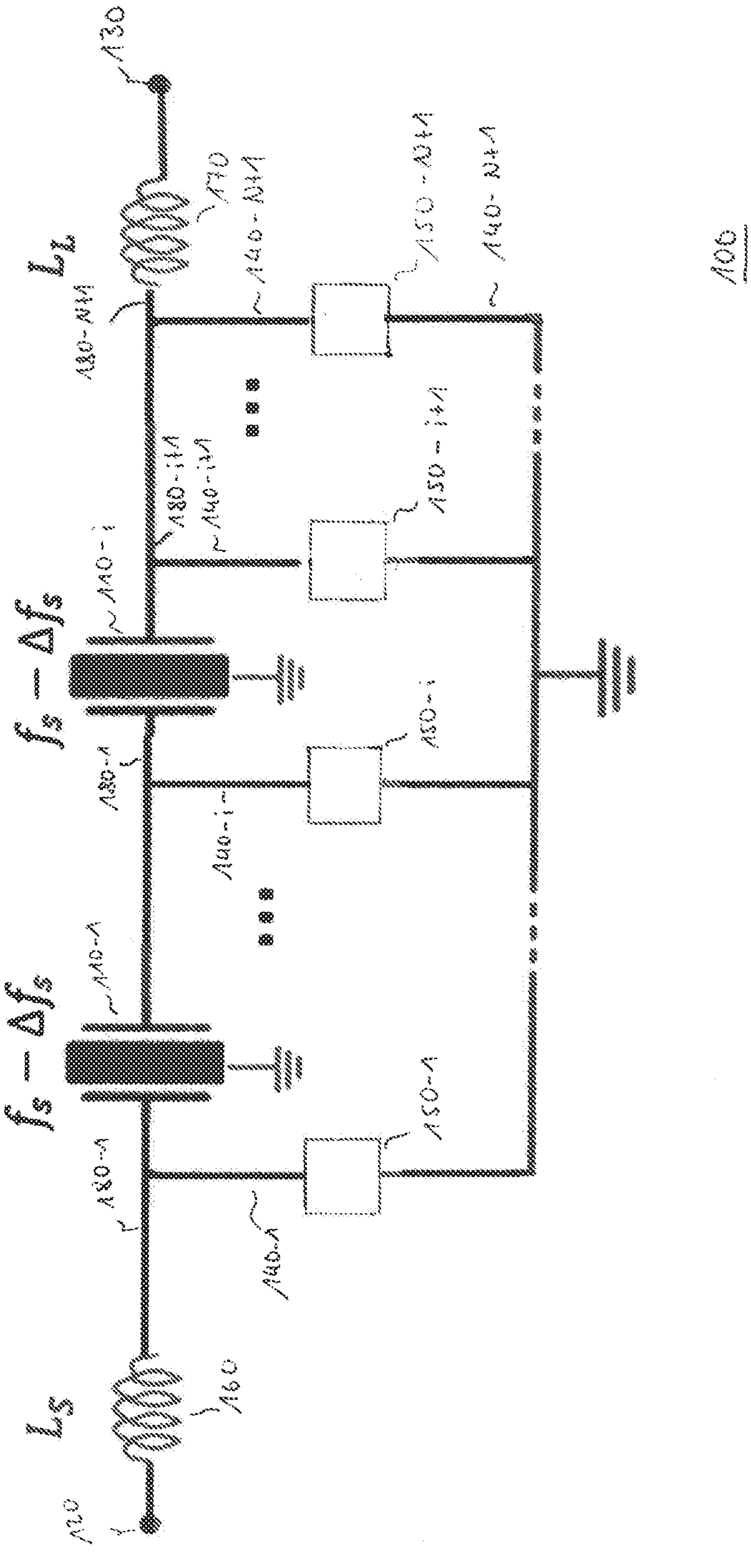
