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Ehara et al.

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(54) **SURFACE-ACOUSTIC-WAVE FILTERS WITH POLES OF ATTENUATION CREATED BY IMPEDANCE CIRCUITS**

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(22) Filed: **Jan. 18, 2000**

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Reissue of:

(64) Patent No.: **5,905,418**  
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(30) **Foreign Application Priority Data**

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Apr. 23, 1997 (JP) ..... 9-105859

**ABSTRACT**

(57)

A surface-acoustic-wave filter couples a two-port surface-acoustic-wave resonator filter circuit coupled in parallel or in series with a two-port impedance circuit. The two-port impedance circuit has an impedance that creates a pole of attenuation, by making the open-circuit impedance of the surface-acoustic-wave filter equal to the short-circuit impedance. High attenuation over a wide range of stopband frequencies is obtained in this way, combined with steep roll-off between the passband and stopband.

(51) **Int. Cl.**<sup>7</sup> ..... **H03H 9/64; H03H 9/72**

(52) **U.S. Cl.** ..... **333/193; 333/133; 333/195**

(58) **Field of Search** ..... **333/193-196, 333/133; 310/313 R, 313 B, 313 C, 313 D**

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**113 Claims, 24 Drawing Sheets**

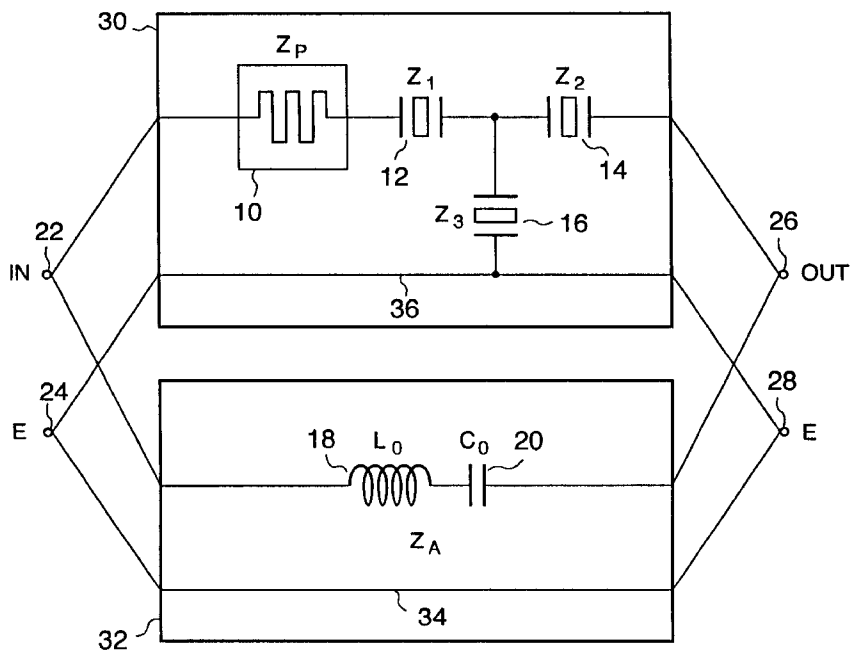


FIG. 1

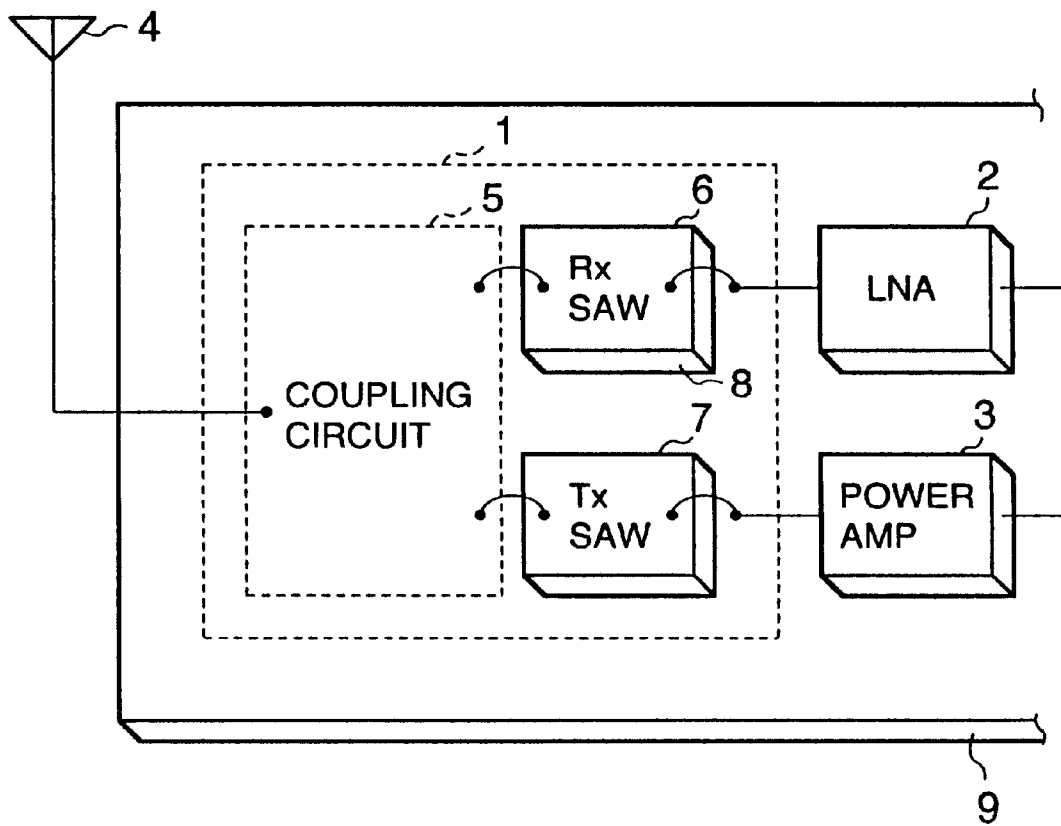


FIG.2

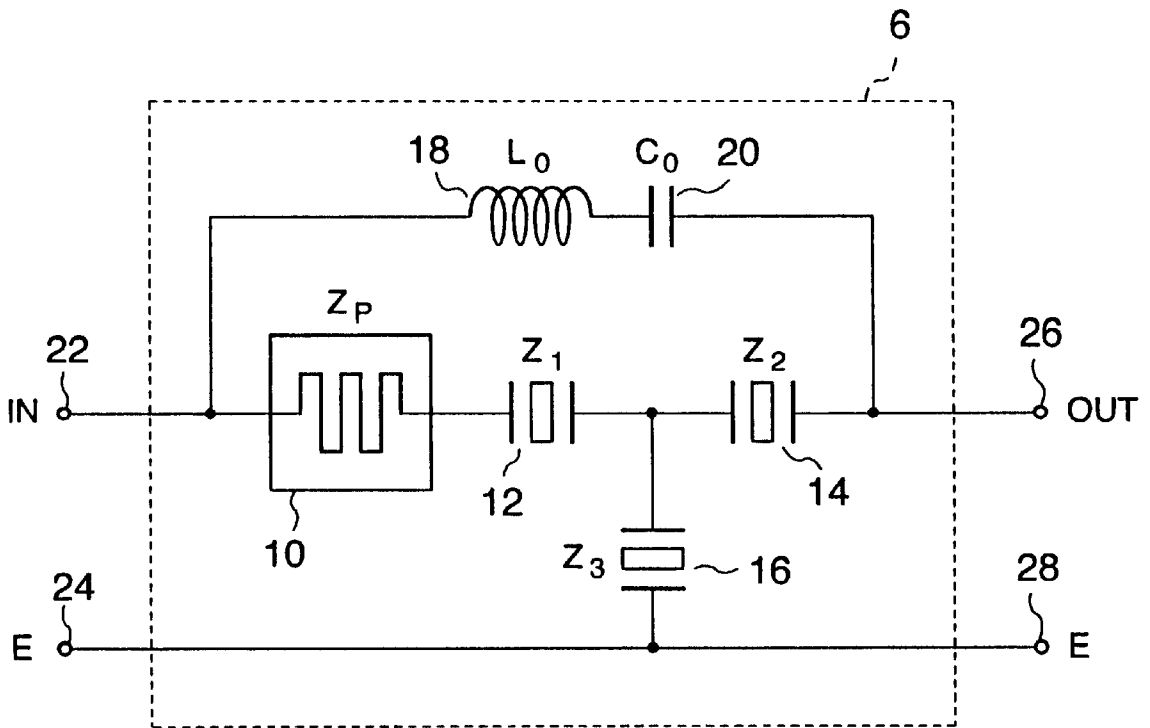


FIG.3

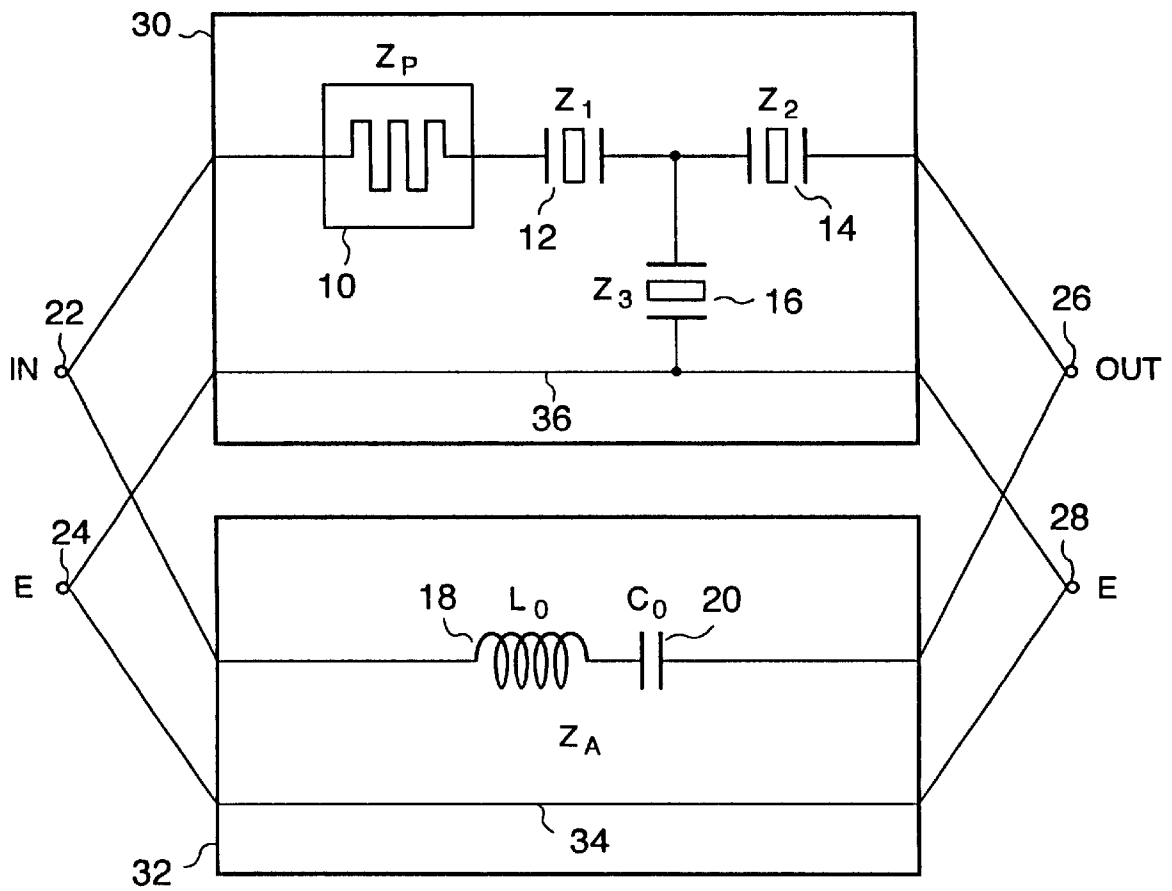


FIG. 4

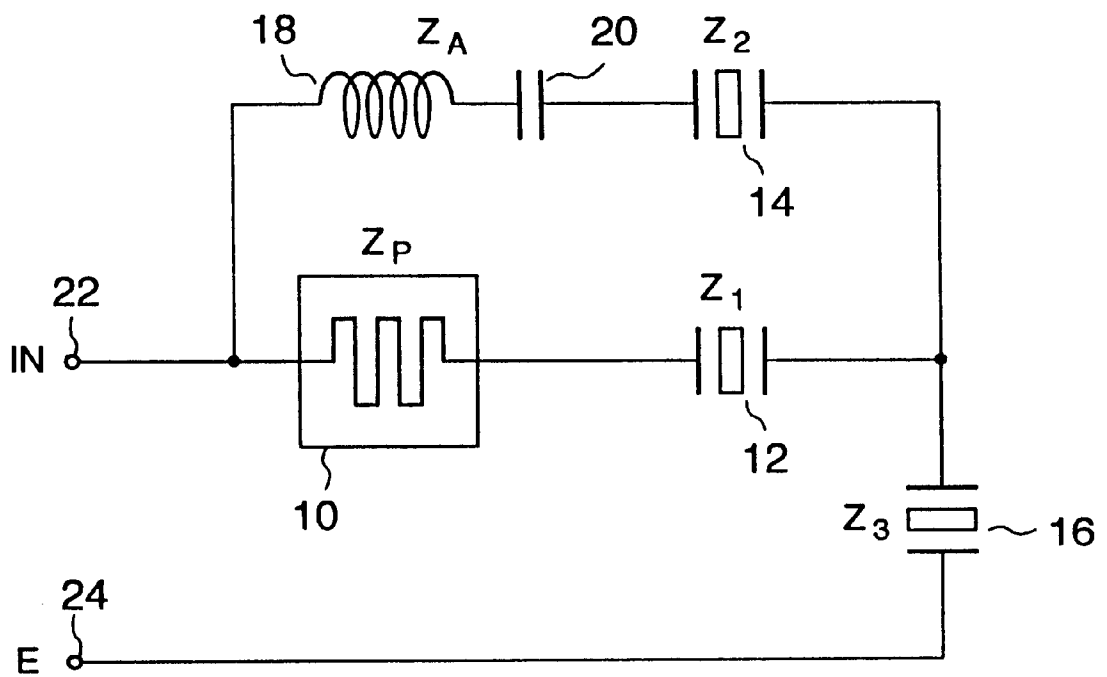


FIG.5

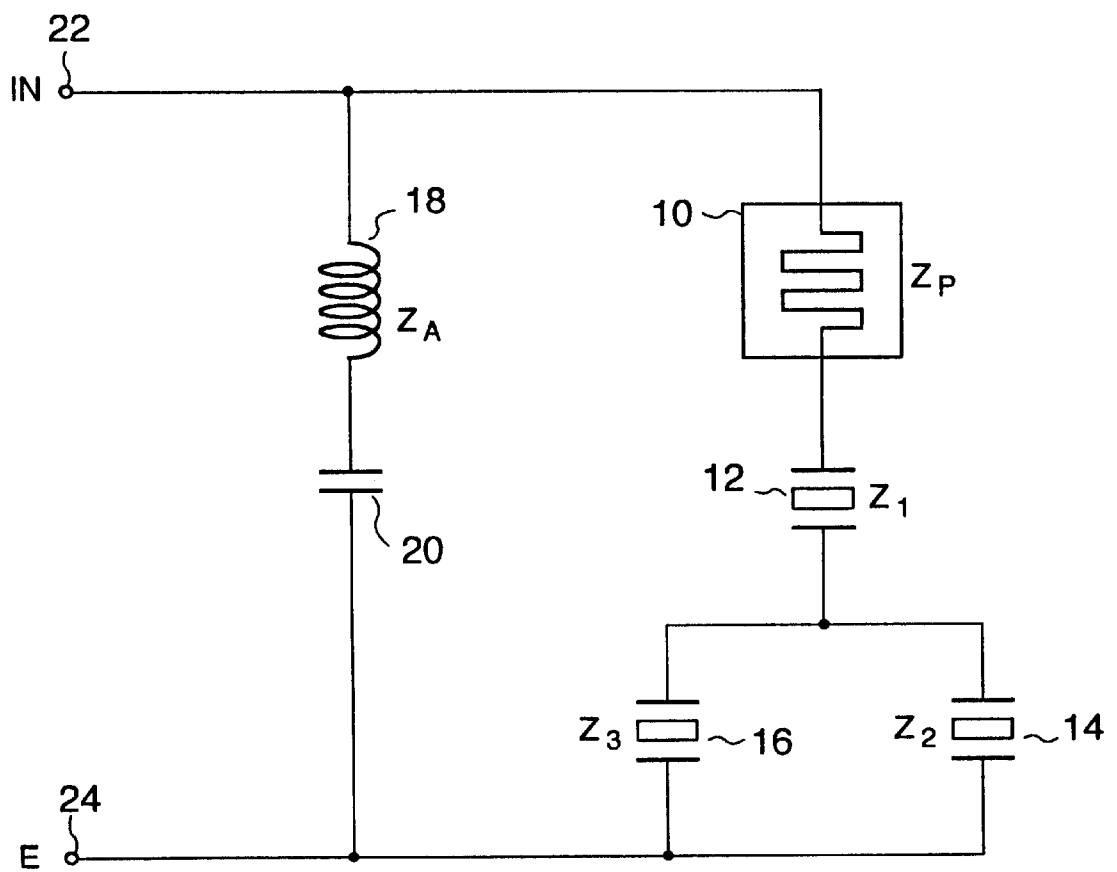


FIG. 6

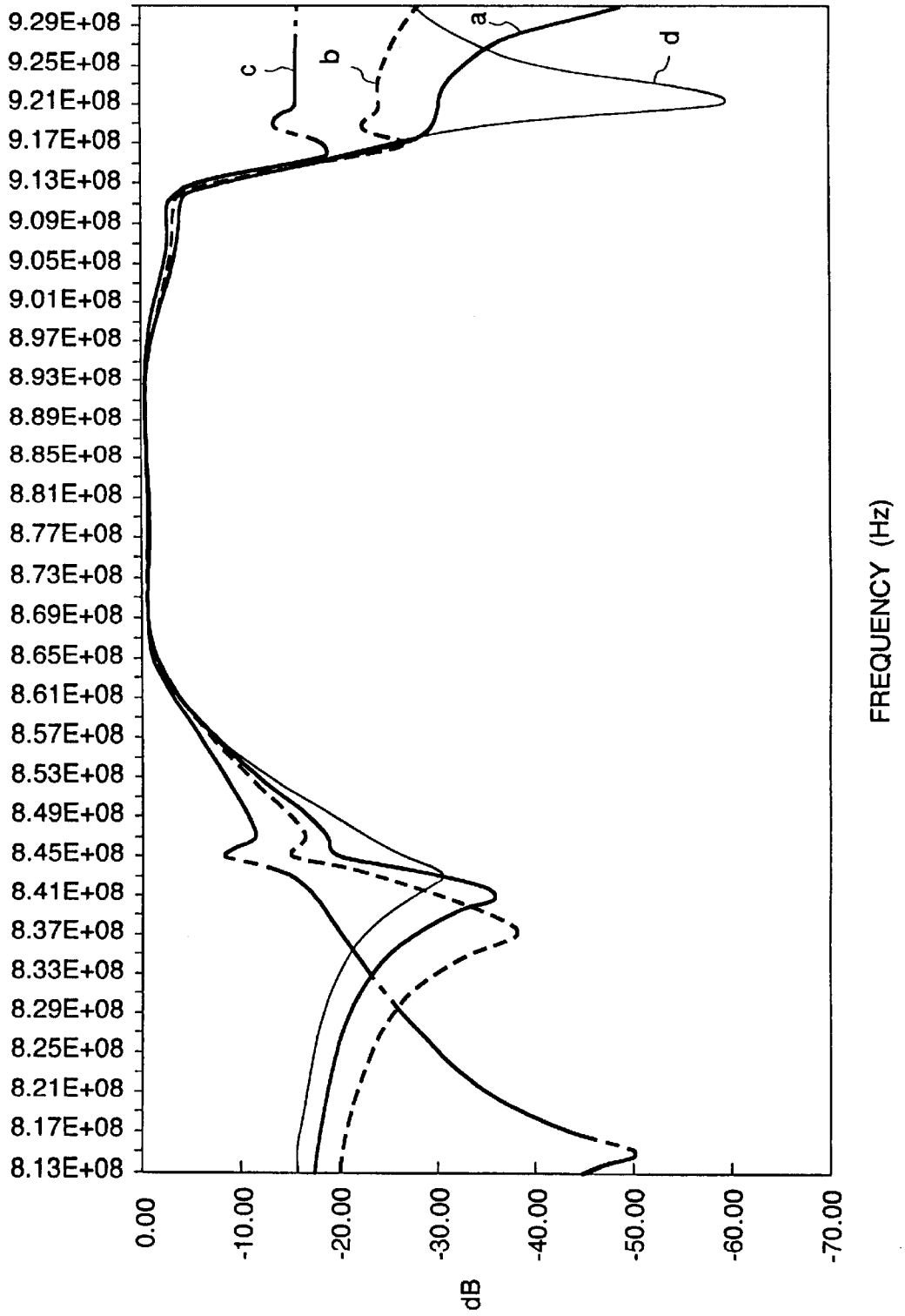


FIG. 7

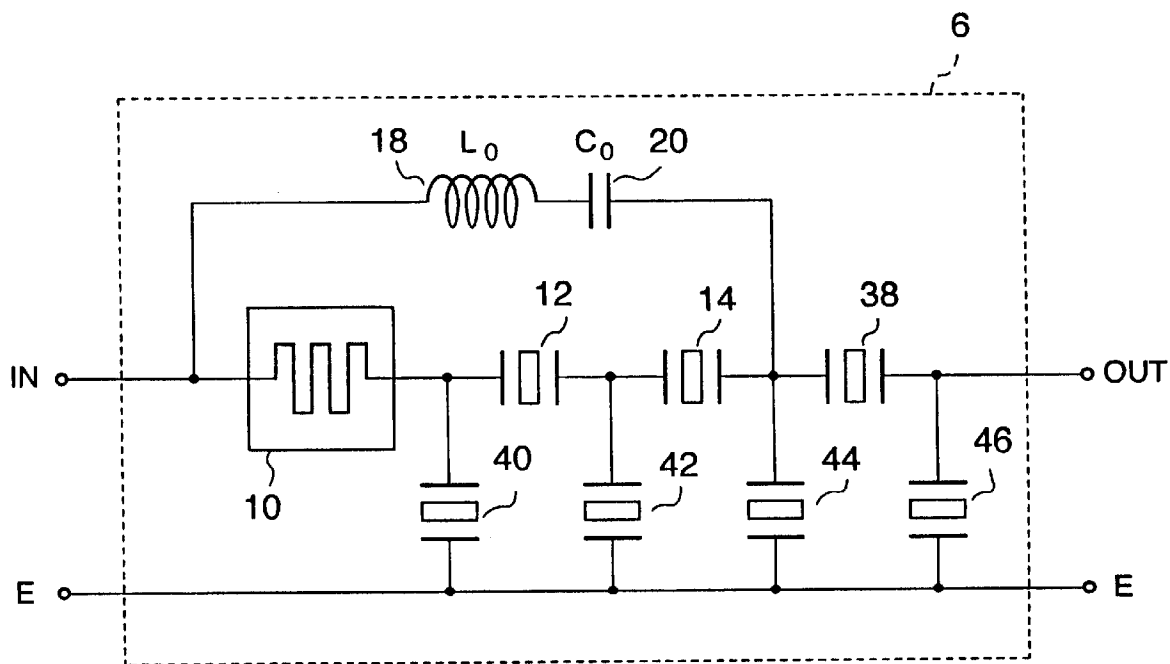


FIG. 8  
PRIOR ART

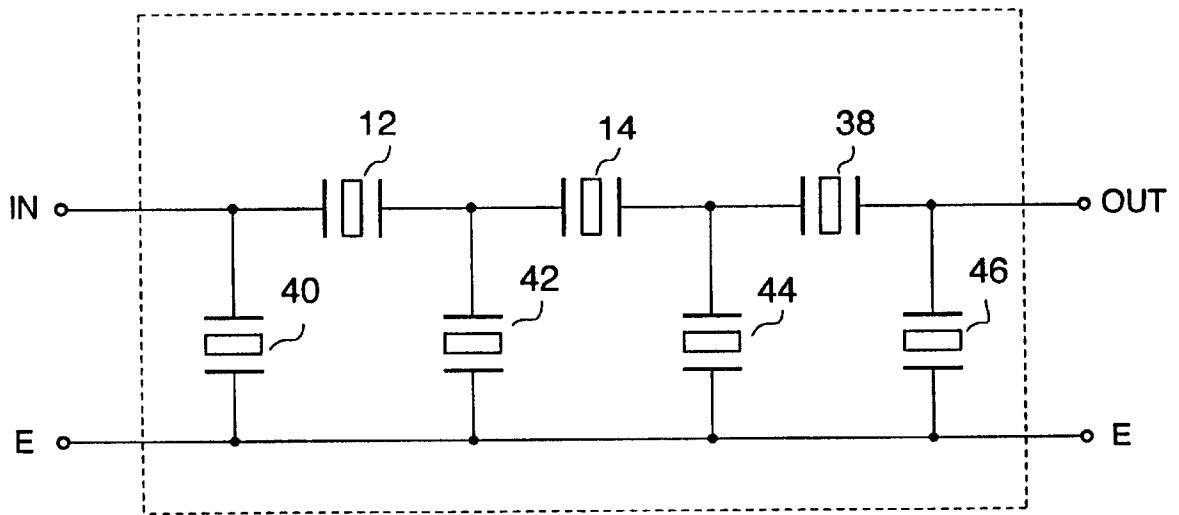
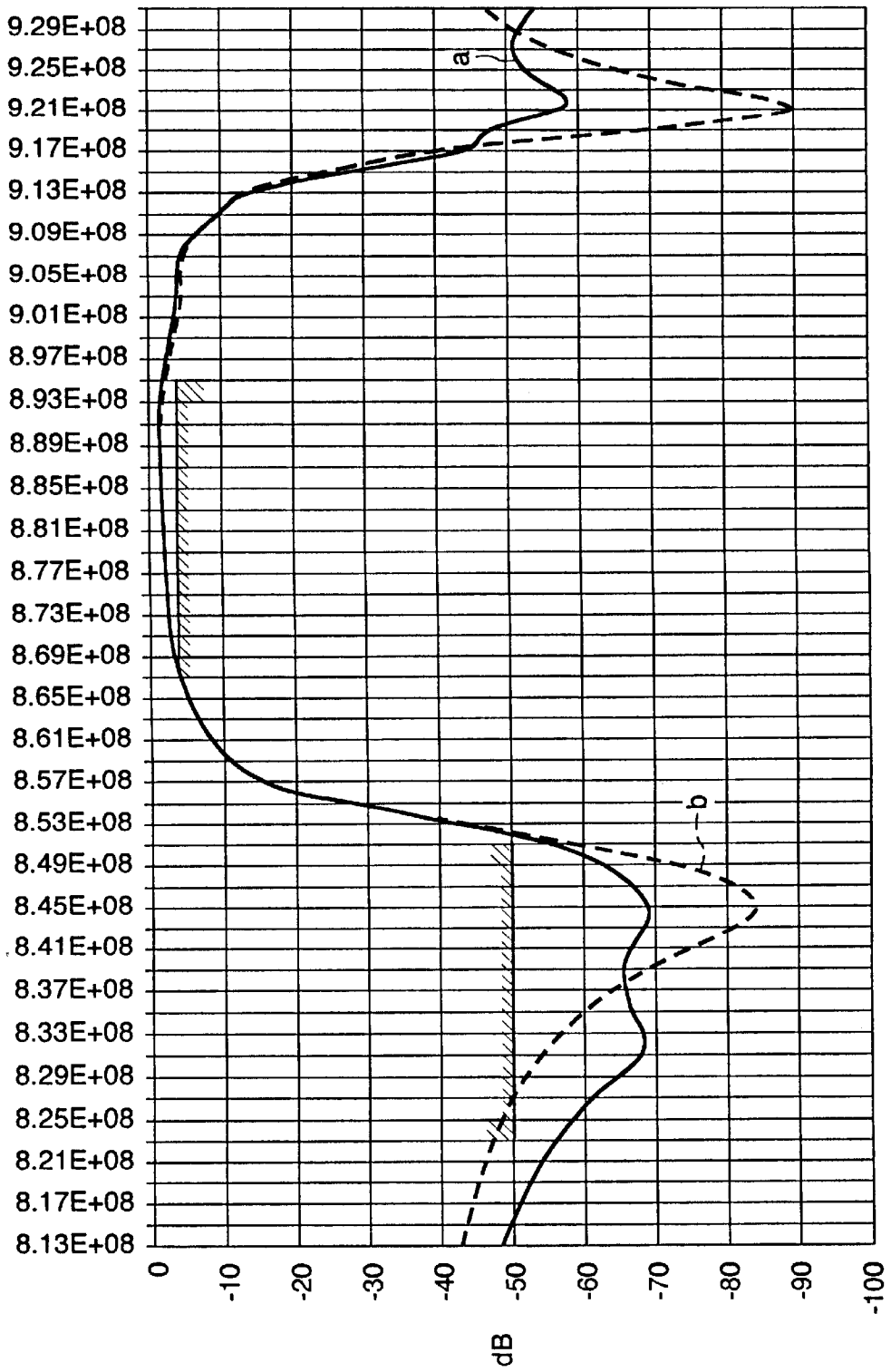


FIG. 9



FREQUENCY (Hz)

