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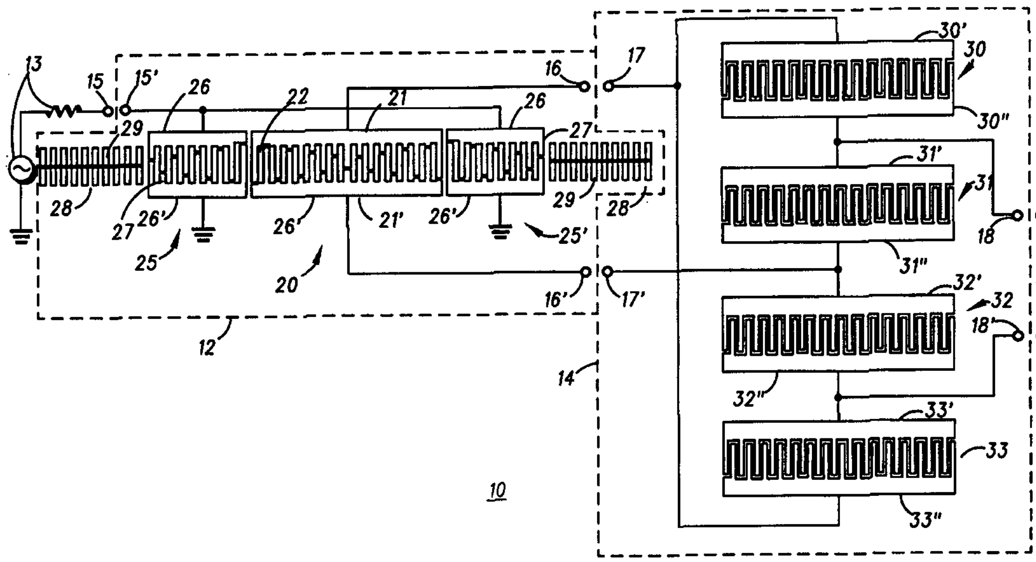
(54) Title: INLINE–COUPLED RESONATOR WITH LATTICE FILTER AND METHOD



(57) Abstract

An acoustic wave filter (10) made by the steps of providing a suitable substrate and processing the substrate to provide a lattice filter (14) having balanced electrical input (17, 17') and output (18, 18') circuits and an inline coupled resonator filter (12), disposed thereon. The processing step further includes steps of (i) disposing a first transducer (20) having a balanced electrical output (16, 16') on the substrate, (ii) disposing a second transducer (25) including an unbalanced electrical input circuit (15') at a first acoustic aperture of the first transducer (20), wherein the second tranducer (25) is acoustically coupled to the first transducer (20) and the first (20) and second (25) transducers comprise the inline coupled resonator filter (12) and (iii) disposing interconnections between the first transducer (20) and the lattice filter (14) to provide a balanced electrical output signal from the first transducer to the balanced electrical input of the lattice filter (14).

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INLINE-COUPLED RESONATOR WITH LATTICE FILTER AND METHOD

Field of the Invention

This invention relates in general to the field of frequency selection components, in particular to surface acoustic wave frequency selection components and more particularly to an improved filter using surface acoustic wave frequency selection components that also is capable of operating with balanced or unbalanced input(s) and/or output(s).

Background of the Invention

There is an ongoing need for component miniaturization in radio wave communication devices. For example, smaller and more efficient components are needed for light-weight, hand-portable cellular telephones, wireless local area networks for linking computer systems within office buildings in a readily reconfigurable fashion, wristwatch- and credit-card-sized paging apparatus and other devices for promoting rapid, efficient and flexible voice and data communication.

Filters are needed for a variety of such communications applications wherein small size, light weight and high performance are simultaneously required. Increasing numbers of products seek to employ fixed spectral resources, often to achieve tasks not previously envisioned. Examples include cellular telephones, inter- and intra-facility computer-computer and/or computer-ancillary equipment linkages as well as a host of other, increasingly complex inter-personal and/or -equipment information sharing requirements. The desire to render increasingly complicated communications nodes portable and even hand-held and/or -portable and/or pocket-sized places extreme demands on filtering technology in the context of increasingly crowded radio frequency resources.

Acoustic wave devices provide filters meeting stringent performance requirements, which filters are (i) extremely robust, (ii) readily mass produced, (iii) adjustment-free over the life of the unit and (iv) which sharply increase the performance-to-size ratio achievable in the frequency range extending from a few tens of megahertz to about several gigahertz. However, need for low passband insertion loss simultaneously coupled with demand for high shape factor and high stopband attenuation pose filter design and performance requirements not easily met by a single acoustic wave filter alone. These problems are exacerbated when it is desirable to couple such a filter between balanced and unbalanced circuitry.