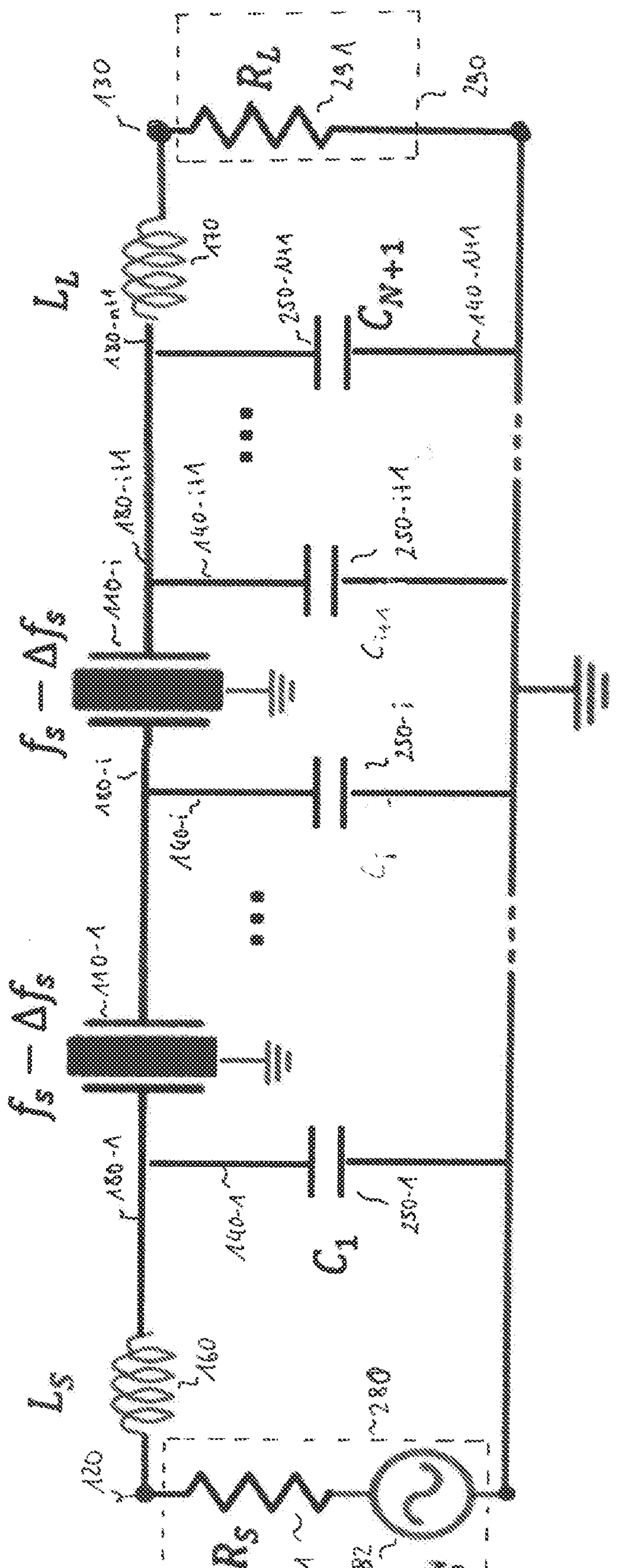