dB

FIG. 10

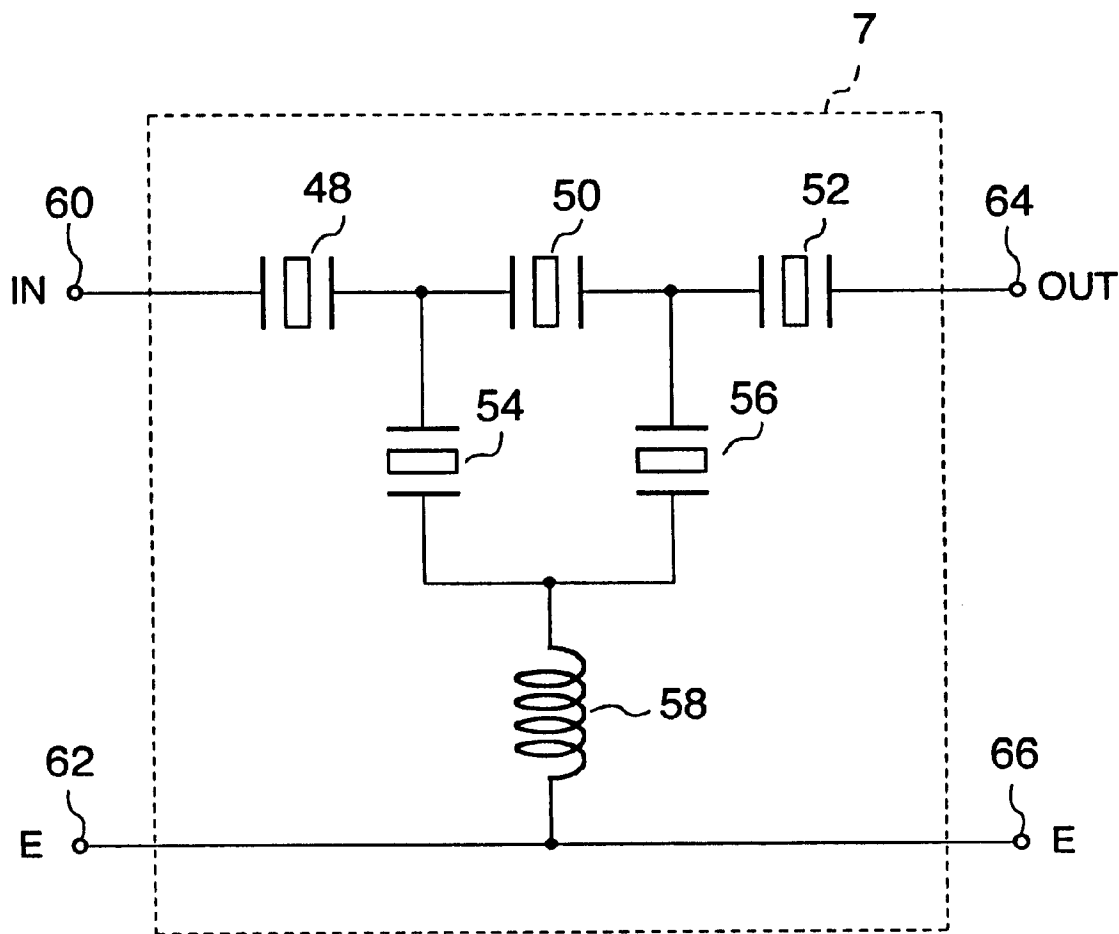


FIG. 11

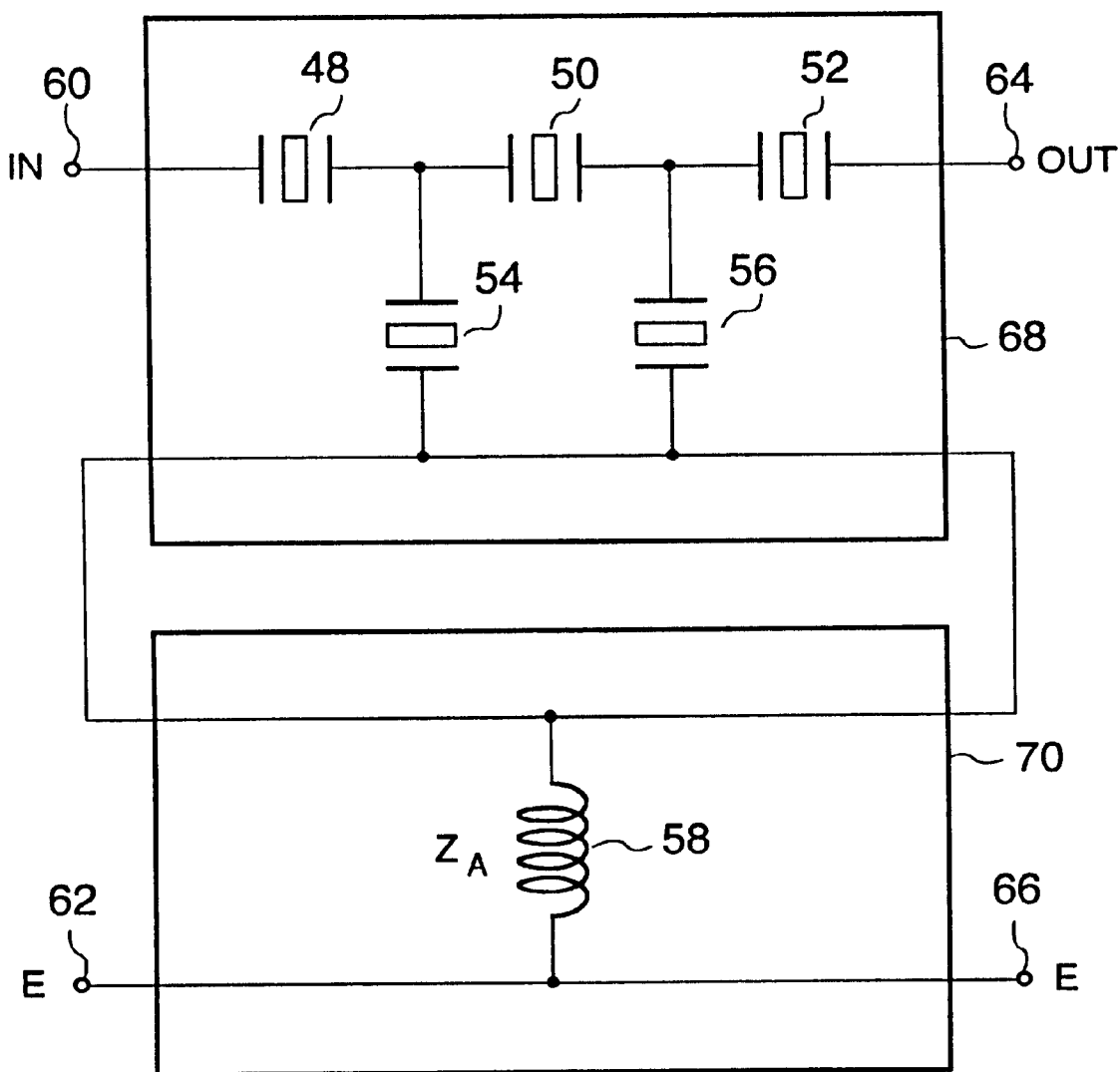


FIG.12

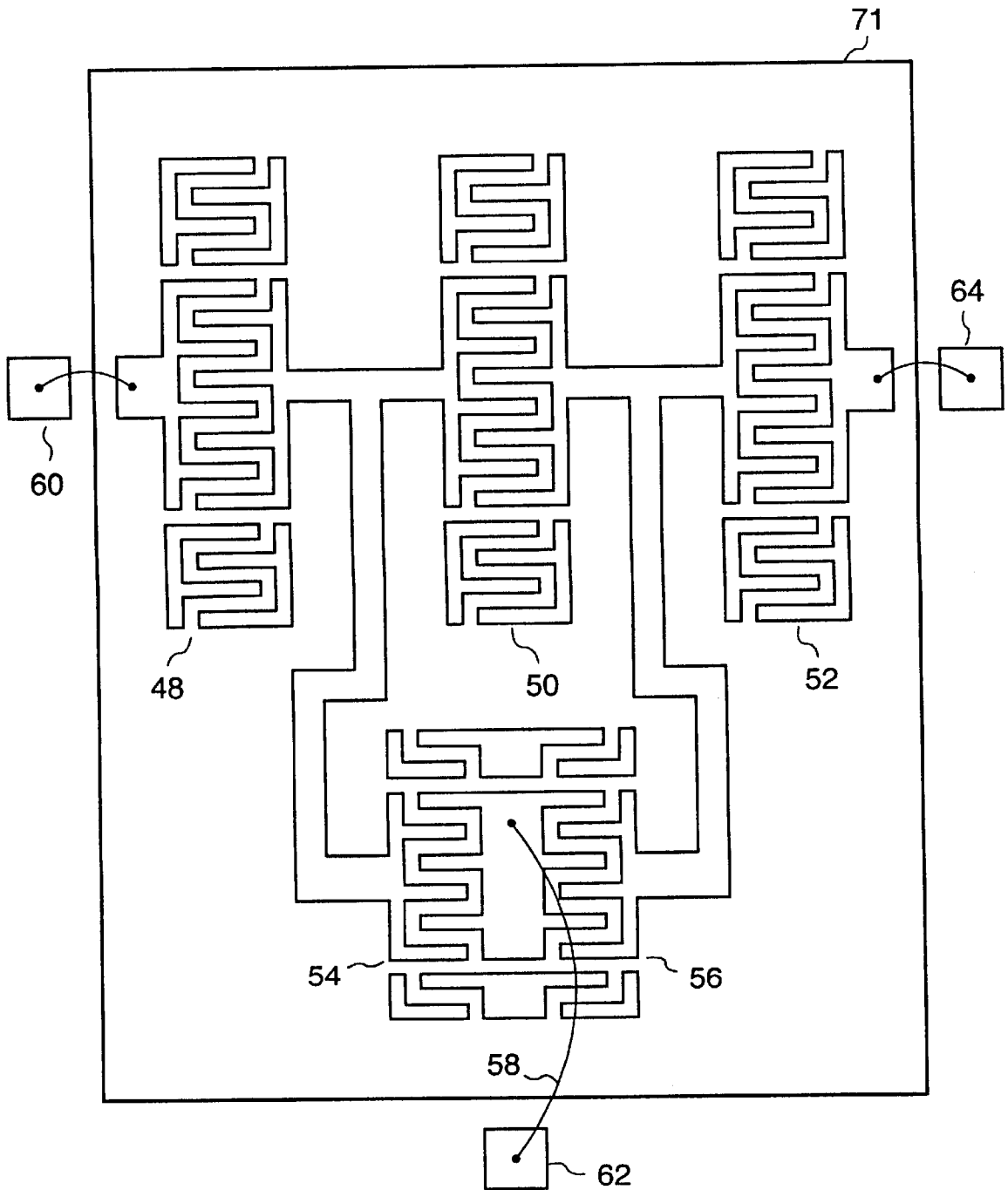


FIG. 13

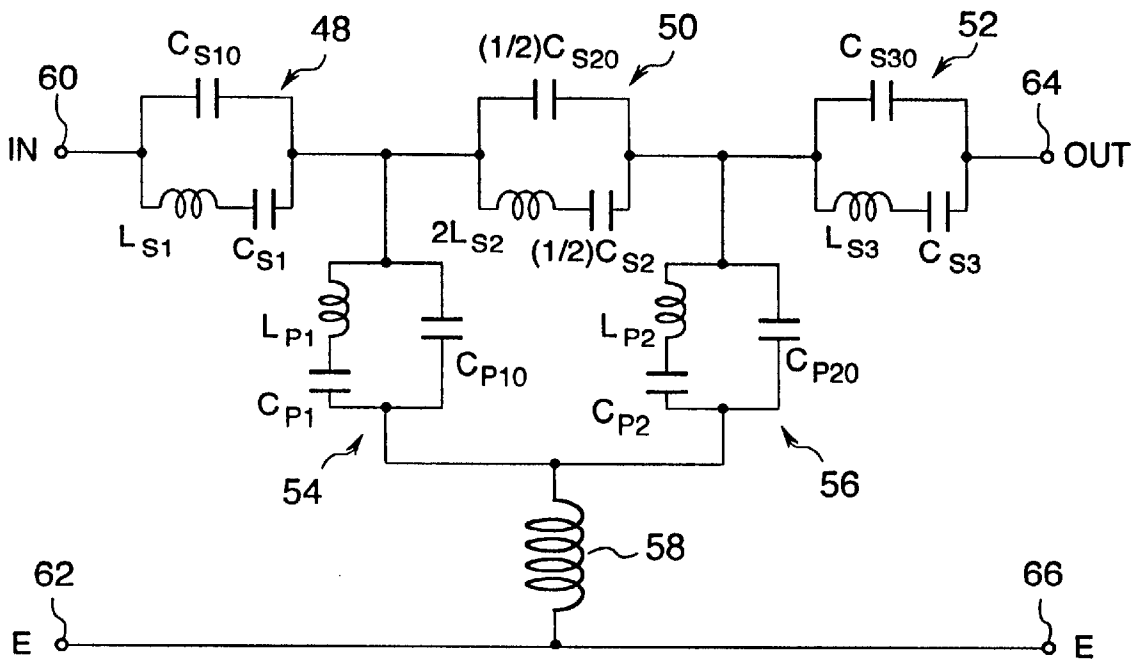


FIG. 14

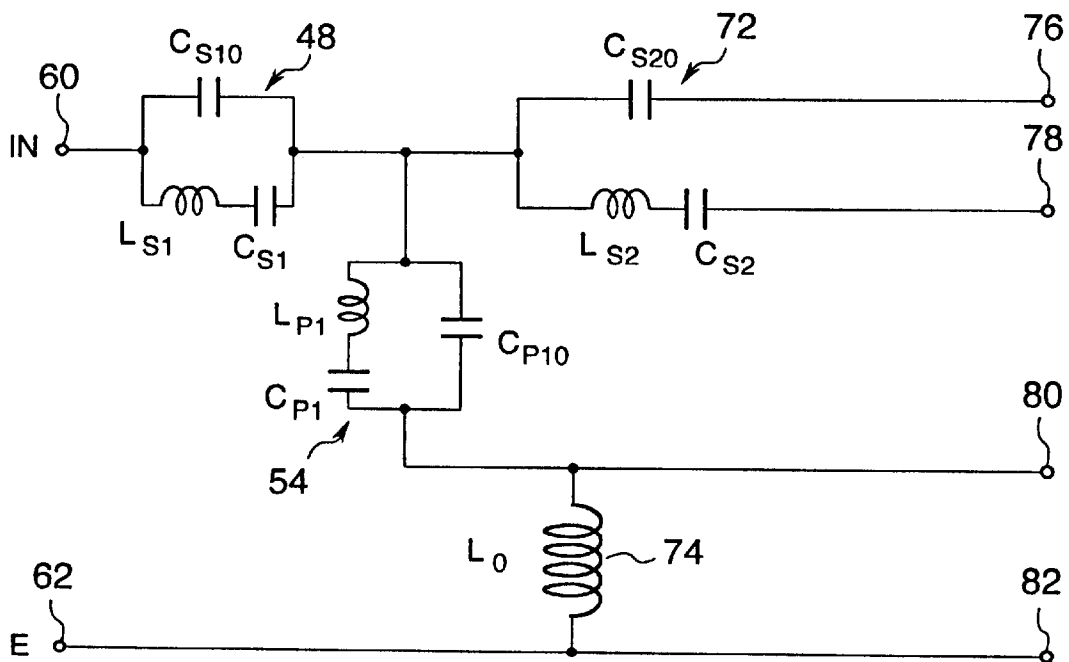


FIG. 15 (PRIOR ART)

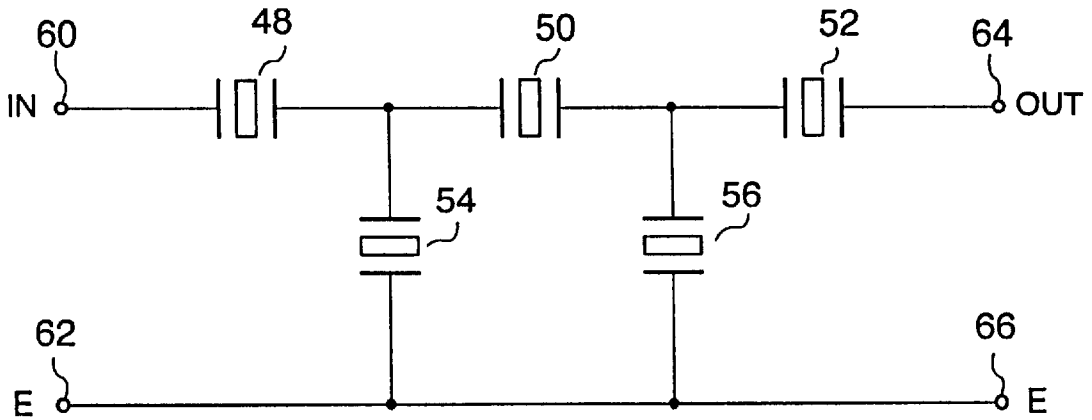


FIG. 16 (PRIOR ART)

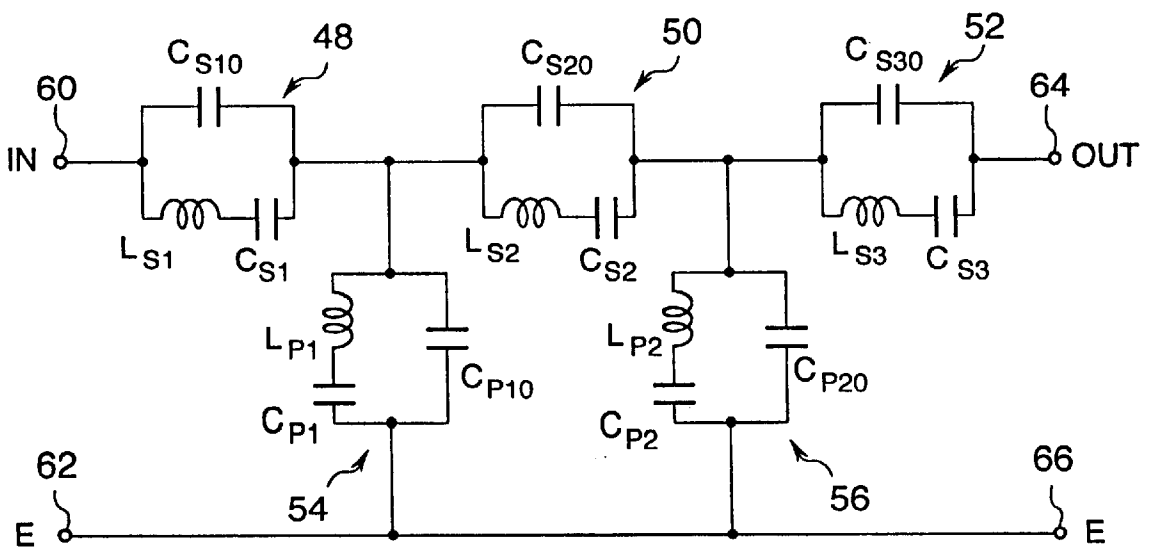


FIG.17 (PRIOR ART)