One approach to satisfying these needs and demands is to cascade two or more acoustic wave filters. This approach realizes increased stopband signal rejection but requires additional matching components (e.g., inductors and/or capacitors) and also multiplies the volume and weight of the acoustic wave filters by the number of such filters cascaded, especially when each filter is separately realized, impedance matched and packaged. Matching components additionally incur major size and weight penalties because each transducer generally requires at least two matching components, each of which is at least as large as an acoustic wave filter die.

Another approach is to provide two or more such filters on a single substrate, wherein the filters are designed to have purely real impedances matched one to another without requiring intervening matching components. One realization includes a cross-coupled arrangement of resonant elements having staggered center frequencies and arranged in a lattice structure, i.e., a structure known as a "lattice filter" and comprising cascaded sections, each including two series resonant elements together with two cross-coupled resonant elements.

Acoustic wave filters including lattice filters formed from groupings of resonators employ generally periodic arrays of electrodes configured to provide discrete elements such as transducers (for converting electrical to mechanical energy and vice versa), optional reflectors (for reversing the direction of propagation of an acoustic wave) and optional gaps for separating transducers and reflectors. These elements are grouped in a generally in-line configuration (e.g., reflector, gap, transducer, gap, reflector) along a principal axis of acoustic wave propagation on a suitable substrate material, with the entire array providing an electrical filtering function associated with the electrical port(s) of the individual transducer(s) and/or the composite filter.

Lattice filters generally are able to provide wide bandwidth and can provide very good stopband attenuation. However, lattice filters must operate in a balanced or differential configuration.

Inline coupled resonators, in which filtering is achieved via a plurality of transducers and in which acoustic waves travel from one transducer to another, can provide sharply selective filtering functions but are limited in terms of the out-of-band rejection that is achievable when designed for wide passband width operation, in comparison to lattice filters designed for wide passband bandwidth. The acoustic propagation between transducers results in higher filter insertion loss than is necessarily the case for lattice filters. However, inline coupled resonators are capable of operation with unbalanced input(s) and/or output(s) and may be designed to accommodate either or both.

Baluns, or balanced-to-unbalanced transformers, are known and might be used to provide this function. However, these are not readily realized in monolithic form and accordingly tend to be relatively large. Additionally, they may incur additional insertion loss, which is highly undesirable.

What is needed is an acoustic wave filter configuration/design methodology providing flexible bandwidth, suitable out-of-band rejection and low in-band insertion loss, drift-free performance and realizable in compact, robust and, desirably, in monolithic form, which can provide the advantages of balanced lattice filters in an environment in which at least one port is unbalanced.

Brief Description of the Drawings

FIG. 1 is a graph of simulated responses for a SAW ladder filter (dashed trace) and a SAW lattice filter (solid trace) using the same transducer designs, showing differences in in-band and out-of-band responses for the two filter types;

FIG. 2 is a simplified plan view of a first embodiment of an acoustic wave filter in accordance with the teachings of the present invention;

FIG. 3 is a simulation of a frequency response for the first embodiment of the present invention;

FIG. 4 is a simplified block diagram of a second embodiment of an acoustic wave filter in accordance with the teachings of the present invention; and

FIG. 5 is a block diagram of a portion of a radio frequency apparatus including acoustic wave filters in accordance with the present invention.

Detailed Description of the Preferred Embodiment

FIG. 1 is a graph of simulated responses for a SAW ladder filter (dashed trace) 7, 8 and a SAW lattice filter (solid trace) 9 using the same transducer designs, showing differences in in-band and out-of-band responses for the two filter types. Each of the simulated filters employs eight SAW resonators with the eight for the lattice filter being identical to the eight for the ladder filter. The ladder filter inband response 7 has sharper cutoff skirts, slightly greater inband insertion loss and slightly less bandwidth than the lattice filer response 9. However, the ladder filter also includes flyback out-of-band rejection characteristics 8 that are not part of response 9 for the lattice filter. The level of flyback response 8 is determined by the capacitance ratio of the series to the shunt transducers in the ladder filter, which act as a simple voltage divider in the out-of-band area, setting a bound for out-of-band rejection achievable by the ladder configuration.

Lattice filter response 9 does not have this inherent limitation that is found with ladder filters, provides improvement in insertion loss and also provides a slightly greater bandwidth, but a lattice filter requires balanced input and output terminals, which are not required by ladder filters and which are not readily accommodated in many types of radio designs. Accordingly, it is desirable in some cases to obtain the benefits of lattice filter response characteristics but from a system that requires an unbalanced input or output configuration.

FIG. 2 is a simplified plan view of first embodiment 10 of an acoustic wave filter in accordance with the teachings of the present invention. First embodiment 10 provides the advantages of lattice filter 14 but also includes unbalanced input port 15' intended to allow coupling of filter 10 to unbalanced signal generator or signal source 13. First embodiment 10 also includes balanced output terminals 18, 18' that couple to load 11 via terminals 19, 19'.

