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Inventor(s)	Binninger; Charles et al.

Double-mode surface-acoustic-wave (DMS) filter having a transition region with a partly uniform geometric property

Abstract

An apparatus for filtering is disclosed that implements a double-mode surface-acoustic-wave filter having a transition region with a partly uniform geometric property. In an example aspect, the double-mode surface-acoustic-wave filter includes at least one interdigital transducer with multiple fingers. The multiple fingers include a first set of fingers having a geometric property and a second set of fingers. The second set of fingers is positioned adjacent to the first set of fingers and is associated with an outer edge of the at least one interdigital transducer. The geometric property across a subset of the second set of fingers is substantially uniform. A value of the geometric property across the subset of the second set of fingers is different than a value of the geometric property across the first set of fingers.

Inventors: **Binninger; Charles (Saint-Jeannet, FR), Damy; Jacques-Antoine (Nice, FR), Bisognin; Aimeric (Antibes, FR), Perois; Xavier (Mouans Sartoux, FR)**

Applicant: **RF360 Singapore Pte. Ltd.** (Singapore, SG)

Family ID: **1000008766275**

Assignee: **RF360 Singapore Pte. Ltd. (Republic Plaza, SG)**

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Primary Examiner: Outten; Samuel S

Attorney, Agent or Firm: Polsinelli

Background/Summary

TECHNICAL FIELD
(1) This disclosure relates generally to wireless transceivers and other components that employ filters and, more specifically, to implementing a double-mode surface-acoustic-wave (DMS) filter that has a transition region with a partly constant geometric property.
BACKGROUND
(2) Electronic devices use radio-frequency (RF) signals to communicate information. These radio-frequency signals enable users to talk with friends, download information, share pictures, remotely control household devices, and receive global positioning information. To transmit or receive the radio-frequency signals within a given frequency band, the electronic device may use filters to pass signals within the frequency band and to suppress (e.g., attenuate) jammers or noise having frequencies outside of the frequency band. It can be challenging, however, to design a filter that

provides filtering for radio-frequency applications, including those that utilize frequencies above 100 megahertz (MHz).

SUMMARY

(3) An apparatus is disclosed that implements a double-mode surface-acoustic-wave filter having a transition region with a partly uniform geometric property. The transition region of the double-mode surface-acoustic-wave filter includes sets of fingers respectively positioned at adjacent outer edges of two interdigital transducers. A geometric property across at least a portion of each set of fingers is substantially uniform. A value of the geometric property is different than a value of the geometric property across other sets of fingers outside of the transition region. Example geometric properties include a pitch and a metallization ratio. In some implementations, a profile of the pitch across the transition region has a trapezoidal shape with a well-type orientation. Additionally or alternatively, a profile of the metallization ratio within the transition region has a trapezoidal shape with a barrier-type orientation or a well-type orientation. These pitch and/or metallization ratio profiles enable suppression of spurious modes within the passband and enable the double-mode surface-acoustic-wave filter to have an aspect ratio that is within process limits. In this way, the double-mode surface-acoustic-wave filter can be integrated within space-constrained devices and can realize sufficient spurious mode suppression in the passband with fewer additional resonators (if any).

(4) In an example aspect, an apparatus for filtering is disclosed. The apparatus includes a double-mode surface-acoustic-wave filter. The double-mode surface-acoustic-wave filter includes at least one interdigital transducer with multiple fingers. The multiple fingers include a first set of fingers having a geometric property and a second set of fingers. The second set of fingers is positioned adjacent to the first set of fingers and is associated with an outer edge of the at least one interdigital transducer. The geometric property across a subset of the second set of fingers is substantially uniform. A value of the geometric property across the subset of the second set of fingers is different than a value of the geometric property across the first set of fingers.

(5) In an example aspect, a method for manufacturing a double-mode surface-acoustic-wave filter having a transition region with a partly uniform geometric property is disclosed. The method includes providing a first set of fingers of at least one interdigital transducer of the double-mode surface-acoustic-wave filter. The first set of fingers has a geometric property. The method also includes providing a second set of fingers of the at least one interdigital transducer of the double-mode surface-acoustic-wave filter. The second set of fingers are positioned adjacent to the first set of fingers and are associated with an outer edge of the at least one interdigital transducer. The geometric property across a subset of the second set of fingers is substantially uniform. A value of the geometric property across the subset of the second set of fingers is different than a value of the geometric property across the first set of fingers.

(6) In an example aspect, an apparatus for filtering is disclosed. The apparatus includes a double-mode surface-acoustic-wave filter with at least two adjacent interdigital transducers. The at least two adjacent interdigital transducers include multiple fingers. A portion of the multiple fingers are positioned within a transition region of the double-mode surface-acoustic-wave filter. A profile of a pitch across the portion of the multiple fingers has a trapezoidal shape with a well-type orientation.

(7) In an example aspect, an apparatus for filtering is disclosed. The apparatus includes a double-mode surface-acoustic-wave filter with at least two adjacent interdigital transducers. The at least two adjacent interdigital transducers include multiple fingers. A portion of the multiple fingers is positioned within a transition region of the double-mode surface-acoustic-wave filter. A profile of a geometric property across the portion of the multiple fingers has a trapezoidal shape.

(8) In an example aspect, an apparatus for filtering is disclosed. The apparatus includes a double-mode surface-acoustic-wave filter with two adjacent interdigital transducers. Each interdigital transducer of the two adjacent interdigital transducers includes multiple fingers. The multiple fingers of each interdigital transducer of the two adjacent interdigital transducers includes a first set

of fingers having a first pitch and a second set of fingers positioned adjacent to the first set of fingers. The second set of fingers is associated with an outer edge of the interdigital transducer. A subset of the second set of fingers has a second pitch that is substantially uniform. A value of the second pitch across the subset of the second set of fingers is less than a value of the first pitch across the first set of fingers. The second sets of fingers of the two adjacent interdigital transducers are adjacent to each other. Values of the second pitches associated with the two adjacent interdigital transducers are less than values of the first pitches associated with the two adjacent interdigital transducers.

Description

BRIEF DESCRIPTION OF DRAWINGS

(1) FIG. **1** illustrates an example operating environment for a double-mode surface-acoustic-wave filter having a transition region with a partly uniform geometric property.

(2) FIG. **2** illustrates an example wireless transceiver including a double-mode surface-acoustic-wave filter having a transition region with a partly uniform geometric property.

(3) FIG. **3** illustrates example components of a double-mode surface-acoustic-wave filter.

(4) FIG. **4-1** illustrates an example implementation of a double-mode surface-acoustic-wave filter using a thin-film surface-acoustic-wave filter stack.

(5) FIG. **4-2** illustrates another example implementation of a double-mode surface-acoustic-wave filter using a high-quality temperature-compensated surface-acoustic-wave filter stack.

(6) FIG. **5** illustrates an example electrode structure of a double-mode surface-acoustic-wave filter.

(7) FIG. **6** illustrates example geometric properties of a double-mode surface-acoustic-wave filter.

(8) FIG. **7** illustrates an example double-mode surface-acoustic-wave filter having a transition region with a partly uniform geometric property.

(9) FIG. **8** illustrates an example pitch profile of a double-mode surface-acoustic-wave filter.

(10) FIG. **9** illustrates an example metallization ratio profile of a double-mode surface-acoustic-wave filter.

(11) FIG. **10** is a flow diagram illustrating an example process for manufacturing a double-mode surface-acoustic-wave filter having a transition region with a partly uniform geometric property.

DETAILED DESCRIPTION

(12) To transmit or receive radio-frequency signals within a given frequency band, an electronic device may use filters to pass signals within the frequency band and to suppress (e.g., attenuate) jammers or noise having frequencies outside of the frequency band. Electroacoustic devices (e.g., “acoustic filters”) can be used to filter high-frequency signals in many applications, such as those with frequencies that are greater than 100 megahertz (MHz). An acoustic filter is tuned to pass certain frequencies (e.g., frequencies within its passband) and attenuate other frequencies (e.g., frequencies that are outside of its passband). Using piezoelectric material as a vibrating medium, the acoustic filter operates by transforming an electrical signal wave that is propagating along an electrical conductor into an acoustic wave (e.g., an acoustic signal wave) that forms across the piezoelectric material. The acoustic wave is then converted back into an electrical filtered signal. The acoustic filter can include an electrode structure that transforms or converts between the electrical and acoustic waves.

(13) The acoustic wave forms across the piezoelectric material and has a velocity with a magnitude that is significantly less than a velocity of an electromagnetic wave. Generally, the magnitude of the velocity of a wave is proportional to a wavelength of the wave. Consequently, after conversion of the electrical signal wave into the acoustic signal wave, the wavelength of the acoustic signal wave is significantly smaller than the wavelength of the electrical signal wave. The resulting smaller wavelength of the acoustic signal wave enables filtering to be performed using a smaller

filter device. This permits acoustic filters to be used in space-constrained devices, including portable electronic devices such as cellular phones.

(14) It can be challenging, however, to design a wideband acoustic filter with a compact design that can provide adequate suppression of a spurious mode (e.g., an undesired mode such as a Rayleigh mode) within a passband of the wideband acoustic filter. Some techniques use a double-mode surface-acoustic-wave (DMS) filter, which can have a smaller footprint compared to other types of acoustic filters. By itself, however, the double-mode surface-acoustic-wave filter might not be able to attenuate spurious modes within the passband by a desired amount. To address this issue, some filter architectures use multiple resonators, such as multiple surface-acoustic-wave filters arranged in a ladder-type structure. These additional filters can significantly increase an overall footprint of a wireless transceiver, which can make it challenging to integrate within space-constrained devices.