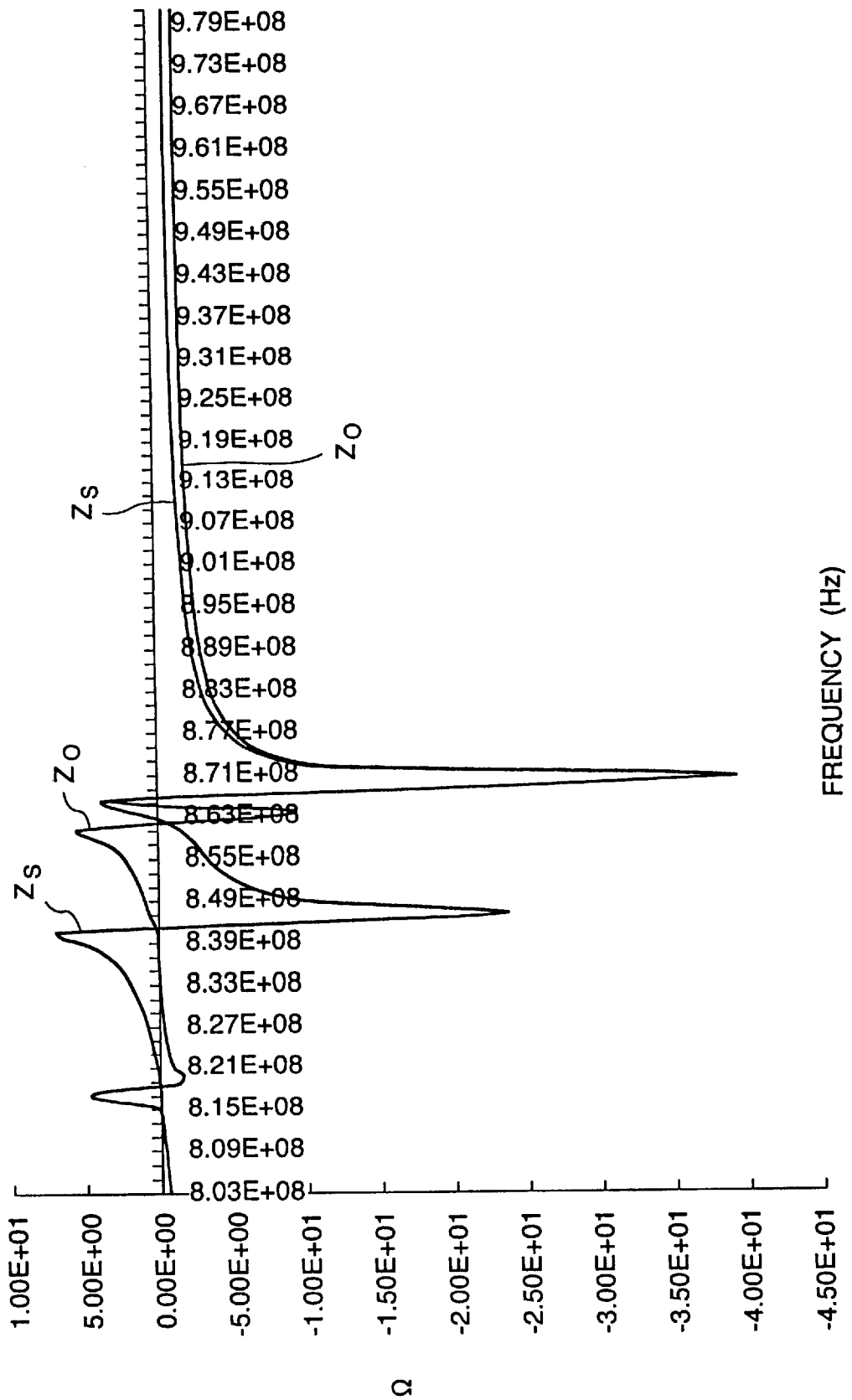


FIG. 18

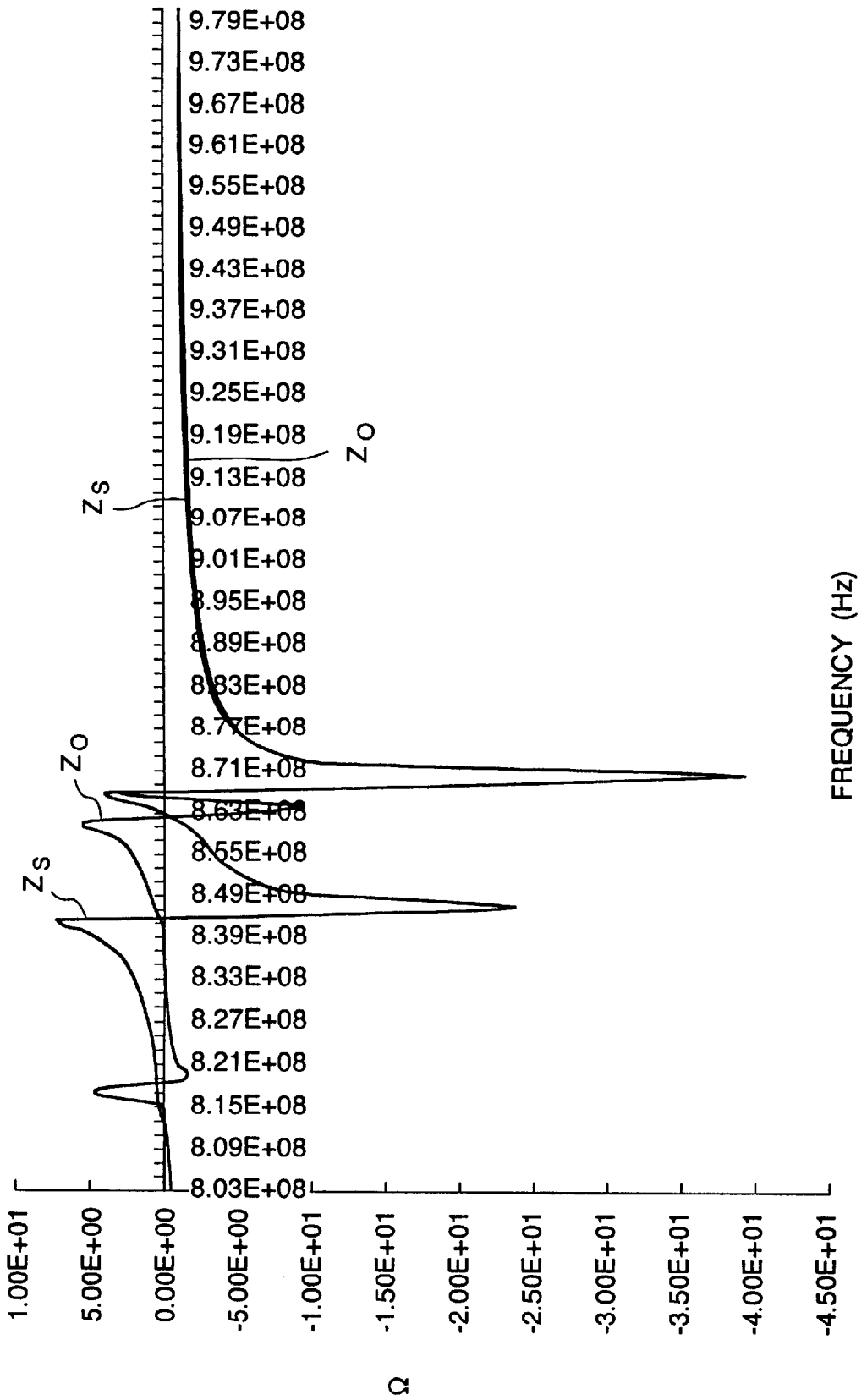


FIG. 19

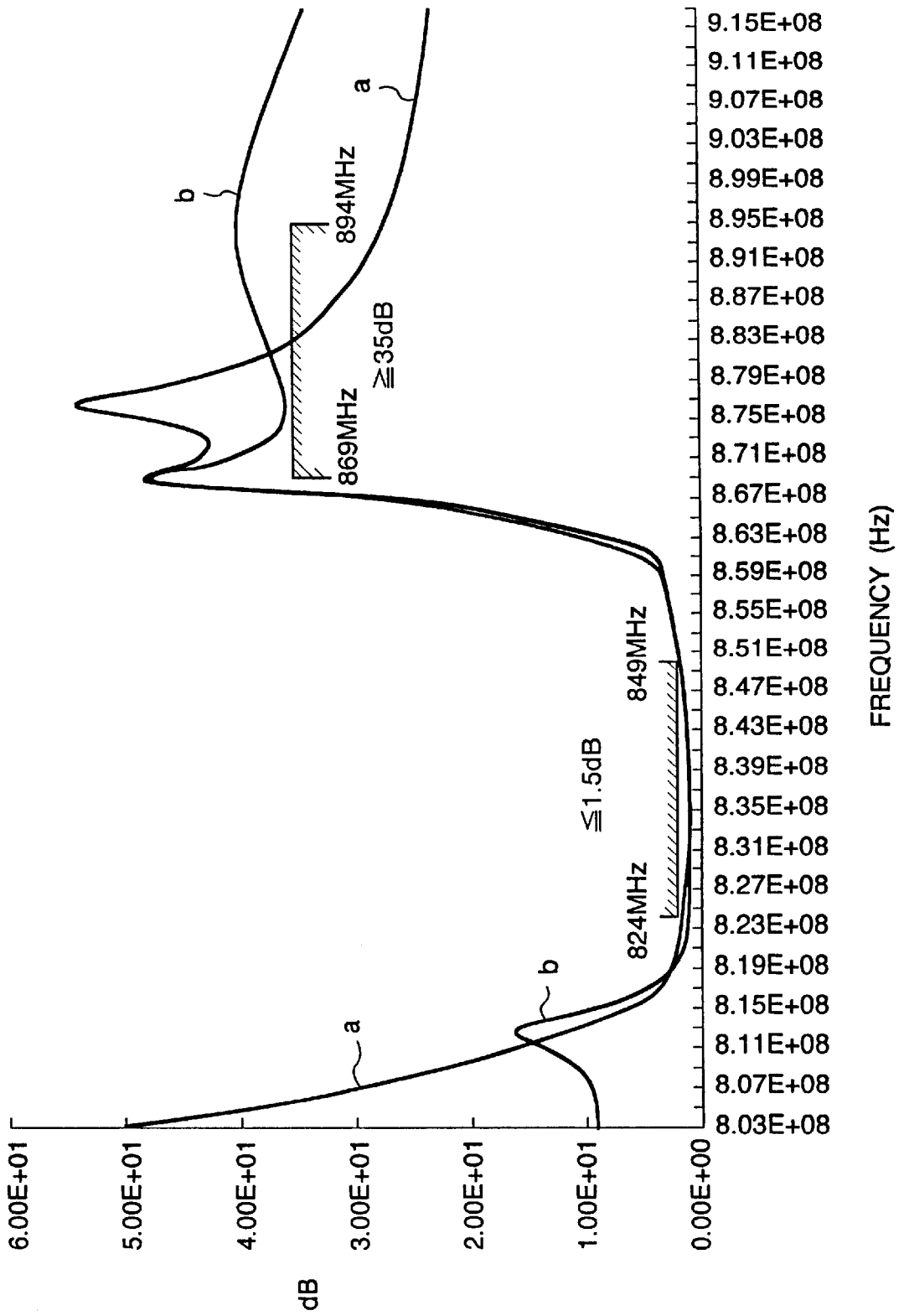


FIG.20

L <sub>0</sub> (nH)	FREQUENCY CHARACTERISTICS					IMPEDANCE CHARACTERISTICS					
						889 MHz		895 MHz		901 MHz	
	823 MHz	849 MHz	869 MHz	895 MHz		Z <sub>S</sub>	Z <sub>O</sub>	Z <sub>S</sub>	Z <sub>O</sub>	Z <sub>S</sub>	Z <sub>O</sub>
0	1.65 dB	1.15 dB	46.9 dB	25.7 dB		-j2.61	-j3.35	-j2.28	-j3.00	-j2.12	-j2.84
4.0	1.13 dB	1.19 dB	46.0 dB	38.8 dB		-j2.61	-j2.91	-j2.28	-j2.55	-j2.12	-j2.39