Applicants have discovered that unbalanced input terminal 15' may be coupled to balanced input terminals 17, 17' of lattice filter 14 via inline coupled resonator filter 12. Inline coupled resonator filter 12 is usefully designed to reduce insertion losses normally associated with coupled resonator filter acoustic propagation losses and is also usefully designed to avoid passband shaping of composite filter 10 frequency response, i.e., coupled resonator 12 is broader in passband bandwidth than is lattice filter 14.

Inline coupled resonator 12 comprises at least one input transducer 25 and preferably two input transducers 25, 25' disposed so as to form an acoustic cavity surrounding transducer 20. Transducer 25 or transducers 25, 25' acoustically couple to transducer 20 via adjacently disposed and aligned acoustic ports or apertures. Transducer 20 comprises fingers or electrodes 22 alternately coupled to bus bars 21, 21' and provides a differential or balanced signal between bus bars 21, 21' when electrodes 22 are insonified (i.e., irradiated with acoustic energy) of an appropriate frequency, wavelength and propagation direction, which acoustic energy derives from electrical signals from signal source 13 that are coupled via bus bars 26, 26' to electrodes 27 comprising transducer 25 or transducers 25, 25'.

Optional reflectors 28 disposed to either end of the acoustic cavity (i.e.. outside of transducers 25, 25', 20) comprising reflection elements 29 may be employed to reduce leakage of acoustic energy from inline coupled resonator 12 and thereby improve inband insertion loss characteristics of both inline coupled resonator 12 and filter 10.

Lattice filter section 14 is formed by disposing first 30, second 31, third 32 and fourth 33 resonators comprising a stage of lattice filter 14 on the substrate. It will be understood that multiple lattice filter sections may be cascaded but this discussion will be in terms of a single section for ease and clarity of explanation and understanding. Each of first 30, second 31, third 32 and fourth 33 resonators includes a pair of bus bars 30', 30"; 31', 31"; 32', 32"; 33', 33", respectively, and a group of finger electrodes disposed therebetween, wherein one bus bar 30', 33" of each of the first 30 and fourth 33 resonators are coupled to first side 17 of the balanced electrical input of said lattice filter 14, one bus bar 31", 32' of each of second 31 and third 32 resonators is coupled to a second side 17' of said balanced electrical input of said lattice filter 14, another bus bar 30", 31' of first 30 and second 31 resonators is coupled to first side 18 of said balanced electrical output of lattice filter 14 and another bus bar 32", 33' of said third 32 and fourth 33 resonators is coupled to a second side 18' of said balanced electrical output of said lattice filter.

Typically, transducers 25, 25', 20, 30, 31, 32, 33, optional reflectors 28 and related features are manufactured by vacuum deposition and photolithographic processes similar to those employed in manufacturing integrated circuitry, on a suitably-prepared surface of a piezoelectric material such as $LiNbO_3$, $LiTaO_3$, $LiBO_4$ (lithium tetraborate) or SiO_2 or the like.

Examples of orientations of such substrata include ST-cut quartz, 128° $LiNbO_3$, 41° $LiNbO_3$, 64° $LiNbO_3$ and 36° $LiTaO_3$, among others.

FIG. 3 is a simulation of frequency response 35 for the first embodiment of the present invention. Frequency response 35 does not include flyback responses 8 of ladder filter response 7, 8 of FIG. 1 and does include a main lobe at a frequency of about a gigahertz, having skirt characteristics similar to those of response 9 of FIG. 1.

FIG. 4 is a simplified block diagram of second embodiment 40 of an acoustic wave filter in accordance with the teachings of the present invention. Second embodiment 40 has the properties of lattice filter 14 with the exception that both input 15' and output 15" are unbalanced. Lattice filter 14 has inputs 17, 17' coupled to outputs 16, 16', respectively, of inline resonator filter 12, analogous to the arrangement of FIG. 2. Lattice filter 14 has output terminals 18, 18' coupled to input terminals 16, 16', respectively, of output inline resonator filter 12', much like a mirror image of inline filter 12 and lattice filter 14 of FIG. 2. Inline coupled resonator filters 12, 12' perform the balanced-to-unbalanced conversions needed to interface lattice filter 14 to unbalanced input and output circuitry and do so without requiring baluns or transformers, providing a single, monolithic component having the filtering characteristics of lattice filters and including input and output characteristics analogous to those of ladder filters, when inline resonator filters 12, 12' are designed in accordance with the criteria outlined supra with respect to FIG. 2 and associated text.

Example

FIG. 5 is a block diagram of portion 1200 of a communications apparatus including one or more microfabricated devices, represented in this example by acoustic wave filters, packaged in accordance with the present invention. Apparatus

1200 includes antenna 1201 and antenna lead 1204, by way of example, employed to receive and/or transmit signals.

Alternatively, antenna 1201 and antenna lead 1204 may replaced by a fiber-optic link or a cable or other signal transmissive media. Diplexer 1209 is coupled to antenna 1201 and antenna lead 1204 and to a transmitter portion (not shown). Diplexer 1209 couples received signals to filter 1215 via lead 1212. Filter 1215 is coupled to amplifier 1227 via lead 1226. In the event that portion 1200 corresponds to a receive-only radio (e.g., pager), diplexer 1209 may not be required and antenna 1201 may be coupled directly or through signal-conditioning circuitry to filter 1215 and thence to amplifier 1227.

