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(54) FREQUENCY-SELECTIVE TRANSFORMER AND MIXER INCORPORATING SAME

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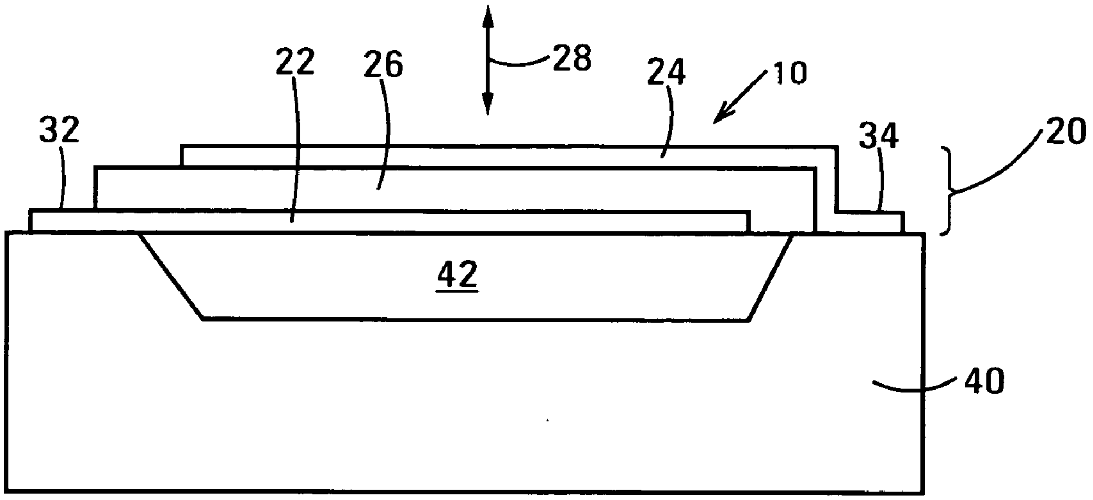
(57) ABSTRACT

The frequency-selective transformer comprises a capacitative transformer and an electromechanical resonator. The capacitative transformer comprises a first port, a second port, and a third port. The electromechanical resonator is connected between the second port and the third port of the capacitative transformer and has a series resonance and a parallel resonance that are closely spaced in frequency.



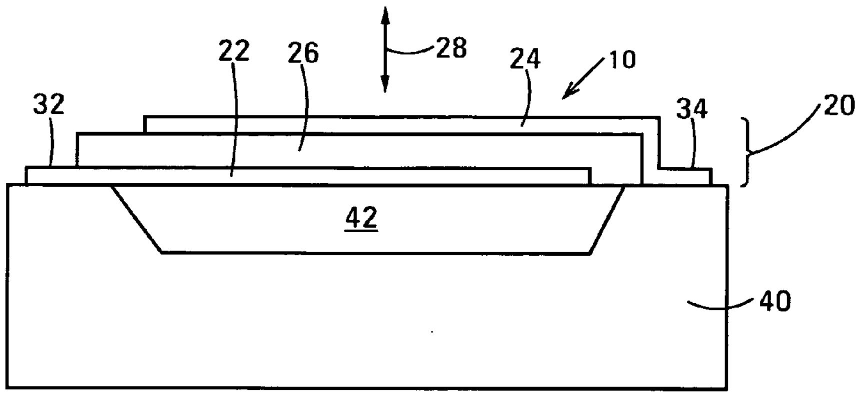


FIG.1A

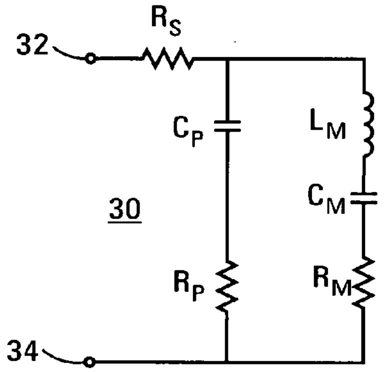


FIG.1B

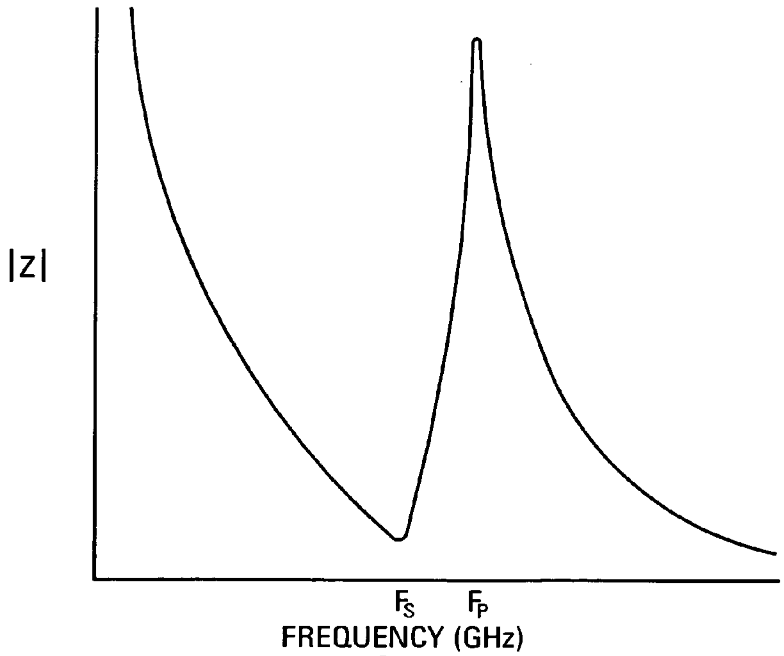


FIG.1C

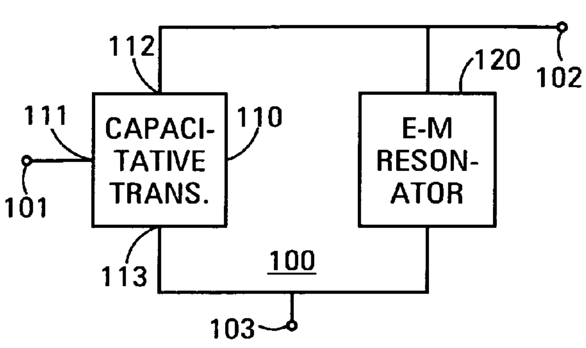


FIG.2A

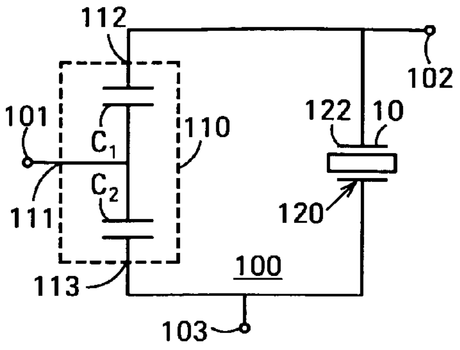


FIG.2B

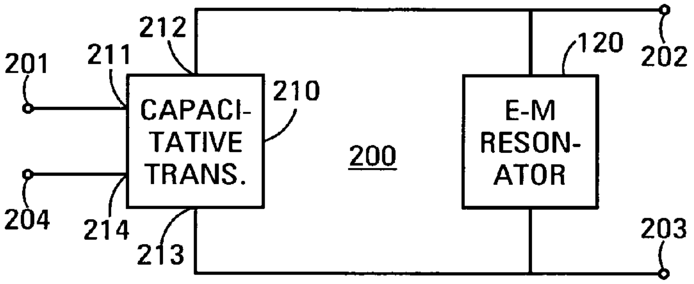


FIG.4A

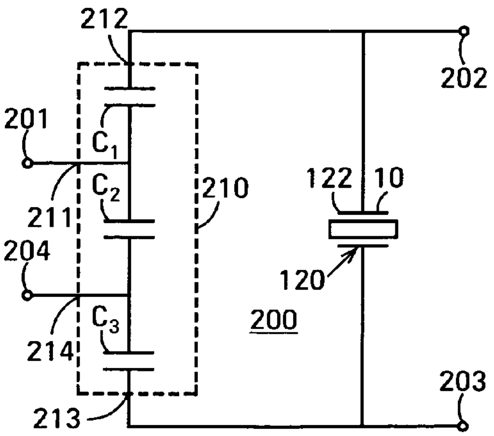


FIG.4B

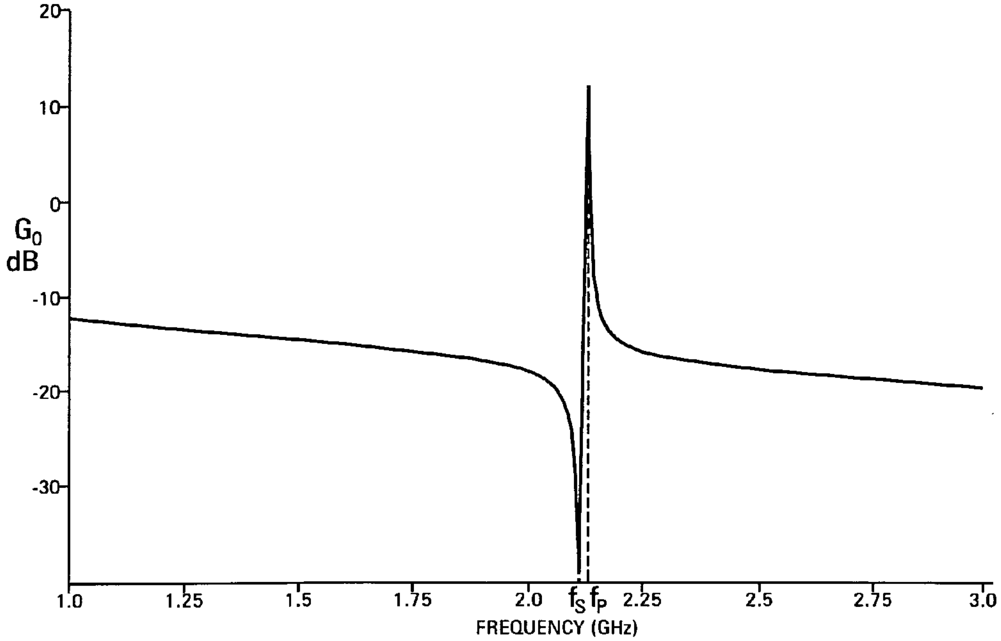

20
10
0
G_0
dB
-10
-20
-30
1.0
1.25
1.5
1.75
2.0
f_S
f_P
2.25
2.5
2.75
3.0
FREQUENCY (GHz)

FIG.3A

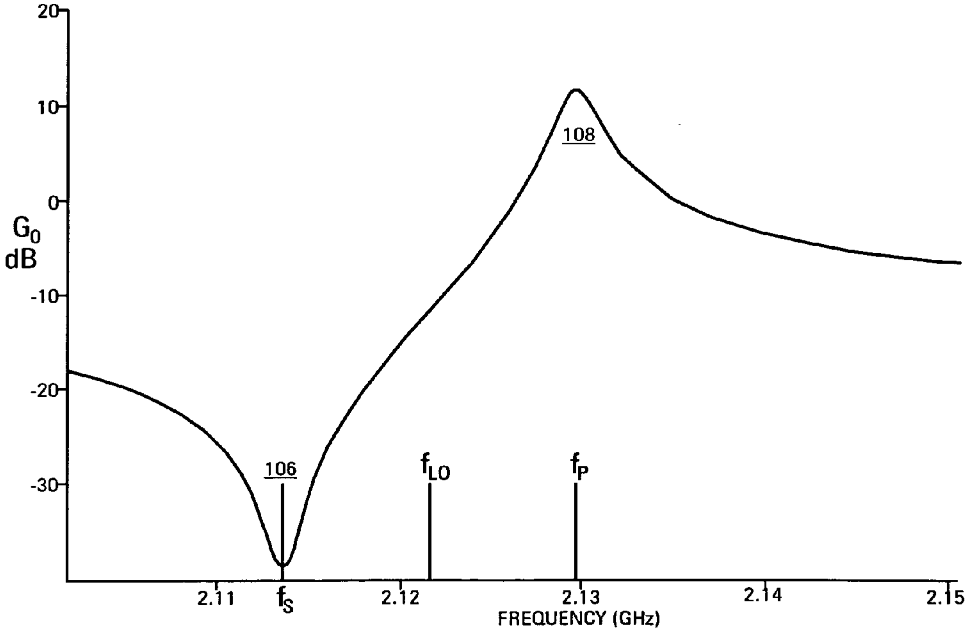

20
10
0
G_0
dB
-10
-20
-30
108
106
f_{LO}
f_P
2.11
f_S
2.12
2.13
2.14
2.15
FREQUENCY (GHz)

