United States Patent

[11] 3,596,212

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[21] Appl. No. **874,629**
[22] Filed **Nov. 6, 1969**
[45] Patented **July 27, 1971**

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[32] Priority **Nov. 19, 1968**
[33] **Great Britain**
[31] **54,791/68**

[54] **ELECTRICAL BAND-PASS FILTER EMPLOYING MONOLITHIC CRYSTALS**
10 Claims, 5 Drawing Figs.

[52] **U.S. Cl.** **333/72,** 310/8.2, 310/9.4
[51] **Int. Cl.** **H03h 7/10**
[50] **Field of Search** 333/72; 310/8.1, 8.2, 9.1, 9.4, 9.8

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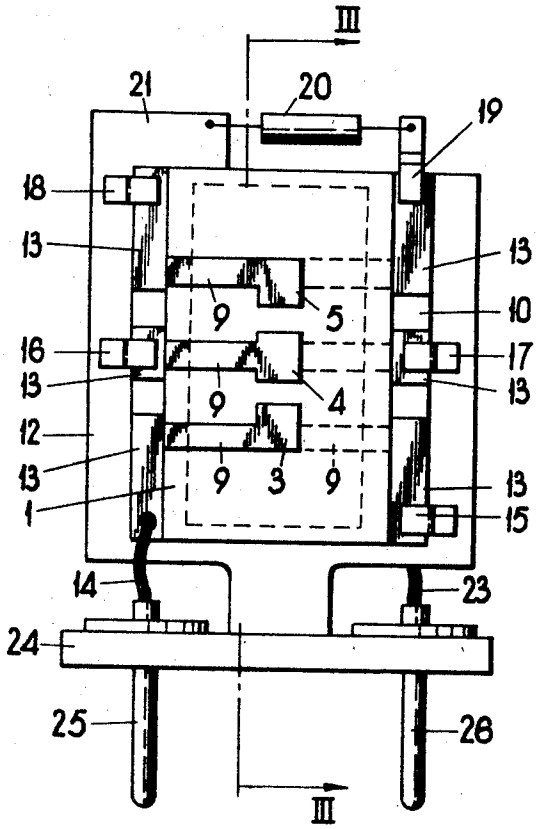
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ABSTRACT: An electrical band-pass filter comprising two quartz slabs each slab having at least two pairs of electrodes each of which pairs sandwiches a portion of the slab to form a mechanical resonator. The resonators are coupled together in a series, adjacent resonators on the same slab being coupled together mechanically, via the material of the slab, and adjacent resonators on different slabs being coupled together electrically, via a capacitor. The construction is effectively a monolithic crystal filter which has been divided into two halves. This reduces mechanical coupling between the input and output of the filter, and thus improves the stop-band performance of the filter. The slabs have different thicknesses and different electrode geometries, thus ensuring that unwanted resonances in the two slabs are at different frequencies. The slabs are mounted back-to-back on a conducting screen which electrically shields the slabs from each other. The filter is designed as a whole to have a Chebyshev-type response.