The output of amplifier 1227 is coupled to filter 1239 via lead 1233. Filter 1239 has an output coupled to a first input of mixer 1265 via lead 1242. The output signal from filter 1239 is combined with a local oscillator signal in mixer 1265.

The local oscillator signal originates in local oscillator 1244 and is coupled to filter 1255 via lead 1249. The output signal from filter 1255 is coupled via lead 1259 to a second input of mixer 1265. The output signal from mixer 1265 is coupled via lead 1271 to filter 1277 to provide an intermediate frequency or IF output signal via lead 1280.

Diplexer 1209, filter 1215, filter 1239, filter 1255 and/or filter 1277 may comprise acoustic wave filters packaged in accordance with the present invention.

Thus, an acoustic wave filter has been described which overcomes specific problems and accomplishes certain advantages relative to prior art methods and mechanisms. The improvements over known technology are significant. The complexities and higher parts count of some forms of prior art devices are avoided. Similarly, advantageous filter characteristics are provided together with flexibility in the input and/or output configuration.

The foregoing description of the specific embodiments will so fully reveal the general nature of the invention that others can, by applying current knowledge, readily modify and/or adapt for various applications such specific embodiments without departing from the generic concept, and therefore such adaptations and modifications should and are intended to be comprehended within the meaning and range of equivalents of the disclosed embodiments.

It is to be understood that the phraseology or terminology employed herein is for the purpose of description and not of limitation. Accordingly, the invention is intended to embrace all such alternatives, modifications, equivalents and variations as fall within the broad scope of the appended claims.

CLAIMS

1. An acoustic wave filter (10) comprising:
a substrate that is an acoustic wave propagating substrate;
a lattice filter (14) having a balanced electrical input circuit (17,17') and a balanced electrical output circuit (18,18') disposed on said substrate; and
an inline coupled resonator filter (12) disposed on said substrate.

2. The acoustic wave filter (10) of claim 1, wherein said inline coupled resonator filter (12) comprises:
a first transducer (20) disposed on said substrate, said first transducer (20) having a balanced electrical output (16,16');
a second transducer (25) disposed at a first acoustic aperture of said first transducer (20), said second transducer (25) including an unbalanced electrical input circuit (15'), said second transducer (25) acoustically coupled to said first transducer (20), said first and second transducers (20,25) comprising said inline coupled resonator filter (12); and
interconnections disposed between said first transducer (20) and said lattice filter (14) to provide a balanced electrical output signal from said first transducer (20) to said balanced electrical input (17,17') of said lattice filter (14).

3. The acoustic wave filter (10) of claim 1, wherein said inline coupled resonator filter (12) comprises:

a first transducer (20) disposed on said substrate, said first transducer (20) having a balanced electrical output (16,16');

a second transducer (25) disposed at a first acoustic aperture of said first transducer (20), said second transducer (25) including an unbalanced electrical input circuit (15'), said second transducer (25) acoustically coupled to said first transducer (20);

a third transducer (25') disposed at a second acoustic aperture of said first transducer (20), said third transducer (25') including an unbalanced electrical input circuit (15'), said third transducer (25') acoustically coupled to said first transducer (20), said first, second and third transducers (25,20,25') comprising said inline coupled resonator filter (12); and

interconnections disposed between said first transducer (20) and said lattice filter (14) to provide a balanced electrical output signal from said first transducer (20) to said balanced electrical input (17,17') of said lattice filter (14).

4. The acoustic wave filter of claim 1, wherein said acoustic wave filter comprises:

a first transducer (20) disposed on said substrate, said first transducer (20) having a balanced electrical output (16,16');

a second transducer (25) disposed at a first acoustic aperture of said first transducer (20), said second transducer (25) including an unbalanced electrical input circuit (15'), said second transducer (25) acoustically coupled to said first transducer (20), said first and second transducers (20,25) comprising said inline coupled resonator filter (12);

first, second, third and fourth resonators (30,31,32,33) comprising a stage of said lattice filter (14) disposed on said substrate, each of said first, second, third and fourth resonators (30,31,32,33) including a pair of bus bars (30',30";31',31";32',32";33',33") and a group of finger electrodes disposed therebetween, wherein one bus bar (30',33") of each of said first and fourth resonators (30,33) are coupled to a first side (17) of said balanced electrical input (17,17') of said lattice filter (14), one bus bar (31",32') of each of said second and third resonators (31,32) is coupled to a second side (17') of said balanced electrical input (17,17') of said lattice filter (14), another bus bar (30",31') of each of said first and second resonators (30,31) is coupled to a first side (18) of said balanced electrical output (18,18') of said lattice filter (14) and another bus bar (32",33') of each of said third and fourth resonators (32,33) is coupled to a second side (18') of said balanced electrical output (18,18') of said lattice filter (14); and

interconnections disposed between said first transducer (20) and said lattice filter (14) to provide a balanced electrical output signal from said first transducer (20) to said balanced electrical input (17,17') of said lattice filter (14).