FIG.21

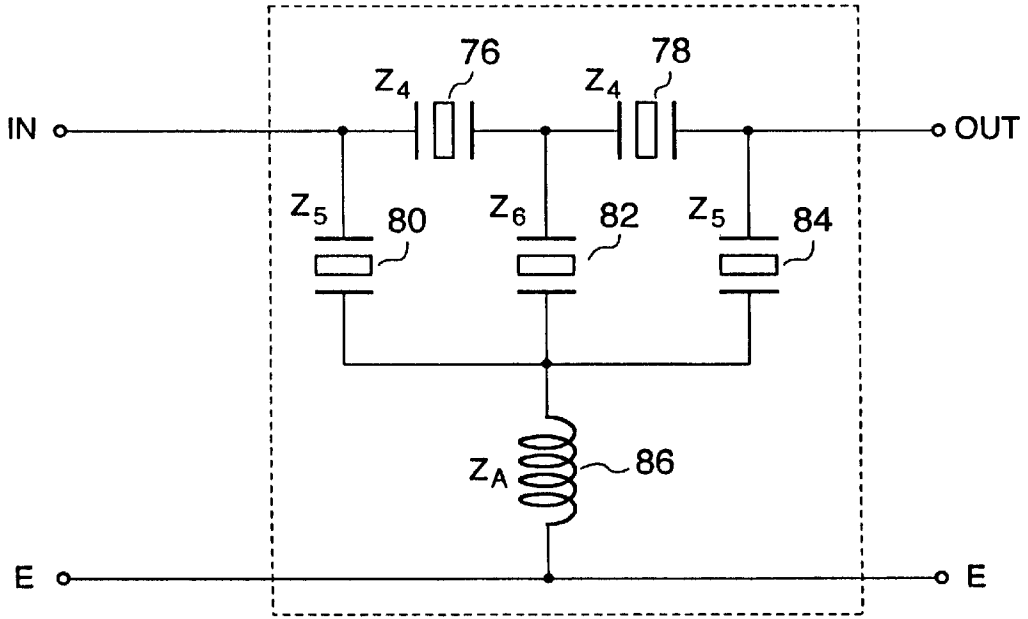


FIG.22

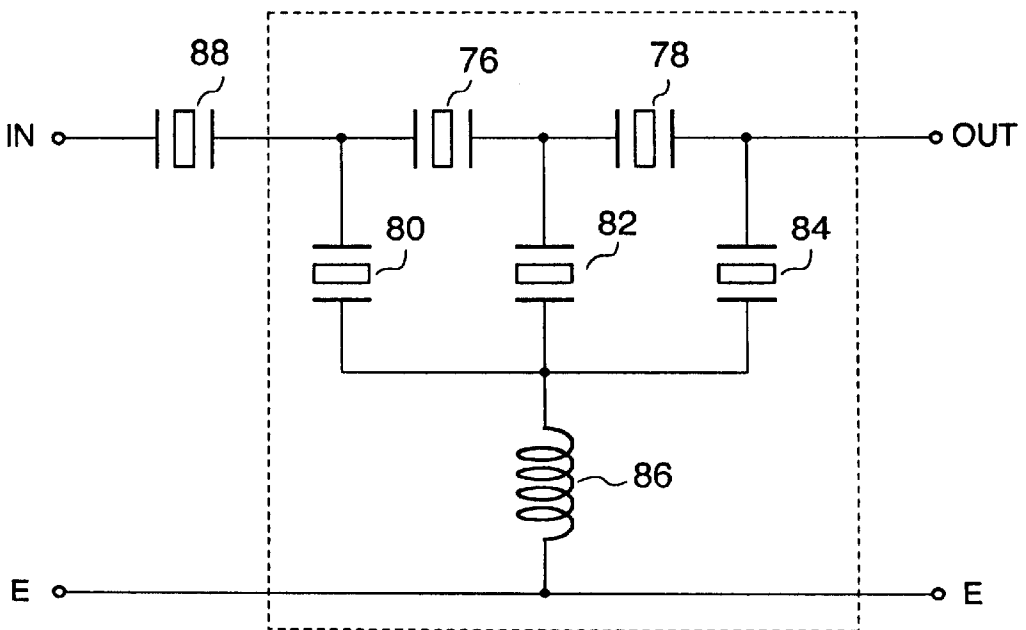


FIG.23

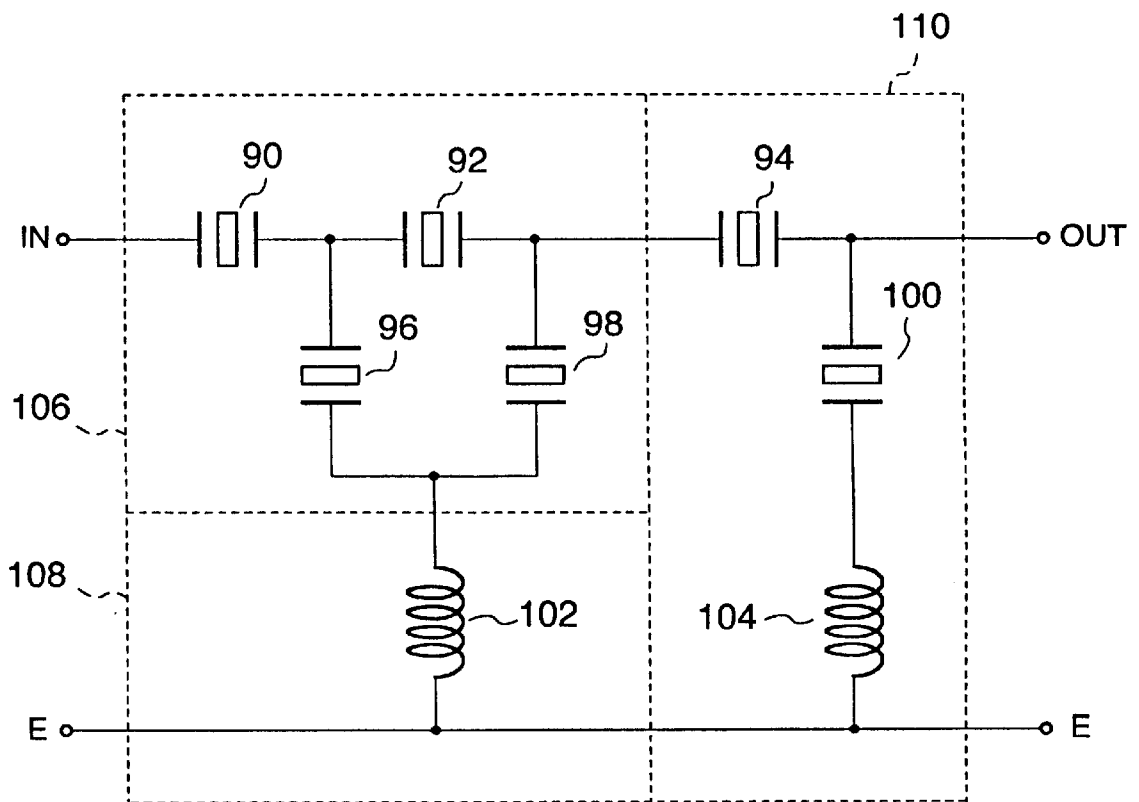


FIG. 24

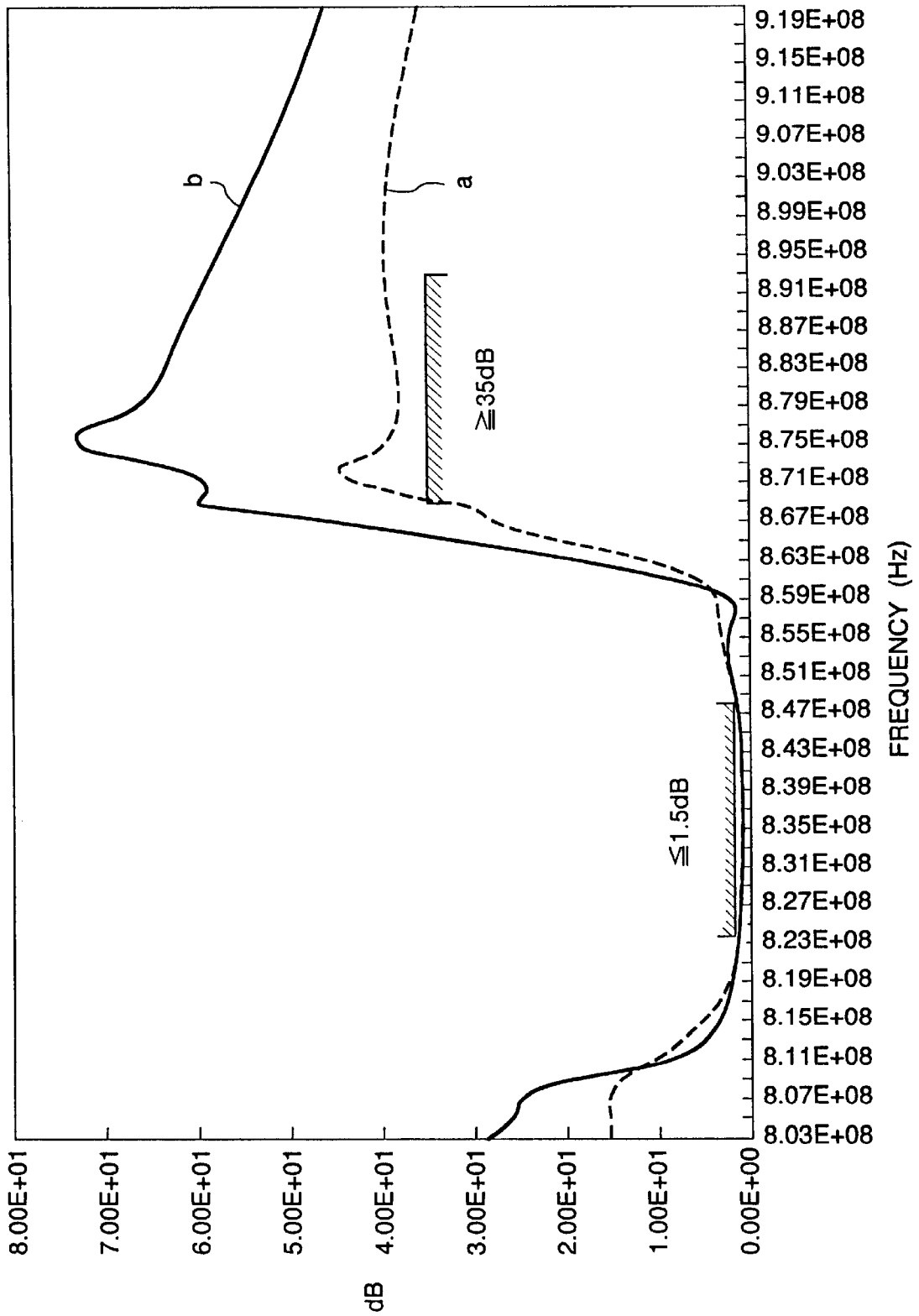


FIG.25

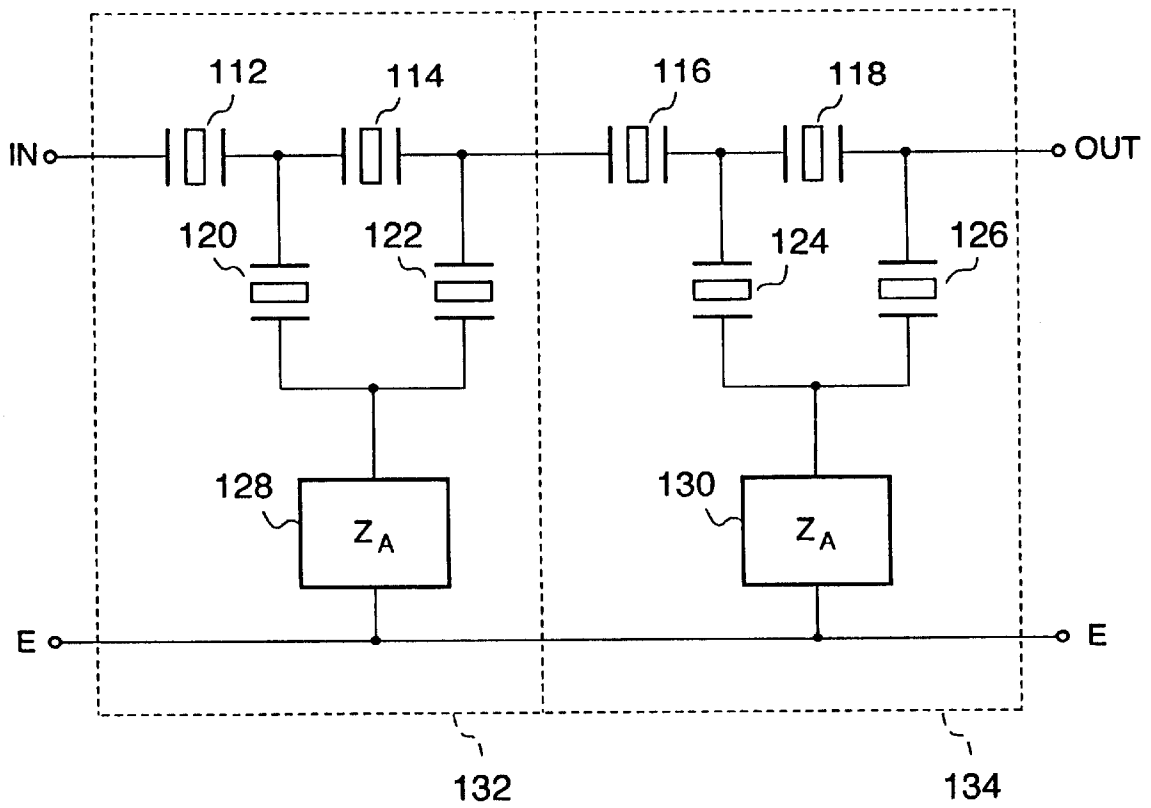


FIG.26

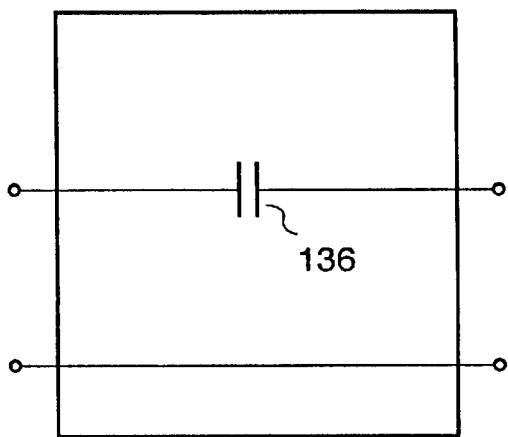


FIG.27

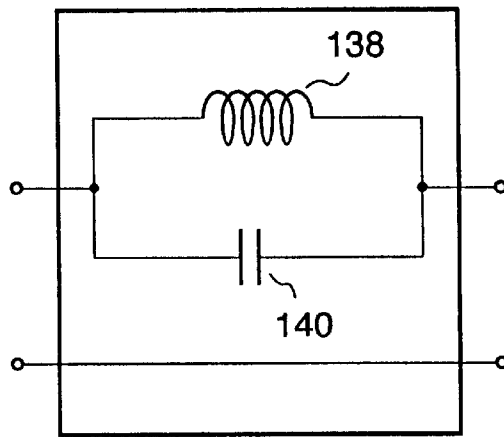


FIG.28

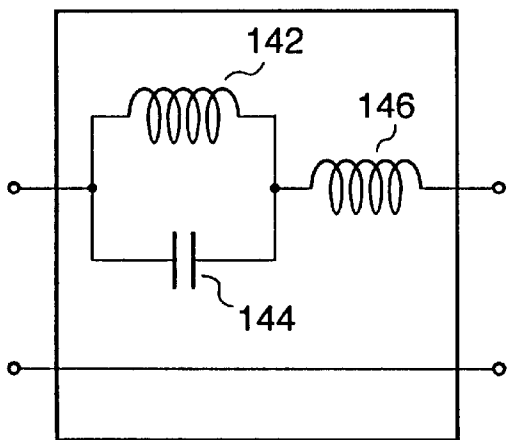


FIG.29

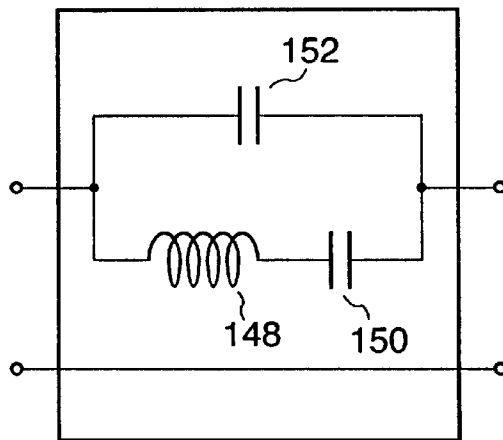


FIG.30

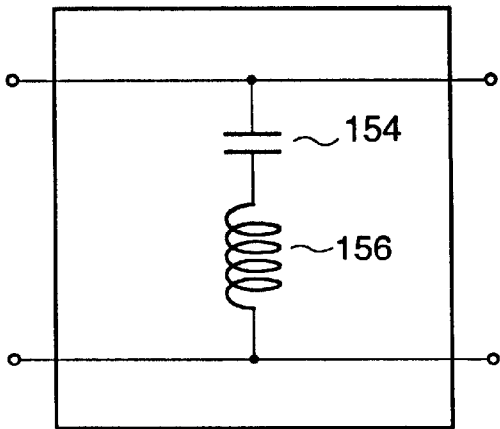


FIG.31

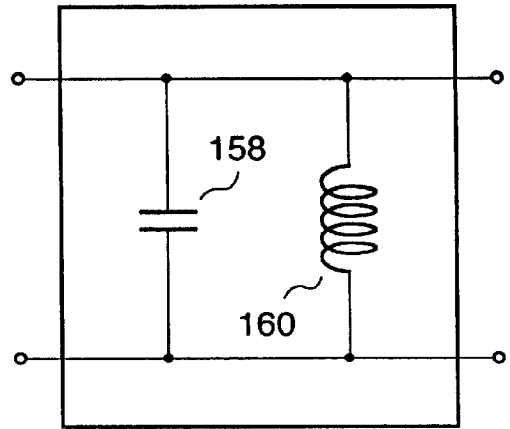


FIG.32

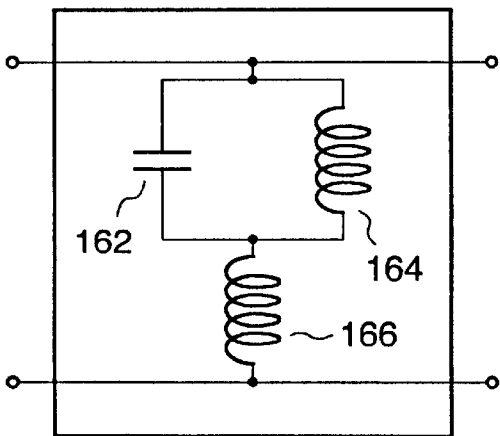
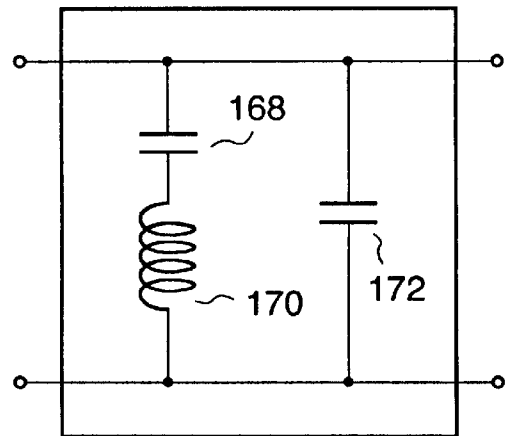


FIG.33



## SURFACE-ACOUSTIC-WAVE FILTERS WITH POLES OF ATTENUATION CREATED BY IMPEDANCE CIRCUITS

**Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.**

### BACKGROUND OF THE INVENTION

The present invention relates generally to surface-acoustic-wave filters having poles, and more particularly to surface-acoustic-wave filters of the resonator type used, for example, in mobile communications equipment.

Like integrated circuits, surface-acoustic-wave filters, referred to below as SAW filters, and lightweight, and can easily be mass-produced. For these reasons, SAW filters are widely used as radio-frequency (RF) filters in devices such as portable telephone sets and pagers.

A portable telephone set of the code division multiple access (CDMA) type, for example, transmits in one frequency band and receives in an adjacent frequency band. The set accordingly requires an antenna duplexer with a pair of filters, one filter passing frequencies in the transmitting band and rejecting frequencies in the receiving band, while the other filter performs the opposite function. Each filter which must provide low passband insertion loss, steep roll-off between the passband and the adjacent stopband, and high attenuation across the full width of the stopband. These requirements are conventionally met by the use of a ladder filter, comprising one or more series-arm SAW resonators and one or more shunt-arm SAW resonators, with stopband attenuation produced by poles in the filter's transfer function.

As increasing performance demands are placed on mobile communications equipment, however, it is becoming difficult to meet the above requirements satisfactorily with a SAW ladder filter. One reason is that the passband width, insertion loss, stopband attenuation, and steepness of the roll-off depend on the properties of the piezoelectric substrate on which the SAW resonators are formed. Providing wide stopbands with the necessary high attenuation is particularly difficult.

These problems are difficult to solve by using the relationships between the passband and stopbands and the resonant frequencies (series resonance frequencies) and antiresonant frequencies (parallel resonance frequencies) of the SAW resonators in a SAW ladder filter, because of restrictions on the width, placement, and spacing of the passband and stopbands. It is particularly difficult to place wide stopbands with high attenuation close to the passband and still maintain a low insertion loss in the passband.

### SUMMARY OF THE INVENTION

A general object of the present invention is to improve the frequency characteristics of SAW ladder filters having poles.

A more specific object is to obtain high stopband attenuation over a wide range of stopband frequencies.

A further object is to obtain steep roll-off between the passband and stopband.

According to a first aspect of the invention, a surface-acoustic-wave filter comprises a two-port surface-acoustic-wave resonator filter circuit and a two-port impedance circuit, coupled in parallel. The two-port surface-acoustic-wave resonator filter circuit has a phase shifter, at least one

series-arm surface-acoustic-wave resonator, and at least one shunt-arm surface-acoustic-wave resonator. The two-port impedance circuit has an impedance that creates a pole of attenuation, by making the open-circuit impedance of the surface-acoustic-wave filter equal to the short-circuit impedance.

According to a second aspect of the invention, a surface-acoustic-wave filter comprises a two-port surface-acoustic-wave resonator filter circuit and a two-port impedance circuit, coupled in series. The two-port surface-acoustic-wave resonator filter circuit has two series-arm surface-acoustic-wave resonators and two shunt-arm surface acoustic-wave resonators. As in the first aspect, the two-port impedance circuit has an impedance that creates a pole of attenuation, by making the open-circuit impedance of the surface-acoustic-wave filter equal to the short-circuit impedance.

In both aspects of the invention, the pole of attenuation created by the impedance circuit improves the frequency characteristic of the filter by increasing the stopband attenuation, enabling a high attenuation to be obtained over a wide range of stopband frequencies, with steep roll-off between the passband and stopband.

### BRIEF DESCRIPTION OF THE DRAWINGS

In the attached drawing:

FIG. 1 is a perspective drawing of the front-end section of a wireless communication device;

FIG. 2 is a schematic diagram of a first embodiment of the invention, suitable for use as the receiving SAW filter in FIG. 1;

FIG. 3 shows FIG. 2 redrawn as a pair of two-port circuits coupled in parallel;

FIG. 4 shows FIG. 2 redrawn for the case of open-circuited output terminals;

FIG. 5 shows FIG. 2 redrawn for the case of short-circuited output terminals;

FIG. 6 shows frequency characteristics of the first embodiment for various capacitance values;

FIG. 7 is a schematic diagram of a second embodiment, also suitable for use as the receiving SAW filter in FIG. 1;

FIG. 8 is a schematic diagram of a conventional filter having the same SAW resonators as in FIG. 7;

FIG. 9 compares the frequency characteristics of the filters in FIGS. 7 and 8;

FIG. 10 is a schematic diagram of a third embodiment, suitable for use as the transmitting SAW filter in FIG. 1;

FIG. 11 shows FIG. 10 redrawn as a pair of two-port circuits coupled in series;

FIG. 12 is simplified drawing of the interdigital transducer patterns in the third embodiment, illustrating the use of a bonding wire as the impedance circuit;

FIG. 13 shows equivalent circuit representations of the SAW resonators in FIG. 10;

FIG. 14 illustrates the left half of FIG. 13;

FIG. 15 illustrates a conventional filter not having an impedance circuit;

FIG. 16 shows equivalent circuit representations of the SAW resonators in FIG. 15;

FIG. 17 shows open-circuited and short-circuited frequency characteristics for the conventional filter in FIG. 15;

FIG. 18 shows open-circuited and short-circuited frequency characteristics for the third embodiment;

FIG. 19 compares frequency characteristics of the filter in FIG. 15 and the third embodiment;

FIG. 20 summarizes the comparison in FIG. 19;

FIG. 21 is a schematic diagram of a four-stage filter having three shunt-arm SAW resonators and a single inductor;

FIG. 22 is a schematic diagram of a five-stage filter having three shunt-arm SAW resonators and a single inductor;

FIG. 23 is a schematic diagram of a fourth embodiment of the invention, also suitable for use as the transmitting SAW filter in FIG. 1;

FIG. 24 compares frequency characteristics of the filters in FIGS. 22 and 23.

FIG. 25 is a schematic diagram of a fifth embodiment of the invention, also suitable for use as the transmitting SAW filter in FIG. 1;

FIGS. 26, 27, 28, and 29 illustrate alternative configurations of the two-port impedance circuit in FIG. 3; and

FIGS. 30, 31, 32, and 33 illustrate alternative configurations of the two-port impedance circuit in FIG. 11.

#### DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the invention will be described with reference to the attached illustrative drawings.

As an example of a system in which the invention can be practiced, FIG. 1 shows part of the RF section of a portable CDMA telephone set, comprising an antenna duplexer 1, low-noise amplifier (LNA) 2, power amplifier (AMP) 3, and other circuits (not visible). The antenna duplex 1, which is the interface between the amplifiers 2 and 3 and an antenna 4, comprises a coupling circuit 5, a receiving (Rx) SAW filter 6, and a transmitting (Tx) SAW filter 7. The coupling circuit 5 comprises interconnecting lines and other components such as inductors and capacitors, not explicitly shown in the drawing. The receiving SAW filter 6 comprises a plurality of SAW resonators having metal-foil interdigital transducers formed on a piezoelectric substrate 8. The transmitting SAW filter 7 has a similar structure, details of which will be shown later. All of these components are mounted on a main substrate 9, such as a ceramic substrate or glass-epoxy substrate.

This telephone set transmits in, for example, a frequency band from eight hundred twenty-four megahertz to eight hundred forty-nine megahertz (824 MHz to 849 MHz), and receives in a frequency band from 869 MHz to 894 MHz. The transmitting SAW filter 7 preferably has an insertion loss of 1.5 decibels (dB) or less in the transmitting band, and an attenuation of at least 35 dB in the receiving band. The receiving SAW filter 6 preferably has an insertion loss of 4 dB or less in the receiving band, and an attenuation of at least 50 dB in the transmitting band.

#### FIRST EMBODIMENT

The first embodiment of the invention is a SAW filter suitable for use as the receiving filter 6 in FIG. 1. Referring to FIG. 2, this embodiment of the receiving filter 6 comprises a phase shifter 10, a pair of series-arm SAW resonators 12 and 14, a shunt-arm SAW resonator 16, an inductor 18, and a capacitor 20. These elements form a two-port circuit, the input port comprising an input terminal 22 and ground or earth (E) terminal 24, and the output port comprising an output terminal 26 and ground terminal 28.