FIG.3B

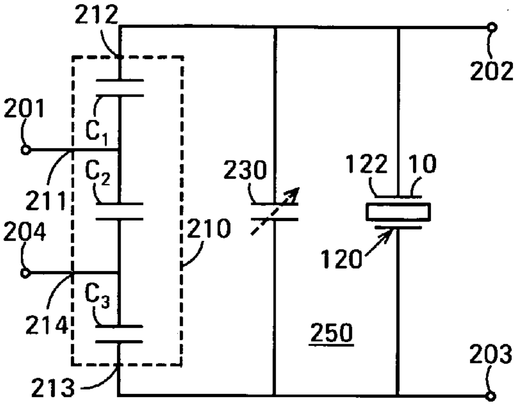


FIG.5A

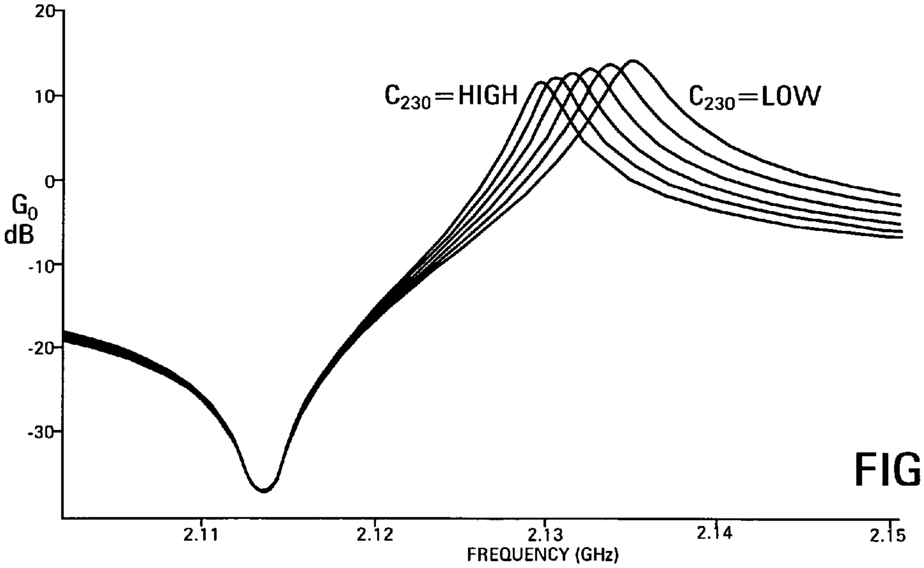


FIG.5B

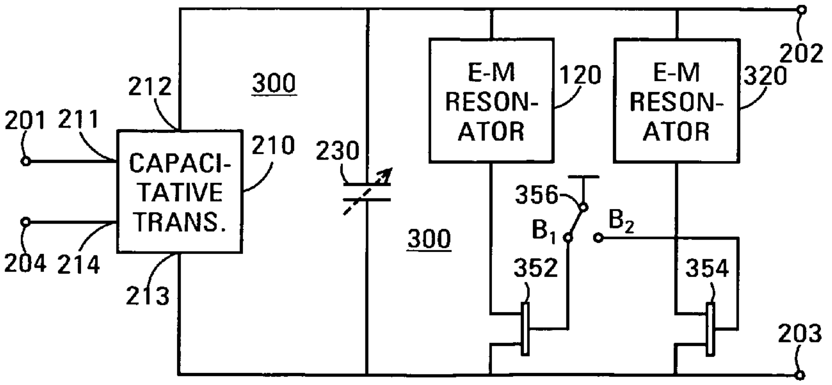


FIG.6

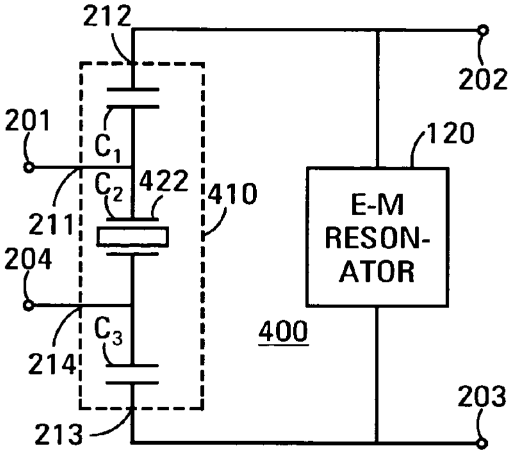

212
202
201
C_1
120
C_2
422
410
E-M RESON-ATOR
211
204
400
C_3
214
203
213

FIG.7A

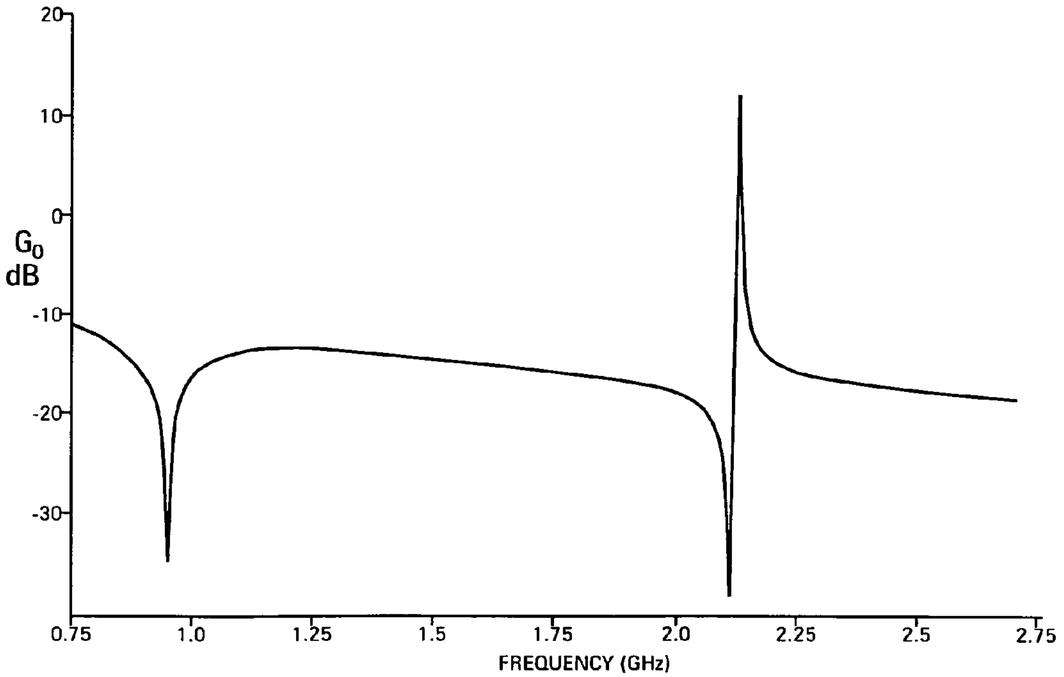

20
10
0
G_0 dB
-10
-20
-30
0.75
1.0
1.25
1.5
1.75
2.0
2.25
2.5
2.75
FREQUENCY (GHz)