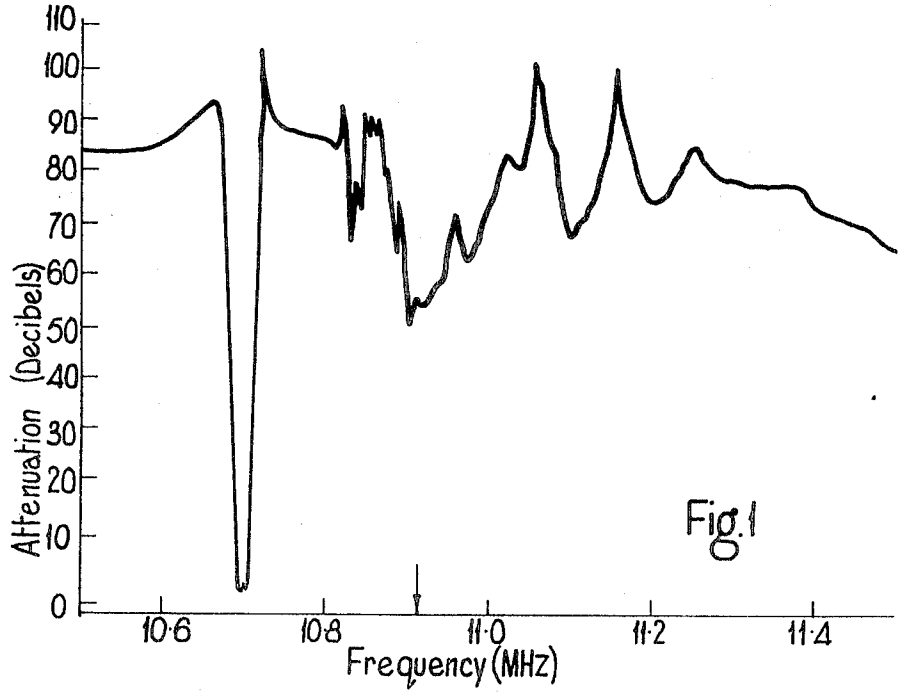


Fig.1

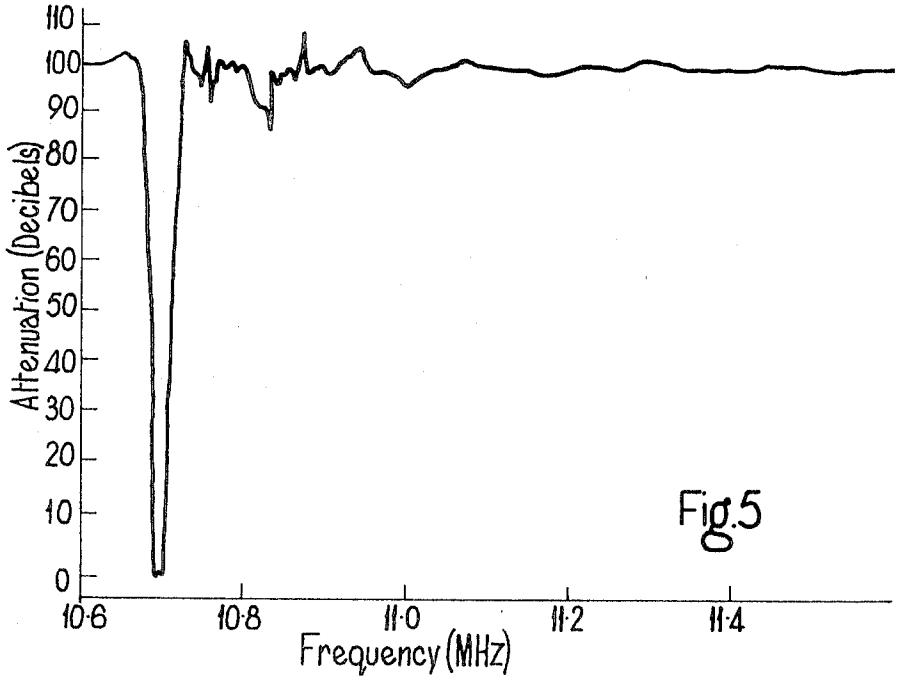


Fig.5

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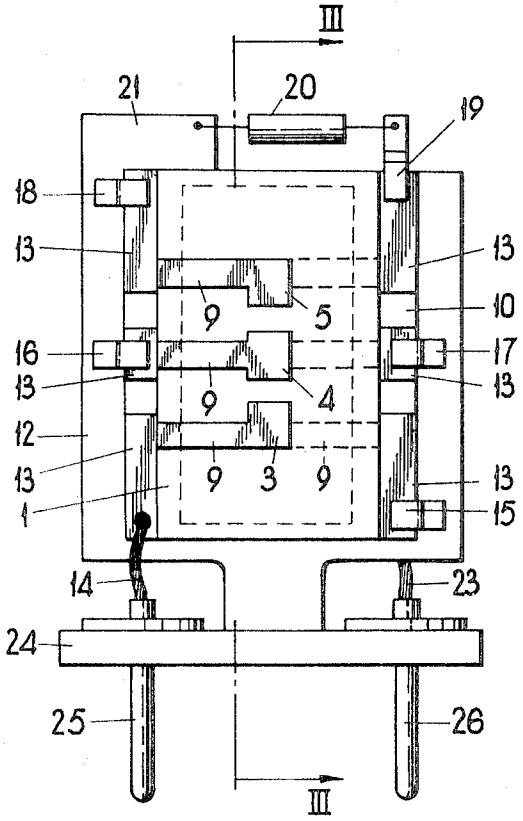