(15) Other techniques may attempt to attenuate the spurious mode within the passband by customizing a geometric property of the electrode structure within a transition region of the double-mode surface-acoustic-wave filter. In some instances, it can be challenging to manufacture the electrode structure with a desired geometric property without causing an aspect ratio of the electrode structure to exceed process limits. If the aspect ratio exceeds the process limits, a sputtering process may have difficulty depositing portions of a compensation layer between fingers of the electrode structure. This can lead to gaps (e.g., holes or voids) within the portions of the compensation layer. These gaps can introduce additional ripples within the passband.

(16) To address these challenges, example techniques for implementing a double-mode surface-acoustic-wave filter having a transition region with a partly uniform geometric property are described. The transition region of the double-mode surface-acoustic-wave filter includes sets of fingers respectively positioned at adjacent outer edges of two interdigital transducers. A geometric property across at least a portion of each set of fingers is substantially uniform. A value of the geometric property is different than a value of the geometric property across other sets of fingers outside of the transition region. Example geometric properties include a pitch and a metallization ratio. In some implementations, a profile of the pitch across the transition region has a trapezoidal shape with a well-type orientation. Additionally or alternatively, a profile of the metallization ratio within the transition region has a trapezoidal shape with a barrier-type orientation or a well-type orientation. These pitch and/or metallization ratio profiles enable suppression of spurious modes within the passband and enable the double-mode surface-acoustic-wave filter to have an aspect ratio that is within process limits. In this way, the double-mode surface-acoustic-wave filter can be integrated within space-constrained devices and can realize sufficient spurious mode suppression in the passband with fewer additional resonators (if any).

(17) FIG. **1** illustrates an example environment **100** for operating a double-mode surface-acoustic-wave filter having a transition region with a partly uniform geometric property. In the environment **100**, a computing device **102** communicates with a base station **104** through a wireless communication link **106** (wireless link **106**). In this example, the computing device **102** is depicted as a smartphone. However, the computing device **102** can be implemented as any suitable computing or electronic device, such as a modem, a cellular base station, a broadband router, an access point, a cellular phone, a gaming device, a navigation device, a media device, a laptop computer, a desktop computer, a tablet computer, a wearable computer, a server, a network-attached storage (NAS) device, a smart appliance or other internet of things (IoT) device, a medical device, a vehicle-based communication system, a radar, a radio apparatus, and so forth.

(18) The base station **104** communicates with the computing device **102** via the wireless link **106**, which can be implemented as any suitable type of wireless link. Although depicted as a tower of a cellular network, the base station **104** can represent or be implemented as another device, such as a satellite, a server device, a terrestrial television broadcast tower, an access point, a peer-to-peer device, a mesh network node, and so forth. Therefore, the computing device **102** may communicate with the base station **104** or another device via a wireless connection.

(19) The wireless link **106** can include a downlink of data or control information communicated from the base station **104** to the computing device **102**, an uplink of other data or control information communicated from the computing device **102** to the base station **104**, or both a downlink and an uplink. The wireless link **106** can be implemented using any suitable communication protocol or standard, such as 2nd-generation (2G), 3rd-generation (3G), 4th-generation (4G), or 5th-generation (5G) cellular; IEEE 802.11 (e.g., Wi-Fi®); IEEE 802.15 (e.g., Bluetooth®); IEEE 802.16 (e.g., WiMAX®); and so forth. In some implementations, the wireless link **106** may wirelessly provide power and the base station **104** or the computing device **102** may comprise a power source.

(20) As shown, the computing device **102** includes an application processor **108** and a computer-readable storage medium **110** (CRM **110**). The application processor **108** can include any type of processor, such as a multi-core processor, that executes processor-executable code stored by the CRM **110**. The CRM **110** can include any suitable type of data storage media, such as volatile memory (e.g., random access memory (RAM)), non-volatile memory (e.g., Flash memory), optical media, magnetic media (e.g., disk), and so forth. In the context of this disclosure, the CRM **110** is implemented to store instructions **112**, data **114**, and other information of the computing device **102**, and thus does not include transitory propagating signals or carrier waves.

(21) The computing device **102** can also include input/output ports **116** (I/O ports **116**) and a display **118**. The I/O ports **116** enable data exchanges or interaction with other devices, networks, or users. The I/O ports **116** can include serial ports (e.g., universal serial bus (USB) ports), parallel ports, audio ports, infrared (IR) ports, user interface ports such as a touchscreen, and so forth. The display **118** presents graphics of the computing device **102**, such as a user interface associated with an operating system, program, or application. Alternatively or additionally, the display **118** can be implemented as a display port or virtual interface, through which graphical content of the computing device **102** is presented.

(22) A wireless transceiver **120** of the computing device **102** provides connectivity to respective networks and other electronic devices connected therewith. The wireless transceiver **120** can facilitate communication over any suitable type of wireless network, such as a wireless local area network (WLAN), peer-to-peer (P2P) network, mesh network, cellular network, ultra-wideband (UWB) network, wireless wide-area-network (WWAN), and/or wireless personal-area-network (WPAN). In the context of the example environment **100**, the wireless transceiver **120** enables the computing device **102** to communicate with the base station **104** and networks connected therewith. However, the wireless transceiver **120** can also enable the computing device **102** to communicate "directly" with other devices or networks.

(23) The wireless transceiver **120** includes circuitry and logic for transmitting and receiving communication signals via an antenna **122**. Components of the wireless transceiver **120** can include amplifiers, switches, mixers, analog-to-digital converters, filters, and so forth for conditioning the communication signals (e.g., for generating or processing signals). The wireless transceiver **120** can also include logic to perform in-phase/quadrature (I/Q) operations, such as synthesis, encoding, modulation, decoding, demodulation, and so forth. In some cases, components of the wireless transceiver **120** are implemented as separate transmitter and receiver entities. Additionally or alternatively, the wireless transceiver **120** can be realized using multiple or different sections to implement respective transmitting and receiving operations (e.g., separate transmit and receive chains). In general, the wireless transceiver **120** processes data and/or signals associated with communicating data of the computing device **102** over the antenna **122**.

(24) In the example shown in FIG. **1**, the wireless transceiver **120** includes at least one double-mode surface-acoustic-wave filter **124** (DMS filter **124**). The double-mode surface-acoustic-wave filter **124** can be implemented as, for example, a longitudinal-coupled double-mode surface-acoustic-wave (LDMS) filter. The double-mode surface-acoustic-wave filter **124** can be implemented using a thin-film surface-acoustic-wave (TFSAW) filter stack or a high-quality

temperature-compensated surface-acoustic-wave (HQTC) filter stack. In general, the double-mode surface-acoustic-wave filter **124** excites at least two wave modes. In an example implementation, the double-mode surface-acoustic-wave filter **124** excites a main wave mode (e.g., a plate mode) and a cavity mode.

(25) The double-mode surface-acoustic-wave filter **124** includes at least two interdigital transducers **126** and at least one transition region **128**, which are further described with respect to FIG. **3**. At least one geometric property **130** of each of the interdigital transducers **126** is substantially uniform (e.g., substantially steady, constant, or static) across a portion of the transition region **128**. In general, the term "substantially uniform" can mean that the geometric property changes by less than ±1% across a portion of the transition region **128** (e.g., across at least two pairs of adjacent fingers within the transition region **128**). For example, the value of the geometric property across the portion of the transition region **128** can change by ±1%, ±0.75%, ±0.5% or less. This amount of variation can account for slight differences caused by process variations. Example geometric properties **130** include a pitch **132** and/or an metallization ratio **134**. The pitch **132** can represent an average distance between adjacent fingers of an interdigital transducer **126**. The metallization ratio **134** represents an average width of adjacent fingers divided by the pitch **132**. The metallization ratio **134** can be represented by the Greek letter eta (η).

(26) Across the transition region **128**, a profile of the geometric property **130** can have a trapezoidal shape. For instance, a profile of the pitch **132** across the transition region **128** can have a trapezoidal shape with a well-type orientation. In this case, a "bottom" of the trapezoidal shape represents the portion of the transition region **128** in which the pitch **132** is substantially uniform. Additionally or alternatively, a profile of the metallization ratio **134** across the transition region **128** can have another trapezoidal shape. The trapezoidal shape of the profile of the metallization ratio can have a barrier-type orientation or a well-type orientation. For the barrier-type orientation, a "top" of the trapezoidal shape represents the portion of the transition region **128** in which the metallization ratio **134** is substantially uniform. The profiles of the pitch **132** and the metallization ratio **134** are further described with respect to FIGS. **8** and **9**, respectively. The trapezoidal shape(s) of the pitch **132** and/or the metallization ratio **134** can differ from other types of double-mode surface-acoustic-wave filters that have a flat shape or a triangular shape. With the partly uniform geometric property **130**, the double-mode surface-acoustic-wave filter **124** can suppress spurious modes within the passband. In this way, the double-mode surface-acoustic-wave filter **124** can have a smaller footprint and a lower cost compared to other double-mode surface-acoustic-wave filters with a constant pitch or a triangular shaped pitch within the transition region.

(27) In some example implementations, a footprint of the double-mode surface-acoustic-wave filter **124** can be approximately 55% smaller than a footprint of another filter that doesn't employ the techniques of a partly uniform geometric property **130** within the transition region **128**. Also, amplitudes of the ripples within the passband of the double-mode surface-acoustic-wave filter **124** can be less than approximately 0.1 decibels.

(28) The double-mode surface-acoustic-wave filter **124** can be implemented as a wideband filter. For instance, a bandwidth of the double-mode surface-acoustic-wave filter **124** can be greater than or equal to approximately 4% of a center frequency of its passband. In some implementations, this bandwidth enables the double-mode surface-acoustic-wave filter **124** to filter frequencies associated with multiple frequency bands. The wireless transceiver **120** is further described with respect to FIG. **2**.