FIG.7B

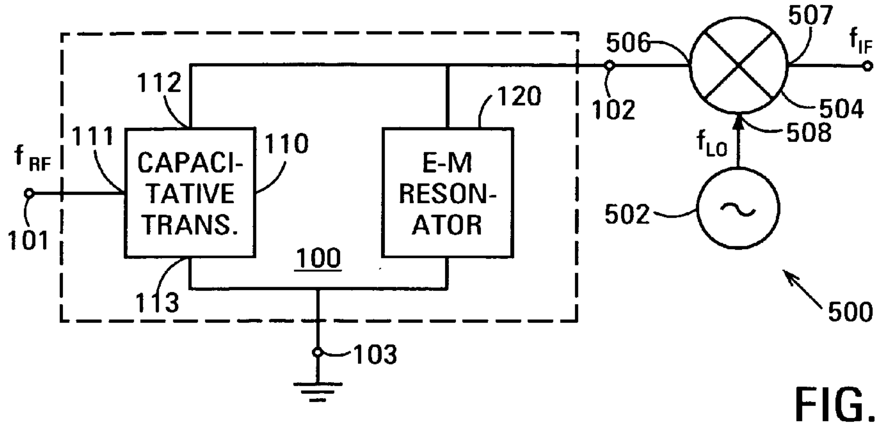


FIG.8A

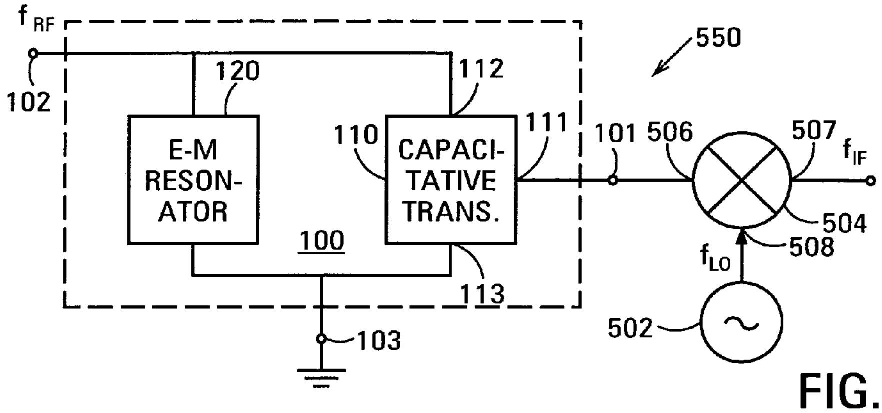


FIG.8B

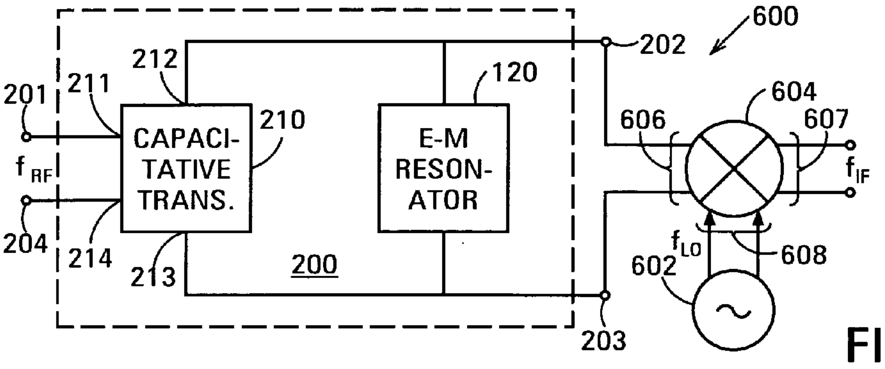


FIG.9A

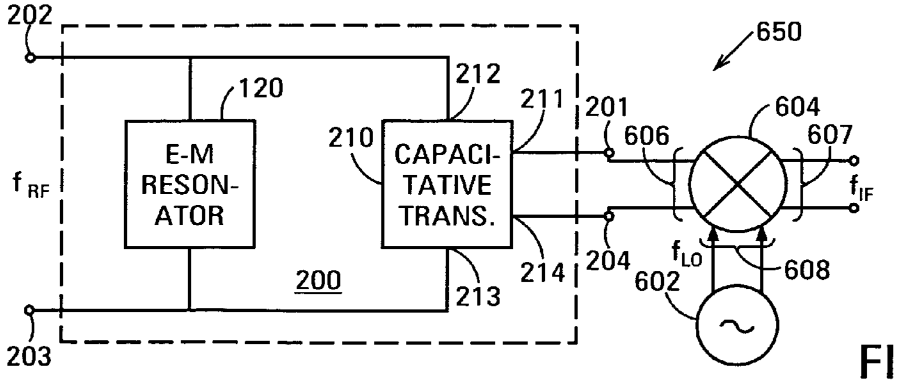


FIG.9B

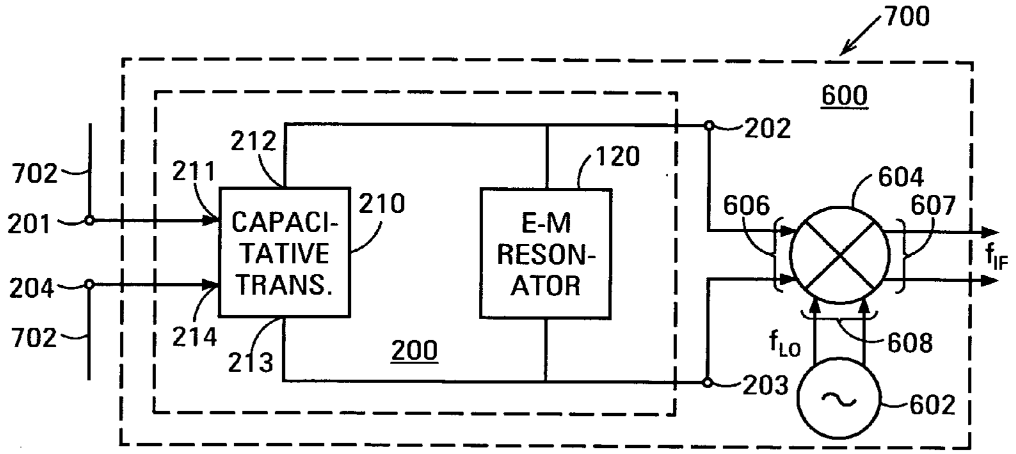


FIG.10A

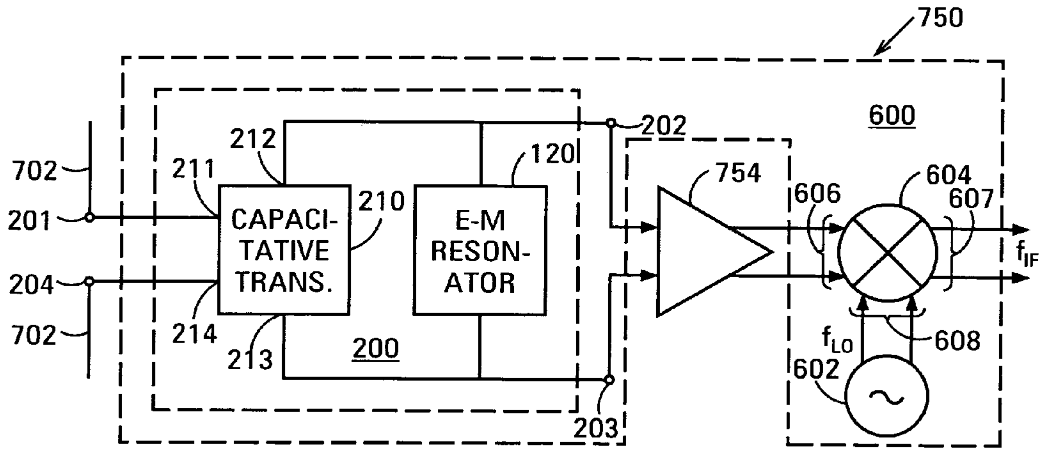


FIG.10B

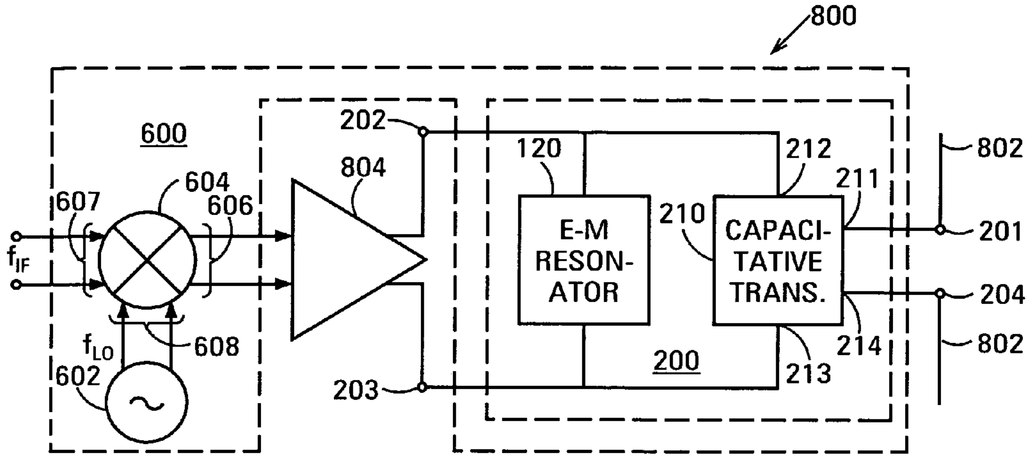


FIG.11A

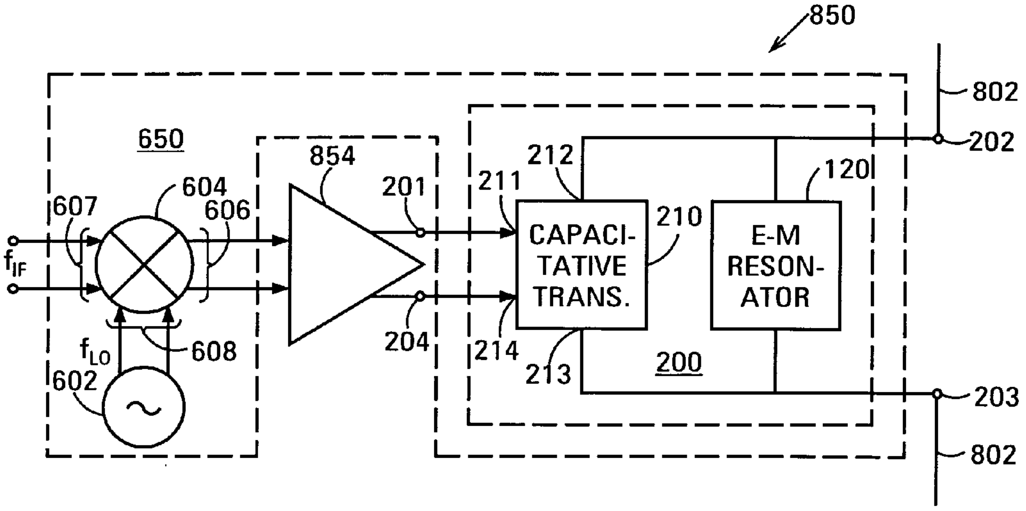


FIG.11B

FREQUENCY-SELECTIVE TRANSFORMER AND MIXER INCORPORATING SAME

BACKGROUND

[0001] In most radio frequency (RF) transmitters and receivers, the signal spectrum containing the information signal is translated to a higher frequency (upconverted) before transmission and is subsequently translated to a lower frequency (downconverted) upon reception. This is done for a variety of reasons, including a marked reduction in antenna dimensions resulting from a shorter transmission wavelength and the larger amount of bandwidth available at high transmission frequencies. Thus, frequency translation is a critical operation in most RF transmitters and receivers. Examples of such RF transmitters and receivers include radio and television transmitters and receivers, mobile telephone handsets and base stations, wireless local area network (WLAN) cards and access points and global positioning system (GPS) satellites and receivers.

[0002] In an RF receiver, frequency translation is typically accomplished by mixing the wanted RF signal output by the antenna at a frequency f_{RF} with a local oscillator signal generated by a local oscillator at a frequency f_{LO}. This results in the spectrum of the information signal carried by the wanted RF signal being shifted to an intermediate frequency (f_{IF}), where $f_{IF}=|f_{RF}-f_{LO}|$. In addition to the wanted RF signal at the frequency $f_{RF}=|f_{LO}+f_{IF}|$ generating an IF signal at the frequency f_{IF}, an image signal at the so-called image frequency $f_{IM}=|f_{LO}-f_{IF}|$ will also generate an IF signal at the frequency f_{IF}. Alternatively, the frequency f_{RF} of the wanted RF signal may be $|f_{Lo}-f_{IF}|$ and the frequency f_{IM} of the image signal may be $|f_{LO}+f_{IF}|$. A receiver tuned to receive the wanted RF signal transmitted at the frequency f_{RF} will in addition receive any signal transmitted at the image frequency f_{IM}, where the frequencies of the wanted RF signal and the image signal are related by: $|f_{RF}-f_{IM}|=2f_{IF}$. To prevent the image signal from causing interference at the receiver, the image frequency must be greatly attenuated prior to the mixer.

[0003] In an RF transmitter, frequency translation is typically accomplished by mixing an

[0004] intermediate-frequency (IF) signal at a frequency f_{IF} with a local oscillator signal generated by a local oscillator at a frequency f_{LO}. This results in the spectrum of the information signal carried by the IF signal being shifted upwards to two radio frequencies, a wanted RF signal at a frequency (f_{RF}), where $f_{RF}=|f_{LO}+f_{IF}|$, and an image signal at a frequency $f_{IM}=|f_{LO}-f_{IF}|$. Alternatively, the frequency f_{RF} of the wanted RF signal may be $|f_{LO}-f_{IF}|$ and the frequency f_{IM} of the image signal may be $|f_{LO}+f_{IF}|$. The transmitted image signal will cause interference in receivers trying to receive a wanted RF signal transmitted at a frequency at or near the frequency of the image signal. To prevent the image signal from causing interference at the receiver, the image signal must be greatly attenuated at the output of the transmitter.

[0005] Examples of ways conventionally used to attenuate the image signal in the receiver include discrete image rejection filters, direct conversion and using a complex mixer. Discrete image rejection filters are radio-frequency notch filters or bandpass filters arranged to attenuate the image frequency before mixing takes place. However, limitations of the slope of conventional filters mean that this approach is only feasible if the intermediate frequency ($f_{IF}=|f_{RF}-f_{LO}|$) is relatively high. Using a high intermediate frequency increases power consumption in the baseband data conversion circuitry. In addition, discrete image rejection filters are typically fabricated from discrete components and have an input impedance and an output impedance of 50 Ω. Such filters are typically bulky and impose a substantial insertion loss on the receiver front-end.

[0006] In direct conversion, the frequency of the local oscillator is made equal to the frequency of the wanted RF signal, i.e., $f_{LO}=f_{RF}$. This results in an intermediate frequency of 0 Hz, and no image frequency. However, direct conversion is highly susceptible to noise created by transconductor 1/f noise coloring and DC offsets created by even-order distortion. In addition, local oscillator self-mixing causes additional DC offsets.

[0007] A complex mixer rejects the image frequency without the need to filter the incoming RF signal. A complex mixer typically involves two or four mixers driven by an in-phase (I) local oscillator signal and a quadrature (Q) local oscillator signal that are exactly 90 degrees out of phase with one another. However, this scheme requires very good gain matching between the I and Q signal paths and a very accurate 90-degree phase shifter. In practice, gain differences and phase errors usually limit the image rejection to less than 40 dB without calibration. In addition, using two or more mixers increases the noise and power consumption of the receiver.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG. **1**A is a schematic drawing showing an example of an FBAR that may be used as an electromechanical resonator in a frequency-selective transformer in accordance with embodiments of the invention.

[0009] FIG. **1**B is a schematic drawing showing the equivalent circuit of the FBAR shown in FIG. **1**A.

[0010] FIG. **1**C is a graph showing the frequency response of the modulus of the impedance |Z| of an example of the FBAR shown in FIG. **1**A.

[0011] FIG. **2**A is a block diagram showing an example of an unbalanced frequency-selective transformer in accordance with an embodiment of the invention.

[0012] FIG. **2**B is a schematic diagram showing a practical example of an unbalanced frequency-selective transformer in accordance with an embodiment of the invention.

[0013] FIGS. **3**A and **3**B are graphs showing the frequency response of an example of a frequency-selective transformer in accordance with an embodiment of the invention.

[0014] FIG. **4**A is a block diagram showing an example of a balanced frequency-selective transformer in accordance with an embodiment of the invention.

[0015] FIG. **4**B is a schematic diagram showing a practical example of a balanced frequency-selective transformer in accordance with an embodiment of the invention.

[0016] FIG. **5**A is a schematic drawing showing an example of a tunable frequency-selective transformer in accordance with an embodiment of the invention.

[**0017**] FIG. **5**B is a graph showing the frequency response of an example of the frequency-selective transformer shown in FIG. **5**A with five different values of its tuning capacitor.

[**0018**] FIG. **6** is a schematic drawing showing an example of a multi-band frequency-selective transformer in accordance with an embodiment of the invention.

[**0019**] FIG. **7**A is a schematic diagram showing an example of a frequency-selective transformer in accordance with another embodiment of the invention.

[**0020**] FIG. **7**B is a graph showing the frequency response of an example of the frequency-selective transformer shown in FIG. **7**A.

[**0021**] FIG. **8**A is a schematic drawing showing an example of an unbalanced mixer in accordance with an embodiment of the invention.

[**0022**] FIG. **8**B is a schematic drawing showing an example of an unbalanced mixer in accordance with another embodiment of the invention.

[**0023**] FIG. **9**A is a schematic drawing showing an example of a balanced mixer in accordance with an embodiment of the invention.

[**0024**] FIG. **9**B is a schematic drawing showing an example of a balanced mixer in accordance with another embodiment of the invention.

[**0025**] FIG. **10**A is a schematic drawing showing an example of a receiver in accordance with an embodiment of the invention.

[**0026**] FIG. **10**B is a schematic drawing showing an example of a receiver in accordance with another embodiment of the invention.

[**0027**] FIG. **11**A is a schematic drawing showing an example of a transmitter in accordance with an embodiment of the invention.

[**0028**] FIG. **11**B is a schematic drawing showing an example of a transmitter in accordance with another embodiment of the invention.

DETAILED DESCRIPTION

[**0029**] Embodiments of the invention provide a frequency-selective transformer that comprises a capacitative transformer and an electromechanical resonator. The capacitative transformer comprises a first port, a second port and a third port. The electromechanical resonator is connected between the second port and the third port of the capacitative transformer and has a series resonance and a parallel resonance that are closely spaced in frequency.

[**0030**] Embodiments of the frequency-selective transformer are bidirectional, i.e., the transformer operates as a step-up transformer in one direction of signal flow, and as a step-down transformer in the opposite direction of signal flow. This allows the frequency-selective transformer to provide, for example, in the front end of a receiver, impedance matching between the output impedance of an antenna and the greater input impedance of a mixer or a low-noise amplifier. In another example, in the output stage of a transmitter, the frequency-selective transformer can provide impedance matching between the output impedance of a power amplifier and the input impedance of an antenna. Depending on whether the output power of the power amplifier is high or low, the output impedance of the power amplifier is respectively smaller than or greater than the input impedance of the antenna.

[**0031**] In the frequency-selective transformer, the series resonance and the parallel resonance of the electromechanical resonator are closely spaced in frequency and collectively determine the frequency response characteristics of the frequency-selective transformer. The frequency response characteristic of the frequency-selective transformer has a pass band centered at the frequency of the parallel resonance of the electromechanical resonator, a stop band centered at the frequency of the series resonance of the electromechanical resonator, and a relatively small frequency difference between the frequencies of the pass band and the stop band. This frequency response characteristic allows the frequency-selective transformer to provide a solution to the above-described image rejection problem and makes the frequency-selective transformer useful in many other applications. A reference in this disclosure to the frequency of a band should be taken to refer to the centerfrequency of the band.

[**0032**] Some embodiments of the frequency-selective transformer are unbalanced, three-terminal devices having an input terminal, an output terminal and a common terminal. Other embodiments are balanced, four-terminal devices having two input terminals and two output terminals.