Fig.2

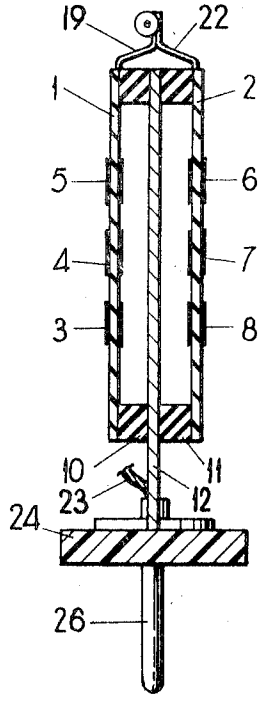


Fig.3

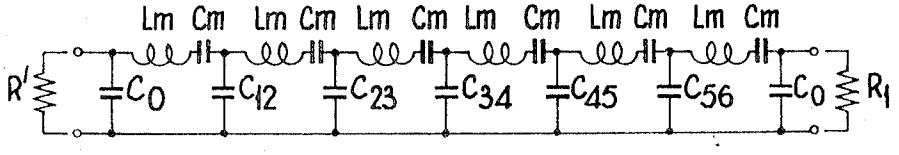


Fig.4

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ELECTRICAL BAND-PASS FILTER EMPLOYING MONOLITHIC CRYSTALS

This invention relates to electrical band-pass filters.

One known kind of electrical band-pass filter, hereinafter referred to as a monolithic crystal filter, comprises a slab of piezoelectric crystalline material having two major faces partially coated with conducting material to provide at least two pairs of electrodes defining a sequence of portions of the slab each of which portions is sandwiched between one of said pairs of electrodes and separated from the or each other such portion by an uncoated portion of the slab. Each such sandwiched portion of the slab acts as a mechanical resonator and forms one section of the filter, and each such resonator is mechanically coupled via an uncoated portion of the slab to the or each adjacent resonator in the sequence.

In use, when the first resonator in the sequence is electrically excited by a voltage of suitable frequency applied to its electrodes, the piezoelectric effect causes mechanical oscillation of that resonator, and that oscillation is communicated in turn to each resonator in the sequence. Finally, an electrical output is obtained from the electrodes of the last resonator in the sequence, by virtue of the piezoelectric effect. Such an arrangement can be designed to act as an electrical band-pass filter of which the input terminals and the output terminals are respectively constituted by the electrodes of the first and of the last resonator in the sequence. The center frequencies of such filters are typically in the range 1—150 MHz.

Each said resonator has a fundamental thickness mode resonance frequency for transverse shear vibrations, this frequency being approximately the intended center frequency of the filter and being the same for all the resonators in the sequence. However, the composite structure comprising the sequence of resonators may also vibrate in anharmonic overtones of the fundamental thickness mode, because of the coupling between the resonators. The frequencies of these anharmonic overtones are higher than, but close to the fundamental frequency. In addition, each resonator may vibrate in other anharmonic overtones of the fundamental mode, due mainly to the fact that each resonator is a distributed rather than a lumped system. The frequencies of these latter anharmonic modes are in general higher than and spaced further from the fundamental frequency than the former anharmonic modes.

The fundamental mode and the former anharmonic overtones constitute the desired resonances which form the pass band of the filter, while the latter anharmonic modes are unwanted and give rise to unwanted responses in the stop band of the filter.

Each resonator may also vibrate in a series of harmonic overtones of the fundamental mode, to each of which similarly correspond a series of anharmonic overtones, and a monolithic crystal filter may alternatively be designed to have one of these harmonic frequencies as its center frequency.

The fundamental frequency of each of the resonators is lower than that of the surrounding uncoated portions of the slab, due mainly to the mass loading by the electrodes, the fractional difference in frequency so caused being known as the "plateback." Consequently, the uncoated portions act, at the fundamental frequency, in a manner similar to a waveguide excited at a frequency below its cutoff frequency, with the result that the vibrations of the resonators at the fundamental frequency are effectively trapped under the electrodes, while such vibrations, at the fundamental frequency, as are transmitted to the uncoated portions of the slab are propagated as an exponentially decaying evanescent mode.

In general, the former anharmonic modes will also be trapped under the electrodes, since they are close in frequency to the fundamental mode. By suitable choice of the material, area, and thickness of each electrode it is possible to arrange that such trapping does not occur for the majority of the latter anharmonic modes. These unwanted modes thus propagate all over the slab and are dissipated at the points of support of the slab.