Fig. 1




200

Fig. 2

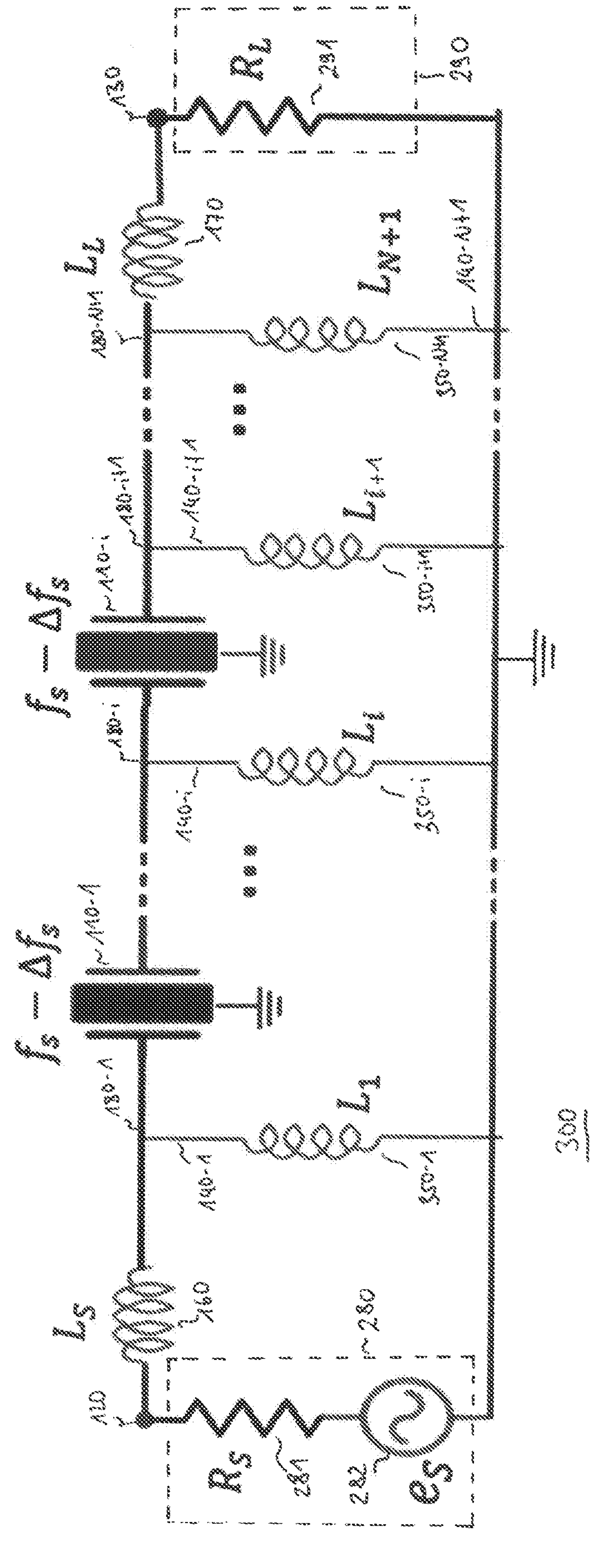



Fig. 3

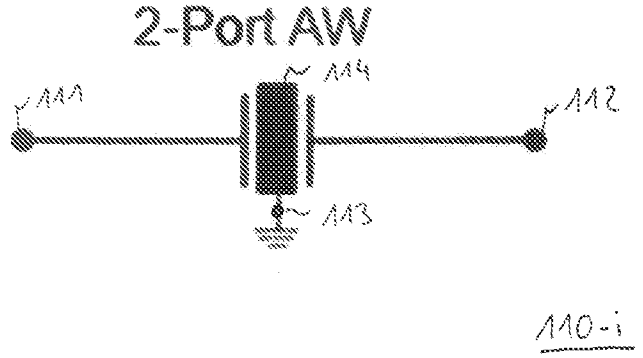
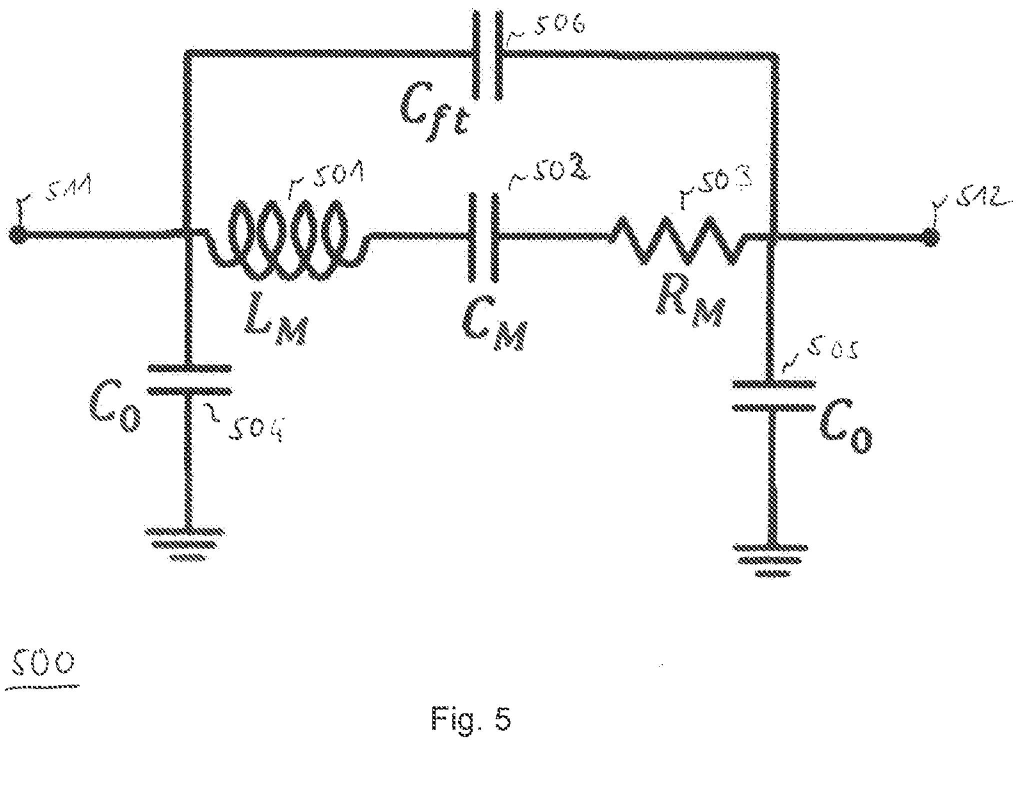

2-Port AW
111
114
112
113
110-i

Fig. 4


506
$C_{ft}$
511
501
502
503
512
$L_M$
$C_M$
$R_M$
505
$C_0$
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$C_0$
500