[**0033**] An embodiment of the frequency-selective transformer suitable for incorporation into the front end of a superheterodyne receiver is configured so that the frequency of the wanted RF signal lies in the pass band of the frequency-selective transformer. The input of the frequency-selective transformer is coupled to an antenna. The output of the frequency-selective transformer and the output of a local oscillator are connected to the inputs of a mixing circuit. The local oscillator is then set to a frequency mid-way between the frequencies of the stop band and the pass band of the frequency-selective transformer. This locates the image frequency of the mixing circuit in the stop band of the frequency-selective transformer. The voltage transformation ratio of the frequency-selective transformer differs by several tens of decibels between the pass band and the stop band. This provides the receiver with a high image rejection. The mixing circuit provides an IF signal at a frequency nominally equal to one-half of the frequency difference between the pass band and the stop band of the frequency-selective transformer. Since the pass band and the stop band can be closely spaced in frequency, the frequency of the IF signal can be low, which allows the receiver to use low-power circuitry to perform baseband data conversion.

[**0034**] While it is hypothetically possible to use conventional capacitors and inductors to construct a frequency-selective transformer having a pass band and stop band closely spaced in frequency, in practice, the relatively low quality factor (Q) of miniature components suitable for use in modem, high density electronic circuits makes such characteristics impossible to achieve using this approach. For example, on-chip planar inductors typically have a Q of less than 20. The low Q of such components limits the achievable transformation ratio and causes the pass band and the stop band of the frequency-selective transformer to have relatively wide bandwidths and gentle side slopes. This would result in an undesirably large minimum frequency spacing between the pass band and the stop band, and the need for an undesirably high intermediate frequency with its consequent high power consumption.

[0035] Embodiments of a frequency-selective transformer in accordance with the invention incorporate an electromechanical resonator instead of a resonator fabricated using discrete capacitors and inductors. As noted above, the electromechanical resonator has a series resonance and a parallel resonance at different but closely-spaced frequencies. Electromechanical resonators having a Q of the order of 2,000 and smaller in size than a conventional planar inductor are commercially available and are relatively inexpensive. The high Q of such an electromechanical resonator results in the electromechanical resonator having narrow resonances with steep side slopes. This allows the frequency-selective transformer to have a narrow pass band and a narrow stop band closely spaced in frequency. Closely spaced means that the pass band and the stop band are spaced by less than 5% of the pass-band frequency. In typical embodiments, pass band and the stop band are spaced by about 1% of the pass-band frequency. Some electromechanical resonators have a Q sufficiently high to allow the pass band and the stop band to be spaced by as little as 0.5% of the pass-band frequency.

[0036] An electromechanical resonator can be regarded as comprising a mechanical element and a transducer. The mechanical element exhibits a mechanical resonance at the frequency of the series resonance of the electromechanical resonator. The transducer is coupled to the resonant mechanical element and converts alternating electrical energy input to the electromechanical resonator into mechanical energy. The mechanical energy output by the transducer is coupled to the mechanical element and causes the resonant mechanical element to vibrate. The parallel resonance of the electromechanical resonator is an electrical resonance between the combined capacitance of the transducer and capacitance of the circuit connected to the transducer and the inductance of the resonant mechanical element.

[0037] The electrical impedance at the input of the electromechanical resonator depends on the relationship between the frequency of the alternating electrical energy and the frequencies of the series and parallel resonances of the electromechanical resonator. The impedance is high at the frequency of the parallel resonance and is low at the frequency of the series resonance.

[0038] Various types of electromechanical resonator are possible. Examples include electrostatic, electromagnetic, piezoelectric and magnetostrictive electromechanical resonators. For example, in an electromagnetic electromechanical resonator, a ferromagnetic particle is compliantly suspended adjacent a coil. The ferromagnetic particle and its suspension constitute a mechanical element having a mechanical resonance at a frequency that depends on the mass of the ferromagnetic particle and the spring constant of the suspension. The coil and the ferromagnetic particle constitute the transducer. An electrical signal that causes current to flow through the coil generates a magnetic field that applies a mechanical force to the ferromagnetic particle. Moreover, the ferromagnetic particle moving in the proximity of the coil induces an opposing electrical signal in the coil.

[0039] In another example, an electrostatic electromechanical resonator has an electret particle compliantly suspended between the plates of a capacitor. The electret particle and its suspension constitute a mechanical element having resonant frequency that depends on the mass of the electret particle and the spring constant of the suspension. The capacitor and the electret particle constitute the transducer. An electrical signal applied between the plates of the capacitor generates an electrostatic field that applies a mechanical force to the electret particle. Moreover, the electret particle moving between the plates of the capacitor induces an opposing electrical signal across the capacitor.

[0040] Bulk acoustic wave (BAW) resonators are known in the art and have been mass produced for use in many applications. One particular type of BAW resonator known as a film bulk acoustic resonator (FBAR) forms the basis of the duplexer used in many modem CDMA cellular telephones. An example of an FBAR will be described below with reference to FIGS. **1A-1C**. The description of the FBAR also applies to electromechanical resonators based on other types of BAW resonators.

[0041] An FBAR is described in U.S. Pat. No. 5,587,620, incorporated by reference. FIG. **1A** is a schematic drawing showing an example of an FBAR **10**. FBAR **10** is composed of a piezoelectric resonator stack **20** and a substrate **40**. Piezoelectric resonator stack **20** is composed of a planar electrode **22**, a planar electrode **24** opposite planar electrode **22**, and a piezoelectric element **26** located between electrodes **22** and **24**. Electrical connections are made to electrodes **22** and **24** via terminals **32** and **34**, respectively.

[0042] A voltage applied between electrodes **22** and **24** subjects piezoelectric element **26** to an electric field that causes piezoelectric element **26** to expand or contract in the direction orthogonal to the plane of the electrodes, as indicated by an arrow **28**. Whether the piezoelectric element expands or contracts, and the magnitude of such expansion or contraction, depend on the magnitude and direction, respectively, of the electric field. Since electrodes **22** and **24** are physically attached to piezoelectric element **26**, the expansion or contraction of piezoelectric element **26** causes piezoelectric resonator stack **20** to expand or contract.

[0043] When acoustically isolated from substrate **40**, piezoelectric resonator stack **20** forms a high-Q electroacoustic resonator. In the example shown, piezoelectric resonator stack **20** is acoustically isolated from substrate **40** by suspending the piezoelectric resonator stack over a cavity **42** defined in the substrate. In this example, piezoelectric resonator stack **20** contacts substrate **40** only at the periphery of piezoelectric element **26**. Alternatively, piezoelectric resonator stack **20** may be acoustically isolated from substrate **40** by interposing an acoustic Bragg reflector (not shown) between electrode **22** and the major surface of the substrate, as described by Larson III et al. in U.S. patent application publication No. 2005 0 104 690, incorporated by reference.

[0044] An a.c. signal applied via terminals **32** and **34** to electrodes **22** and **24** causes piezoelectric resonator stack **20** to vibrate at the frequency of the a.c. signal. Piezoelectric resonator stack **20** has a mechanical resonance at a frequency equal to the velocity of sound in the piezoelectric resonator stack divided by twice the weighted thickness of the stack, i.e., $f_r=c/2t_0$, where f_r is the resonant frequency, c is the velocity of sound in the stack and t_0 is the weighted thickness of the stack. The weighted thickness of piezoelectric resonator stack **20** differs from the physical thickness of the piezoelectric resonator stack in that, in calculating the weighted thickness, the physical thickness of each layer (i.e., electrodes **22** and **24** and piezoelectric element **26**) constituting the piezoelectric resonator stack is divided by the velocity of sound in the layer.

[**0045**] In a practical embodiment of FBAR **10** having a resonance at about 2,100 MHz, substrate **40** is part of a wafer of single-crystal silicon, piezoelectric element **26** is a layer of aluminum nitride (AIN) about 1.3 μm thick and electrodes **22** and **24** are each a layer of molybdenum about 270 nm thick. In a plane parallel to the major surface of substrate **40**, electrodes **22** and **24** have an asymmetrical shape with an area of about 11,000 μm^2. The asymmetrical shape minimizes lateral acoustic modes in FBAR **10**, as described by Larson III et al. in U.S. Pat. No. 6,215,375, incorporated by reference.

[**0046**] Electrodes **22** and **24** constitute a significant portion of the mass of piezoelectric resonator stack **20**, so the acoustic properties of the material of the electrodes have a significant effect on the Q of the piezoelectric resonator stack. Molybdenum has acoustic properties superior to those of more typical electrode materials such as gold and aluminum. Using molybdenum as the material of electrodes **22** and **24** gives FBAR **10** higher Q than using other typical electrode materials as the material of the electrodes. Other electrode materials with superior acoustic properties include tungsten, niobium and titanium. The electrodes may have a multi-layer structure. Further details of the structure and fabrication of FBARs are disclosed by Ruby et al. in U.S. Pat. No. 6,060,818, incorporated by reference.

[**0047**] FIG. **1**B is a schematic drawing showing an equivalent circuit **30** of FBAR **10**. A shunt capacitance C_P, which is the capacitance of a capacitor formed by electrodes **22** and **24** and piezoelectric layer **26** as dielectric, provides the main reactive component of circuit **30**. A resistor R_P represents the series resistance of shunt capacitance C_P. An inductance L_M and a capacitance C_M represent the inductance and capacitance of piezoelectric resonator stack **20**. A resistor R_M represents loss in the piezoelectric resonator stack. A resistor R_S represents the series electrical resistance of the connections between terminals **32** and **34** and piezoelectric resonator stack **20**.

[**0048**] FIG. **1**C is a graph showing the frequency response of the modulus of the impedance |Z| measured between terminals **32** and **34** of an example of FBAR **10**. As the frequency increases, the impedance gradually falls due to the falling impedance of shunt capacitance C_P. The impedance eventually reaches a minimum at the frequency F_S of the series resonance between mechanical inductance L_M and mechanical capacitance C_M, i.e.:

$$F_S = \frac{1}{2\pi\sqrt{L_M C_M}}$$

[**0049**] The impedance of circuit **30** then sharply increases and reaches a maximum at the frequency F_P of the parallel resonance between mechanical inductance L_M and the series combination of mechanical capacitance C_M and shunt capacitance C_P, i.e.,

$$F_P = \frac{1}{2\pi\sqrt{L_M \frac{C_M C_P}{C_M + C_P}}}$$

[**0050**] Since shunt capacitance C_P is typically about 20 times mechanical capacitance C_M, the difference between the frequency F_S of the series resonance and the frequency F_P of the parallel resonance is small.

[**0051**] The impedance of circuit **30** then falls steeply as the frequency increases above the frequency F_P of the parallel resonance.

[**0052**] FIG. **2**A is a block diagram showing an example of an unbalanced frequency-selective transformer **100** in accordance with an embodiment of the invention. A balanced example will be described below with reference to FIGS. **4**A and **4**B. Frequency-selective transformer **100** is composed of a capacitative transformer **110** and an electromechanical resonator **120**. Capacitative transformer **110** has a first port **111**, a second port **112** and a third port **113**. Electromechanical resonator **120** is connected between the second port **112** and the third port **113** of capacitative transformer **110**. Electromechanical resonator **120** has a series resonance and a parallel resonance closely spaced in frequency, as exemplified by the series resonance and the parallel resonance of FBAR **10** described above with reference to FIGS. **1**A-**1**C.

[**0053**] Frequency-selective transformer **100** is a three-terminal device. Terminals **101**, **102** and **103** are shown. Terminal **101** is connected to the first port **111** of capacitative transformer **110**, terminal **102** is connected to the second port **112** of capacitative transformer **110** and to one end of electromechanical resonator **120**, and terminal **103** is connected to the third port **113** of capacitative transformer **110** and to the other end of electromechanical resonator **120**. In an application in which frequency-selective transformer **100** is used as a step-up transformer, terminal **101** is the input terminal and terminal **102** is the output terminal of the frequency-selective transformer. In an application in which frequency-selective transformer is used as a step-down transformer, terminal **102** is the input terminal and terminal **101** is the output terminal of the frequency-selective transformer. Terminal **103** is the signal ground terminal.

[**0054**] In an example in which frequency-selective transformer **100** is used as a step-up transformer, an input signal is applied between terminals **101** and **103**, and frequency-selective transformer **100** provides an output signal between terminals **102** and **103**. In the pass band of frequency-selective transformer **100**, the output impedance between terminals **102** and **103** is greater than the input impedance between terminals **101** and **103** by a ratio that depends on the impedance transformation ratio of capacitative transformer **110**. In an example in which frequency-selective transformer **100** is used as a step-down transformer, an input signal is applied between terminals **102** and **103**, and frequency-selective transformer **100** provides an output signal between terminals **101** and **103**. In the pass band of frequency-selective transformer **100**, the output impedance between terminals **101** and **103** is smaller than the input impedance between terminals **102** and **103** by a ratio that depends on the impedance transformation ratio of capacitative transformer **110**. The frequency response of frequency-selective transformer **100** and its dependence on the resonances of electromechanical resonator **120** will be described below with reference to FIGS. **3**A and **3**B.

[0055] FIG. **2**B is a schematic diagram showing a practical example of unbalanced frequency-selective transformer **100** in accordance with an embodiment of the invention. In frequency-selective transformer **100**, capacitative transformer **110** is composed of a capacitative element C_1 and a capacitative element C_2, and electromechanical resonator **120** is embodied as a bulk acoustic wave (BAW) resonator **122**. In capacitative transformer **110**, capacitative element C_1 and capacitative element C_2 are connected in series between second port **112** and third port **113**, and the node between capacitative elements C_1 and C_2 is connected to first port **111**. In the example shown in FIG. **2**B, conventional capacitors are used as capacitative elements C_1 and C_2, and FBAR **10** described above with reference to FIGS. **1**A-**1**C is used as BAW resonator **122**. Another type of electromechanical resonator that may be used as electromechanical resonator **120** is a dielectric resonator, such as one of the dielectric resonators sold by First Technology, Southfield, Mich. Such dielectric resonator is not itself electrically connected to capacitative transformer **130**, but instead is electromagnetically coupled to capacitative transformer **130** by locating it in a cavity electrically connected to capacitative transformer **130**.