5. The acoustic wave filter (10) of claim 1, wherein said acoustic wave filter (10) comprises:

a first transducer (20) disposed on said substrate, said first transducer (20) having a balanced electrical output (16,16');

a second transducer (25) disposed at a first acoustic aperture of said first transducer (20), said second transducer (25) including an unbalanced electrical input circuit (15'), said second transducer (25) acoustically coupled to said first transducer (20);

a third transducer (25') disposed at a second acoustic aperture of said first transducer (20), said third transducer (25') including an unbalanced electrical input circuit (15'), said third transducer (25') acoustically coupled to said first transducer (20), said first, second and third transducers (25,20,25') comprising said inline coupled resonator filter (12);

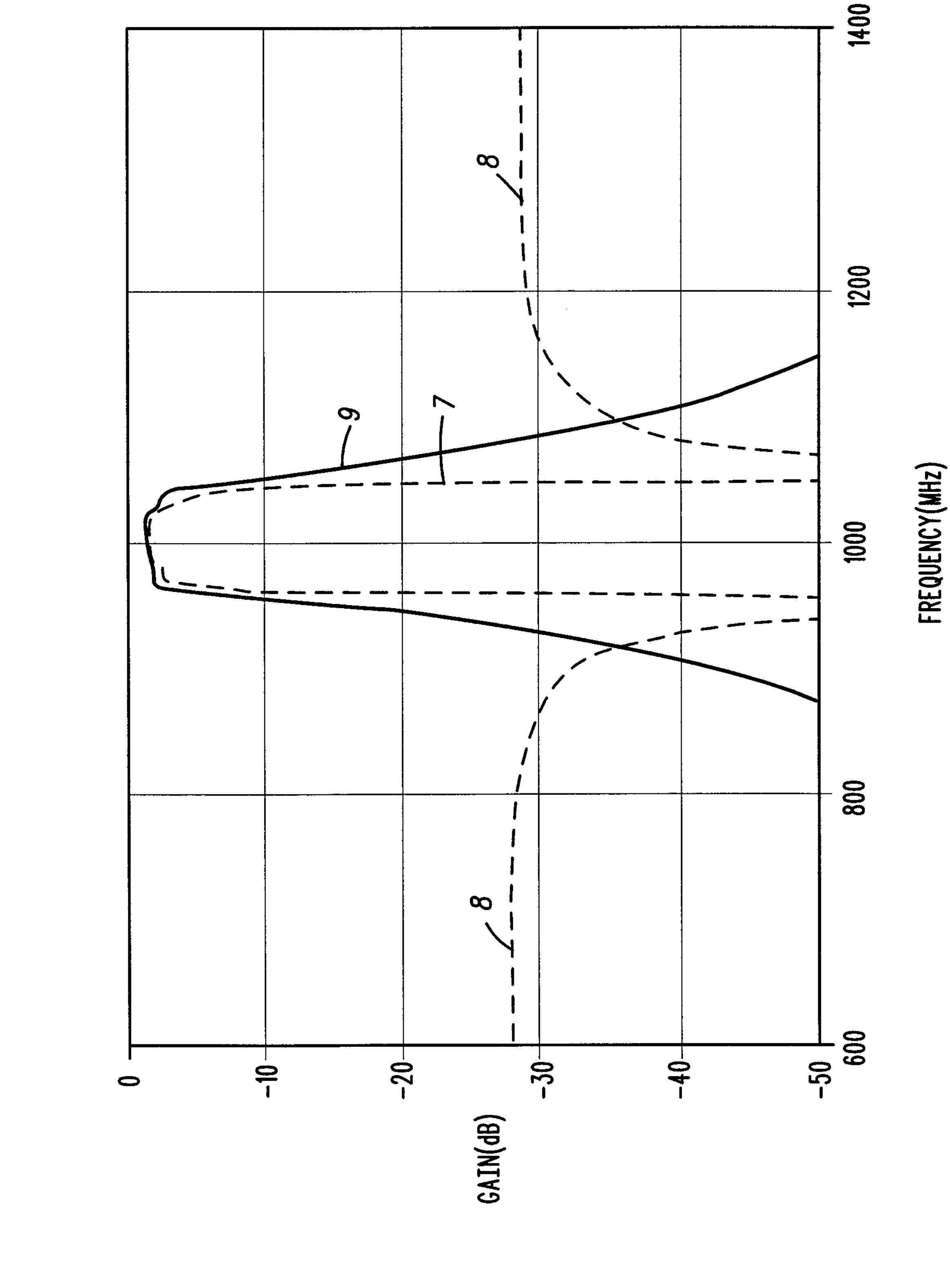
first, second, third and fourth resonators (30,31,32,33) comprising a stage of said lattice filter (14) disposed on said substrate, each of said first, second, third and fourth resonators (30,31,32,33) including a pair of bus bars (30',30";31',31";32',32";33',33") and a group of finger electrodes disposed therebetween, wherein one bus bar (30',33") of each of said first and fourth resonators (30,33) are coupled to a first side (17) of said balanced electrical input (17,17') of said lattice filter (14), one bus bar (31",32') of each of said second and third resonators (31,32) is coupled to a second side (17') of said balanced electrical input (17,17') of said lattice filter (14), another bus bar (30",31') of each of said first and second resonators (30,31) is coupled to a first side (18) of said balanced electrical output (18,18') of said lattice filter (14) and another bus bar (32",33') of each of said third and fourth resonators (32,33) is coupled to a second side (18') of said balanced electrical output (18,18') of said lattice filter (14); and

