United States Patent

Braun

[15] **3,656,180**

[45] **Apr. 11, 1972**

[54] **CRYSTAL FILTER**

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[73] Assignee: **Bell Telephone Laboratories, Incorporated,** Murray Hill, N.J.

[22] Filed: **Aug. 12, 1970**

[21] Appl. No.: **63,204**

[52] **U.S. Cl.** **333/71,** 333/72, 310/7.7

[51] **Int. Cl.** **H03h 7/10,** H03h 7/00

[58] **Field of Search** 333/72, 71; 310/9.7, 9.8

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Primary Examiner—Eli Lieberman
Assistant Examiner—Saxfield Chatmon, Jr.
Attorney—R. J. Guenther and Edwin B. Cave

[57] **ABSTRACT**

In a monolithic crystal filter which employs a combination of mass loading and acoustic coupling, a secondary mechanical wave generating resonator with short-circuited, nongrounded electrodes is employed between the input and output resonators. The input wave is applied to the intermediate resonator as well as to the input resonator, resulting in sharp peaks of attenuation which bracket the passband of the filter.

12 Claims, 21 Drawing Figures

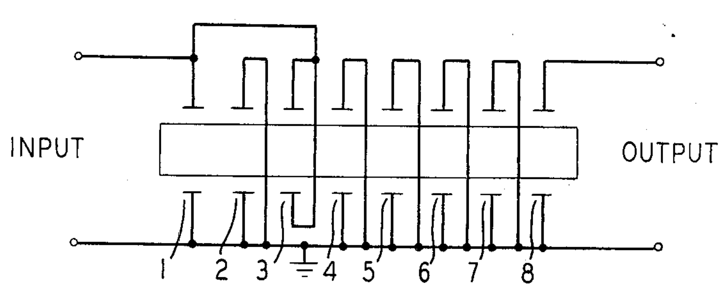


FIG. 1

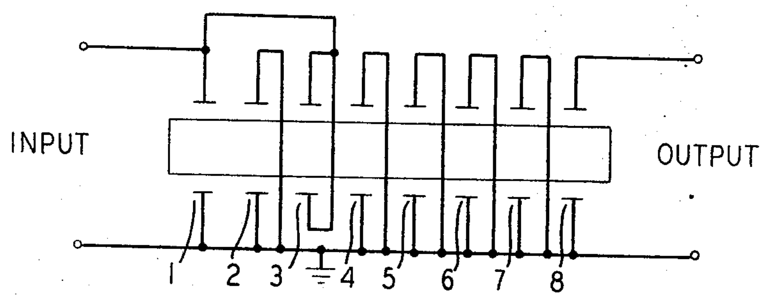


FIG. 10

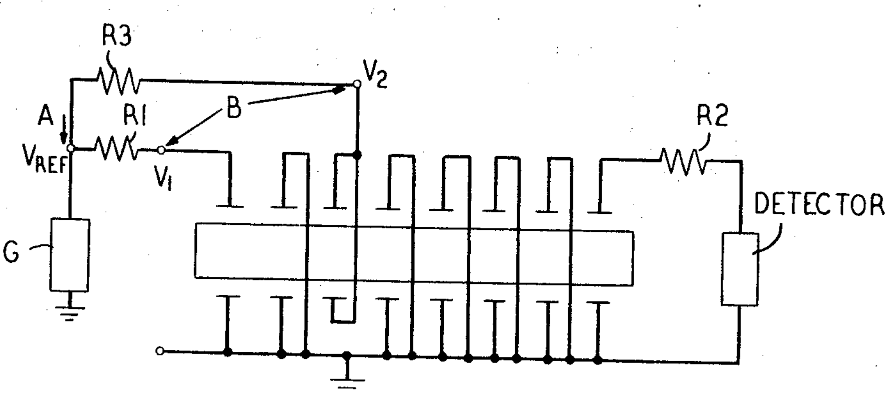
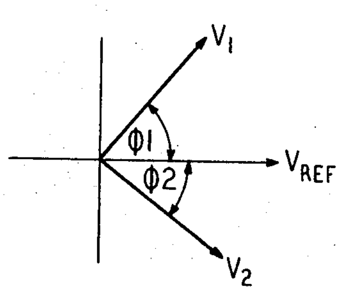
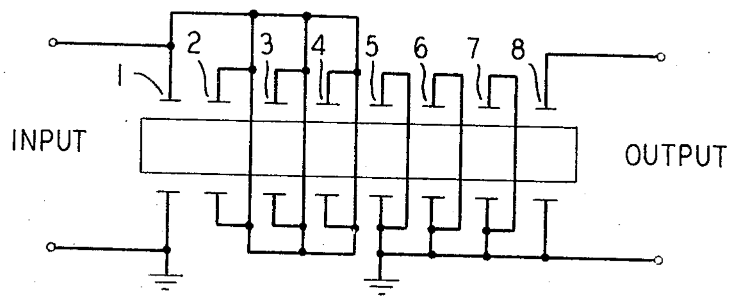