[0056] In the example shown, connecting capacitative transformer **110** in parallel with FBAR **10** decreases the frequency F_P of the parallel resonance of FBAR **10**. Consequently, the frequency f_P of the pass band of frequency-selective transformer **100** is less than frequency F_P. Referring additionally to FIG. **1**B, connecting capacitative transformer **110** in parallel with FBAR **10** connects the series combination of capacitative elements C_1 and C_2 in parallel with the shunt capacitance C_P of FBAR **10**. Since shunt capacitance C_P in part determines the frequency F_P of the parallel resonance of FBAR **10**, connecting capacitative transformer **110** in parallel with FBAR **10** reduces the frequency F_P. The resulting frequency f_P of the pass band of frequency-selective transformer **100** is given by:

$$f_P = \frac{1}{2\pi\sqrt{L_M \frac{C_M(C_P + C_S)}{C_M + C_P + C_S}}}$$

where C_S is the capacitance of the series combination of capacitative elements C_1 and C_2, i.e.:

$$C_S = \frac{C_1 C_2}{C_1 + C_2}.$$

[0057] Connecting capacitative transformer **110** in parallel with FBAR **10** to form frequency-selective transformer **100** leaves the frequency F_S of the series resonance of FBAR **10** unchanged. Thus, the frequency f_s of the stop band of frequency-selective transformer **100** is the same as the frequency FS of the series resonance of FBAR **10** in isolation.

[0058] In capacitative transformer **110**, capacitative element C_2 is typically larger in capacitance than capacitative element C_1. Consequently, the impedance Z_2 between ports **112** and **113** is greater than the impedance Z_1 between ports **111** and **113** by a ratio that depends on the capacitances of capacitative elements C_1 and C_2. In the pass band of frequency-selective transformer **100**, the impedance presented by electromechanical resonator **120** between the second port **112** and third port **113** of capacitative transformer **110** is very high, as shown in FIG. **1**C. Consequently, in frequency-selective transformer **100**, the impedance between ports **112** and **113** is the impedance of the source resistance between terminals **101** and **103** reflected through capacitive transformer **110**. The impedance Z_2 between terminals **102** and **103** is therefore greater than the impedance Z_1 between terminals **101** and **103**. The impedance transformation ratio Z_2/Z_1 of frequency-selective transformer **100** is given by:

$$\frac{Z_2}{Z_1} = \left(\frac{C_1 + C_2}{C_1}\right)^2,$$

where C_1 and C_2 are the capacitances of capacitative elements C_1 and C_2, respectively.

[0059] In the pass band of frequency-selective transformer **100**, the voltage V_2 between terminals **102** and **103** is also greater than the voltage V_1 between terminals **101** and **103**. The voltage transformation ratio V_2/V_1 of frequency-selective transformer **100** in its pass band is given by:

$$\frac{V_2}{V_1} = \frac{C_1 + C_2}{C_1}.$$

[0060] At the frequency f_S of the stop band of frequency-selective transformer **100**, i.e., at the frequency F_S of the series resonance of FBAR **10**, the impedance presented by FBAR **10** between the second port **112** and third port **113** of capacitative transformer **110** is very low, as shown in FIG. **1**C. Thus, at the stop band frequency f_S, FBAR **10** presents substantially a short circuit between second port **112** and third port **113**, the impedance and voltage between ports **112** and **113** is very low, and the voltage transformation ratio between terminal **101** and terminal **102** of frequency-selective transformer **100** is also very low.

[0061] At frequencies outside its pass band and its stop band, frequency-selective transformer **100** functions as a capacitive load between terminal **101** and terminal **102**. At such frequencies, FBAR **10** appears principally as shunt capacitance C_P (FIG. **1**B) connected in parallel with ports **112** and **113** of capacitative transformer **110**. Shunt capacitance C_P of FBAR **10** and the capacitative element C_1 of capacitative transformer **110** collectively form a capacitative voltage divider having an input at terminal **101** and an output at terminal **102**.

[0062] FIGS. **3**A and **3**B are graphs showing the frequency response of an exemplary embodiment of unbalanced frequency-selective transformer **100** described above with reference to FIG. **2**B. The frequency response of unbalanced frequency-selective transformer **100** described above with reference to FIG. **2**A is similar, as are the frequency responses of the embodiments that will be described below with reference to FIGS. **4**A and **4**B. The frequency responses shown in FIGS. **3**A and **3**B show the frequency dependence of the voltage transformation ratio G_0 (expressed in decibels (dB)) between the output signal output between terminals **102** and **103** and an input signal applied between terminals **101** and **103**. FIG. **3**B has an expanded frequency scale to enable the pass band **106** and the stop band **108** of the frequency-selective transformer to be depicted more clearly.

[**0063**] At input signal frequencies below the frequency f_S of the stop band of frequency-selective transformer **100**, the capacitance of FBAR **10** and the capacitative element C_1 of capacitative transformer **110** form a capacitative divider. As a result, the voltage transformation ratio of frequency-selective transformer **100** between terminals **101** and **103** and terminals **102** and **103** is less than unity. In this frequency range, the voltage transformation ratio remains relatively constant with frequency, as shown.

[**0064**] As the frequency of the input signal applied between terminals **101** and **103** approaches the stop band **106** of frequency-selective transformer **100**, the impedance of FBAR **10** sharply falls, as described above. This sharply increases the attenuation of the input signal by FBAR **10**, and sharply decreases the voltage transformation ratio of frequency-selective transformer **100**. At the center frequency f_S of stop band **106**, i.e., at the frequency of the series resonance of FBAR **10**, the impedance of the FBAR is very low, and the attenuation of the input signal by FBAR **10** is a maximum. The voltage transformation ratio of frequency-selective transformer **100** is therefore very low with respect to input signals, such as image signals, at frequencies within stop band **106**. The stop band **106** of frequency-selective transformer **100** can be regarded as encompassing a range of frequencies in which the voltage transformation ratio of frequency-selective transformer **100** is within a specified ratio, e.g., 3 dB, of the minimum voltage transformation ratio.

[**0065**] As the frequency of the input signal increases above the stop band **106** of frequency-selective transformer **100**, the impedance of FBAR **10** sharply increases toward its off-resonance value and the attenuation of the input signal by FBAR **10** sharply decreases towards its off-resonance value. Then, as the frequency of the input signal approaches the pass band **108** of frequency-selective transformer **100**, the impedance of FBAR **10** sharply increases, as described above, which sharply increases the voltage transformation ratio of frequency-selective transformer **100**. Closer to pass band **108**, the impedance of FBAR **10** increases to a point at which the voltage transformation ratio of frequency-selective transformer **100** becomes greater than unity, i.e., frequency-selective transformer **100** becomes a step-up transformer.

[**0066**] At the center frequency f_P of pass band **108**, i.e., the frequency of the parallel resonance of FBAR **10**, the impedance of the FBAR is very high, and the voltage transformation ratio of frequency-selective transformer **100** reaches a maximum. The maximum voltage transformation ratio is determined by the voltage transformation ratio of capacitative transformer **110**, as described above. Frequency-selective transformer **100** therefore has a significant voltage transformation ratio with respect to input signals, such as wanted RF signals, at frequencies within pass band **108**. The pass band **108** of frequency-selective transformer **100** can be regarded as encompassing a range of frequencies in which the voltage transformation ratio of the frequency-selective transformer is within a specified ratio, e.g., 3 dB, of the maximum voltage transformation ratio.

[**0067**] As the frequency of the input signal increases above pass band **108**, the impedance of FBAR **10** sharply decreases, the attenuation of the input signal by FBAR **10** sharply increases towards its off-resonance value, and the voltage transformation ratio of frequency-selective transformer **100** sharply decreases towards its off-resonance value.

[**0068**] FIG. **4**A is a block diagram showing an example of a balanced frequency-selective transformer **200** in accordance with an embodiment of the invention. Frequency-selective transformer **200** is composed of a capacitative transformer **210** and electromechanical resonator **120**. Capacitative transformer **210** has a first port **211**, a second port **212**, a third port **213** and a fourth port **214**. Electromechanical resonator **120** is connected between the second port **212** and the third port **213** of capacitative transformer **210**. Electromechanical resonator **120** has a series resonance and a parallel resonance closely spaced in frequency, as described above.

[**0069**] Frequency-selective transformer **200** is a bidirectional, four-terminal device. Terminals **201**, **202**, **203** and **204** are shown. Terminal **201** is connected to the first port **211** of capacitative transformer **210**, terminal **202** is connected to the second terminal **212** of capacitative transformer **210** and to one end of electromechanical resonator **120**, terminal **203** is connected to the third port **213** of capacitative transformer **210** and to the other end of electromechanical resonator **120**, and terminal **204** is connected to the fourth port **214** of capacitative transformer **210**.

[**0070**] In an example in which frequency-selective transformer **200** is used as a step-up transformer, an input signal is applied between terminals **201** and **204**, and frequency-selective transformer **200** provides an output signal between terminals **202** and **203**. In the pass band of frequency-selective transformer **200**, the output impedance between terminals **202** and **203** is greater than the input impedance between terminals **201** and **204** by a ratio that depends on the impedance transformation ratio of capacitative transformer **210**. In an example in which frequency-selective transformer **200** is used as a step-down transformer, an input signal is applied between terminals **202** and **204**, and frequency-selective transformer **200** provides an output signal between terminals **201** and **204**. In the pass band of frequency-selective transformer **200**, the output impedance between terminals **201** and **204** is smaller than the input impedance between terminals **202** and **203** by a ratio that depends on the impedance transformation ratio of capacitative transformer **210**. The frequency response of frequency-selective transformer **200** and its dependence on the resonances of electromechanical resonator **120** are similar to those described above with reference to FIGS. **3**A and **3**B.

[**0071**] FIG. **4**B is a schematic diagram showing a practical example of balanced frequency-selective transformer **200** in accordance with an embodiment of the invention. In frequency-selective transformer **200**, capacitative transformer **210** is composed of a capacitative element C_1, a capacitative element C_2 and a capacitative element C_3, and electromechanical resonator **120** is embodied as a bulk acoustic wave (BAW) resonator **122**. In capacitative transformer **210**, capacitative element C_1, capacitative element C_2 and capacitative element C_3 are connected in order in series between second port **212** and third port **213**, the node between capacitative elements C_1 and C_2 is connected to first port **211** and the node between capacitative elements C_2 and C_3 is connected to fourth port **214**. In the example shown in FIG. **4**B, conventional capacitors are used as capacitative elements C_1, C_2 and C_3, and FBAR **10** described above with reference to FIGS. **1**A-**1**C is used as BAW resonator **122**.

[**0072**] In the example shown, connecting capacitative transformer **210** in parallel with FBAR **10** decreases the frequency F_P of the parallel resonance of FBAR **10**. Consequently, the frequency f_P of the pass band of frequency-selective transformer **200** is less than frequency F_P. Referring additionally to FIG. **1**B, connecting capacitative transformer **210** in parallel with FBAR **10** connects the series combination of capacitative elements C_1, C_2 and C_3 in parallel with the shunt capacitance C_P of FBAR **10**. Since shunt capacitance C_P in part determines the frequency F_P of the parallel resonance of FBAR **10**, connecting capacitative transformer **210** in parallel with FBAR **10** reduces the frequency F_P. The resulting frequency f_P of the pass band of frequency-selective transformer **200** is given by:

$$f_P = \frac{1}{2\pi\sqrt{L_M \frac{C_M(C_P + C_S)}{C_M + C_P + C_S}}}$$

where C_S is the capacitance of the series combination of capacitative elements C_1, C_2 and C_3, i.e.:

$$C_S = \frac{C_1 C_2}{C_1 + 2C_2},$$

assuming $C_3 = C_1$

[**0073**] Connecting capacitative transformer **210** in parallel with FBAR **10** to form frequency-selective transformer **200** leaves the frequency F_s of the series resonance of FBAR **10** unchanged. Thus, the frequency f_S of the stop band of frequency-selective transformer **200** is the same as the frequency F_P of the series resonance of FBAR **10** in isolation.