The phase shifter 10 and series-arm SAW resonators 12 and 14 are coupled in series between the input terminal 22 and output terminal 26. The inductor 18 and capacitor 20 are also coupled in series between the input terminal 22 and output terminal 26, in parallel with the phase shifter 10 and series-arm SAW resonators 12 and 14. The shunt-arm SAW resonator 16 is coupled, on one side, to a node disposed between the two series-arm SAW resonators 12 and 14, and on the other side to the ground terminals 24 and 28.

The phase shifter 10 and saw resonators 12, 14, and 16 are formed on a common piezoelectric substrate. The phase shifter 10 comprises a stripline with a total length of eleven centimeters (11 cm). Each of the two series-arm SAW resonators 12 and 14 comprises an interdigital transducer with one hundred pairs of electrode fingers that mesh over a distance, referred to as an aperture, or fifty micrometers (50  $\mu\text{m}$ ). The shunt-arm SAW resonator 16 comprises an interdigital transducer with eighty-six pairs of interdigital fingers and an aperture of 86  $\mu\text{m}$ . The phase shifter 10 has a certain impedance  $Z_p$ . The SAW resonators 12, 14, and 16 have respective impedances  $Z_1$ ,  $Z_2$ , and  $Z_3$ . The inductor 18 comprises a bonding wire with an inductance  $L_o$  of three nano henries (3.0 nH). The capacitor 20 has a capacitance  $C_o$  of, for example, 0.1 picofarad (0.1 pF).

The first embodiment is a two-stage SAW filter. The first stage comprises series-arm SAW resonator 12 and shunt-arm SAW resonator 16. The second stage comprises shunt-arm SAW resonator 16 and series-arm SAW resonator 14. In SAW filters in general, each adjacent pair of series- and shunt-arm SAW resonators constitute one stage of the filter.

Referring to FIG. 3, this filter circuit can also be described as comprising a pair of two-port circuits coupled in parallel between the input terminal 22 and output terminal 26, and between the ground terminals 24 and 28. One two-port circuit is a SAW filter circuit 30 comprising the phase shifter 10 and SAW resonators 12, 14, and 16. The other two-port circuit is an impedance circuit 32 comprising the inductor 18 and capacitor 20, and a ground line 34. For an input signal with a frequency  $f$  and angular frequency  $\omega$  equal to  $2\pi f$ , the inductor 18 and capacitor 20 combine to provide the impedance circuit 32 with an impedance  $Z_A$  equal to  $j\omega L_o + 1/(j\omega C_o)$ , where  $j$  represents the square root of minus one.

The two-port description of the impedance circuit 32 is useful in computing the frequency characteristic of the filter. The parallel connection, for example, means that the admittance matrices of the two-port circuits 30 and 32 combine additively. In the general case, the two-port circuit 32 may have various configurations other than those shown in FIG. 3, some of which will be illustrated later.

Next, the operation of this embodiment will be described.

The operation of the circuit in FIG. 2 can be analyzed by calculating the impedance  $Z_o$  between the input terminal 22 and ground terminal 24 when the output terminal 26 and ground terminal 28 are open-circuited, and the impedance  $Z_s$  between the input terminal 22 and ground terminal 24 when the output terminal 26 and ground terminal 28 are short-circuited.  $Z_o$  and  $Z_s$  can also be given in terms of ABCD transfer parameters,  $Z_o$  being equal to  $A/C$  and  $Z_s$  to  $B/D$ . Definitions of the ABCD parameters can be found in, for example, the Electronics Engineer's Handbook edited by Fink et al., published by McGraw-Hill.

The quantities  $Z_o$  and  $Z_s$  depend on the angular frequency  $\omega$  of the input signal. When expressed in decibels, the frequency characteristics  $\alpha(\omega)$  of the circuit in FIG. 2 is given by the following equation (1), in which Log represents the logarithm.

$$\alpha(\omega) = 20.0 \times \text{Log} \left| \frac{(1 + Z_O)(1 + Z_S)}{(Z_O - Z_S)} \right| \quad (1)$$

It can be seen that this frequency characteristic has poles at frequencies at which  $Z_O$  is infinite, at frequencies at which  $Z_S$  is infinite, and at frequencies at which  $Z_O$  is equal to  $Z_S$ . The last case is of interest here.

The open-circuited configuration can be redrawn as shown in FIG. 4. It can be seen that  $Z_O$  has the following value.

$$Z_O = \frac{(Z_A + Z_2)(Z_P + Z_1)}{Z_A + Z_P + Z_1 + Z_2} + Z_3 \quad (2)$$

The short-circuited configuration can be redrawn as shown in FIG. 5. It can be seen that  $Z_S$  has the following value.

$$Z_S = \frac{Z_A \times Z_{SS}}{Z_A + Z_{SS}} \quad (3)$$

where

$$Z_{SS} = Z_P + Z_1 + \frac{Z_2 \times Z_3}{Z_2 + Z_3} \quad (4)$$

At the stopband frequencies in the present embodiment,  $Z_A$  is much smaller than the impedances  $Z_1$ ,  $Z_2$ , and  $Z_3$  of the SAW resonators 12, 14, and 16, so the above equations (2) and (3) can be simplified as follows.

$$Z_O = \frac{Z_2 \times (Z_P + Z_1)}{Z_P + Z_1 + Z_2} + Z_3 \quad (5)$$

$$Z_S = Z_A \quad (6)$$

Since  $Z_O$  is substantially independent of  $Z_A$ , and  $Z_S$  is substantially equal to  $Z_A$ , a pole of attenuation can be produced at a desired frequency by selecting  $Z_A$  so that  $Z_O$  is equal to  $Z_S$  at this frequency. Moreover, since  $Z_O$  depends on  $Z_P$ , and  $Z_S$  is substantially independent of  $Z_P$ , the value of  $Z_P$  can be selected to adjust  $Z_O$  without strongly affecting  $Z_S$ . The range of frequencies over which impedance matching between  $Z_O$  and  $Z_S$  is achieved can be extended in this way.

Adjustment of  $Z_P$  also increases the range of frequencies over which impedance matching between the SAW filter and external circuits is achieved.

FIG. 6 illustrates the effect of adjusting  $Z_A$ , more specifically, of adjusting the capacitance  $C_O$  of the capacitor 20. The horizontal axis represents frequency; the vertical axis represents attenuation in decibels. The curve marked 'a' was obtained by numerical simulation with  $C_O$  set to the value 0.1 pF used in the present embodiment.  $C_O$  was set to 0.2 pF for curve 'b,' to 0.5 pF for curve 'c,' and to zero for curve 'd.' Curve 'd' corresponds to the case in which the impedance circuit comprising the inductor 18 and capacitor 20 is not present.

These variations in  $C_O$  have only a minor effect on the passband from 864 MHz to 894 MHz, but have a major effect on the upper and lower stopbands. A comparison of curves 'a' and 'd' shows that in both stopbands, the first embodiment widens the range of frequencies over which a given attenuation is attained.

## SECOND EMBODIMENT

To improve the stopband attenuation characteristics, further SAW resonators can be added as shown in FIG. 7. As in the first embodiment, the impedance circuit comprises an inductor 18 with an impedance  $L_O$  of 3.0 nH, and a capacitor 20 with a capacitance  $C_O$  of 0.1 pF. The phase shifter 10 is again an 11-cm stripline. Each of the series-arm SAW resonators 12, 14, and 38 comprises an interdigital transducer with one hundred pairs of electrode fingers and an aperture of 50  $\mu\text{m}$ . As in the first embodiment, the inductor 18 and capacitor 20 are coupled in parallel with the phase shifter 10 and the first pair of series-arm SAW resonators 12 and 14.

The second embodiment has four shunt-arm SAW resonators 40, 42, 44, and 46, which are coupled in a ladder configuration with the series-arm SAW resonators. The first and last shunt-arm SAW resonators 40 and 46 each have an interdigital transducer with sixty pairs of electrode fingers and an aperture of 60  $\mu\text{m}$ . The two inner shunt-arm SAW resonators each have an interdigital transducer with eighty-five pairs of electrode fingers and an aperture of 85  $\mu\text{m}$ .

Incidentally, it is possible to couple the impedance circuit, comprising the inductor 18 and capacitor 20, in parallel with all three series-arm SAW resonators 12, 14, and 38, but the inventors have found that better characteristics are obtained when the impedance circuit is coupled in parallel with just two series-arm SAW resonators.

FIG. 8 shows a conventional SAW ladder filter obtained by removing the phase shifter 10, inductor 18, and capacitor 20 from the second embodiment. FIG. 9 compares the frequency characteristic, marked 'a,' of the second embodiment with the frequency characteristic, marked 'b,' of this conventional SAW ladder filter. Both filters have substantially identical characteristics in the passband from 864 MHz to 894 MHz, with an insertion loss of less than four decibels (4 dB). In the lower stopband, however, the second embodiment satisfies the requirement of an attenuation of at least 50 dB over the full range from 824 MHz to 851 MHz, while the conventional SAW ladder filter does not.

A similar improvement can also be seen in the upper stopband.

## THIRD EMBODIMENT

The third embodiment is a SAW filter suitable for use as the transmitting SAW filter 7 in FIG. 1. Referring to FIG. 10, this embodiment of the transmitting SAW filter 7 comprises three series-arm SAW resonators 48, 50, and 52, two shunt-arm SAW resonators 54 and 56, and an inductor 58. These elements form a two-port circuit with an input terminal 60 and ground terminal 62 on the input side, and an output terminal 64 and ground terminal 66 on the output side.

Each of the series-arm SAW resonators 48, 50 and 52 comprises an interdigital transducer with one hundred twenty pairs of electrode fingers and an aperture of 120  $\mu\text{m}$ . Each of the shunt-arm SAW resonators 54 and 56 comprises an interdigital transducer with sixty pairs of electrode fingers and an aperture of 90  $\mu\text{m}$ . The inductor 58 has an inductance of 4.0 nH.

Referring to FIG. 11, this filter circuit can be represented as a pair of two-port circuits coupled in series. One two-port circuit 68 is a SAW filter comprising the SAW resonators 48, 50, 52, 54, and 56. The other two-port circuit 70 is an impedance circuit comprising the inductor 58, providing an impedance  $Z_A$ . The series coupling of these two-port circuits 68 and 70 means that their impedance matrices combine additively.

Referring to FIG. 12, the SAW resonators **48**, **50**, **52**, **54**, and **56** in the third embodiment are formed as metal-foil interdigital transducer patterns on a piezoelectric substrate **71**. The two shunt-arm SAW resonators **54** and **56** are disposed back-to-back, sharing a common central electrode pattern. The inductor **58** is a length of bonding wire that couples this common electrode pattern to an external ground bonding pad **62**. This bonding pad **62** combines the functions of the ground terminals **62** and **66** in FIG. 10. The inductance of the bonding-wire inductor **58** is determined by the point of attachment of the bonding-wire inductor **58** to the SAW resonators **54** and **56**.

The number of electrode fingers of the interdigital transducers in FIG. 12 has been greatly reduced, to simplify the drawing.

Next, the operation of the third embodiment will be described.

FIG. 13 shows the SAW resonators **48**, **50**, **52**, **54**, and **56** represented by equivalent lumped-constant circuits. Series-arm SAW resonator **48** is represented by an inductance  $L_{S1}$  and a capacitance  $C_{S1}$  coupled in series, paralleled by a capacitance  $C_{S10}$ . Shunt-arm SAW resonator **54** is represented by an inductance  $L_{P1}$  and a capacitance  $C_{P1}$  coupled in series, paralleled by a capacitance  $C_{P10}$ . The central series-arm SAW resonator **50** is represented by an inductance of  $2L_{S2}$  and a capacitance of  $(\frac{1}{2})C_{S2}$  coupled in series paralleled by a capacitance of  $(\frac{1}{2})C_{S20}$ .

This circuit is symmetrical, and can be analyzed by considering only the left half, as shown in FIG. 14. The central series-arm SAW resonator **50** in FIG. 13, when divided in half, yields the equivalent circuit **72** shown in FIG. 14, comprising an inductance  $L_{S2}$  and a capacitance  $C_{S2}$  coupled in series, paralleled by a capacitance  $C_{S20}$ ; these circuit elements being coupled to a pair of terminals **76** and **78**. Similarly, the inductor **58** in FIG. 12 becomes an inductor **74** with inductance  $L_O$  in FIG. 14, coupled between a pair of terminals **80** and **82**.

The impedance  $Z_O$  between terminals **60** and **62** in FIG. 14 when terminals **76**, **78**, **80**, and **82** are left open, and the impedance  $Z_S$  when these terminals are short-circuited, are related to  $L_O$  and the impedances  $Z_1$ ,  $Z_2$ , and  $Z_3$  of resonators **48**, **72**, and **54** by the following equations (7) and (8), in which  $S$  is equal to  $j\omega$ ,  $\omega$  being the angular frequency of the input signal.

$$Z_O = Z_1 + Z_3 + SL_O \quad (7)$$

$$Z_S = Z_1 + \frac{Z_2 \times Z_3}{Z_2 + Z_3} \quad (8)$$

The values of  $Z_1$ ,  $Z_2$ , and  $Z_3$  are given by the following equations (9), (10), and (11).

$$Z_1 = (1 + S^2 L_{S1} C_{S1}) / (S C_{S10} + S C_{S1} + S^3 L_{S1} C_{S1} C_{S10}) \quad (9)$$

$$Z_2 = (1 + S^2 L_{S2} C_{S2}) / (S C_{S20} + S C_{S2} + S^3 L_{S2} C_{S2} C_{S20}) \quad (10)$$

$$Z_3 = (1 + S^2 L_{P1} C_{P1}) / (S C_{P10} + S C_{P1} + S^3 L_{P1} C_{P1} C_{P10}) \quad (11)$$

The inductance  $L_O$  does not appear in the equation (8) for  $Z_S$ , because  $L_O$  is short-circuited by the connection of terminal **80** to terminal **82**.

The frequency characteristic of circuit in FIG. 14 is given by the same equation (1) as in the first embodiment. As in the first embodiment, a pole of attenuation can be produced by making  $Z_O$  equal to  $Z_S$ , and this can be done by suitable selection of the inductance  $L_O$ , since  $Z_O$  depends on  $L_O$ , while  $Z_S$  does not.

The condition of equality between  $Z_O$  and  $Z_S$  is given by the following equation (12).

$$SL_O = \frac{-Z_3^2}{Z_2 + Z_3} \quad (12)$$

The third embodiment is designed so that this condition is satisfied over a wide range of high frequencies, as will be illustrated below.

For comparison, FIG. 15 shows a conventional SAW filter lacking the inductor **58** of the third embodiment. FIG. 16 shows the corresponding equivalent lumped-constant circuit representation. The circuit constants in FIG. 16 are the same as the corresponding constants in FIG. 13.

Graphs of the open-circuited impedance  $Z_O$  and short-circuited impedance  $Z_S$  of this conventional SAW filter are shown in FIG. 17. The horizontal axis indicates frequency in hertz (Hz); the vertical axis indicates impedance in ohms ( $\Omega$ ).  $Z_O$  and  $Z_S$  were calculated from equations (7) to (11) with  $L_O$  set equal to zero. The difference between  $Z_O$  and  $Z_S$  in the frequencies above about 875 MHz should be noted, as these frequencies are located in the desired upper stopband of the filter.

FIG. 18 shows the open-circuited impedance  $Z_O$  and short-circuited impedance  $Z_S$  of the third embodiment, calculated from the same equations (7) to (11), with  $L_O$  set equal to 4.0 nH. The horizontal and vertical axes have the same meaning as in FIG. 17. Compared with FIG. 17, the difference between  $Z_O$  and  $Z_S$  in the upper stopband is greatly reduced.

FIG. 19 compares the frequency characteristic, marked 'a,' of the conventional filter in FIG. 15 with the frequency characteristic, marked 'b,' of third embodiment. The horizontal axis indicates frequency in hertz, while the vertical axis indicates attenuation in decibels. In the passband, both filters satisfy the requirement of an insertion loss not exceeding 1.5 dB at all frequencies from 824 MHz to 849 MHz. In the upper stopband, the third embodiment also satisfies the requirement for an attenuation of at least 35 dB at all frequencies from 869 MHz to 894 MHz, but the conventional filter does not.

FIG. 20 summarizes the information in FIGS. 17 to 19 in the form of a table.

The right part of FIG. 20 gives values of the open-circuited impedance  $Z_O$  and short-circuited impedance  $Z_S$  at three frequencies near the high end of the upper stopband (889 MHz, 895 MHz, and 901 MHz). When  $L_O$  is zero, the difference between  $Z_O$  and  $Z_S$  is  $-j0.72$  or greater. When  $L_O$  is 4.0 nH, the difference between  $Z_O$  and  $Z_S$  is reduced to  $-j0.30$  or less.

The left part of FIG. 20 gives impedance values at the two ends of the passband (823 MHz and 849 MHz) and the two ends of the upper stopband (869 MHz and 895 MHz). At the high end of the upper stopband (895 MHz), the attenuation of the third embodiment ( $L_O=4.0$  nH) exceeds the attenuation of the conventional filter ( $L_O=0$  nH) by about thirteen decibels, a substantial improvement.

For further comparison with the third embodiment, FIG. 21 shows a four-stage SAW filter comprising two series-arm SAW resonators **76** and **78**, three shunt-arm SAW resonators **80**, **82**, and **84**, and a single inductor **86**. The inductor **86** is coupled between the ground line E—E and all three shunt-arm SAW resonators **80**, **82**, and **84**.