interconnections disposed between said first transducer (20) and said lattice filter (14) to provide a balanced electrical output signal from said first transducer (20) to said balanced electrical input (17,17') of said lattice filter (14).

6. The acoustic wave filter (10) of claim 1, wherein said inline coupled resonator filter (12) includes an inline coupled resonator filter (12) having a bandwidth greater than a bandwidth of said lattice filter (14).

7. The acoustic wave filter (10) of claim 1, further including another inline coupled resonator filter disposed on said substrate.

8. The acoustic wave filter of claim 7, wherein said inline coupled resonator filter (12) comprises:
a first transducer (20) disposed on said substrate, said first transducer (20) having a balanced electrical output (16,16');
a second transducer (25) disposed at a first acoustic aperture of said first transducer (20), said second transducer (25) including an unbalanced electrical input circuit (15'), said second transducer (25) acoustically coupled to said first transducer (20), said first and second transducers (20,25) comprising said inline coupled resonator filter (12); and
interconnections disposed between said first transducer (20) and said lattice filter (14) to provide a balanced electrical output signal from said first transducer (20) to said balanced electrical input (17,17') of said lattice filter (14); and wherein said another inline coupled resonator filter comprises:
another first transducer disposed on said substrate, said another first transducer having a balanced electrical input;
another second transducer disposed at a first acoustic aperture of said another first transducer, said another second transducer including an unbalanced electrical output circuit, said another second transducer acoustically coupled to said another first transducer, said another first and another second transducers comprising said another inline coupled resonator filter; and said acoustic wave filter (10) comprises:
interconnections disposed between said another first transducer and said lattice filter (14) to provide a balanced electrical input signal to said another first transducer from said balanced electrical output (18,18') of said lattice filter (14).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600
800
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1200
1400
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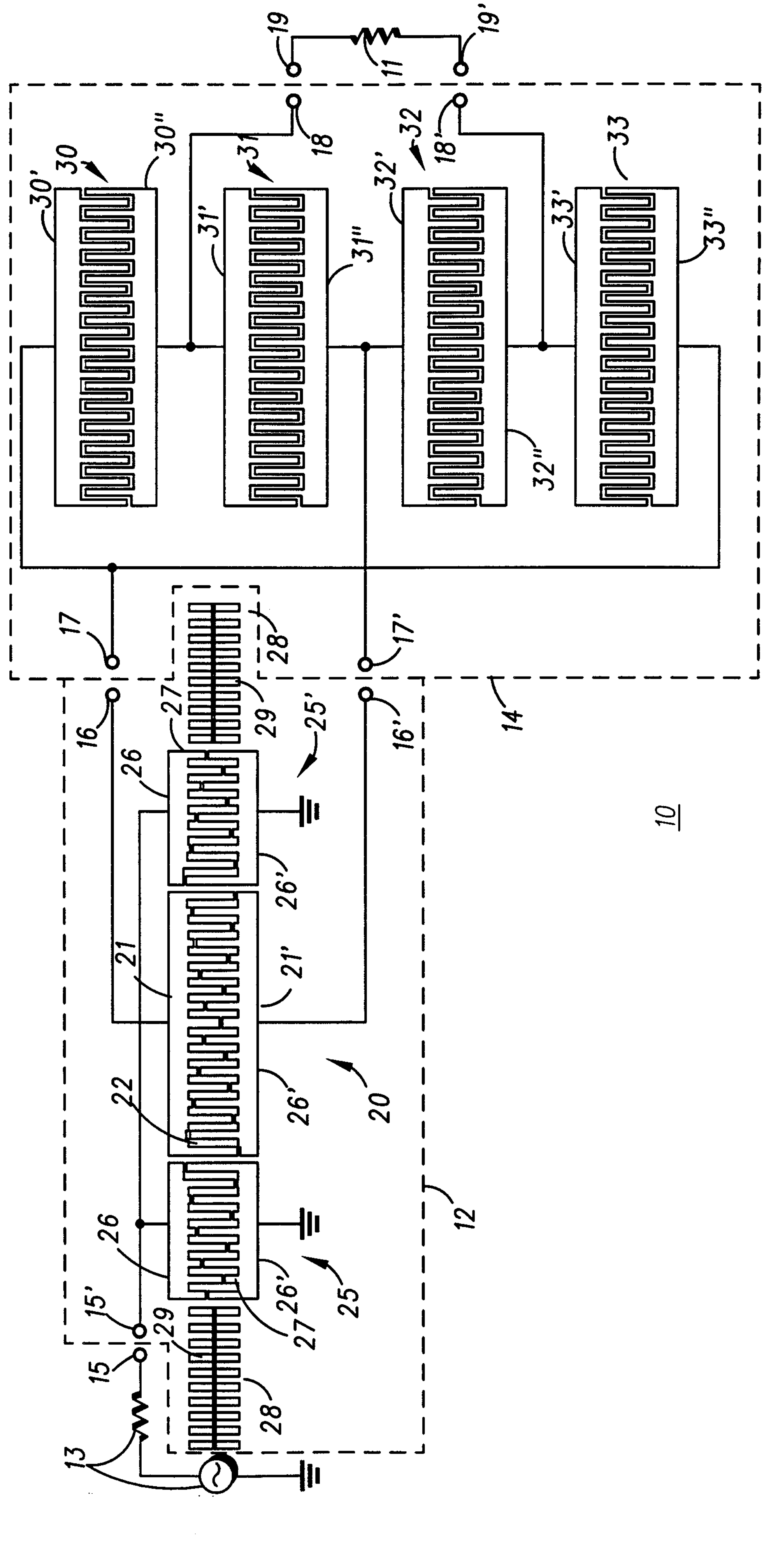
7
8
8