[**0074**] In capacitative transformer **210**, capacitative element C_1 and capacitative element C_3 nominally have equal capacitances, and capacitative element C_2 is typically larger in capacitance than capacitative elements C_1 and C_3. Consequently, the impedance Z_2 between ports **212** and **213** is greater than the impedance Z_1 between ports **211** and **214** by a ratio that depends on the capacitances of capacitative elements C_1, C_2 and C_3. In the pass band of frequency-selective transformer **200**, the impedance presented by electromechanical resonator **120** between the second port **212** and third port **213** of capacitative transformer **210** is very high, as shown in FIG. **1**C. Consequently, in frequency-selective transformer **200**, the impedance between terminals **202** and **203** is the impedance of the source resistance between terminals **201** and **204** reflected through capacitative transformer **210**. The impedance Z_2 between terminals **202** and **203** is therefore greater than the impedance Z_1 between terminals **201** and **204**. Assuming that capacitative elements C_1 and C_3 are equal in capacitance, the impedance transformation ratio Z_2/Z_1 of frequency-selective transformer **200** is given by:

$$\frac{Z_2}{Z_1} = \left(\frac{C_1 + (C_2/2)}{C_1}\right)^2.$$

[**0075**] In the pass band of frequency-selective transformer **200**, the voltage V_2 between terminals **202** and **203** is also greater than the voltage V_1 between terminals **201** and **204**. Assuming that capacitative elements C_1 and C_3 are equal in capacitance, the pass band voltage transformation ratio V_2/V_1 of frequency-selective transformer **200** is given by:

$$\frac{V_2}{V_1} = \frac{C_1 + (C_2/2)}{C_1}.$$

[**0076**] At the frequency f_S of the stop band of frequency-selective transformer **200**, i.e., at the frequency F_S of the series resonance of FBAR **10**, the impedance presented by FBAR **10** between the second port **212** and third port **213** of capacitative transformer **210** is very low, as shown in FIG. **1**C. Thus, at the stop band frequency f_S, FBAR **10** presents substantially a short circuit between second port **212** and third port **213**, the impedance and voltage between ports **212** and **213** is very low, and the voltage transformation ratio between terminals **201**/**204** and terminals **202**/**203** of frequency-selective transformer **200** is also very low.

[**0077**] At frequencies outside its pass band and its stop band, frequency-selective transformer **200** functions as a capacitive load between terminals **201**/**204** and terminals **202**/**203**. At such frequencies, FBAR **10** appears principally as shunt capacitance C_P (FIG. **1**B) connected in parallel with ports **212** and **213** of capacitative transformer **210**. Shunt capacitance C_P of FBAR **10** and the capacitative elements C_1 and C_3 of capacitative transformer **210** collectively form a capacitative voltage divider having an input at terminals **201**/**204** and an output at terminals **202**/**203**.

[**0078**] FIG. **5**A is a schematic drawing showing an example of a tunable frequency-selective transformer **250** in accordance with an embodiment of the invention. Frequency-selective transformer **250** is based on frequency-selective transformer **200** described above with reference to FIG. **4**B with the addition of a tuning capacitor **230** in parallel with FBAR **10**. Tuning capacitor **230** is used to change the frequency f_P of the pass band of frequency-selective transformer **250**. As noted above with reference to FIG. **2**B, connecting capacitance in parallel with FBAR **10** decreases the frequency F_P of the parallel resonance of the FBAR. Changing the frequency of the parallel resonance of the FBAR in turn changes the frequency of the pass band of frequency-selective transformer **200**.

[0079] FIG. **5**B is a graph showing the frequency response of an example of frequency-selective transformer **250** with five different values C_{230} of tuning capacitor **230** ranging from low to high. In some embodiments, tuning capacitor **230** is a variable capacitor that allows the frequency of the pass band of frequency-selective transformer **200** to be tuned to any frequency within a given frequency range.

[0080] Frequency-selective transformer **200** described above with reference to FIG. **4**A may also be modified by connecting a tuning capacitor similar to tuning capacitor **230** in parallel with electromechanical resonator **120**. Frequency-selective transformer **100** described above with reference to FIGS. **2**A and **2**B may be modified by connecting a tuning capacitor in parallel with electromechanical resonator **120**. However, for a given capacitance of the tuning capacitor, the change in the frequency of the pass band is approximately one half in unbalanced frequency-selective transformer **100** than in balanced frequency-selective transformer **250** due to the Miller multiplication inherent in the differentially-driven balanced embodiments.

[0081] FIG. **6** is a schematic drawing showing an example of a multi-band frequency-selective transformer **300** in accordance with an embodiment of the invention. Frequency-selective transformer **300** is a multi-band frequency-selective transformer based on frequency-selective transformer **200** described above with reference to FIG. **4**A. In frequency-selective transformer **300**, a switch **352** is connected in series with electromechanical resonator **120**. Frequency-selective transformer **300** additionally comprises a tuning capacitor **230**, an additional electromechanical resonator **320** and an additional switch **354**. Optional tuning capacitor **230** is connected between the ports **212** and **213** of capacitative transformer **210**. Electromechanical resonator **320** and switch **354** are connected in series between ports **212** and **213**.

[0082] In the example shown, switch **352** and switch **354** are embodied as respective switching transistors. The control electrodes, e.g., gates, of switches **352** and **354** are connected to respective poles of a band selector switch **356**. In one position B_1 of band selector switch **356**, switch **352** is activated and switch **354** is deactivated so that the frequencies of the stop band and of the pass band of frequency-selective transformer **300** are defined by the frequencies of the series resonance and the parallel resonance, respectively, of electromechanical resonator **120**. In the other position B_2 of band selector switch **356**, switch **354** is activated and switch **352** is deactivated so that the frequencies of the stop band and of the pass band of frequency-selective transformer **300** are defined by the frequencies of the series resonance and the parallel resonance, respectively, of electromechanical resonator **320**. In embodiments in which switches **352** and **354** are implemented as CMOS transistors, each of switches **352** and **354** has an additional CMOS transistor switch (not shown) connected between its gate and ground. When switch **352** is activated, the additional CMOS transistor switch connected to the gate of switch **354** is activated to deactivate switch **354**, and vice versa.

[0083] Electromechanical resonator **320** is similar to electromechanical resonator **120** but is structured so that its parallel resonance differs in frequency from that of electromechanical resonator **120**. Thus, when frequency-selective transformer **300** operates with electromechanical resonator **320** activated, the frequency of its pass band differs from that when it is operated with electromechanical resonator **120** activated.

[0084] Electromechanical resonator **320** may additionally be structured so that its series resonance differs in frequency from that of electromechanical resonator **120**. For example, when frequency-selective transformer **300** is connected to a mixer (not shown), as will be described in more detail below, each of electromechanical resonator **120** and electromechanical resonator **320** is structured such that its series resonance and its parallel resonance differ in frequency by twice the frequency of the intermediate frequency circuitry connected to the mixer. This way, the image frequency lies in the stop band of frequency-selective transformer **300** regardless of the setting of band selector switch **356**.

[0085] Other embodiments of frequency-selective transformer have more than the two bands of the example shown FIG. **6**. In such embodiments the number of electromechanical resonators and the number of poles in band selector switch **356** are each equal to the number of bands.

[0086] In the examples described above, conventional capacitors are used as the capacitative elements C_1 and C_2 of capacitative transformer **110** and the capacitative elements C_1, C_2 and C_3 of capacitative transformer **210**. Other capacitative devices may alternatively be used as capacitative elements C_1, C_2 and C_3. As noted above with reference to FIGS. **1**A-**1**C, BAW resonators are essentially capacitative at frequencies outside the frequency ranges of their series and parallel resonances. Accordingly, BAW resonators, and, specifically, FBARs, may be used as one or more of capacitative elements C_1, C_2 and C_3.

[0087] Using BAW resonators as respective capacitative elements C_1, C_2 and C_3 allows the size of the frequency-selective transformer to be reduced since the BAW resonators providing capacitative elements C_1, C_2 and C_3 can be fabricated on the same substrate and using the same processing as the BAW resonator providing electromechanical resonator **120**. The capacitative elements use the same layer of piezoelectric material for their respective dielectrics as that used to provide the piezoelectric element **26** (FIG. **1**A) of the BAW resonator that provides electromechanical resonator **120**. The different capacitances of the capacitative elements and electromechanical resonator **120** (collectively components) are obtained simply by differences in the areas of the electrodes (corresponding to electrodes **22** and **24** of FBAR **10**) of the respective components. The layers of metal that are patterned to define the electrodes of the capacitative elements and of the electromechanical resonator are additionally patterned to define electrical traces that interconnect the components to form the frequency-selective transformer.

[0088] FIG. **7**A is a schematic diagram showing an example of a frequency-selective transformer **400** in accordance with an embodiment of the invention. Frequency-selective transformer **400** is based on frequency-selective transformer **200** described above with reference to FIG. **4**B. Frequency-selective transformer **100** described above with reference to FIG. **2**B may be similarly modified.

[0089] In frequency-selective transformer **400**, a BAW resonator **422** provides capacitative element C_2 in capacitative transformer **410**. The series resonance of BAW resonator **422** is used to provide frequency-selective transformer **400** with additional frequency selection, specifically, an additional stop band.

[**0090**] In the example shown, BAW resonator **422** is structured to have its series resonance at the frequency of the additional stop band. At the frequency of the series resonance of BAW resonator **422**, the impedance of BAW resonator **422** is very low, as described above. Thus, at the frequency of the series resonance, BAW resonator **422** provides a short circuit between terminal **201** and terminal **204**, which significantly attenuates any signal applied between the terminals and provides frequency-selective transformer **400** with an additional stop band. At the parallel resonance of BAW resonator **422**, the capacitive load presented between terminals **201**/**204** decreases since the capacitance of capacitative element C_2 is tuned out by BAW resonator **422**. This does not significantly affect the frequency response of frequency-selective transformer **400**.

[**0091**] Capacitative elements C_1 and C_3 are shown as conventional capacitors, but BAW resonators may alternatively be used as capacitative elements C_1 and C_3. A BAW resonator may be used as one or both of capacitative elements C_1 and C_2 in the capacitative transformer **110** of unbalanced frequency-selective transformer **100** described above with reference to FIGS. **2**A and **2**B. The frequencies of the pass band and the two stop bands may differ from those in this example.

[**0092**] FIG. **7**B is a graph showing the frequency response of an example of frequency-selective transformer **400**. Frequency-selective transformer **400** has a pass band in the 2.1 GHz PCS band and a stop band covering the band of image frequencies corresponding to the PCS band, as described above. Additionally, in the 900 MHz mobile band, frequency-selective transformer **400** has an additional stop band provided by the series resonance of BAW resonator **422** used as capacitative element C_2 in capacitative transformer **410**. The additional stop band isolates circuitry downstream of the terminals **202**/**203** of frequency-selective transformer **400** from signals at frequencies in the additional stop band.

[**0093**] Embodiments of the invention additionally provide an unbalanced mixer comprising an unbalanced frequency-selective transformer in accordance with an embodiment of the invention, a local oscillator circuit and a mixing circuit. The mixing circuit comprises a radio-frequency (RF) port, an intermediate frequency (IF) port and a local oscillator (LO) port. The LO port is connected to the local oscillator. The frequency-selective transformer comprises a capacitative transformer and an electromechanical resonator. The capacitative transformer has a first port, a second port and a third port. The capacitative transformer is coupled to the RF port of the mixing circuit via either the first port or the second port. The electromechanical resonator is connected between the second port and the third port of the capacitative transformer. The electromechanical resonator has a series resonance and a parallel resonance that are closely spaced in frequency. In the mixer, the frequency-selective transformer operates as a step-up transformer when the capacitative transformer is coupled to the RF port of the mixing circuit via the first port. Alternatively, the frequency-selective transformer operates as a step-down transformer when the capacitative transformer is coupled to the RF port of the mixing circuit via the second port.

[**0094**] FIG. **8**A is a schematic drawing showing an example of an unbalanced mixer **500** in accordance with an embodiment of the invention. Unbalanced mixer **500** is composed of unbalanced frequency-selective transformer **100** in accordance with an embodiment of the invention, a local oscillator **502** and a mixing circuit **504**. Mixing circuit **504** has an RF port **506**, an IF port **507** and a local oscillator port **508**. Local oscillator port **508** is connected to the output of local oscillator **502**.

[**0095**] In this embodiment, terminal **101**, terminal **102** and terminal **103** of unbalanced frequency-selective transformer **100** are connected as follows. Terminal **101** is connected to the first port **111** of capacitative transformer **110** and provides the RF terminal of mixer **500**. Hence, the RF terminal of mixer **500** will be referred to as RF terminal **101**. Terminal **102** is connected to the second port **112** of capacitative transformer **110** and to the RF port **506** of mixing circuit **504**. Terminal **103** is connected to the third port **113** of capacitative transformer **110** and to signal ground. The IF port **507** of mixing circuit **504** provides the IF terminal of mixer **500**. Hence, the IF terminal of mixer **500** will be referred to as IF terminal **507**

[**0096**] Unbalanced mixer **500** is bidirectional. In a downconverter, such as that found in a receiver, an RF signal is received at RF terminal **101** and an IF signal is output at IF terminal **507** at a frequency less that that of the RF signal. In an upconverter, such as that found in a transmitter, an IF signal is received at IF terminal **507** and an RF signal is output at RF terminal **101** at a frequency greater that that of the IF signal.

[**0097**] With the connections just described, frequency-selective transformer **100** provides a step up in impedance between RF terminal **101** and the RF port **506** of mixing circuit **504** and a step down in impedance between the RF port **506** of mixing circuit **504** and RF terminal **101**.

[**0098**] FIG. **8**B is a schematic drawing showing an example of an unbalanced mixer **550** in accordance with an embodiment of the invention. Unbalanced mixer **550** is composed of unbalanced frequency-selective transformer **100** in accordance with an embodiment of the invention, local oscillator **502** and mixing circuit **504**, as described above. Mixing circuit **504** has an RF port **506**, an IF port **507** and a local oscillator port **508**. Local oscillator port **508** is connected to the output of local oscillator **502**.

[**0099**] In this embodiment, terminal **101**, terminal **102** and terminal **103** of unbalanced frequency-selective transformer **100** are connected as follows. Terminal **101** is connected to the first port **111** of capacitative transformer **110** and to the RF port **506** of mixing circuit **504**. Terminal **102** is connected to the second port **112** of capacitative transformer **110** and provides the RF terminal of mixer **550**. Hence, the RF terminal of mixer **550** will be referred to as RF terminal **102**. Terminal **103** is connected to the third port **113** of capacitative transformer **110** and to signal ground. IF port **507** of mixing circuit **504** provides the IF terminal of mixer **550**. Hence, the IF terminal of mixer **550** will be referred to as IF terminal **507**.