Such a monolithic crystal filter is described in our copending U.S. application No. 830055, which also describes a method of mounting the slab so that these untrapped modes may be dissipated more effectively. However, even with this method of mounting, it is found that unwanted responses occur outside the desired pass band of the filter, due to mechanical coupling between the input and output of the filter via the unwanted modes. These unwanted responses occur particularly in the region of the fundamental thickness shear frequency of the uncoated slab, and it is difficult to further reduce these by increased mechanical damping without adversely affecting the filter performance in the pass band.

The object of the invention is to provide an electrical band-pass filter wherein this difficulty is alleviated.

According to the present invention, an electrical band-pass filter comprises at least two single-crystal slabs of piezoelectric crystalline material, each having two major faces; at least two pairs of electrodes on each slab, one electrode of each pair on each said major face, each said pair sandwiching a portion of the slab so as to form a mechanical resonator, and each said pair being separated from other electrodes on that slab by an uncoated portion of the slab, each said slab having a first set of thickness modes of vibration having resonance frequencies within the pass band of the filter and in which modes the vibrations are substantially trapped under said electrodes and a second set of modes of vibration having resonance frequencies outside the pass band of the filter; and input and output terminals between which said resonators are coupled in a series, the coupling between resonators on the same slab being mechanical only, by way of an evanescent mode in a said uncoated portion, and the coupling between resonators on different slabs being by way of electrical coupling means interconnecting the electrodes of those resonators.

With a filter designed in this way using two or more quartz blanks, instead of one as in a monolithic filter, the mechanical coupling between the input and output of the filter via unwanted modes is decreased considerably, thus reducing unwanted responses in the stop band of the filter.

Preferably, the slab thickness and/or the shape of said electrodes varies from slab to slab. In this way any unwanted resonances which occur in the slabs are centered at different frequencies, and thus the filter as a whole does not exhibit these resonances.

An electrical band pass filter in accordance with the invention may suitably comprise two slabs mounted parallel to each other and spaced apart in a direction normal to said major faces. Conveniently each slab is mounted on a support member the support members being mounted back to back on a common support member, which conveniently serves to screen the two slabs electrically from one another.

One electrical band pass filter in accordance with the invention will now be described by way of example with reference to the accompanying drawings of which:

FIG. 1 is a graph showing the response curve of a known six-resonator monolithic crystal filter;

FIG. 2 is a diagrammatic elevational view of the filter, in accordance with the invention, to be described by way of example;

FIG. 3 is a cross-sectional view of the filter shown in FIG. 2 along the line III–III;

FIG. 4 is a circuit diagram of an equivalent electrical circuit to the filter shown in FIGS. 2 and 3; and

FIG. 5 is a graph showing the response curve of the filter shown in FIGS. 2 and 3.

Referring to FIG. 1, the attenuation, in decibels, between the input and output terminals of a six-pole monolithic crystal filter of the kind described in the above-mentioned copending application has been measured as a function of frequency. The resulting response curve shows a pass band around 10.7 MHz, but also shows a series of further, unwanted responses at high frequencies, especially near the fundamental thickness shear

resonance frequency of the uncoated portion of the slab, marked by an arrow in FIG. 1. At this resonance frequency, the attenuation is around 50 decibels, which would be insufficient for some purposes.

Referring now to FIGS. 2 and 3, the electrical band-pass filter in accordance with the invention comprises two AT-cut quartz slabs 1, 2 each with a pair of accurately parallel faces. Slabs 1, 2 are each provided with three pairs of electrodes 3, 4, 5 and 6, 7, 8, respectively, formed by a coating of gold which is vacuum evaporated on to the respective faces of the slabs through a mask to form the desired pattern. These masks are all made with the same punch, so that the electrodes all have the same area. This coating process also forms connecting strips 9 through which electrical contact to the electrodes can be made. Each electrode pair 3—8 sandwiches a portion of the respective slab 1 or 2, these portions acting as mechanical resonators, and being separated from each other by uncoated portions of the slab.

The quartz slabs 1, 2 are respectively mounted on insulating support frames 10, 11 each of which has a cutaway center portion and is attached to the respective slab around the slab edges by a layer of adhesive, for example an epoxy resin such as "Araldite" (Registered Trade Mark), which is ultrasonically more lossy than the slab.