(29) FIG. **2** illustrates an example wireless transceiver **120**. In the depicted configuration, the wireless transceiver **120** includes a transmitter **202** and a receiver **204**, which are respectively coupled to a first antenna **122-1** and a second antenna **122-2**. In other implementations, the transmitter **202** and the receiver **204** can be connected to a same antenna through a duplexer (not shown). The transmitter **202** is shown to include at least one digital-to-analog converter **206** (DAC **206**), at least one first mixer **208-1**, at least one amplifier **210** (e.g., a power amplifier), and at least

one filter **240**. The filter **240** can be implemented as an acoustic filter. The receiver **204** includes at least one double-mode surface-acoustic-wave filter **124**, at least one amplifier **212** (e.g., a low-noise amplifier), at least one second mixer **208-2**, and at least one analog-to-digital converter **214** (ADC **214**). The first mixer **208-1** and the second mixer **208-2** are coupled to a local oscillator **216**. Although not explicitly shown, the digital-to-analog converter **206** of the transmitter **202** and the analog-to-digital converter **214** of the receiver **204** can be coupled to the application processor **108** (of FIG. **1**) or another processor associated with the wireless transceiver **120** (e.g., a modem).

(30) In some implementations, the wireless transceiver **120** is implemented using multiple circuits (e.g., multiple integrated circuits), such as a transceiver circuit **236** and a radio-frequency front-end (RFFE) circuit **238**. As such, the components that form the transmitter **202** and the receiver **204** are distributed across these circuits. As shown in FIG. **2**, the transceiver circuit **236** includes the digital-to-analog converter **206** of the transmitter **202**, the mixer **208-1** of the transmitter **202**, the mixer **208-2** of the receiver **204**, and the analog-to-digital converter **214** of the receiver **204**. In other implementations, the digital-to-analog converter **206** and the analog-to-digital converter **214** can be implemented on another separate circuit that includes the application processor **108** or the modem. The radio-frequency front-end circuit **238** includes the amplifier **210** of the transmitter **202**, the filter **240** of the transmitter **202**, the double-mode surface-acoustic-wave filter **124** of the receiver **204**, and the amplifier **212** of the receiver **204**.

(31) During transmission, the transmitter **202** generates a radio-frequency transmit signal **218**, which is transmitted using the antenna **122-1**. To generate the radio-frequency transmit signal **218**, the digital-to-analog converter **206** provides a pre-upconversion transmit signal **220** to the first mixer **208-1**. The pre-upconversion transmit signal **220** can be a baseband signal or an intermediate-frequency signal. The first mixer **208-1** upconverts the pre-upconversion transmit signal **220** using a local oscillator (LO) signal **222** provided by the local oscillator **216**. The first mixer **208-1** generates an upconverted signal, which is referred to as a pre-filter transmit signal **224**. The pre-filter transmit signal **224** can be a radio-frequency signal and include some noise or unwanted frequencies, such as a harmonic frequency. The amplifier **210** amplifies the pre-filter transmit signal **224** and passes the amplified pre-filter transmit signal **224** to the filter **240**.

(32) The filter **240** filters the amplified pre-filter transmit signal **224** to generate a filtered transmit signal **226**. As part of the filtering process, the filter **240** attenuates the noise or unwanted frequencies within the pre-filter transmit signal **224**. The transmitter **202** provides the filtered transmit signal **226** to the antenna **122-1** for transmission. The transmitted filtered transmit signal **226** is represented by the radio-frequency transmit signal **218**.

(33) During reception, the antenna **122-2** receives a radio-frequency receive signal **228** and passes the radio-frequency receive signal **228** to the receiver **204**. The double-mode surface-acoustic-wave filter **124** accepts the received radio-frequency receive signal **228**, which is represented by a pre-filter receive signal **230**. The double-mode surface-acoustic-wave filter **124** filters any noise or unwanted frequencies within the pre-filter receive signal **230** to generate a filtered receive signal **232**.

(34) The amplifier **212** of the receiver **204** amplifies the filtered receive signal **232** and passes the amplified filtered receive signal **232** to the second mixer **208-2**. The second mixer **208-2** downconverts the amplified filtered receive signal **232** using the local oscillator signal **222** to generate the downconverted receive signal **234**. The analog-to-digital converter **214** converts the downconverted receive signal **234** into a digital signal, which can be processed by the application processor **108** or another processor associated with the wireless transceiver **120** (e.g., the modem).

(35) FIG. **2** illustrates one example configuration of the wireless transceiver **120**. Other configurations of the wireless transceiver **120** can support multiple frequency bands and share an antenna **122** across multiple transceivers. One of ordinary skill in the art can appreciate the variety of other configurations for which the double-mode surface-acoustic-wave filter **124** may be included. For example, the double-mode surface-acoustic-wave filter **124** can be integrated within a

duplexer or diplexer of the wireless transceiver **120**. Also, some implementations of the wireless transceiver **120** can implement the filter **240** using another double-mode surface-acoustic-wave filter **124**. An example implementation of the double-mode surface-acoustic-wave filter **124** is further described with respect to FIG. **3**.

(36) FIG. **3** illustrates example components of the double-mode surface-acoustic-wave filter **124**. In the depicted configuration, the double-mode surface-acoustic-wave filter **124** includes an electrode structure **302**, a piezoelectric layer **304**, and at least one substrate layer **306**. The electrode structure **302** comprises an electrically conductive material, such as metal, and can include one or more layers. The one or more layers can include one or more metal layers and can optionally include one or more adhesion layers. As an example, the metal layers can be composed of aluminium (Al), copper (Cu), silver (Ag), gold (Au), tungsten (W), platinum (Pt), or some combination or doped version thereof. The adhesion layers can be composed of chromium (Cr), titanium (Ti), molybdenum (Mo), or some combination thereof.

(37) The electrode structure **302** can include two or more interdigital transducers **126**. The interdigital transducers **126** convert an electrical signal into an acoustic wave and converts the acoustic wave into a filtered electrical signal. Each interdigital transducer **126** includes at least two comb-shaped structures **308-1** and **308-2**. Each comb-shaped structure **308-1** and **308-2** includes a busbar **310** (e.g., a conductive segment or rail) and multiple fingers **312** (e.g., electrode fingers). The electrode structure **302** can also optionally include two or more reflectors **314**. In an example implementation, the interdigital transducers **126** are arranged between two reflectors **314**, which reflect the acoustic wave back towards the interdigital transducers **126**. Examples of the electrode structure **302** and the interdigital transducers **126** are further described with respect to FIGS. **4-1** to **6**.

(38) One or more physical characteristics of the interdigital transducers **126** can be characterized by the geometric property **130**. In particular, the geometric property **130** describes the positioning and/or physical characteristic(s) of the fingers **312** within the electrode structure **302**. Example geometric properties **130** include the pitch **132** and the metallization ratio **134**, which can vary across the electrode structure **302**.

(39) The transition region **128** represents sets of fingers **312** respectively positioned at adjacent outer edges of two adjacent interdigital transducers **126**. The transition region **128** is further described with respect to FIGS. **5** and **6**. A profile of the geometric property **130** (e.g., a geometric profile **316**) across a portion of the transition region **128** can be substantially uniform. Example geometric profiles **316** include a profile of the pitch **132** (e.g., a pitch profile **318**) and/or a profile of the metallization ratio **134** (e.g., a metallization ratio (MR) profile **320**). A profile of the geometric property **130** can have a trapezoidal shape **322**, as further described with respect to FIGS. **8** and **9**.

(40) This trapezoidal shape **322** enables the double-mode surface-acoustic-wave filter **124** to achieve a target amount of spurious mode suppression within the passband while having an aspect ratio **324** within process limits. The aspect ratio **324** represents an average thickness (or height) of adjacent fingers **312** divided by a distance of the physical gap between the adjacent fingers. An example process limit can specify the aspect ratio **324** to be less than or equal to approximately 50%. In this case, the interdigital transducers **126** can have an aspect ratio **324** that is approximately 50%, 45%, 40%, and so forth. Other limitations of the aspect ratio **324** are also possible. With an appropriate aspect ratio **324**, the double-mode surface-acoustic-wave filter **124** can be readily manufactured without introducing significant ripples in the passband. For instance, the aspect ratio **324** can be sufficient to enable a sputtering process to deposit a compensation layer, such as a silicon dioxide layer, between adjacent fingers **312** of the interdigital transducer **126** without introducing gaps (e.g., holes or voids) within the compensation layer.

(41) In general, the limits placed on the aspect ratio **324** can vary for different types of manufacturing processes and can vary for different types of filter stacks. Designing the double-

mode surface-acoustic-wave filter **124** to have an aspect ratio **324** that satisfies the process limit can be particularly applicable for implementations that include a compensation layer disposed on the electrode structure **302**. Generally speaking, the techniques for designing a double-mode surface-acoustic-wave filter **124** having a transition region **128** with a partly uniform geometric property **130** can apply to filter stacks that do not include the compensation layer (e.g., the thin-film surface-acoustic-wave filter stack of FIG. **4-1**) and filter stacks that include the compensation layer (e.g., the high-quality temperature-compensated filter stack of FIG. **4-2**).

(42) In example implementations, the piezoelectric layer **304** can be implemented using a variety of different materials that exhibit piezoelectric properties (e.g., can transfer mechanical energy into electrical energy or electrical energy into mechanical energy). Example types of material include lithium niobate ($LiNbO_3$), lithium tantalate ($LiTaO_3$), quartz, aluminium nitride (AlN), aluminium scandium nitride (AlScN), or some combination thereof. In general, the material that forms the piezoelectric layer **304** has a crystalline structure. This crystalline structure is defined by an ordered arrangement of particles (e.g., atoms, ions, or molecules). In some implementations, the piezoelectric layer **304** has an electromechanical coupling factor (k^2) that is greater than or equal to approximately 4%.