[**0100**] Unbalanced mixer **550** is bidirectional. In a downconverter, such as that found in a receiver, an RF signal is received at RF terminal **102** and an IF signal is output at IF terminal **507** at a frequency less that that of the RF signal.

In an upconverter, such as that found in a transmitter, an IF signal is received at IF terminal **507** and an RF signal is output at RF terminal **102** at a frequency greater that that of the IF signal.

[0101] With the connections just described, frequency-selective transformer **100** provides a step down in impedance between RF terminal **102** and the RF port **506** of mixing circuit **504** and a step up in impedance between the RF port **506** of mixing circuit **504** and RF terminal **102**.

[0102] In unbalanced mixers **500** and **550**, frequency-selective transformer **100** subjects an RF spectrum received at first terminal **101** or second terminal **102** to impedance transformation and additionally subjects the RF spectrum to frequency selection such that frequency-selective transformer **100** passes with a step up in voltage the portion of the RF spectrum in its pass band, attenuates the portion of the RF spectrum outside its pass band and significantly attenuates the portion of the RF spectrum in its stop band.

[0103] In unbalanced mixers **500** and **550**, the frequency f_{LO} of the local oscillator signal generated by local oscillator **502**, the frequency f_{RF} of the wanted RF signal at RF terminal **101** or the wanted RF signal at RF terminal **102** and the frequency f_{IF} of the IF signal at IF terminal **507** are related as follows: $f_{RF}=|f_{LO}+f_{IF}|$. Frequency-selective transformer **100** is configured such that the frequency f_{RF} of the RF signal is within its pass band and the frequency f_{IM} ($f_{IM}=|f_{LO}-f_{IF}|$) of the image signal is within its stop band. Optimum results are obtained when the frequencies of the pass band and the stop band are nominally aligned with the frequencies of the wanted RF signal and the image signal, respectively. The frequency of the local oscillator is set mid-way between the nominal frequencies of the pass band and the stop band of frequency-selective transformer **100**. The intermediate frequency is nominally one half of the frequency difference between the frequencies of the pass band and the stop band. Since the electromechanical resonator that forms part of frequency-selective transformer **100** allows the pass band and the stop band to be closely spaced in frequency, the frequency f_{IF} of the IF signal can be relatively low. In the example shown in FIG. **3**B, in which the frequency of the pass band is about 2.13 GHz, the frequency f_P of the pass band is about 16 MHz greater than the frequency f_S of the stop band, which corresponds to the IF signal having a frequency f_{IF} of about 8 MHz, a relatively low frequency.

[0104] FIG. **9**A is a schematic drawing showing an example of a balanced mixer **600** in accordance with an embodiment of the invention. Balanced mixer **600** is composed of balanced frequency-selective transformer **200** in accordance with an embodiment of the invention, a local oscillator **602** and a mixing circuit **604**. Mixing circuit **604** has an RF port **606**, an IF port **607** and a local oscillator port **608**, all of which are balanced in the example shown. In other examples, not all of the ports are balanced. Local oscillator port **608** is connected to the output of local oscillator **602**.

[0105] In this embodiment, terminal **201**, terminal **202**, terminal **203** and terminal **204** of balanced frequency-selective transformer **200** are connected as follows. Terminal **201** and Terminal **204** are connected to the first port **211** and the fourth port **214**, respectively, of capacitative transformer **210**, and additionally provide the RF terminals of mixer **600**. Hence, the RF terminals of mixer **600** will be referred to as RF terminals **201**/**204**. Terminal **202** and terminal **203** are connected to the second port **212** and the third port **213**, respectively, of capacitative transformer **210** and to electromagnetic resonator **120**, and are additionally connected to the RF port **606** of mixing circuit **604**. IF port **607** of mixing circuit **604** provides the IF terminals of mixer **600**. Hence, the IF terminals of mixer **600** will be referred to as IF terminals **607**

[0106] Balanced mixer **600** is bidirectional. In a downconverter, such as that found in a receiver, an RF signal is received at RF terminals **201**/**204** and an IF signal is output at IF terminals **607** at a frequency less that that of the RF signal. In an upconverter, such as that found in a transmitter, an IF signal is received at IF terminals **607** and an RF signal is output at RF terminals **201**/**204** at a frequency greater that that of the IF signal.

[0107] With the connections just described, frequency-selective transformer **200** provides a step up in impedance between RF terminals **201**/**204** and the RF port **606** of mixing circuit **604** and a step down in impedance between the RF port **606** of mixing circuit **604** and RF terminals **201**/**204**.

[0108] FIG. **9**B is a schematic drawing showing an example of a balanced mixer **650** in accordance with an embodiment of the invention. Balanced mixer **620** is composed of balanced frequency-selective transformer **200** in accordance with an embodiment of the invention, local oscillator **602** and mixing circuit **604**, as described above. Mixing circuit **604** has an RF port **606**, an IF port **607** and a local oscillator port **608**, all of which are balanced in the example shown. In other examples, not all of the ports are balanced. Local oscillator port **608** is connected to the output of local oscillator **602**.

[0109] In this embodiment, terminal **201**, terminal **202**, terminal **203** and terminal **204** of balanced frequency-selective transformer **200** are connected as follows. Terminal **201** and terminal **204** are connected to the first port **211** and the fourth port **214**, respectively, of capacitative transformer **210** and are additionally connected to the RF port **606** of mixing circuit **604**. Terminal **202** and terminal **203** are connected to the second port **212** and the third port **213**, respectively, of capacitative transformer **210** and to electromagnetic resonator **120**, and additionally provide the RF terminals of mixer **650**. Hence, the RF terminals of mixer **650** will be referred to as RF terminals **202**/**203**. IF port **607** of mixing circuit **604** provides the IF terminals of mixer **650**. Hence, the IF terminals of mixer **650** will be referred to as IF terminals **607**

[0110] Balanced mixer **650** is bidirectional. In a downconverter, such as that found in a receiver, an RF signal is received at RF terminals **202**/**203** and an IF signal is output at IF terminals **607** at a frequency less that that of the RF signal. In an upconverter, such as that found in a transmitter, an IF signal is received at IF terminals **607** and an RF signal is output at RF terminals **202**/**203** at a frequency greater that that of the IF signal.

[0111] With the connections just described, frequency-selective transformer **200** provides a step down in impedance between RF terminals **202**/**203** and the RF port **606** of mixing circuit **604** and a step up in impedance between the RF port **606** of mixing circuit **604** and RF terminals **202**/**203**.

[0112] In balanced mixers **600** and **650**, frequency-selective transformer **200** subjects an RF spectrum received at terminal **201** and terminal **204**, or at terminal **202** and terminal **203** to impedance transformation and additionally subjects the RF spectrum to frequency selection such that frequency-selective transformer passes with a step up in voltage the portion of the RF spectrum in its pass band, attenuates the portion of the RF spectrum outside its pass band and significantly attenuates the portion of the RF spectrum in its stop band.

[0113] In balanced mixers **600** and **650**, the frequency f_{Lo} of the local oscillator signal generated by local oscillator **602**, the frequency f_{RF} of the wanted RF signal at RF terminals **201/204** or the wanted RF signal at RF terminals **202/203**, and the frequency f_{IF} of the IF signal at IF terminals **607** are related as follows: $f_{RF}=|f_{LO}+f_{IF}|$. Frequency-selective transformer **200** is configured such that the frequency f_{RF} of the RF signal is within its pass band and the frequency f_{IM} of the image signal ($f_{IM}=|f_{LO}-f_{IF}|$) is within its stop band. Optimum results are obtained when the frequencies of the pass band and the stop band are nominally aligned with the frequencies of the wanted RF signal and the image signal, respectively. The frequency of the local oscillator is set mid-way between the nominal frequencies of the pass band and the stop band of frequency-selective transformer **200**. The intermediate frequency is nominally one half of the frequency difference between the center frequencies of the pass band and the stop band. Since the electromechanical resonator that forms part of frequency-selective transformer **200** allows the pass band and the stop band to be closely spaced in frequency, the frequency f_{IF} of the IF signal can be relatively low, as described above.

[0114] A number of examples of receiver front ends and transmitter output stages incorporating the embodiments of balanced mixers **600** and **650** described above with reference to FIGS. **9**A and **9**B, respectively, will now be described with reference to FIGS. **10**-**13**. The examples described below can easily be modified to incorporate corresponding embodiments of unbalanced mixers **500** and **550** described above with reference to FIGS. **8**A and **8**B. Relevant points of difference between the balanced and unbalanced embodiments will be described as they arise.

[0115] FIG. **10**A is a schematic drawing showing an example of the front end of a receiver **700** incorporating an embodiment of mixer **600** described above with reference to FIG. **9**A. Receiver **700** comprises mixer **600** and an antenna **702**. The RF terminals **201/204** of mixer **600** are connected to antenna **702**. Mixer **600** provides an IF signal at IF port **607**.

[0116] In receiver **700**, mixer **600** receives an RF spectrum at its RF terminals **201/204** from antenna **702**. The RF spectrum includes a wanted RF signal at a frequency f_{RF} and may additionally include an image signal at a frequency f_{IM} that differs from frequency f_{RF} by twice the IF frequency f_{IF}. In mixer **600**, frequency-selective transformer **200** subjects the RF spectrum received at RF terminals **201/204** to a step up in impedance, a step up in voltage and frequency-selective filtering. The filtering selects the wanted RF signal from the RF spectrum, and additionally significantly attenuates any image signal present in the RF spectrum. Frequency-selective transformer **200** provides the wanted RF signal at frequency f_{RF} to the RF port **606** of mixing circuit **604**. Mixing circuit **604** additionally receives the local oscillator signal at frequency f_{Lo} at its local oscillator port **608**. Mixing circuit **604** mixes the signals received at its RF and local oscillator ports to generate an IF signal at a frequency $f_{IF}=|f_{RF}-f_{LO}|$. Since frequency-selective transformer **200** significantly attenuates any image signal present in the RF spectrum received by antenna **702**, the contribution of such image signal to the IF signal is negligible. Mixing circuit **604** outputs the IF signal from IF port **607** to the IF portion (not shown) of receiver **700**.

[0117] In mixer **600**, frequency-selective transformer **200** provides a step up in impedance and a step up in voltage between RF terminals **201/204** and the RF port **606** of mixing circuit **604**. The step up in impedance provided by frequency-selective transformer **200** better matches the output impedance of antenna **702** (typically 50 Ω to 300 Ω) to the greater input impedance of RF port **606**. Additionally, the step up in voltage provided by frequency-selective transformer **200** increases the signal level at the RF port **606** of mixing circuit **604** and, hence, the signal-to-noise ratio of the IF signal output at IF port **607**. Additionally, frequency-selective transformer **200** is configured as described above to provide significant attenuation at the frequency of the image signal so that receiver **700** has good image rejection performance.

[0118] In an embodiment of receiver **700** incorporating an embodiment of unbalanced mixer **500** described above with reference to FIG. **8**A, the antenna is connected to the RF terminal **101** of mixer **500**.

[0119] In many applications, the step-up in voltage provided by frequency-selective transformer **200** is sufficient to allow receiver **700** to meet its sensitivity specifications without the need for amplification ahead of mixing circuit **604**. In applications that require greater sensitivity, a low-noise amplifier may be incorporated into the receiver front-end. FIG. **10**B is a schematic drawing showing an example of a receiver **750** whose front end incorporates a low-noise amplifier.

[0120] Receiver **750** comprises mixer **600**, antenna **702** and a low-noise amplifier **752**. In receiver **750**, the RF terminals **201/204** of mixer **600** are connected to antenna **702** and mixer **600** provides an IF signal at IF port **607**, as described above. In the example shown, low noise amplifier **754** is interposed between frequency-selective transformer **200** and the RF port **606** of mixing circuit **604**. Specifically, low-noise amplifier **754** has its inputs connected to terminals **202/203** of frequency-selective transformer **200** and its outputs connected to the RF port **606** of mixing circuit **604**. Thus, in this embodiment, low-noise amplifier **754** couples RF port **606** to the second port **212** and the third port **213** of capacitative transformer **210** that forms part of frequency-selective transformer **200**.

[0121] The step up in impedance provided by frequency-selective transformer **200** better matches the output impedance of antenna **702** to the greater input impedance of low noise amplifier **754**. Additionally, the step up in voltage provided by frequency-selective transformer **200** increases the signal level at the input of low-noise amplifier **754** and, hence, increases the signal-to-noise ratio of the amplified RF signal output by low-noise amplifier **754** and the signal-to-noise ratio of the IF signal output at IF port **607**. The attenuation of the image signal by frequency-selective transformer **200** additionally reduces the possibility of such signal overloading low-noise amplifier **754**.

[0122] Low-noise amplifier **754** may alternatively be interposed between antenna **702** and the RF terminals **201/204** of mixer **600**. However, some of the above-described performance advantages are lost with such alternative location of low-noise amplifier **754**.

[0123] In an embodiment of receiver **750** incorporating an embodiment of unbalanced mixer **500** described above with reference to FIG. **8**B, the antenna is connected to the RF terminal **101** of mixer **500**, the input of the low-noise amplifier is connected to terminal **102** of frequency-selective transformer **100** and the output of the low-noise amplifier is connected to the IF port **506** of mixing circuit **504**.