FIG.1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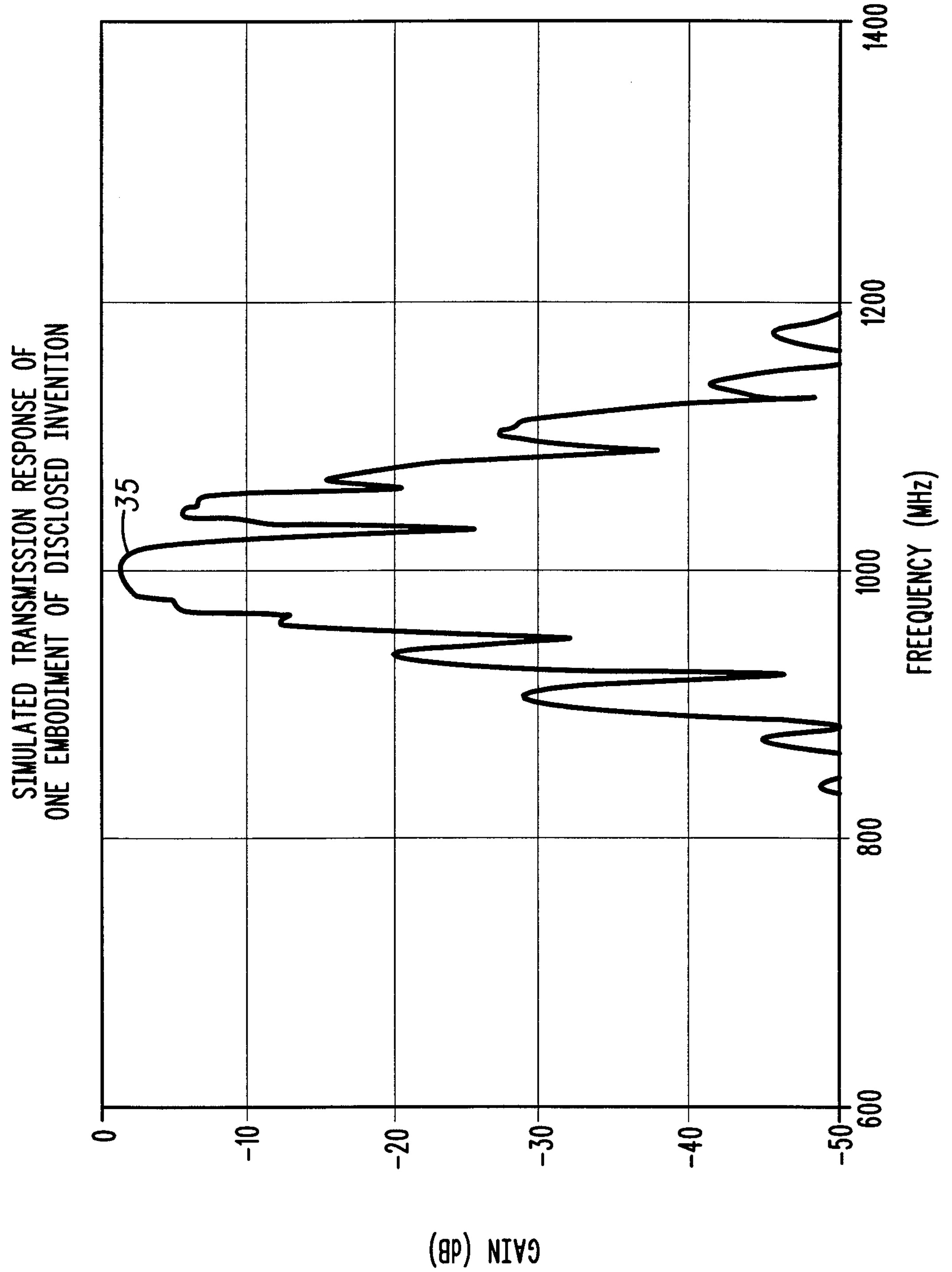
15'
13
10