(43) The substrate layer **306** includes one or more sublayers that can support passivation, temperature compensation, power handling, mode suppression, and so forth. As an example, the substrate layer **306** can include at least one compensation layer **326**, at least one charge-trapping layer **328**, at least one support layer **330**, or some combination thereof. These sublayers can be considered part of the substrate layer **306** or their own separate layers.

(44) The compensation layer **326** can provide temperature compensation to enable the double-mode surface-acoustic-wave filter **124** to achieve a target temperature coefficient of frequency based on the thickness of the piezoelectric layer **304**. In some implementations, a thickness of the compensation layer **326** can be tailored to provide mode suppression (e.g., suppress a spurious plate mode). In example implementations, the compensation layer **326** can be implemented using at least one silicon dioxide (SiO_2) layer, at least one doped silicon dioxide layer, at least one silicon nitride layer, at least one silicon oxynitride layer, or some combination thereof. In some applications, the substrate layer **306** may not include, for instance, the compensation layer **326** to reduce cost of the double-mode surface-acoustic-wave filter **124**.

(45) The charge-trapping layer **328** can trap induced charges at the interface between the compensation layer **326** and the support layer **330** in order to, for example, suppress nonlinear substrate effects. The charge-trapping layer **328** can include at least one polysilicon (poly-Si) layer (e.g., a polycrystalline silicon layer or a multicrystalline silicon layer), at least one amorphous silicon layer, at least one silicon nitride (SiN) layer, at least one silicon oxynitride (SiON) layer, at least one aluminium nitride (AlN) layer, diamond-like carbon (DLC), diamond, or some combination thereof.

(46) The support layer **330** can enable the acoustic wave to form across the surface of the piezoelectric layer **304** and reduce the amount of energy that leaks into the substrate layer **306**. In some implementations, the support layer **330** can also act as a compensation layer **326**. In general, the support layer **330** is composed of material that is non-conducting and provides isolation. For example, the support layer **330** can be formed using silicon (Si) material (e.g., a doped high-resistive silicon material), sapphire material (e.g., aluminium oxide (Al_2O_3)), silicon carbide (SiC) material, fused silica material, quartz, glass, diamond, or some combination thereof. In some implementations, the support layer **330** has a relatively similar thermal expansion coefficient (TEC) as the piezoelectric layer **304**. The support layer **330** can also have a particular crystal orientation to support the suppression or attenuation of spurious modes.

(47) In some aspects, the double-mode surface-acoustic-wave filter **124** can be considered a resonator or formed from multiple resonators. Sometimes the double-mode surface-acoustic-wave filter **124** can be connected to other resonators associated with the same or different layer stacks

than the double-mode surface-acoustic-wave filter **124**. The electrode structure **302**, the piezoelectric layer **304**, and the substrate layer **306** are further described with respect to FIGS. **4-1** and **4-2**.

(48) FIG. **4-1** illustrates an example implementation of the double-mode surface-acoustic-wave filter **124** using a thin-film surface-acoustic-wave filter stack. A three-dimensional perspective view **400-1** of the double-mode surface-acoustic-wave filter **124** is shown at the top of FIG. **4-1**, and a two-dimensional cross-section view **400-2** of the double-mode surface-acoustic-wave filter **124** is shown at the bottom of FIG. **4-1**.

(49) The double-mode surface-acoustic-wave filter **124** includes at least one electrode structure **302**, at least one piezoelectric layer **304**, and at least one substrate layer **306**. In the depicted configuration shown in the two-dimensional cross-section view **400-2**, the piezoelectric layer **304** is disposed between the electrode structure **302** and the substrate layer **306**. A portion of the electrode structure **302** depicted in FIG. **4-1** includes at least a portion of one interdigital transducer **126**. The electrode structure **302** can include additional interdigital transducers **126** not explicitly shown in FIG. **4-1**. Also, the interdigital transducer **126** depicted in FIG. **4-1** can include additional fingers **312** not explicitly shown in FIG. **4-1**.

(50) In the three-dimensional perspective view **400-1**, the interdigital transducer **126** is shown to have the two comb-shaped structures **308-1** and **308-2** with fingers **312** extending from two busbars **310** towards each other. The fingers **312** are arranged in an interlocking manner in between the two busbars **310** of the interdigital transducer **126** (e.g., arranged in an interdigitated manner). In other words, the fingers **312** connected to a first busbar **310** extend towards a second busbar **310** but do not connect to the second busbar **310**. As such, there is a barrier region **402** (e.g., a transversal gap region) between the ends of these fingers **312** and the second busbar **310**. Likewise, fingers **312** connected to the second busbar **310** extend towards the first busbar **310** but do not connect to the first busbar **310**. There is therefore a barrier region **402** between the ends of these fingers **312** and the first busbar **310**.

(51) In the direction along the busbars **310**, there is an overlap region **404** where a portion of one finger **312** overlaps with a portion of an adjacent finger **312**. This overlap region **404** may be referred to as the aperture, track, or active region where electric fields are produced between fingers **312** to cause an acoustic wave **406** to form at least in this region of the piezoelectric layer **304**.

(52) A physical periodicity of the fingers **312** is referred to as the pitch **132** of the interdigital transducer **126**. The pitch **132** may be indicated in various ways. For example, in certain aspects, the pitch **132** may correspond to a magnitude of a distance between adjacent fingers **312** of the interdigital transducer **126** in the overlap region **404**. This distance may be defined, for example, as the distance between center points of each of the fingers **312**. The distance may be generally measured between a right (or left) edge of one finger **312** and the right (or left) edge of an adjacent finger **312** when the fingers **312** have uniform widths. In certain aspects, an average of distances between adjacent fingers **312** of the interdigital transducer **126** may be used for the pitch **132**. The frequency at which the piezoelectric layer **304** vibrates is a main-resonance frequency of the electrode structure **302**. The frequency is determined at least in part by the pitch **132** of the interdigital transducer **126** and other properties of the double-mode surface-acoustic-wave filter **124**.

(53) In the three-dimensional perspective view **400-1**, the double-mode surface-acoustic-wave filter **124** is defined by a first (X) axis **408**, a second (Y) axis **410**, and a third (Z) axis **412**. The first axis **408** and the second axis **410** are parallel to a planar surface of the piezoelectric layer **304**, and the second axis **410** is perpendicular to the first axis **408**. The third axis **412** is normal (e.g., perpendicular or orthogonal) to the planar surface of the piezoelectric layer **304**. The busbars **310** of the interdigital transducer **126** are oriented to be parallel to the first axis **408**. The fingers **312** of the interdigital transducer **126** are orientated to be parallel to the second axis **410**. Also, an

orientation of the piezoelectric layer **304** causes the acoustic wave **406** to mainly form in a direction of the first axis **408**. As such, the acoustic wave **406** forms in a direction that is substantially perpendicular or orthogonal to the direction of the fingers **312** of the interdigital transducer **126**.

(54) FIG. **4-2** illustrates an example implementation of the double-mode surface-acoustic-wave filter **124** using a high-quality temperature-compensated surface-acoustic-wave filter stack. A three-dimensional perspective view **400-3** of the double-mode surface-acoustic-wave filter **124** is shown at the top of FIG. **4-2**, and a two-dimensional cross-section view **400-4** of the double-mode surface-acoustic-wave filter **124** is shown at the bottom of FIG. **4-2**.

(55) The double-mode surface-acoustic-wave filter **124** includes at least one electrode structure **302**, at least one piezoelectric layer **304**, and at least one compensation layer **326**. The compensation layer **326** can provide temperature compensation to enable the double-mode surface-acoustic-wave filter **124** to achieve a target temperature coefficient of frequency. In example implementations, the compensation layer **326** can be implemented using at least one silicon dioxide layer.

(56) In the depicted configuration shown in the two-dimensional cross-section view **400-4**, the electrode structure **302** is disposed between the piezoelectric layer **304** and the compensation layer **326**. The piezoelectric layer **304** can form a substrate of the double-mode surface-acoustic-wave filter **124**.

(57) The electrode structure **302** of the high-quality temperature-compensated filter stack can be similar to the electrode structure **302** described above with respect to the thin-film surface-acoustic-wave filter stack of FIG. **4-1**. Likewise, the piezoelectric layer **304** of the high-quality temperature-compensated filter stack can be similar to the piezoelectric layer **304** described above with respect to the thin-film surface-acoustic-wave filter stack of FIG. **4-1**. The piezoelectric layer **304** of the high-quality temperature-compensated surface-acoustic-wave filter stack, however, can be thicker than the piezoelectric layer **304** of the thin-film surface-acoustic-wave filter stack of FIG. **4-1**. Similar to the thin-film surface-acoustic-wave filter stack of FIG. **4-1**, the high-quality temperature-compensated surface-acoustic-wave filter stack of FIG. **4-2** can also include the barrier region **402** and the central region **404**.

(58) One of ordinary skill in the art can appreciate the variety of filter stacks in which the double-mode surface-acoustic-wave filter **124** can be implemented. It should be appreciated that while a certain number of fingers **312** are illustrated in FIGS. **4-1** and **4-2**, the number of actual fingers and lengths and width of the fingers **312** and busbars **310** may be different in an actual implementation. Such parameters depend on the particular application and desired filter characteristics. In addition, the double-mode surface-acoustic-wave filter **124** can include multiple interdigital transducers **126** to achieve a desired filter transfer function. An example electrode structure **302** with multiple interdigital transducers **126** is further described with respect to FIG. **5**.