If this circuit is analyzed in the same way as the third embodiment was analyzed writing  $Z_4$  for the impedance of each of the series-arm SAW resonators **76** and **78**,  $Z_5$  for the impedance of the two outer shunt-arm SAW resonators **80**

and **84**,  $Z_6$  for the impedance of the central shunt-arm SAW resonator **82**, and  $Z_A$  for the impedance furnished by the inductor **86**, the total open-circuit impedance  $Z_O$  and total short-circuit impedance  $Z_S$  are given by the following equations (13) and (14).

$$Z_O = \frac{Z_5 \times (Z_4 + Z_6)}{Z_5 + Z_4 + Z_6} + Z_A \quad (13)$$

$$Z_S = \frac{Z_4 \times Z_5}{Z_4 + Z_5} \quad (14)$$

As in the third embodiment,  $Z_O$  can be made equal to  $Z_S$  at a given frequency by suitable selection of  $Z_A$ . A major improvement in the frequency characteristic of the filter cannot be expected, however, because the condition for equality of  $Z_O$  and  $Z_S$  is now given by the following equation (15).

$$Z_A = \frac{-Z_4^2 Z_6}{(Z_4 + Z_5)(Z_4 + Z_5 + Z_6)} \quad (15)$$

This condition is more complex than the condition given by equation (12). It is not easy to design a filter with the configuration in FIG. 21 so that equation (15) is satisfied over a wide range of frequencies.

A consequence is that when further SAW resonators are added to the filter to achieve greater stopband attenuation, the filter design should be based on the model in FIG. 11 rather than the model in FIG. 21. FIG. 22, for example, shows a non-preferred five-stage SAW filter obtained by adding one more SAW resonator **88** to the series arm in FIG. 21. The part enclosed in the dotted line in FIG. 22 is the same as in FIG. 21. The equations above indicate that less improvement can be expected in this filter design than in a design based on FIG. 11, which will be illustrated in the fourth embodiment below.

#### FOURTH EMBODIMENT

Referring to FIG. 23, the fourth embodiment is a five-stage SAW filter comprising three series-arm SAW resonators **90**, **92**, and **94**, three shunt-arm SAW resonators **96**, **98**, **100**, and two inductors **102** and **104**. Inductor **102** is a bonding wire coupled between the first two shunt-arm SAW resonators **96** and **98** and the ground line E—E. These two shunt-arm SAW resonators **96** and **98** are preferably disposed back-to-back, like the SAW resonators **54** and **56** in FIG. 12. Inductor **104** is a bonding wire coupled between the third shunt-arm SAW resonator **100** in FIG. 23 and the ground line.

Each of the series-arm SAW resonators **90**, **92**, and **94** has an interdigital transducer with one hundred pairs of electrode fingers and an aperture of 120  $\mu\text{m}$ . Each of the shunt-arm SAW resonators **96**, **98**, and **100** has an interdigital transducer with eighty pairs of electrode fingers and an aperture of 90  $\mu\text{m}$ . The inductance of the inductor **102** is 0.1 nH; the inductance of inductor **104** is also 0.1 nH.

This filter can be considered to consist of three sub-parts: a SAW filter circuit **106** comprising the first two series-arm SAW resonators **90** and **92** and the first two shunt-arm SAW resonators **96** and **98**; an impedance circuit **108**, comprising inductor **102**, which is coupled series with SAW filter circuit **106**; and a SAW filter circuit **110** comprising the third series-arm SAW resonator **94**, third shunt-arm SAW resonator **100**, and inductor **104**, SAW filter circuit **106** and impedance circuit **108** combine to form a filter section that

is connected in cascade with SAW filter circuit **110**. The two SAW filter circuits **106** and **110** combine to form a SAW ladder filter.

FIG. 24 compares the frequency characteristic marked 'a,' of the non-preferred filter in FIG. 22 with the frequency characteristic, marked 'b,' of fourth embodiment. The inductor **86** in FIG. 22 is assumed to have the same 0.1-nH inductance as the inductors **102** and **104** in FIG. 23. Both filters meet the requirement for an insertion loss of 1.5 dB or less in the passband from 824 MHz to 849 MHz. The filter in FIG. 22, however, does not entirely meet the requirement for an attenuation of at least 35 dB in the stopband from 869 mHz to 894 MHz. The fourth embodiment has a steeper roll-off between the passband and stopband, and clears this 35-dB requirement by a wide margin, providing excellent stopband attenuation.

#### FIFTH EMBODIMENT

Referring to FIG. 25, a fifth embodiment of the invention extends the concept of the third and fourth embodiments to a six-stage SAW filter having four series-arm SAW resonators **112**, **114**, **116**, and **118**, four shunt-arm SAW resonators **120**, **122**, **124**, and **126**, and two inductors **128** and **130**.

This filter can be divided into two sections **132** and **134**, each similar in design to the section comprising the SAW filter circuit **106** and impedance circuit **108** in FIG. 23. The impedance  $Z_A$  in each section can be selected to provide high attenuation across a wide range of stopband frequencies. The two filter sections **132** and **134** are cascaded, so that their ABCD transfer parameters combine by matrix multiplication.

Referring again to FIG. 10, the third embodiment can also be described as comprising a two-port SAW filter circuit with two series-arm SAW resonators **48** and **50** and two shunt-arm SAW resonators **54** and **56**, coupled in series with a two-port impedance circuit comprising the inductor **58**, these two circuits forming a first filter section, which is cascaded with a second filter section comprising SAW resonator **52**.

The impedance circuits employed in the present invention are not limited to the circuits shown in the preceding embodiments.

In the first embodiment, for example, the impedance circuit **32** shown in FIG. 3 can be replaced with one of the impedance circuits shown in FIGS. 26, 27, 28, and 29. The circuit in FIG. 26 comprises a capacitor **136**. The circuit in FIG. 27 comprises an inductor **138** and capacitor **140** coupled in parallel. The circuit in FIG. 28 comprises an inductor **142** and capacitor **144** coupled in parallel, both also coupled in series with an inductor **146**. The circuit in FIG. 29 comprises an inductor **148** and capacitor **150** coupled in series, paralleled by a capacitor **152**. Similar replacements are possible in the second embodiment.

In the third embodiment, the impedance circuit **70** shown in FIG. 11 can be replaced with one of the impedance circuits shown in FIGS. 30, 31, 32, and 33. The circuit in FIG. 30 comprises a capacitor **154** coupled in series with an inductor **156**. The circuit in FIG. 31 comprises a capacitor **158** and an inductor **160** coupled in parallel. The circuit in FIG. 32 comprises a capacitor **162** and an inductor **164** coupled in parallel, both also coupled in series with an inductor **166**. The circuit in FIG. 33 comprises a capacitor **168** and an inductor **170** coupled in series, paralleled by a capacitor **172**. Similar replacements are possible in the fourth and fifth embodiments.

The phase shifter **10** in the first and second embodiments is not limited to a stripline formed on the same piezoelectric

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substrate as the SAW resonators. Referring again to FIG. 1, part or all of the phase shifter 10 may be disposed on the main substrate 9. For example, the phase shifter 10 may comprise both a stripline formed on the piezoelectric substrate 8 and a stripline formed on the main substrate 9, as part of the coupling circuit 5. It is advantageous to have at least part of the phase shifter 10 disposed on the main substrate 9, as modifications to the characteristics of the phase shifter are more easily made on the main substrate 9 than on the piezoelectric substrate 8.

Those skilled in the art will recognize that further variations are possible within the scope claimed below.

What is claimed is:

1. A surface-acoustic-wave filter with poles, comprising:
  - a two-port surface-acoustic-wave resonator filter circuit having a phase shifter, at least one series-arm surface-acoustic-wave resonator coupled in series with said phase shifter, and at least one shunt-arm surface-acoustic-wave resonator; and
  - a two-port impedance circuit coupled in parallel with said two-port surface-acoustic-wave resonator filter circuit, having an impedance that creates a pole of attenuation by making an open-circuit impedance of said surface-acoustic-wave filter equal to a short-circuit impedance of said surface-acoustic-wave filter.
2. The surface-acoustic-wave filter of claim 1, wherein said two-port surface-acoustic-wave resonator filter circuit has just two series-arm surface-acoustic-wave resonators.
3. The surface-acoustic-wave filter of claim 1, wherein said two-port impedance circuit comprises a first capacitor.
4. The surface-acoustic-wave filter of claim 3, wherein said two-port impedance circuit also comprises a first inductor.
5. The surface-acoustic-wave filter of claim 4, wherein said first inductor comprises a bonding wire having a certain inductive impedance.
6. The surface-acoustic-wave filter of claim 4, wherein said first capacitor and said first inductor are coupled in series.
7. The surface-acoustic-wave filter of claim 6, wherein said two-port impedance circuit further comprises a second capacitor coupled in parallel with said first capacitor and said first inductor.
8. The surface-acoustic-wave filter of claim 4, wherein said first capacitor and said first inductor are coupled in parallel.
9. The surface-acoustic-wave filter of claim 8, wherein said two-port impedance circuit further comprises a second inductor coupled in series with said first capacitor and said first indicator.
10. The surface-acoustic-wave filter of claim 1, wherein said surface-acoustic-wave filter is disposed in an antenna duplexer, and said phase shifter comprises an interconnecting line in said antenna duplexer.
11. The surface-acoustic-wave filter of claim 1, wherein said at least one series-arm surface-acoustic-wave resonator, said at least one shunt-arm surface-acoustic-wave resonator, and said phase shifter are formed on a piezoelectric substrate.
12. The surface-acoustic-wave filter of claim 11, wherein said phase shifter comprises a stripline formed on said piezoelectric substrate.
13. The surface-acoustic-wave filter of claim 1, wherein said at least one series-arm surface-acoustic-wave resonator, and said at least one shunt-arm surface-acoustic-wave resonator are formed on a piezoelectric substrate, said piezoelectric substrate is mounted on a main substrate, and said phase shifter is formed on said main substrate.

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14. The surface-acoustic wave filter of claim 1, wherein said at least one series-arm surface-acoustic-wave resonator, and said at least one shunt-arm surface-acoustic-wave resonator are formed on a piezoelectric substrate, said piezoelectric substrate is mounted on a main substrate, and said phase shifter is formed partly on said piezoelectric substrate and partly on said main substrate.

15. A surface-acoustic-wave filter with poles, comprising:
 

- a two-port surface-acoustic-wave resonator filter circuit having two series-arm surface-acoustic-wave resonators coupled in series with a phase shifter, and two shunt-arm surface-acoustic-wave resonators; and
- a two-port impedance circuit coupled in series with said two-port surface-acoustic-wave resonator filter circuit, having an impedance that creates a pole of attenuation by making an open-circuit impedance of said surface-acoustic-wave filter equal to a short-circuit impedance of said surface-acoustic-wave filter.

16. The surface-acoustic-wave filter of claim 15, wherein said two-port impedance circuit comprises a first inductor.

17. The surface-acoustic-wave filter of claim 16, wherein said first inductor comprises a bonding wire having a certain inductive impedance.

18. The surface-acoustic-wave filter of claim 16, wherein said two-port impedance circuit also comprises a first capacitor.

19. The surface-acoustic-wave filter of claim 18, wherein said first inductor and said first capacitor are coupled in parallel.

20. The surface-acoustic-wave filter of claim 19, wherein said two-port impedance circuit further comprises a second inductor coupled in series with said first capacitor and said first inductor.

21. The surface-acoustic-wave filter of claim 18, wherein said first inductor and said first capacitor are coupled in series.

22. The surface-acoustic-wave filter of claim 21, wherein said two-port impedance circuit further comprises a second capacitor coupled in parallel with said first inductor and said first capacitor.

23. The surface-acoustic-wave filter of claim 15, wherein said two shunt-arm surface-acoustic-wave resonators are coupled back-to-back, sharing a common central electrode.

24. The surface-acoustic-wave filter of claim 23, wherein said two-port impedance circuit comprises a bonding wire attached to said common central electrode.

25. The surface-acoustic-wave filter of claim 15, wherein said two-port surface-acoustic-wave resonator filter circuit and said two-port impedance circuit form a first filter section, and said surface-acoustic-wave filter further comprises a second filter section cascaded with said first filter section.

26. The surface-acoustic-wave filter of claim 25, wherein said second filter section, when combined with said a two-port surface-acoustic-wave resonator filter circuit, forms a surface-acoustic-wave ladder filter.

27. The surface-acoustic-wave filter of claim 25, wherein said second filter section is similar in configuration to said first filter section, comprising a two-port surface-acoustic-wave resonator filter circuit having two series-arm SAW resonators and two shunt-arm SAW resonators, coupled in series with a two-port impedance circuit.

28. A surface-acoustic-wave filter comprising a plurality of surface-acoustic-wave filters as described in claim 15, coupled in cascade.

29. A surface-acoustic-wave filter with poles, comprising:
 

- a two-port surface-acoustic-wave resonator filter circuit having two series-arm surface-acoustic-wave resonators and two shunt-arm surface-acoustic-wave resonators; and

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a two-port impedance circuit coupled in series with said two-port surface-acoustic-wave resonator filter circuit, having an impedance that creates a pole of attenuation by making an open-circuit impedance of said surface-acoustic-wave filter equal to a short-circuit impedance of said surface-acoustic-wave filter.

30. The surface-acoustic-wave filter of claim 29, wherein said two-port impedance circuit comprises a first inductor.

31. The surface-acoustic-wave filter of claim 30, wherein said first inductor comprises a bonding wire having a certain inductive impedance.

32. The surface-acoustic-wave filter of claim 30, wherein said two-port impedance circuit further comprises a first capacitor.

33. The surface-acoustic-wave filter of claim 32, wherein said first inductor and said first capacitor are coupled in parallel.

34. The surface-acoustic-wave filter of claim 33, wherein said two-port impedance circuit further comprises a second inductor coupled in series with said first capacitor and said first inductor.

35. The surface-acoustic-wave filter of claim 32, wherein said first inductor and said first capacitor are coupled in series.

36. The surface-acoustic-wave filter of claim 35, wherein said two-port impedance circuit further comprises a second capacitor coupled in parallel with said first inductor and said first capacitor.

37. The surface-acoustic-wave filter of claim 29, wherein said two-shunt-arm surface-acoustic-wave resonators are coupled back-to-back, sharing a common central electrode.

38. The surface-acoustic-wave filter of claim 37, wherein said two-port impedance circuit comprises a bonding wire attached to said common central electrode.

39. The surface-acoustic-wave filter of claim 29, wherein said two-port surface-acoustic-wave resonator filter circuit and said two-port impedance circuit form a first filter section, and said surface-acoustic-wave filter further comprises a second filter section cascaded with said first filter section.

40. The surface-acoustic-wave filter of claim 39, wherein said second filter section is combined with said two-port surface-acoustic-wave resonator filter circuit, forming a surface-acoustic-wave ladder filter.

41. The surface-acoustic-wave filter on claim 39, wherein said second filter section is similar in configuration to said first filter section, said second filter section comprising a two-port surface-acoustic-wave resonator filter circuit having two series-arm SAW resonators and two shunt-arm SAW resonators coupled in series with a two-port impedance circuit.

42. The surface-acoustic-wave filter of claim 29, further comprising a plurality of surface-acoustic-wave filters coupled in cascade.

43. A surface-acoustic-wave duplexer having a transmitting surface-acoustic-wave filter circuit and receiving surface-acoustic-wave filter circuit and a coupling circuit, the transmitting surface-acoustic-wave filter circuit comprising:

a two-port surface-acoustic-wave resonator filter circuit having two series-arm surface-acoustic-wave resonators and two shunt-arm surface-acoustic-wave resonators; and

a two-port impedance circuit coupled in series with said two-port surface-acoustic-wave resonator filter circuit, having an impedance that creates a pole of attenuation by making an open-circuit impedance of said transmit-

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ting surface-acoustic-wave filter equal to a short-circuit impedance of said transmitting surface-acoustic-wave filter.

44. The surface-acoustic-wave duplexer of claim 43, wherein said two-port surface-acoustic-wave resonator filter circuit forms a ladder surface-acoustic-wave resonator filter; and said two-port impedance circuit is coupled in series with said two shunt-arm surface-acoustic-wave resonators.

45. A surface-acoustic-wave filter with poles, comprising:  
a first series-arm surface-acoustic-wave resonator coupled to an input terminal;

a second series-arm surface-acoustic-wave resonator coupled to said first series-arm surface-acoustic-wave resonator;

a third series-arm surface-acoustic-wave resonator coupled between said second series-arm surface-acoustic-wave resonator and an output terminal;

a first shunt-arm surface-acoustic-wave resonator coupled to said first and second series-arm surface-acoustic-wave resonators;

a second shunt-arm surface-acoustic-wave resonator coupled to said second and third series-arm surface-acoustic-wave resonators; and

an impedance circuit having first and second ends, wherein said first end is coupled only to said first and second shunt-arm surface-acoustic-wave resonators and said second end is coupled to a ground terminal, and wherein said impedance circuit has an impedance that creates a pole of attenuation by making an open-circuit impedance of said surface-acoustic-wave filter substantially equal to a short-circuit impedance of said surface-acoustic-wave filter.

46. The surface-acoustic-wave filter of claim 45, further comprising a phase shifter coupled between said input terminal and said first series-arm surface-acoustic-wave resonator.

47. The surface-acoustic-wave filter of claim 45, wherein said impedance circuit comprises a first inductor.

48. The surface-acoustic-wave filter of claim 47, wherein said first inductor comprises a bonding wire having a certain inductive impedance.

49. The surface-acoustic-wave filter of claim 47, wherein said impedance circuit further comprises a first capacitor.

50. The surface-acoustic-wave filter of claim 49, wherein said first inductor and said first capacitor are coupled in parallel.

51. The surface-acoustic-wave filter of claim 50, wherein said impedance circuit further comprises a second inductor coupled in series to said first capacitor and said first inductor.

52. The surface-acoustic-wave filter of claim 49, wherein said first inductor and said first capacitor are coupled in series.