The support frames are mounted, back-to-back, on a common support member consisting of a beryllium copper screen 12 which electrically screens electrode pairs 3—5 from electrode pairs 6—8. The slabs 1, 2 are thus mounted parallel to each other, and spaced apart in a direction normal to the major faces. Connection is made from the connecting strips 9 to copper strips 13 on the support frames 10, 11, by means of electrically conducting paint or cement.

Thus, one electrode of the pair 3 is connected via a connecting strip 9 and a copper strip 13 to an input lead 14, the other electrode of this pair being connected via a connecting strip 9, a copper strip 13, and a leadoff tab 15 to the earthed screen 12; both electrodes of the pair 4 are connected, via leadoff tabs 16, 17 to the screen 12; and one electrode of the pair 5 is connected, via a leadoff tab 18 to the screen 12, the other electrode of the pair 5 being connected via leadoff tab 19 to one end of a capacitor 20, the other end of which is connected to a projecting lug 21 of the earthed screen 12. Similarly, one electrode of the pair 6 is connected via a leadoff tab 22 also to said one end of the capacitor 20, the other electrode of this pair being connected via a leadoff tab (not shown) to the screen 12; both electrodes of the pair 7 are connected to the screen 12; and one electrode of the pair 8 is connected to the screen 12, the other being connected to an output lead 23.

The screen 12 is attached to a base 24, through which pins 25, 26 are insulatingly sealed, and the input and output leads 14, 23 are respectively connected to these pins. The completed unit is encased in a can (not shown) which is attached to the base 24.

Thus, if an alternating voltage of suitable frequency is applied between the input pin 25 and the earthed screen 12, and hence across the electrode pair 3, the piezoelectric effect causes mechanical oscillation of the mechanical resonator defined by this electrode pair. This oscillation is communicated in turn to the resonators defined by electrode pair 4 and by electrode pair 5 via the uncoated portions of the slab 1, and finally an electrical output is obtained, by virtue of the piezoelectric effect, from the electrode pair 5. This electrical output is coupled to the electrode pair 6 with the capacitor 20 acting as a coupling capacitor. The piezoelectric effect then causes mechanical oscillation of the resonator defined by the electrode pair 6, and this oscillation is communicated mechanically as before, until finally an electrical output is obtained from the electrode pair 8, and this appears between the output pin 26 and earth.

The quartz slabs 1, 2 have different thicknesses, and therefore different fundamental resonance frequencies, but the value of the plateback produced by the electrode is so chosen that the coated portions of both slabs have the same resonance frequency.

Referring now to FIG. 4, the filter may be represented by an equivalent electrical circuit, where the mechanical components of the system are represented by electrical components. The equivalent circuit is a ladder network, having six series branches, each formed by an inductance L_m in series with a capacitance C_m, a shunt capacitance C_{12}—C_{56} being connected between each series branch, and the network being terminated at each end by a shunt capacitance C_o. R^1 and R_1, represents the resistances by which the filter is designed to be terminated.

Each inductance L_m represents the motional mass of one of the resonators, each capacitance C_m representing the mechanical compliance of that resonator. Because the electrodes all have the same area, and because the resonance frequency is the same for each resonator the values of L_m are the same for all the resonators, and similarly for C_m.

The capacitances C_{12},C_{23}, C_{45}, and C_{56} represent the mechanical coupling between the successive resonators in the sequence, their values being determined by the thickness of the slabs, the plateback, the size of the electrodes, and by the spacing between the electrodes of adjacent resonators. Capacitances C_o are the electrostatic capacitances between the electrodes of pairs 3, 8. Since electrode pairs 4 and 7 are short-circuited, the corresponding electrostatic capacitance for each of these pairs has been omitted in FIG. 4, and the capacitance C_{34} takes account of the electrostatic capacitances of each of the electrode pairs 5, 6, as well as that of the actual coupling capacitor 20.

The filter described herein by way of example is designed utilizing the values given in Dishal's tables for filters of Chebyshev-type response (see "Reference Data for Engineers", International Telephone and Telegraph corporation, 6th Edition, Sept. 1956, Chapter 7). The design procedure is as follows.

The center frequency, bandwidth, and number of sections of the filter are chosen to meet the required shape factor and ripple requirement. In this case, the filter is designed to have a center frequency of 10.7 MHz, a bandwidth of 9 kHz. and, as already mentioned, to have six sections. The pass band ripple is required to be 0.1 db.