(59) FIG. **5** illustrates an example electrode structure **302** of a double-mode surface-acoustic-wave filter **124**. In the depicted configuration, the electrode structure **302** includes interdigital transducers **126-1** to **126**-N, where N represents a positive integer. In example implementations, the variable N can be equal to 3, 4, 5, 7, and so forth.

(60) The electrode structure **302** also includes reflectors **314-1** and **314-2**. The interdigital transducers **126-1** to **126**-N are arranged between the reflectors **314-1** and **314-2**. In this way, the reflectors **314-1** and **314-2** reflect the acoustic wave **406** back towards the interdigital transducers **126-1** to **126**-N. Each reflector **314-1** and **314-2** within the electrode structure **302** can have two busbars **310** and a grating structure of conductive fingers **312** that connect to both busbars **310**. In some implementations, a pitch of the reflector **314** can be similar to the pitch **132** of the interdigital transducer **126** to reflect the acoustic wave **406** in the resonant frequency range.

(61) Each interdigital transducer **126** includes a first busbar **310-1**, a second busbar **310-2**, and fingers **312-1** to **312**-B, where B represents a positive integer. The first busbar **310-1** and the

fingers **312-1** to **312**-A form at least a portion of the first comb-shaped structure **308-1**, where A represents a positive integer that is less than B. The fingers **312-1** to **312**-A are connected to the first busbar **310-1** and extend along the second (Y) axis **410** towards the second busbar **310-2** without connecting to the second busbar **310-2**. The second busbar **310-2** and the fingers **312**-(A+1) to **312**-B form at least a portion of the second comb-shaped structure **308-2**. The fingers **312**-(A+1) to **312**-B are connected to the second busbar **310-2** and extend along the second (Y) axis **410** towards the first busbar **310-1** without connecting to the first busbar **310-1**.

(62) The fingers **312** within the interdigital transducer **126** can be associated with a first transition region **128-1**, a central region **502**, or a second transition region **128-2**. The central region **502** is positioned between the first and second transition regions **128-1** and **128-2** along the first axis **408**. The first and second transition regions **128-1** and **128-2** are associated with opposite outer edges of the interdigital transducer **126**. For instance, the first transition region **128-1** is associated with a "left" edge of the interdigital transducer **126**, and the second transition region **128-2** is associated with a "right" edge of the interdigital transducer **126**. Although not explicitly shown, the first and second transition regions **128-1** and **128-2** can also include fingers **312** of an adjacent interdigital transducer **126**. The central region **502** is associated with a center of the interdigital transducer **126** and does not include additional fingers **312** associated with the adjacent interdigital transducer **126**.

(63) In general, the transition region **128** includes portions of two adjacent interdigital transducers **126** that form a smooth, continuous transition with quasi-periodic grating between adjacent elements. The pitch **132** and the metallization ratio **134** of the interdigital transducers **126** can vary across the first axis **408**, as further described with respect to FIG. **6**.

(64) FIG. **6** illustrates example geometric properties **130** of the double-mode surface-acoustic-wave filter **124**. A portion of the double-mode surface-acoustic-wave filter **124** includes two adjacent interdigital transducers **126-1** and **126-2** of the electrode structure **302**, which are disposed on the piezoelectric layer **304**. Each interdigital transducer **126** includes multiple fingers **312**. In particular, each of the interdigital transducers **126-1** and **126-2** includes a first set of fingers **602-1** positioned within the central region **502** (e.g., outside of the transition region **128**). Additionally, each of the interdigital transducers **126-1** and **126-2** includes a second set of fingers **602-2** that are positioned adjacent to the first set of fingers **602-1** and are within the transition region **128**. In general, the second set of fingers **604-2** are proximate to an outer edge of the interdigital transducer **126** (e.g., proximate to the adjacent interdigital transducer **126**). The term "proximate" can refer to the second set of fingers **602-2** being closer to the outer edge of the interdigital transducer **126** compared to a center of the interdigital transducer **126**.

(65) In general, the first set of fingers **602-1** represents fingers **312** that are not associated with the transition region **128**. At least some of the fingers **312** within the first set of fingers **602-1** can be proximate to a center of the interdigital transducer **126** (e.g., closer to a center of the interdigital transducer **126** compared to an outer edge). Although not explicitly shown, each interdigital transducer **126** can include a third set of fingers that are positioned adjacent to the first set of fingers **602-1** and are within another transition region **128** that is associated with another outer edge of the interdigital transducer **126**.

(66) In some implementations, the first set of fingers **602-1** includes a larger quantity of fingers than the second set of fingers **602-2**. In example implementations, the second set of fingers **604-2** includes at least four fingers **312** (e.g., four fingers, five fingers, or more). As such, the transition region **128** associated with the two adjacent interdigital transducers **126** can include eight or more fingers **312** (e.g., ten fingers).

(67) Individual pitches **132** between adjacent fingers **312** can vary across each interdigital transducer **126**. In one aspect, the pitch **132** can be substantially uniform across the first set of fingers **602-1**, as represented by a pitch **132-1**. Additionally, the pitch **132** can be substantially uniform across a first subset **604-1** of the second set of fingers **604-2**, as represented by a pitch **132-2**. A value of the pitch **132-2** can be different than the value of the pitch **132-1**. In particular,

the value of the pitch **132-2** can be less than a value of the pitch **132-1**.
(68) The pitch **132** can vary across a second subset **604-2** of the second set of fingers **604-2**, as represented by a pitch **132-3**. For instance, a value of the pitch **132-3** can incrementally increase or decrease between the value of the pitch **132-1** and the value of the pitch **132-2**. Based on the values of the pitches **132-2** and **132-3**, the pitch profile **318** across the transition region **128** can have a trapezoidal shape **322**, as further described with respect to FIG. **8**. The first subset **604-1** and the second subset **604-2** can be considered proper subsets of the second set of fingers **602-2**.
(69) Optionally, individual metallization ratios **134** between adjacent fingers **312** can vary across each interdigital transducer **126**. In one aspect, the metallization ratio **134** can be substantially uniform across the first set of fingers **602-1**, as represented by a metallization ratio **134-1** (MR **134-1**). Additionally, the metallization ratio **134** can be substantially uniform across the first subset **604-1** of the second set of fingers **604-2**, as represented by a metallization ratio **134-2** (MR **134-2**). In some implementations, a value of the metallization ratio **134-2** is different than a value of the metallization ratio **134-1**. In particular, the value of the metallization ratio **134-2** can be less than or greater than the value of the metallization ratio **134-1**. In other implementations, a value of the metallization ratio **134-2** can be substantially similar to a value of the metallization ratio **134-1** (e.g., within ±1%).
(70) The metallization ratio **134** can also vary across the second subset **604-2** of the second set of fingers **604-2**, as represented by a metallization ratio **134-3** (MR **134-3**). For instance, a value of the metallization ratio **134-3** can incrementally increase or decrease between the value of the metallization ratio **134-1** and the value of the metallization ratio **134-2**. Based on the values of the metallization ratios **134-2** and **134-3**, the metallization ratio profile **320** across the transition region **128** can have a trapezoidal shape **322**, as further described with respect to FIG. **9**.
(71) The quantity of fingers **312** within the second set of fingers **604-2** can be tailored to realize a target frequency offset between the cavity mode and the main wave mode of the double-mode surface-acoustic-wave filter **124**. In general, the first subset **604-1** includes at least two pairs of adjacent fingers **312** (e.g., at least three fingers **312**). The quantity of fingers **312** within the second subset **604-2** of the second set of fingers **604-2** includes one or more fingers **312**. The electrode structure **302** can have multiple transition regions **128**, as further described with respect to FIG. **7**.
(72) FIG. **7** illustrates an example double-mode surface-acoustic-wave filter **124** having at least one transition region **128** with a partly uniform geometric property **130**. The double-mode surface-acoustic-wave filter **124** includes an input port **702** and an output port **704**. In this example, the double-mode surface-acoustic-wave filter **124** includes seven interdigital transducers **126** (e.g., interdigital transducers **126-1**, **126-2**, **126-3**, **126-4**, **126-5**, **126-6**, and **126-7**). Other implementations are also possible in which the double-mode surface-acoustic-wave filter **124** includes two, three, four, five, or more interdigital transducers **126**.
(73) In general, at least two of the interdigital transducers **126** have first busbars **310-1** coupled to the input port **702** and second busbars **310-2** coupled to a ground **706**. At least one of the interdigital transducers **126** has a first busbar **310-1** coupled to the output port **704** and a second busbar **310-2** coupled to the ground **706**. The at least one interdigital transducer **126** that is coupled to the output port **704** is interspersed between the at least two interdigital transducers **126** coupled to the input port **702**.
(74) In this example, four interdigital transducers **126** (e.g., interdigital transducers **126-1**, **126-3**, **126-5**, and **126-7**) have first busbars **310-1** coupled to the input port **702** and second busbars **310-2** coupled to the ground **706**. Also, three interdigital transducers **126** (e.g., interdigital transducers **126-2**, **126-4**, and **126-6**) are interspersed between the four interdigital transducers **126** and have first busbars **310-1** coupled to the output port **704** and second busbars **310-2** coupled to the ground **706**.
(75) The double-mode surface-acoustic-wave filter **124** includes multiple transition regions **128** (e.g., transition regions **128-1**, **128-2**, **128-3**, **128-4**, **128-5**, and **128-6**). The pitch **132-2** within the