53. The surface-acoustic-wave filter of claim 52, wherein said impedance circuit further comprises a second capacitor coupled in parallel to said first capacitor and said first inductor.

54. The surface-acoustic-wave filter of claim 45, wherein said first and second shunt-arm surface-acoustic-wave resonators are coupled back-to-back, sharing a common central electrode.

55. The surface-acoustic-wave filter of claim 54, wherein said impedance circuit comprises a bonding wire attached to said common central electrode.

56. A surface-acoustic-wave duplexer, comprising:  
 a transmitting surface-acoustic-wave filter circuit; and  
 a receiving surface-acoustic-wave filter circuit;  
 wherein said transmitting surface-acoustic-wave filter  
 circuit comprises:  
 a first series-arm surface-acoustic-wave resonator  
 coupled to an input terminal;  
 a second series-arm surface-acoustic-wave resonator  
 coupled to said first series-arm surface-acoustic-  
 wave resonator;  
 a third series-arm surface-acoustic-wave resonator  
 coupled between said second series-arm surface-  
 acoustic-wave resonator and an output terminal;  
 a first shunt-arm surface-acoustic-wave resonator  
 coupled to said first and second series-arm surface-  
 acoustic wave resonators;  
 a second shunt-arm surface-acoustic-wave resonator  
 coupled to said second and third series-arm surface-  
 acoustic-wave resonators; and  
 an impedance circuit having first and second ends,  
 wherein said first end is coupled only to said first and  
 second shunt-arm surface-acoustic-wave resonator  
 and said second end is coupled to a ground terminal,  
 and wherein said impedance circuit has an imped-  
 ance that creates a pole of attenuation by making an  
 open-circuit impedance of said transmitting surface-  
 acoustic-wave filter substantially equal to a short-  
 circuit impedance of said transmitting surface-  
 acoustic-wave filter.

57. A surface-acoustic-wave filter with poles, comprising:  
 two series-arm surface-acoustic-wave resonators coupled  
 in series between an input terminal and an output  
 terminal;  
 two shunt-arm surface-acoustic-wave resonators coupled  
 to said two series-arm surface-acoustic-wave resona-  
 tors;  
 an impedance circuit having first and second ends,  
 wherein said first end is coupled only to said two  
 shunt-arm surface-acoustic-wave resonators and said  
 second end is coupled to a ground terminal, and  
 wherein said impedance circuit has an impedance that  
 creates a pole of attenuation by making an open circuit  
 impedance of said surface-acoustic-wave filter sub-  
 stantially equal to a short-circuit impedance of said  
 surface-acoustic-wave filter.

58. The surface-acoustic-wave filter of claim 57, further  
 comprising a phase shifter coupled between said input  
 terminal and said first series-arm surface-acoustic-wave  
 resonator.

59. The surface-acoustic-wave filter of claim 57, wherein  
 said impedance circuit comprises a first inductor.

60. The surface-acoustic-wave filter of claim 59, wherein  
 said first inductor comprises a bonding wire having a  
 certain inductive impedance.

61. The surface-acoustic-wave filter of claim 59, wherein  
 said impedance circuit further comprises a first capacitor.

62. The surface-acoustic-wave filter of claim 61, wherein  
 said first inductor and said first capacitor are coupled in  
 parallel.

63. The surface-acoustic-wave filter of claim 62, wherein  
 said impedance circuit further comprises a second inductor  
 coupled in series to said first capacitor and said first  
 inductor.

64. The surface-acoustic-wave filter of claim 61, wherein  
 said first inductor and said first capacitor are coupled in  
 series.

65. The surface-acoustic-wave filter of claim 64, wherein  
 said impedance circuit further comprises a second capacitor  
 coupled in parallel to said first capacitor and said first  
 inductor.

66. The surface-acoustic-wave filter of claim 57, wherein  
 said two shunt-arm surface-acoustic-wave resonators are  
 coupled back-to-back and share a common central elec-  
 trode.

67. The surface-acoustic-wave filter of claim 66, wherein  
 said impedance circuit comprises a bonding wire attached to  
 said common central electrode.

68. The surface-acoustic-wave filter of claim 57, further  
 comprising a filter section cascaded with said surface-  
 acoustic-wave filter.

69. The surface-acoustic-wave filter of claim 68, wherein  
 said filter section and said surface-acoustic-wave filter form  
 a surface-acoustic-wave ladder filter.

70. The surface-acoustic-wave filter of claim 68, wherein  
 said filter section is similar in configuration to said surface-  
 acoustic-wave filter, and wherein said filter section com-  
 prises:  
 a second surface-acoustic-wave filter with poles having  
 two series-arm surface-acoustic-wave resonators;  
 two shunt-arm surface-acoustic-wave resonators; and  
 an impedance circuit, said impedance circuit being  
 coupled in series to said two shunt-arm surface-  
 acoustic-wave resonators.

71. The surface-acoustic-wave filter of claim 57, further  
 comprising a plurality of surface-acoustic-wave filters  
 coupled in cascade.

72. A surface-acoustic-wave duplexer, comprising:  
 a receiving surface-acoustic-wave filter circuit; and  
 a transmitting surface-acoustic-wave filter circuit com-  
 prising:  
 two series-arm surface-acoustic-wave resonators  
 coupled in series between an input terminal and an  
 output terminal;  
 two shunt-arm surface-acoustic-wave resonators  
 coupled to said two series-arm surface-acoustic-  
 wave resonators; and  
 an impedance circuit having first and second ends,  
 wherein said first end is coupled only to said two  
 shunt-arm surface-acoustic-wave resonators and  
 said second end is coupled to a ground terminal, and  
 wherein said impedance circuit has an impedance  
 that creates a pole of attenuation by making an  
 open-circuit impedance of said transmitting surface-  
 acoustic-wave filter substantially equal to a short-  
 circuit impedance of said transmitting surface-  
 acoustic-wave filter.

73. A surface-acoustic-wave filter with poles, comprising:  
 first and second series-arm surface-acoustic-wave reso-  
 nators coupled in series between an input terminal and  
 an output terminal;  
 first and second shunt-arm surface-acoustic-wave reso-  
 nators coupled respectively to said first and second  
 series-arm surface-acoustic-wave resonators; and  
 a first impedance circuit having first and second ends,  
 wherein said first end is coupled only to said first and  
 second shunt-arm surface-acoustic-wave resonators  
 and said second end is coupled to a ground terminal,  
 wherein said first impedance circuit has a first imped-  
 ance that creates a pole of attenuation by making an  
 open-circuit impedance of said surface-acoustic-wave  
 filter substantially equal to a short-circuit impedance of  
 said surface-acoustic wave filter.

74. The surface-acoustic-wave filter of claim 73, further comprising a phase shifter coupled between said input terminal and said first series-arm surface-acoustic-wave resonator.

75. The surface-acoustic-wave filter of claim 73, wherein said impedance circuit comprises a first inductor.

76. The surface-acoustic-wave filter of claim 75, wherein said first inductor comprises a bonding wire having a certain inductive impedance.

77. The surface-acoustic-wave filter of claim 75, wherein said impedance circuit further comprises a first capacitor.

78. The surface-acoustic-wave filter of claim 77, wherein said first inductor and said first capacitor are coupled in parallel.

79. The surface-acoustic-wave filter of claim 78, wherein said impedance circuit further comprises a second inductor coupled in series to the first capacitor and the first inductor.

80. The surface-acoustic-wave filter of claim 77, wherein said first inductor and said first capacitor are coupled in series.

81. The surface-acoustic-wave filter of claim 80, wherein said impedance circuit further comprises a second capacitor coupled in parallel to said first capacitor and said first inductor.

82. The surface-acoustic-wave filter of claim 73, wherein said first and second shunt-arm surface-acoustic-wave resonators are coupled back-to-back, sharing a common central electrode.

83. The surface-acoustic-wave filter of claim 82, wherein said impedance circuit comprises a bonding wire attached to said common central electrode.

84. The surface-acoustic-wave filter of claim 73, further comprising a filter section cascaded with said surface-acoustic-wave filter.

85. The surface-wave filter of claim 84, wherein said filter section and said surface-acoustic-wave filter forms a surface-acoustic-wave ladder filter.

86. The surface-acoustic-wave filter of claim 73, further comprising a plurality of surface-acoustic-wave filters coupled in cascade.

87. The surface acoustic-wave filter of claim 73, further comprising another surface-acoustic-wave filter with poles, and another surface-acoustic-wave filter comprising:  
 third and fourth series-arm surface-acoustic-wave resonators coupled in series between said second series-arm surface-acoustic-wave resonator and said output terminal;  
 third and fourth shunt-arm surface-acoustic-wave resonators coupled respectively to said third and fourth series-arm surface-acoustic-wave resonators; and  
 a second impedance circuit having third and fourth ends, wherein said third end is coupled only to said third and fourth shunt-arm surface-acoustic-wave resonators and said fourth end is coupled to a ground terminal, wherein said second impedance circuit has a second impedance that creates a pole of attenuation by making an open-circuit impedance of said another surface-acoustic-wave filter substantially equal to a short-circuit impedance of said another surface-acoustic-wave filter.

88. A surface-acoustic-wave duplexer, comprising:  
 a receiver surface-acoustic-wave filter circuit; and  
 a transmitting surface-acoustic-wave filter circuit comprising:  
 first and second series-arm surface-acoustic-wave resonators coupled in series between an input terminal and an output terminal;

first and second shunt-arm surface-acoustic-wave resonators coupled respectively to said first and second series-arm surface-acoustic-wave resonators; and  
 a first impedance circuit having first and second ends, wherein said first end is coupled only to said first and second shunt-arm surface-acoustic-wave resonators and said second end is coupled to a ground terminal, wherein said first impedance circuit has a first impedance that creates a pole of attenuation by making an open-circuit impedance of said transmitting surface-acoustic-wave filter substantially equal to a short-circuit impedance of said transmitting surface-acoustic-wave filter.

89. The surface-acoustic-wave duplexer of claim 88, further comprising a first surface-acoustic-wave filter including:  
 third and fourth series-arm surface-acoustic-wave resonators coupled in series between second series-arm surface-acoustic-wave resonator and said output terminal;  
 third and fourth shunt-arm surface-acoustic-wave resonators coupled respectively to said third and fourth series-arm surface-acoustic-wave resonators; and  
 a second impedance circuit having third and fourth ends, wherein said third end is coupled only to said third and fourth shunt-arm surface-acoustic-wave resonators and said fourth end is coupled to a ground terminal, wherein said second impedance circuit has a second impedance that creates a pole of attenuation by making an open-circuit impedance of said first surface-acoustic-wave filter substantially equal to a short-circuit impedance of said first surface-acoustic-wave filter.

90. A surface-acoustic-wave filter comprising:  
 a first series-arm surface-acoustic-wave resonator having a first series-arm terminal coupled to receive an input signal and a second series-arm terminal;  
 a second series-arm surface-acoustic-wave resonator having a third series-arm terminal connected to said second series-arm terminal of said first series arm surface-acoustic-wave resonator and a fourth series-arm terminal;  
 a third series-arm surface-acoustic-wave resonator having a fifth series-arm terminal connected to said fourth series-arm terminal of said second series-arm surface-acoustic-wave resonator and a sixth series-arm terminal coupled to output an output signal;  
 a first shunt-arm surface-acoustic-wave resonator having a first shunt-arm terminal connected to said second series-arm terminal of said first series-arm surface-acoustic-wave resonator and a second shunt-arm terminal;  
 a second shunt-arm surface-acoustic-wave resonator having a third shunt-arm terminal connected to said fourth series-arm terminal of said second series-arm surface-acoustic-wave resonator and a fourth shunt-arm terminal connected to said second shunt-arm terminal of said first shunt-arm surface-acoustic-wave resonator; and  
 a first impedance circuit having a first terminal connected to said second shunt-arm terminal of said first shunt-arm surface-acoustic-wave resonator and a second terminal connected to a ground terminal, wherein said first terminal of said first impedance circuit is connected only to said second and fourth shunt-arm terminals of said first and second shunt-arm surface-

acoustic-wave resonators, and wherein said first impedance circuit has a first impedance that creates a pole of attenuation by making an open-circuit impedance of said surface-acoustic-wave filter substantially equal to a short-circuit impedance of said surface-acoustic-wave filter. 5

91. The surface-acoustic-wave filter according to claim 90, further comprising:

an input terminal receiving the input signal; and  
a phase shifter connected between said input terminal and said first series-arm terminal of said first series-arm surface-acoustic-wave resonator. 10

92. The surface-acoustic-wave filter according to claim 90, wherein said first impedance circuit comprises a first inductor. 15

93. The surface-acoustic-wave filter according to claim 92, wherein said first inductor is a bonding wire connected between said second shunt-arm terminal of said first shunt-arm surface-acoustic-wave resonator, said bonding wire having a certain inductive impedance. 20

94. The surface-acoustic-wave filter according to claim 92, wherein said first impedance circuit further comprises a first capacitor.

95. The surface-acoustic-wave filter according to claim 94, wherein said first inductor and said first capacitor are connected in parallel. 25

96. The surface-acoustic-wave filter according to claim 95, wherein said first impedance circuit further comprises a second inductor connected in series to said first capacitor and said first inductor. 30

97. The surface-acoustic-wave filter according to claim 94, wherein said first inductor and said first capacitor are connected in series.

98. The surface-acoustic-wave filter according to claim 97, wherein said first impedance circuit further comprises a second capacitor coupled in parallel to said first capacitor and said first inductor. 35

99. The surface-acoustic-wave filter according to claim 90, wherein said first and second shunt-arm surface-acoustic-wave resonators have a common central electrode. 40

100. The surface-acoustic-wave filter according to claim 99, wherein said first impedance circuit is a bonding wire connected to said common central electrode.

101. The surface-acoustic-wave filter according to claim 90, further comprising:

a third shunt-arm surface-acoustic-wave resonator having a fifth shunt-arm terminal connected to said sixth series-arm terminal of said third series-arm surface-acoustic-wave resonator and a sixth shunt-arm terminal; and

a second impedance circuit having a third terminal connected to said sixth shunt-arm terminal of said third shunt-arm surface-acoustic-wave resonator and a fourth terminal connected to said ground terminal. 45

102. A surface-acoustic-wave duplexer, comprising:

a receiving surface-acoustic-wave filter circuit; and  
a transmitting surface-acoustic-wave filter circuit comprising:

a first series-arm surface-acoustic-wave resonator having a first series-arm terminal coupled to receive an input signal and a second series-arm terminal;

a second series-arm surface-acoustic-wave resonator having a third series-arm terminal connected to said second series-arm terminal of said first series-arm surface-acoustic-wave resonator and a fourth series-arm terminal; 50

a third series-arm surface-acoustic-wave resonator having a fifth series-arm terminal connected to said fourth series-arm terminal of said second series-arm surface-acoustic-wave resonator and a sixth series-arm terminal coupled to output an output signal;

a first shunt-arm surface-acoustic-wave resonator having a first shunt-arm terminal connected to said second series-arm terminal of said first series-arm surface-acoustic-wave resonator and a second shunt-arm terminal;

a second shunt-arm surface-acoustic-wave resonator having a third shunt-arm terminal connected to said fourth series-arm terminal of said second series-arm surface-acoustic-wave resonator and a fourth shunt-arm terminal connected to said second shunt-arm terminal of said first shunt-arm surface-acoustic-wave resonator; and

a first impedance circuit having a first terminal connected to said second shunt-arm terminal of said first shunt-arm surface-acoustic-wave resonator and a second terminal connected to a ground terminal, wherein said first terminal of said first impedance circuit is connected only to said second and fourth shunt-arm terminals of said first and second shunt-arm surface-acoustic-wave resonators, and wherein said first impedance circuit has a first impedance that creates a pole of attenuation by making an open circuit impedance of said transmitting surface-acoustic-wave filter substantially equal to a short-circuit impedance of said transmitting surface-acoustic-wave filter. 55

103. The surface-acoustic-wave duplexer according to claim 102, further comprising:

an input terminal receiving the input signal; and

a phase shifter connected between said input terminal and said first series-arm terminal of said first series-arm surface-acoustic-wave resonator. 60

104. The surface-acoustic-wave duplexer according to claim 102, wherein said first impedance circuit comprises a first inductor.

105. The surface-acoustic-wave duplexer according to claim 104, wherein said first inductor is a bonding wire connected between said second shunt-arm terminal of said first shunt-arm surface-acoustic-wave resonator, said bonding wire having a certain inductive impedance.

106. The surface-acoustic-wave duplexer according to claim 104, wherein said first impedance circuit further comprises a first capacitor. 55

107. The surface-acoustic-wave duplexer according to claim 106, wherein said first inductor and said first capacitor are connected to parallel.

108. The surface-acoustic-wave duplexer according to claim 107, wherein said first impedance circuit further comprises a second inductor connected in series to said first capacitor and said first inductor.

109. The surface-acoustic-wave duplexer according to claim 106, wherein said first inductor and said first capacitor are connected in series.

110. The surface-acoustic-wave duplexer according to claim 109, wherein said first impedance circuit further comprises a second capacitor coupled in parallel to said first capacitor and said first inductor.

111. The surface-acoustic-wave duplexer according to claim 102, wherein said first and second shunt-arm surface-acoustic-wave resonators have a common central electrode. 65

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112. The surface-acoustic-wave duplexer according to claim 111, wherein said impedance circuit is a bonding wire connected to said common central electrode.

113. The surface-acoustic-wave duplexer according to claim 102, further comprising:

a third shunt-arm surface-acoustic-wave resonator having a fifth shunt-arm terminal connected to said sixth series-arm terminal of said third series-arm surface-

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acoustic-wave resonator and a sixth shunt-arm terminal; and

a second impedance circuit having a third terminal connected to said sixth shunt-arm terminal of said third shunt-arm surface-acoustic-wave resonator and a fourth terminal connected to said ground terminal.

\* \* \* \* \*