A punch is chosen for forming the masks used to produce the electrodes, and the electrode size produced by this punch is determined. In this example, the size was found to be 2.09×2.09 mm.

Different plateback values are chosen for the slabs 1 and 2, the values being 0.008 and 0.02 respectively. From this, the thicknesses of the slabs are calculated, such that the fundamental resonance frequencies of the resonators on the two slabs are all equal to the required center frequency of the filter, 10.7 MHz. The slabs 1, 2 are both 16×10 mm. in size, and their thicknesses calculated as described above are 0.1539 mm. and 0.1521 mm. respectively.

Having determined the thicknesses of the slabs 1, 2, the area of the electrodes, and the plateback values, the values of L_m,C_m and C_o in the equivalent circuit are effectively known, and from these values the values of C_{12}—C_{56} can be calculated, using the figures given by Dishal's tables for the required degree of ripple.

From the values of C_{12},C_{23},C_{45}, and C_{56} can be calculated the required spacings between the electrodes of adjacent resonators of the slabs. Thus the spacing between electrode pairs 3 and 4 is 1.264 mm.; that between pairs 4 and 5 is 1.430 mm.; that between pairs 6 and 7 is 0.961 mm.; and that between pairs 7 and 8 is 0.849 mm. The required value of C_{34} is 15.09 pf., and this is obtained by suitably choosing the value of the capacitor 20. In practice, this is done experimentally. Finally, the input and output impedances of the filter, R^1 and R_1, are calculated to be 1630 ohms.

Thus, the filter is effectively designed as a whole, and in general either slab 1 or 2 on its own would not operate very effectively as a filter.

Referring now to FIG. 5, the attenuation in decibels between the input and output terminals of this filter is measured as a function of frequency. The resulting response curve

shows a pass band around 10.7 MHz as in FIG. 1, but in this case the unwanted resonances at higher frequencies are suppressed by about 90 decibels.

In a modification of the filter described above by way of example, the electrodes on one slab are made rectangular instead of square, but still with the same area. The spacings between adjacent electrode pairs on that slab are so chosen that the values of C_{12}—C_{56} in the equivalent circuit maintain their design values.

It will be appreciated that many variations to the filter described above by way of example are possible within the scope of the invention. For example, the filter could be designed to have a different number of resonators, and the resonators could be divided between the slabs in different ways, not necessarily with the same number of resonators on each slab. Moreover, the filter could be designed using the known image impedance method of design. In some applications of the invention, a different constructional layout might be more convenient. For example, both the support frames might be mounted on the same side of a base plate.

We claim:

1. An electrical band-pass filter comprising: at least two single-crystal slabs of piezoelectric crystalline material, each having two major faces; at least two pairs of electrodes on each slab, one electrode of each pair on each said major face, each said pair sandwiching a portion of the slab so as to form a mechanical resonator, and each said pair being separated from other electrodes on that slab by an uncoated portion of the slab, each said slab having a first set of thickness modes of vibration having resonance frequencies within the pass band of the filter and in which modes the vibrations are substantially trapped under said electrodes and a second set of modes of vibration having resonance frequencies outside the pass band of the filter; and input and output terminals between which said resonators are coupled in a series, the coupling between resonators on the same slab being mechanical only, by way of an evanescent mode in a said uncoated portion, and the coupling between resonators on different slabs being by way of electrical coupling means interconnecting the electrodes of those resonators.

2. An electrical band-pass filter according to claim 1, wherein the resonance frequencies of said second set of modes of vibration are different for each slab.

3. An electrical band-pass filter according to claim 2 wherein the slab thickness varies from slab to slab.

4. An electrical band-pass filter according to claim 2 wherein the shape of the electrodes varies from slab to slab.

5. An electrical band-pass filter according to claim 2 wherein both the slab thickness and the shape of the electrodes vary from slab to slab.

6. An electrical band-pass filter according to claim 1 wherein the two said slabs are mounted parallel to each other and are spaced apart in a direction normal to said plane parallel faces.

7. An electrical band-pass filter according to claim 6 wherein each of the two slabs is mounted on a support member, and the support members are mounted back-to-back on a common support member.

8. An electrical band-pass filter according to claim 7 wherein said common support member serves to screen the two said slabs electrically from one another.

9. An electrical band-pass filter according to claim 1 wherein said electrical coupling means comprises a capacitance.

10. An electrical band-pass filter according to claim 1, having a Chebyshev-type response.