first subset **604-1** of the second set of fingers **602-2** can be similar or different between two or more of the transition regions **128-1** to **128-6**. Likewise, the metallization ratio **134-4** within the first subset **604-1** of the second set of fingers **602-2** can be similar or different between two or more of the transition regions **128-1** to **128-6**. The pitch profile **318** and/or the metallization ratio profile **320** can have a trapezoidal shape **322** within one or more of the transition regions **128-1** to **128-6**, as further described with respect to FIGS. **8** and **9**.
(76) FIG. **8** illustrates an example pitch profile **318** of the double-mode surface-acoustic-wave filter **124** depicted in FIG. **7**. The pitch profile **318** depicts the pitch **132** between different pairs of adjacent fingers **312** across the interdigital transducers **126-1** to **126-7**. The different pairs of adjacent fingers **312** correspond to different positions along the first axis **408**. In this example, the pitch **132** is partly uniform within the transition regions **128-1** to **128-6**. In some implementations, the pitch profile **318** is approximately symmetrical across an axis of symmetry **802**, as shown at the top of FIG. **8**.
(77) Consider the transition region **128-2**, which is also depicted at the bottom of FIG. **8**. In this case, a value of the pitch **132-2** across the first subset **604-1** of the second set of fingers **602-2** is less than a value of the pitch **132-1** across the first set of fingers **602-1**. Also, a value of the pitch **132-3** varies between the value of the pitch **132-1** and the value of the pitch **132-2**. In some implementations, the pitch **132** within the transition region **128** is substantially symmetrical about an axis of symmetry **804**. In other words, slopes of the pitches **132-3** on each side of the transition region **128** are approximately equal in magnitude but opposite in sign. In other cases, the pitch **132** within the transition region **128** is not symmetrical.
(78) In general, the pitch profile **318** within the transition region **128** has a trapezoidal shape **322-1**. In this case, the trapezoidal shape **322-1** has a well-type orientation **806** because the value of the pitch **132-2** is less than the value of the pitch **132-1**. The value of the pitch **132-2** can be between approximately 5% and 30% of the value of the pitch **132-1**. In example implementations, the value the pitch **132-2** is between approximately 10% and 20% of the value of the pitch **132-1**. In general, the term “approximately” can mean that the pitch **132-2** can be within ±2% of a specified value (e.g., within ±1.5%, ±1%, or ±0.5% of the specified value). A value of the pitch **132-2** can vary between different transition regions **128**.
(79) A difference between the pitches **132-1** and **132-2** can be based, at least in part, on a bandwidth of the double-mode surface-acoustic-wave filter **124**. In general, double-mode surface-acoustic-wave filters **124** with larger bandwidths have a smaller difference between the values of the pitches **132-1** and **132-2**.
(80) In contrast, other double-mode surface-acoustic-wave filters can have a pitch profile with a triangular shape within the transition region. The triangular shape does not include a substantially uniform portion. This triangular shape may not enable the other double-mode surface-acoustic-wave filter to attenuate spurious modes within the passband using an aspect ratio that is within manufacturing process limits.
(81) By having a partly uniform pitch **132** within the transition region **128**, a velocity of the cavity mode increases at a higher rate than the velocity of another main wave mode of the double-mode surface-acoustic-wave filter **124**. This enables at least a portion of the pitch **132** within the transition region **128** to be higher than the pitch associated with the triangular shape. This higher pitch enables the double-mode surface-acoustic-wave filter **124** to have an aspect ratio **324** that is within process limits.
(82) FIG. **9** illustrates an example metallization ratio profile **320** of the double-mode surface-acoustic-wave filter **124** depicted in FIG. **7**. The metallization ratio profile **320** depicts the metallization ratio **134** between different pairs of adjacent fingers **312** across the interdigital transducers **126-1** to **126-7**. The different pairs of adjacent fingers **312** correspond to different positions along the first axis **408**. In this example, the metallization ratio **134** is partly uniform within the transition regions **128-1** to **128-6**. In some implementations, the metallization ratio

profile **320** is approximately symmetrical across an axis of symmetry **902**, as shown at the top of FIG. **9**. The axis of symmetry **902** can also be the axis of symmetry **802** shown in FIG. **8**.
(83) Consider the transition region **128-2**, which is also depicted at the bottom of FIG. **9**. In this case, a value of the metallization ratio **134-2** across the first subset **604-1** of the second set of fingers **602-2** is greater than a value of the metallization ratio **134-1** across the first set of fingers **602-1**. Also, a value of the metallization ratio **134-3** varies between the value of the metallization ratio **134-1** and the value of the metallization ratio **134-2**. In some implementations, the metallization ratio **134** within the transition region **128** is substantially symmetrical about an axis of symmetry **904**. In other words, slopes of the metallization ratios **134-3** on each side of the transition region **128** are approximately equal in magnitude but opposite in sign. In other implementations, the metallization ratio **134** within the transition region **128** is not symmetrical.
(84) In general, the metallization ratio profile **320** within the transition region **128** has a trapezoidal shape **322-2**. In this case, the trapezoidal shape **322-2** has a barrier-type orientation **906** because the value of the metallization ratio **134-2** is greater than the value of the metallization ratio **134-1**. Although described with respect to a barrier-type orientation **906**, other implementations of the double-mode surface-acoustic-wave filter **124** can have a metallization ratio profile **320** with a trapezoidal shape **322-2** having the well-type orientation **806**. In other words, the trapezoidal shapes **322-1** and **322-2** of the pitch profile **318** and the metallization ratio profile **320** can have a similar orientation (e.g., both well-type orientations **806**) or different orientations.
(85) In general, the value of the metallization ratio **134-2** can be between approximately 50% and 150% of the value of the metallization ratio **134-1**. For well-type orientations, the value of the metallization ratio **134-2** can be between approximately 50% and 100% of the value of the metallization ratio **134-1**. In particular, the value of the metallization ratio **134-2** can be approximately equal to 50%, 75%, or 100% of the value of the metallization ratio **134-1**. For barrier-type orientations, the value of the metallization ratio **134-2** can be between 100% and 150% of the value of the metallization ratio **134-1**. In particular, the value of the metallization ratio **134-2** can be approximately equal to 100%, 125%, or 150% of the value of the metallization ratio **134-1**. If the metallization ratio **134-2** is approximately equal to 100% of the value of the metallization ratio **134-1**, the metallization ratio profile **320** can be considered to have a substantially flat shape instead of the trapezoidal shape **322**.
(86) In an example implementation, the value of the metallization ratio **134-2** is between approximately 103% and 105% of the value of the metallization ratio **134-1**. For instance, the value of the metallization ratio **134-2** can be approximately equal to 103%, 104%, or 105%. In general, the term “approximately” can mean that the metallization ratio **134-2** can be within ±2% of a specified value (e.g., within ±1.5%, ±1%, or ±0.5% of the specified value). A value of the metallization ratio **134-2** can vary between different transition regions **128**.
(87) In general, the value of the metallization ratio **134-2** within the transition region **128** can be chosen to enable suppression of a spurious mode that impacts (or is close in frequency to) the cavity mode. The value of the metallization ratio **134-1** within the central region **502** can be chosen to enable suppression of a spurious mode that impacts (or is close in frequency to) the main wave mode. With both of the metallization ratios **134-1** and **134-2** designed for spurious mode suppression, the double-mode surface-acoustic-wave filter can have a relatively smooth passband.
(88) Values of the metallization ratios **134-1** and **134-2** can vary based on a passband of the double-mode surface-acoustic-wave filter **124**. For a passband that includes frequency bands **20** and **28**, for instance, the metallization ratio **134-1** can be approximately 0.52 and the metallization ratio **134-2** can be approximately 0.54. With the described pitch profile **318** and/or metallization ratio profile **320**, the double-mode surface-acoustic-wave filter **124** can achieve a relatively smooth passband using an aspect ratio **324** within process limits.
(89) In contrast, other double-mode surface-acoustic-wave filters can have a metallization ratio profile with a triangular shape within the transition region. The triangular shape does not include a

substantially uniform portion. This triangular shape may not enable the other double-mode surface-acoustic-wave filter to attenuate spurious modes using an aspect ratio that is within manufacturing process limits.

(90) In general, the partly uniform metallization ratio **134** within the transition region **128** facilitates suppression of a spurious mode, such as a spurious Rayleigh mode, within the passband. At least a portion of the metallization ratio **134** within the transition region **128** can be lower than the metallization ratio associated with the triangular shape. In some cases, this lower metallization ratio **134** enables the double-mode surface-acoustic-wave filter **124** to have an aspect ratio **324** that satisfies process limits.

(91) FIG. **10** is a flow diagram illustrating an example process **1000** for manufacturing a double-mode surface-acoustic-wave filter having a transition region with a partly uniform geometric property. The process **1000** is described in the form of a set of blocks **1002** and **1004** that specify operations that can be performed. However, operations are not necessarily limited to the order shown in FIG. **10** or described herein, for the operations may be implemented in alternative orders or in fully or partially overlapping manners. Also, more, fewer, and/or different operations may be implemented to perform the process **1000**, or an alternative process. Operations represented by the illustrated blocks of the process **1000** may be performed to manufacture a double-mode surface-acoustic-wave filter **124** (e.g., of FIG. **1**, **4-1**, **4-2**, or **7**). More specifically, the operations of the process **1000** may be performed, at least in part, to manufacture one or more interdigital transducers **126** (e.g., of FIG. **3**, **5**, **6**, or **7**).

(92) At **1002**, a first set of fingers of at least one interdigital transducer of the double-mode surface-acoustic-wave filter is provided. The first set of fingers have a geometric property. For example, the manufacturing process provides the first set of fingers **602-1** of at least one interdigital transducer **126** of the double-mode surface-acoustic-wave filter **124**, as shown in FIG. **6**. The first set of fingers **602-1** has the geometric property **130**, which can include the pitch **132-1**, the metallization ratio **134-1**, or both. The first set of fingers **602-1** can be associated with the central region **502**.