FIG.2


SIMULATED TRANSMISSION RESPONSE OF
ONE EMBODIMENT OF DISCLOSED INVENTION
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GAIN (dB)
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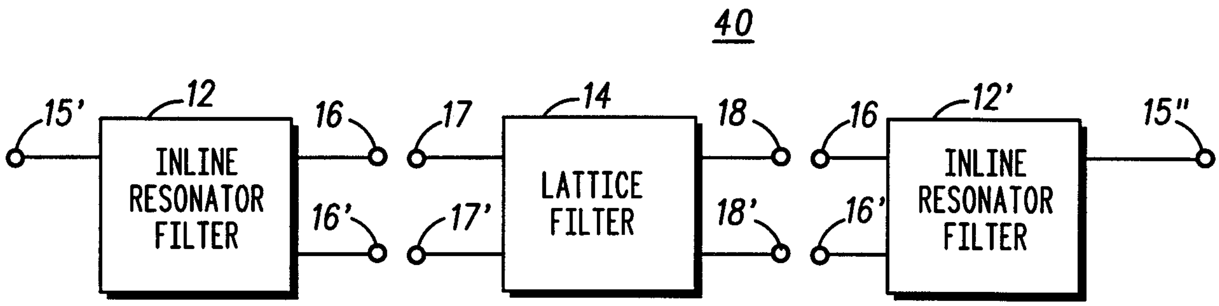
-30
-40
-50
600
800
1000
1200
1400
FREQUENCY (MHz)

FIG. 3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RESONATOR
FILTER
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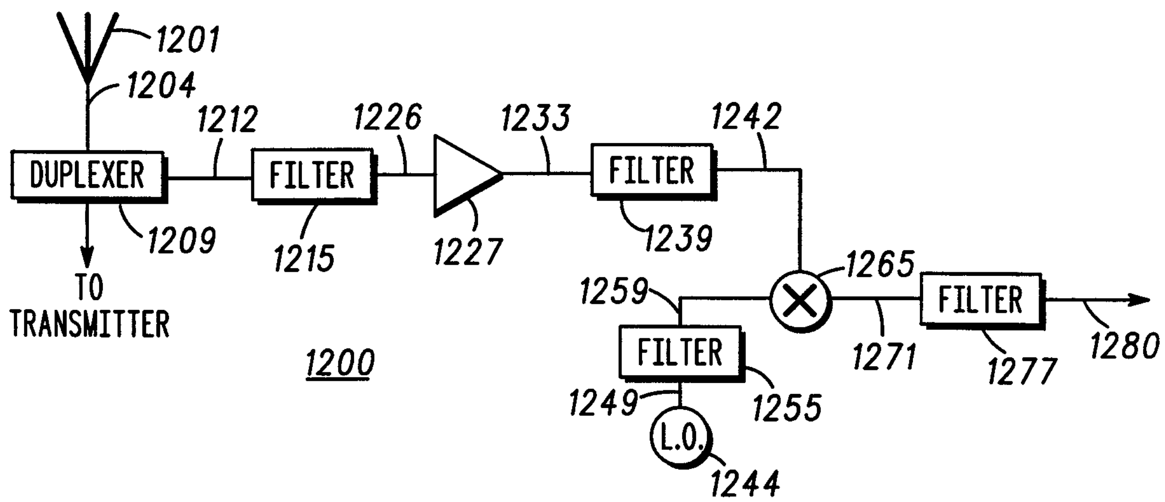
FIG.4


1201
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TO
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1239
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1265
1259
FILTER
1249
L.O.
1244
1255
1271
FILTER
1277
1280
1200

FIG.5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/21361

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H03H 9/64
US CL :333/193, 194; 310/313R, 313B
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 333/193, 194, 195, 196; 310/313R, 313B, 313C, 313D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

U.S. PTO APS
search terms: surface acoustic wave, acoustic wave, surface wave, filter, and lattice or bridge.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:	
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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	SHARIF et al. 'Coupled Resonator Filters With Differential Input And/Or Differential Output.' In: 1995 IEEE Ultrasonics Symposium Proceedings. Edited by M. Levy et al. New York: IEEE, 1995, Vol. 1, p. 67-70.	1-8