[0124] FIG. **11**A is a schematic drawing showing an example of the output stage of a transmitter **800** incorporating an embodiment of mixer **600** described above with reference to FIG. **9**A. Transmitter **800** comprises mixer **600**, an antenna **802** and a power amplifier **804**. Transmitter **800** is a relatively low power transmitter in which power amplifier **804** has an output impedance substantially greater than the input impedance of antenna **802**.

[0125] In transmitter **800**, mixer **600** receives an IF signal at the IF port **607** of mixing circuit **604**. Power amplifier **804** is interposed between the RF port **606** of mixing circuit **604** and frequency-selective transformer **200**. Specifically, power amplifier **802** has its inputs connected to RF port **607** and its outputs connected to terminals **202/203** of frequency-selective transformer **200**. Thus, in this embodiment, power amplifier **804** couples RF port **606** to the second port **212** and the third port **213** of capacitative transformer **210** that forms part of frequency-selective transformer **200**. The RF terminals **201/204** of mixer **600** are connected to antenna **802**.

[0126] In another embodiment, the RF port **606** of mixing circuit **604** provides sufficient power to drive antenna **802** at the maximum rated power output of transmitter **800**. In this case, power amplifier **804** is omitted and RF port **606** is connected directly to terminals **202/203** of frequency-selective transformer **200**.

[0127] In mixer **600**, mixing circuit **604** receives the IF signal at a frequency f_{IF} at its IF port **607** and additionally receives the local oscillator signal at a frequency f_{LO} at its local oscillator port **608**. Mixing circuit **604** mixes the signals received at its IF and local oscillator ports to generate a wanted RF signal at a frequency $f_{RF}=|f_{LO}+f_{IF}|$ and an image signal at a frequency $f_{IM}=|f_{LO\text{-}fIF}|$. Power amplifier **804** amplifies the RF signal and the image signal and provides them to frequency-selective transformer **200**. At the frequency of the wanted RF signal, frequency-selective transformer **200** provides a step down in impedance and a step down in voltage between its terminals **202/203** and its terminals **201/204**, which provide the RF terminals **201/204** of mixer **600**. The RF terminals **201/204** of mixer **600** are connected to antenna **802**. The step down in impedance provided by frequency-selective transformer **200** better matches the output impedance of power amplifier **804** to the smaller input impedance (typically 50 Ω to 300 Ω) of antenna **802**.

[0128] Frequency-selective transformer **200** is configured as described above to provide significant attenuation at the frequency of the image signal. As a result, the level of the image signal transmitted by transmitter **800** is acceptably low.

[0129] In an embodiment of transmitter **800** incorporating an embodiment of unbalanced mixer **500** described above with reference to FIG. **8**A, the output of the power amplifier is connected to terminal **102** of frequency-selective transformer **100** and the antenna is connected to the RF terminal **101** of mixer **500**. In an embodiment incorporating mixer **500** in which the RF port **506** of mixing circuit **504** provides sufficient power to drive antenna **802** at the maximum rated power output of the transmitter, the power amplifier is omitted and RF port **506** is connected directly to terminal **102** of frequency-selective transformer **100**.

[0130] FIG. **11**B is a schematic drawing showing an example of the output stage of a transmitter **850** incorporating an embodiment of mixer **650** described above with reference to FIG. **9**B.

[0131] Transmitter **850** comprises mixer **650**, antenna **802** and a power amplifier **854**. Transmitter **800** is a relatively high power transmitter in which power amplifier **854** has an output impedance substantially smaller than the input impedance of antenna **802**.

[0132] In transmitter **850**, mixer **650** receives an IF signal at the IF port **607** of mixing circuit **604**. Power amplifier **854** is interposed between the RF port **606** of mixing circuit **604** and frequency-selective transformer **200**. Specifically, power amplifier **804** has its inputs connected to RF port **607** and its outputs connected to terminals **201/204** of frequency-selective transformer **200**. Thus, in this embodiment, power amplifier **854** couples RF port **606** to the first port **211** and the fourth port **214** of capacitative transformer **210** that forms part of frequency-selective transformer **200**. The RF terminals **202/203** of mixer **650** are connected to antenna **802**.

[0133] In mixer **650**, mixing circuit **604** receives the IF signal at a frequency f_{IF} at its IF port **607** and additionally receives the local oscillator signal at a frequency fLo at its local oscillator port **608**. Mixing circuit **604** mixes the signals received at its IF and local oscillator ports to generate a wanted RF signal at a frequency $f_{RF}=|f_{LO}+f_{IF}|$ and an image signal at a frequency $f_{IM}=|f_{LO}-f_{IF}|$. Power amplifier **854** amplifies the RF signal and the image signal and provides them to frequency-selective transformer **200**. At the frequency of the wanted RF signal, frequency-selective transformer **200** provides a step up in impedance and a step up in voltage between its terminals **201/204** and its terminals **202/203**, which provide the RF terminals **202/203** of mixer **650**. Mixer **650** provides the RF signal to antenna **802** via RF terminals **202/203**. The step up in impedance provided by frequency-selective transformer **200** better matches the output impedance of power amplifier **854** to the greater input impedance of antenna **802** (typically 50 Ω to 300 Ω). Additionally, the step up in voltage provided by frequency-selective transformer **200** increases the voltage swing driving antenna **802** for a given voltage swing at the output of power amplifier **854**.

[0134] Frequency-selective transformer **200** is configured as described above to provide significant attenuation at the frequency of the image signal. As a result, the level of the image signal transmitted by transmitter **850** is acceptably low.

[0135] In an embodiment of transmitter **850** incorporating an embodiment of unbalanced mixer **550** described above with reference to FIG. **8**B, the output of the power amplifier is connected to terminal **101** of frequency-selective transformer **100** and the antenna is connected to the RF terminal **102** of mixer **550**.

[0136] This disclosure describes the invention in detail using illustrative embodiments. However, the invention defined by the appended claims is not limited to the precise embodiments described.

I claim:

1. A frequency-selective transformer, comprising:

a capacitative transformer comprising a first port, a second port, and a third port; and

an electromechanical resonator connected between the second port and the third port of the capacitative transformer, the electromechanical resonator having a series resonance and a parallel resonance, the resonances closely spaced in frequency.

2. The frequency-selective transformer of claim 1, in which the series resonance and the parallel resonance differ in frequency by a predetermined frequency difference.

3. The frequency-selective transformer of claim 1, in which the capacitative transformer comprises:

a first capacitative element connected between the first port and the second port; and

a second capacitative element connected between the first port and the third port.

4. The frequency-selective transformer of claim 3, in which at least one of the capacitative elements comprises a capacitor.

5. The frequency-selective transformer of claim 3, in which at least one of the capacitative elements comprises a bulk acoustic wave (BAW) resonator.

6. The frequency-selective transformer of claim 3, in which the third port is connected to signal ground.

7. The frequency-selective transformer of claim 1, in which the capacitative transformer additionally comprises:

a fourth port;

a first capacitative element connected between the first port and the second port;

a second capacitative element connected between the first port and the fourth port; and

a third capacitative element connected between the fourth port and the third port.

8. The frequency-selective transformer of claim 7, in which at least one of the capacitative elements comprises a capacitor.

9. The frequency-selective transformer of claim 7, in which at least one of the capacitative elements comprises a bulk acoustic wave (BAW) resonator.

10. The frequency-selective transformer of claim 1, additionally comprising a capacitor connected in parallel with the electromagnetic resonator.

11. The frequency-selective transformer of claim 9, in which the capacitor is a variable capacitor.

12. The frequency-selective transformer of claim 1, in which the resonator comprises a bulk acoustic wave (BAW) resonator.

13. The frequency-selective transformer of claim 12, in which the bulk acoustic wave resonator comprises a film bulk acoustic resonator (FBAR).

14. The frequency-selective transformer of claim 1, in which:

the electromagnetic resonator is a first electromagnetic resonator; and

the frequency-selective transformer additionally comprises:

a second electromagnetic resonator having a parallel resonance differing in frequency from the parallel resonance of the first electromagnetic resonator, and

a switching element operable to select one of the first electromagnetic resonator and the second electromagnetic resonator.

15. An unbalanced mixer, comprising:

a local oscillator;

a mixing circuit comprising a radio-frequency (RF) port, an intermediate frequency (IF) port and a local oscillator (LO) port, the LO port connected to the local oscillator; and

a frequency-selective transformer, comprising:

a capacitative transformer comprising a first port, a second port and a third port, the capacitative transformer coupled to the RF port of the mixing circuit via one of the first port and the second port, and

an electromechanical resonator connected between the second port and the third port of the capacitative transformer, the electromechanical resonator having a series resonance and a parallel resonance, the resonances closely spaced in frequency.

16. The mixer of claim 15, in which the capacitative transformer comprises:

a first capacitative element connected between the first port and the second port; and

a second capacitative element connected between the first port and the third port.

17. The mixer of claim 16, in which at least one of the capacitative elements comprises a bulk acoustic wave (BAW) resonator.

18. The mixer of claim 15, in which:

the series resonance and the parallel resonance have respective resonant frequencies that differ by a predetermined frequency difference;

the local oscillator has a frequency mid-way between the resonant frequencies; and at the IF port of the mixing circuit, an IF signal exists at a frequency equal to one-half of the predetermined frequency difference.

19. A receiver, comprising the unbalanced mixer of claim 15.

20. The receiver of claim 19, in which the capacitative transformer comprises:

a first capacitative element connected between the first port and the second port; and a second capacitative element connected between the first port and the third port.

21. The receiver of claim 18, in which:

the receiver additionally comprises an antenna input coupled to the first port; and the RF port of the mixing circuit is coupled to the second port.

22. The receiver of claim 21, in which:

the series resonance and the parallel resonance of the resonator have respective resonant frequencies that differ by a predetermined frequency difference;

the local oscillator has a frequency mid-way between the resonant frequencies; and

at the IF port of the mixing circuit, an IF signal exists at a frequency equal to one-half of the predetermined frequency difference.

23. A transmitter, comprising the unbalanced mixer of claim 15.

24. The transmitter of claim 23, in which the capacitative transformer comprises:

a first capacitative element connected between the first port and the second port; and

a second capacitative element connected between the first port and the third port.

25. The transmitter of claim 23, in which the IF port is connected to receive an intermediate-frequency signal.

26. The transmitter of claim 25, in which:

the series resonance and the parallel resonance have respective resonant frequencies that differ by a predetermined frequency difference;

the local oscillator generates a local oscillator signal at a frequency mid-way between the resonant frequencies; and

at the RF port of the mixing circuit, an RF signal exists differing in frequency from the local oscillator signal by one-half of the predetermined frequency difference.

27. A balanced mixer, comprising:

a local oscillator;

a mixing circuit comprising a radio-frequency (RF) port, an intermediate frequency (IF) port and a local oscillator (LO) port, the LO port connected to the local oscillator; and

a frequency-selective transformer, comprising:

a capacitative transformer comprising a first port, a second port, a third port and a fourth port, the capacitative transformer coupled to the RF port of the mixing circuit via one of (a) the first port and the fourth port, and (b) the second port and the third port;

an electromechanical resonator connected between the second port and the third port of the capacitative transformer, the resonator having a series resonance and a parallel resonance, the resonances closely spaced in frequency.

28. The mixer of claim 27, in which the capacitative transformer additionally comprises:

a first capacitative element connected between the first port and the second port;

a second capacitative element connected between the first port and the fourth port; and

a third capacitative element connected between the fourth port and the third port.

29. The mixer of claim 28, in which at least one of the capacitative elements comprises a bulk acoustic wave (BAW) resonator.

30. The mixer of claim 27, in which:

the series resonance and the parallel resonance have respective resonant frequencies that differ by a predetermined frequency difference;

the local oscillator has a frequency mid-way between the resonant frequencies; and

at the IF port of the mixing circuit, an IF signal exists at a frequency equal to one-half of the predetermined frequency difference.

31. A receiver, comprising the balanced mixer of claim 27.

32. The receiver of claim 31, in which the capacitative transformer additionally comprises:

a first capacitative element connected between the first port and the second port;

a second capacitative element connected between the first port and the fourth port; and

third capacitative element connected between the fourth port and the third port.

33. The receiver of claim 31, in which:

the receiver additionally comprises an antenna input coupled to the first port and the fourth port; and

the RF port of the mixing circuit is coupled to the second port and the third port.

34. The receiver of claim 33, in which:

the series resonance and the parallel resonance of the resonator have respective resonant frequencies that differ by a predetermined frequency difference;

the local oscillator has a frequency mid-way between the resonant frequencies; and

at the IF port of the mixing circuit, an IF signal exists at an intermediate frequency equal to one-half of the predetermined frequency difference.

35. A transmitter, comprising the balanced mixer of claim 27.

36. The transmitter of claim 35, in which the capacitative transformer additionally comprises:

a first capacitative element connected between the first port and the second port;

a second capacitative element connected between the first port and the fourth port; and

a third capacitative element connected between the fourth port and the third port.

37. The transmitter of claim 35, in which the IF port of the mixing circuit is connected to receive an intermediate-frequency signal.

38. The transmitter of claim 37, in which:

the series resonance and the parallel resonance have respective resonant frequencies that differ by a predetermined frequency difference;

the local oscillator generates a local oscillator signal at a frequency mid-way between the resonant frequencies; and

at the RF port of the mixing circuit, an RF signal exists differing in frequency from the local oscillator signal by one-half of the predetermined frequency difference.

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