(93) At **1004**, a second set of fingers of the at least one interdigital transducer of the double-mode surface-acoustic-wave filter is provided. The second set of fingers is positioned adjacent to the first set of fingers and is associated with an outer edge of the at least one interdigital transducer. The geometric property across a subset of the second set of fingers is substantially uniform. A value of the geometric property across the subset of the second set of fingers is different than a value of the geometric property across the first set of fingers.

(94) For example, the manufacturing process provides the second set of fingers **602-2** of the at least one interdigital transducer **126** of the double-mode surface-acoustic-wave filter **124**, as shown in FIG. **6**. The second set of fingers **602-2** is positioned adjacent to the first set of fingers **602-1** and is associated with an outer edge of the at least one interdigital transducer **126**. The geometric property **130** across the first subset **604-1** of the second set of fingers **602-2** is substantially uniform (e.g., varies by less than ±1%). A value of the geometric property **130** across the first subset **604-1** of the second set of fingers **602-2** is different than the value of the geometric property **130** across the first set of fingers **602-1**. For instance, the pitch **132-2** is substantially uniform and has a different value than the pitch **132-1**. Additionally or alternatively, the metallization ratio **134-2** is substantially uniform and has a different value than the metallization ratio **134-1**. The second set of fingers **602-2** are associated with the transition region **128**, as shown in FIG. **6**.

(95) Some aspects are described below.

(96) Aspect 1: An apparatus comprising: a double-mode surface-acoustic-wave filter comprising: at least one interdigital transducer comprising multiple fingers, the multiple fingers comprising: a first set of fingers having a geometric property; and a second set of fingers positioned adjacent to the first set of fingers and associated with an outer edge of the at least one interdigital transducer, the geometric property across a subset of the second set of fingers being substantially uniform, a value of the geometric property across the subset of the second set of fingers being different than a value

of the geometric property across the first set of fingers.
(97) Aspect 2: The apparatus of aspect 1, wherein the subset of the second set of fingers comprises at least three fingers of the multiple fingers.
(98) Aspect 3: The apparatus of any previous aspect, wherein the geometric property across the subset of the second set of fingers is substantially uniform such that the value of the geometric property across the subset of the second set of fingers changes by less than ±1%.
(99) Aspect 4: The apparatus of any previous aspect, wherein: the subset of the second set of fingers comprises a first subset of fingers; the second set of fingers comprises a second subset of fingers positioned between the first set of fingers and the first subset of fingers; and the geometric property across the second subset of fingers incrementally increases or decreases between the value of the geometric property across the first set of fingers and the value of the geometric property across the first subset of fingers.
(100) Aspect 5: The apparatus of any previous aspect, wherein: the geometric property comprises a pitch; and a value of the pitch across the subset of the second set of fingers is less than a value of the pitch across the first set of fingers.
(101) Aspect 6: The apparatus of aspect 5, wherein the pitch represents an average distance between adjacent fingers.
(102) Aspect 7: The apparatus of aspect 5 or 6, wherein the value of the pitch across the subset of the second set of fingers is between approximately 5% and 30% of the value of the pitch across the first set of fingers.
(103) Aspect 8: The apparatus of aspect 7, wherein the value of the pitch across the subset of the second set of fingers is between approximately 10% and 20% of the value of the pitch across the first set of fingers.
(104) Aspect 9: The apparatus of any previous aspect, wherein: the geometric property comprises a metallization ratio; and a value of the metallization ratio across the subset of the second set of fingers is greater than a value of the metallization ratio across the first set of fingers.
(105) Aspect 10: The apparatus of aspect 9, wherein the metallization ratio represents an average width of adjacent fingers divided by an average distance between the adjacent fingers.
(106) Aspect 11: The apparatus of aspect 9 or 10, wherein a value of the metallization ratio across the subset of the second set of fingers is between approximately 50% and 150% a value of the metallization ratio across the first set of fingers.
(107) Aspect 12: The apparatus of aspect 11, wherein the value of the metallization ratio across the subset of the second set of fingers is approximately 103% and 105% of the value of the metallization ratio across the first set of fingers.
(108) Aspect 13: The apparatus of any previous aspect, wherein an aspect ratio of the at least one interdigital transducer is approximately 50% or less based on a value of the geometric property across the subset of the second set of fingers.
(109) Aspect 14: The apparatus of any previous aspect, wherein: multiple fingers of the at least one interdigital transducer comprise a third set of fingers positioned adjacent to the first set of fingers and associated with another outer edge of the at least one interdigital transducer; the geometric property across a subset of the third set of fingers is substantially uniform; and a value of the geometric property across the subset of the third set of fingers is different than the value of the geometric property across the first set of fingers.
(110) Aspect 15: The apparatus of aspect 14, wherein the value of the geometric property across the subset of the third set of fingers is substantially similar to the value of the geometric property across the subset of the second set of fingers.
(111) Aspect 16: The apparatus of aspect 14, wherein the value of the geometric property across the subset of the third set of fingers is different than the value of the geometric property across the subset of the second set of fingers.
(112) Aspect 17: The apparatus of any previous aspect, wherein: the at least one interdigital

transducer comprises two adjacent interdigital transducers; and the subset of the second set of fingers of each of the two adjacent interdigital transducers are positioned proximate to each other.
(113) Aspect 18: The apparatus of any previous aspect, wherein: the double-mode surface-acoustic-wave filter comprises: an input port; and an output port; the at least one interdigital transducer comprises: at least two first interdigital transducers each having: a first busbar coupled to the input port; and a second busbar coupled to ground; and at least one second interdigital transducer interspersed between the at least two first interdigital transducers and having: a first busbar coupled to the output port; and a second busbar coupled to the ground.
(114) Aspect 19: The apparatus of claim **18**, wherein: the at least two first interdigital transducers comprise four first interdigital transducers; and the at least one second interdigital transducer comprises three second interdigital transducers.
(115) Aspect 20: The apparatus of any previous aspect, further comprising: a wireless transceiver coupled to at least one antenna, the wireless transceiver comprising the double-mode surface-acoustic-wave filter and configured to filter, using the double-mode surface-acoustic-wave filter, a wireless signal communicated via the at least one antenna.
(116) Aspect 21: A method of manufacturing a double-mode surface-acoustic-wave filter, the method comprising: providing a first set of fingers of at least one interdigital transducer of the double-mode surface-acoustic-wave filter, the first set of fingers having a geometric property; and providing a second set of fingers of the at least one interdigital transducer of the double-mode surface-acoustic-wave filter, the second set of fingers positioned adjacent to the first set of fingers and associated with an outer edge of the at least one interdigital transducer, the geometric property across a subset of the second set of fingers being substantially uniform, a value of the geometric property across the subset of the second set of fingers being different than a value of the geometric property across the first set of fingers.
(117) Aspect 22: The method of aspect 21, wherein: the geometric property comprises a pitch; and a value of the pitch across the subset of the second set of fingers is between approximately 5% and 30% a value of the pitch across the first set of fingers.
(118) Aspect 23: The method of aspect 21 or 22, wherein: the geometric property comprises an metallization ratio; and a value of the metallization ratio across the subset of the second set of fingers is between approximately 50% and 150% a value of the metallization ratio across the first set of fingers.
(119) Aspect 24: An apparatus comprising: a double-mode surface-acoustic-wave filter comprising at least two adjacent interdigital transducers, the at least two adjacent interdigital transducers comprising multiple fingers, a portion of the multiple fingers being positioned within a transition region of the double-mode surface-acoustic-wave filter, wherein a profile of a geometric property across the portion of the multiple fingers has a trapezoidal shape.
(120) Aspect 25: The apparatus of aspect 24, wherein the geometric property comprises at least one of the following: a pitch; or a metallization ratio.
(121) Aspect 26: The apparatus of aspect 25, wherein: the geometric property comprises the pitch; and the trapezoidal shape has a barrier-type orientation.
(122) Aspect 27: The apparatus of aspect 25 or 26, wherein: the geometric property comprises the metallization ratio; and the trapezoidal shape has a barrier-type orientation.
(123) Aspect 28: An apparatus comprising: a double-mode surface-acoustic-wave filter comprising: two adjacent interdigital transducers, each interdigital transducer of the two adjacent interdigital transducers comprising multiple fingers, the multiple fingers of each interdigital transducer of the two adjacent interdigital transducers comprising: a first set of fingers having a first pitch; and a second set of fingers positioned adjacent to the first set of fingers and associated with an outer edge of the interdigital transducer, a subset of the second set of fingers having a second pitch that is substantially uniform, a value of the second pitch across the subset of the second set of fingers being less than a value of the first pitch across the first set of fingers, wherein: the second set of

fingers of the two adjacent interdigital transducers are adjacent to each other; and values of the second pitches associated with the two adjacent interdigital transducers are less than values of the first pitches associated with the two adjacent interdigital transducers.
(124) Aspect 29: The apparatus of aspect 28, wherein: the first set of fingers has a first metallization ratio; the subset of the second set of fingers has a second metallization ratio that is substantially uniform; and a value of the second metallization ratio across the subset of the second set of fingers of each interdigital transducer is greater than a value of the first metallization ratio across the first set of fingers of the interdigital transducer.
(125) Aspect 30: The apparatus of aspect 29, wherein: a profile of the second pitches across the second set of fingers of the two adjacent interdigital transducers has a trapezoidal shape with a well-type orientation; and a profile of the second metallization ratios across the second set of fingers of the two adjacent interdigital transducers has another trapezoidal shape with a barrier-type orientation.
(126) Unless context dictates otherwise, use herein of the word “or” may be considered use of an “inclusive or,” or a term that permits inclusion or application of one or more items that are linked by the word “or” (e.g., a phrase “A or B” may be interpreted as permitting just “A,” as permitting just “B,” or as permitting both “A” and “B”). As used herein, a phrase referring to “at least one of” a list of items refers to any combination of those items, including single members. As an example, “at least one of: a, b, or c” is intended to cover: a, b, c, a-b, a-c, b-c, and a-b-c, as well as any combination with multiples of the same element (e.g., a-a, a-a-a, a-a-b, a-a-c, a-b-b, a-c-c, b-b, b-b-b, b-b-c, c-c, and c-c-c or any other ordering of a, b, and c). Further, items represented in the accompanying figures and terms discussed herein may be indicative of one or more items or terms, and thus reference may be made interchangeably to single or plural forms of the items and terms in this written description. Finally, although subject matter has been described in language specific to structural features or methodological operations, it is to be understood that the subject matter defined in the appended claims is not necessarily limited to the specific features or operations described above, including not necessarily being limited to the organizations in which features are arranged or the orders in which operations are performed.