Fig. 5

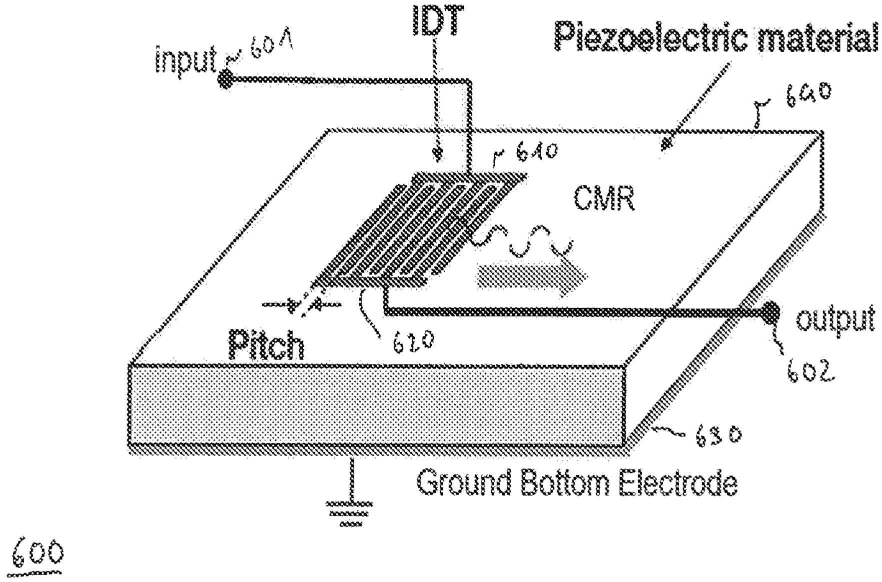
IDT
Piezoelectric material
input
601
640
610
CMR
output
620
602
Pitch
630
Ground Bottom Electrode
600

Fig. 6

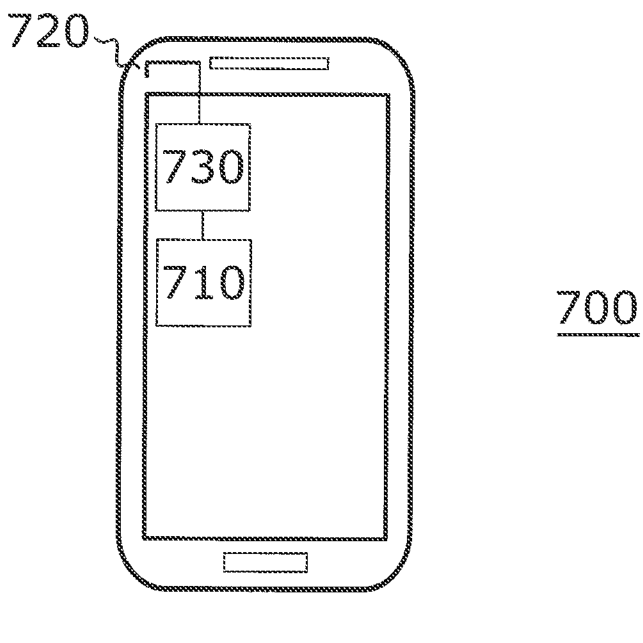
720
730
710
700

Fig. 7

# INTERNATIONAL SEARCH REPORT

International application No
PCT/US2019/039363

**A. CLASSIFICATION OF SUBJECT MATTER**
INV. H03H9/52 H03H9/54 H03H9/64 H03H9/56 H03H9/60
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

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
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| Y | pages 2,4-16; figures 1,2,4,6,7 | 20-22 |
| X | US 2013/120081 A1 (ZUO CHENGJIE [US] ET AL) 16 May 2013 (2013-05-16) | 1-5, 13-25 |
| Y | paragraphs [0043] - [0051], [0066] - [0071], [0108] - [0114]; figures 5,15,17 | 17-22 |
| X | US 5 382 930 A (STOKES ROBERT B [US] ET AL) 17 January 1995 (1995-01-17) | 1,4,5, 13-16, 23-25 |
| Y | column 2, lines 13-26; figures 3,4 column 4, line 5 - column 5, line 38 | 17-22 |

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 5 March 2020 | 13/03/2020 |

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

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# INTERNATIONAL SEARCH REPORT

International application No
PCT/US2019/039363

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
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Form PCT/ISA/210 (continuation of second sheet) (April 2005)

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**Information on patent family members**

International application No
PCT/US2019/039363

| Patent document cited in search report | | Publication date | Patent family member(s) | | | Publication date |
|---|---|---|---|---|---|---|
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| | | | US | 2006091978 | A1 | 04-05-2006 |