Claims

1. An apparatus comprising: a double-mode surface-acoustic-wave filter comprising: at least one interdigital transducer comprising multiple fingers, the multiple fingers comprising: a first set of fingers having a geometric property; and a second set of fingers positioned adjacent to the first set of fingers and associated with an outer edge of the at least one interdigital transducer, wherein each finger of the first set of fingers and the second set of fingers has a uniform width with respect to other fingers of the first set of fingers and the second set of fingers, the geometric property across a first subset of the second set of fingers being substantially uniform, a value of the geometric property across the first subset of the second set of fingers being different than a value of the geometric property across the first set of fingers, wherein the geometric property across a second subset of the second set of fingers incrementally increases or decreases between the value of the geometric property across the first subset of the second set of fingers and the value of the geometric property across the first set of fingers.
2. The apparatus of claim 1, wherein: the geometric property comprises a pitch; and a value of the pitch across at least one of the first subset or the second subset of the second set of fingers is less than a value of the pitch across the first set of fingers.
3. The apparatus of claim 2, wherein the value of the pitch across at least one of the first subset or the second subset of the second set of fingers is between approximately 5% and 30% of the value of the pitch across the first set of fingers.
4. The apparatus of claim 3, wherein the value of the pitch across at least one of the first subset or

the second subset of the second set of fingers is between approximately 10% and 20% of the value of the pitch across the first set of fingers.
5. The apparatus of claim 2, wherein the pitch represents an average distance between adjacent fingers.
6. The apparatus of claim 1, wherein: the geometric property comprises a metallization ratio; and a value of the metallization ratio across at least one of the first subset or the second subset of the second set of fingers is greater than a value of the metallization ratio across the first set of fingers.
7. The apparatus of claim 6, wherein a value of the metallization ratio across at least one of the first subset or the second subset of the second set of fingers is between approximately 50% and 150% a value of the metallization ratio across the first set of fingers.
8. The apparatus of claim 7, wherein the value of the metallization ratio across at least one of the first subset or the second subset of the second set of fingers is approximately 103% and 105% of the value of the metallization ratio across the first set of fingers.
9. The apparatus of claim 6, wherein the metallization ratio represents an average width of adjacent fingers divided by an average distance between the adjacent fingers.
10. The apparatus of claim 1, wherein: multiple fingers of the at least one interdigital transducer comprise a third set of fingers positioned adjacent to the first set of fingers and associated with another outer edge of the at least one interdigital transducer; the geometric property across a subset of the third set of fingers is substantially uniform; and a value of the geometric property across the subset of the third set of fingers is different than the value of the geometric property across the first set of fingers.
11. The apparatus of claim 10, wherein the value of the geometric property across the subset of the third set of fingers is substantially similar to the value of the geometric property across the subset of the second set of fingers.
12. The apparatus of claim 10, wherein the value of the geometric property across the subset of the third set of fingers is different than the value of the geometric property across at least one of the first subset or the second subset of the second set of fingers.
13. The apparatus of claim 1, wherein: the double-mode surface-acoustic-wave filter comprises: an input port; and an output port; the at least one interdigital transducer comprises: at least two first interdigital transducers each having: a first busbar coupled to the input port; and a second busbar coupled to ground; and at least one second interdigital transducer interspersed between the at least two first interdigital transducers and having: a first busbar coupled to the output port; and a second busbar coupled to the ground.
14. The apparatus of claim 13, wherein: the at least two first interdigital transducers comprise four first interdigital transducers; and the at least one second interdigital transducer comprises three second interdigital transducers.
15. The apparatus of claim 1, wherein the first subset of the second set of fingers comprises at least three fingers of the multiple fingers.
16. The apparatus of claim 1, wherein the geometric property across the first subset of the second set of fingers is substantially uniform such that the value of the geometric property across the first subset of the second set of fingers changes by less than ±1%.
17. The apparatus of claim 1, wherein an aspect ratio of the at least one interdigital transducer is approximately 50% or less based on a value of the geometric property across at least one of the first subset or the second subset of the second set of fingers.
18. The apparatus of claim 1, wherein: the at least one interdigital transducer comprises two adjacent interdigital transducers; and the second set of fingers of each of the two adjacent interdigital transducers are positioned proximate to each other.
19. The apparatus of claim 1, further comprising: a wireless transceiver coupled to at least one antenna, the wireless transceiver comprising the double-mode surface-acoustic-wave filter and configured to filter, using the double-mode surface-acoustic-wave filter, a wireless signal

communicated via the at least one antenna.

20. An apparatus comprising: a double-mode surface-acoustic-wave filter comprising at least two adjacent interdigital transducers, the at least two adjacent interdigital transducers comprising a first set of fingers having a geometric property and a second set of fingers including a first subset of fingers and a second subset of fingers, the second set of fingers being positioned within a transition region of the double-mode surface-acoustic-wave filter, wherein each finger of the first set of fingers and the second set of fingers has a uniform width with respect to other fingers of the first set of fingers and the second set of fingers, and wherein a profile of a geometric property across the second set of fingers has a trapezoidal shape based on a geometric property across a second subset of the second set of fingers incrementally increasing or decreasing between a value of the geometric property across the first subset of fingers of the second set of fingers and a value of the geometric property across the first set of fingers.

21. The apparatus of claim 20, wherein the geometric property comprises at least one of the following: a pitch; or a metallization ratio.

22. The apparatus of claim 21, wherein: the geometric property comprises the pitch; and the trapezoidal shape has a barrier-type orientation.

23. The apparatus of claim 21, wherein: the geometric property comprises the metallization ratio; and the trapezoidal shape has a barrier-type orientation.

24. An apparatus comprising: a double-mode surface-acoustic-wave filter comprising: two adjacent interdigital transducers, each interdigital transducer of the two adjacent interdigital transducers comprising multiple fingers, the multiple fingers of each interdigital transducer of the two adjacent interdigital transducers comprising: a first set of fingers having a first pitch; and a second set of fingers positioned adjacent to the first set of fingers and associated with an outer edge of each interdigital transducer, wherein each finger of the first set of fingers and the second set of fingers has a uniform width with respect to other fingers of the first set of fingers and the second set of fingers, a first subset of the second set of fingers having a second pitch that is substantially uniform, a value of the second pitch across the first subset of the second set of fingers being less than a value of the first pitch across the first set of fingers, wherein: the second set of fingers of each of the two adjacent interdigital transducers are adjacent to each other; values of the second pitch associated with each of the two adjacent interdigital transducers are less than values of the first pitch associated with each of the two adjacent interdigital transducers; and a value of a pitch across a second subset of the second set of fingers incrementally increases or decreases between the value of the second pitch across the first subset of the second set of fingers and the first pitch across the first set of fingers.

25. The apparatus of claim 24, wherein: the first set of fingers has a first metallization ratio; at least one of the first subset or the second subset of the second set of fingers has a second metallization ratio that is substantially uniform; and a value of the second metallization ratio across at least one of the first subset or the second subset of the second set of fingers of each interdigital transducer is greater than a value of the first metallization ratio across the first set of fingers of each interdigital transducer.

26. The apparatus of claim 25, wherein: a profile of the second pitch across the second set of fingers of each of the two adjacent interdigital transducers has a trapezoidal shape with a well-type orientation; and a profile of the second metallization ratio across the second set of fingers of each of the two adjacent interdigital transducers has another trapezoidal shape with a barrier-type orientation.

27. A method of manufacturing a double-mode surface-acoustic-wave filter, the method comprising: providing a first set of fingers of at least one interdigital transducer of the double-mode surface-acoustic-wave filter, the first set of fingers having a geometric property; and providing a second set of fingers of the at least one interdigital transducer of the double-mode surface-acoustic-wave filter, the second set of fingers positioned adjacent to the first set of fingers and associated

with an outer edge of the at least one interdigital transducer, wherein each finger of the first set of fingers and the second set of fingers has a uniform width with respect to other fingers of the first set of fingers and the second set of fingers, the geometric property across a first subset of the second set of fingers being substantially uniform, a value of the geometric property across the first subset of the second set of fingers being different than a value of the geometric property across the first set of fingers, wherein the geometric property across a second subset of the second set of fingers incrementally increases or decreases between the value of the geometric property across the first subset of the second set of fingers and the value of the geometric property across the first set of fingers.

28. The method of claim 27, wherein: the geometric property comprises a pitch; and a value of the pitch across at least one of the first subset or the second subset of the second set of fingers is between approximately 5% and 30% a value of the pitch across the first set of fingers.

29. The method of claim 27, wherein: the geometric property comprises an metallization ratio; and a value of the metallization ratio across at least one of the first subset or the second subset of the second set of fingers is between approximately 50% and 150% a value of the metallization ratio across the first set of fingers.