FIG. 10A



INVENTOR
A. R. BRAUN
BY [signature]
ATTORNEY

FIG. 2


1
2
3
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5
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8
INPUT
OUTPUT

FIG. 2A

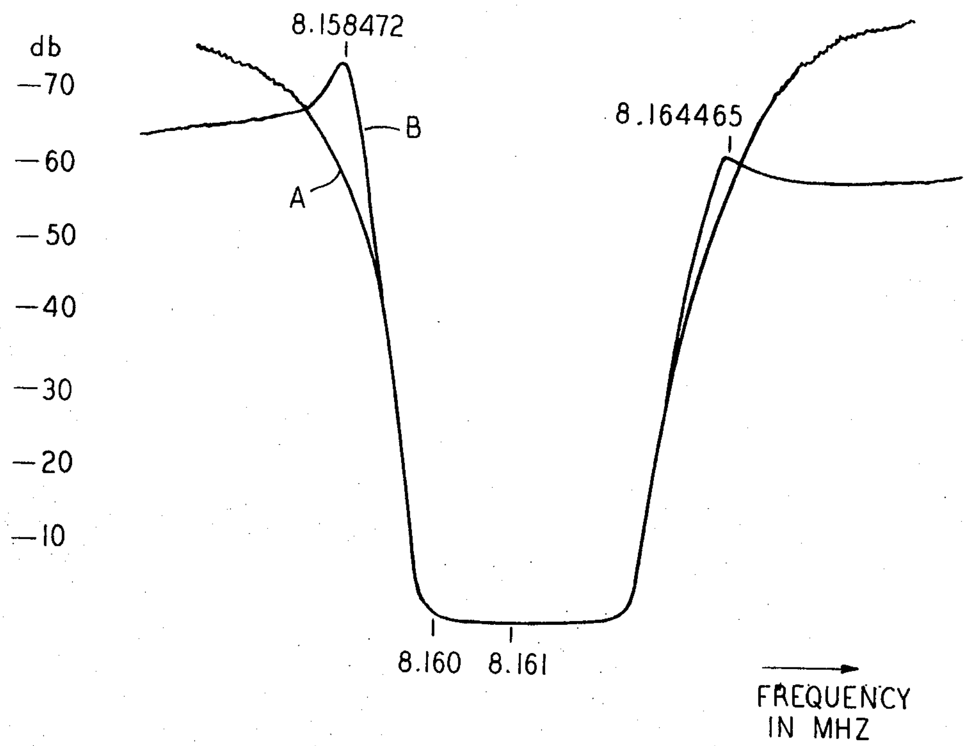
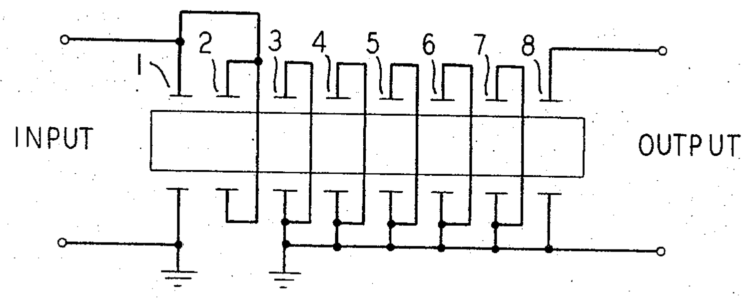

db
—70
—60
—50
—40
—30
—20
—10
8.158472
8.164465
A
B
8.160
8.161
FREQUENCY
IN MHZ

FIG. 3


1
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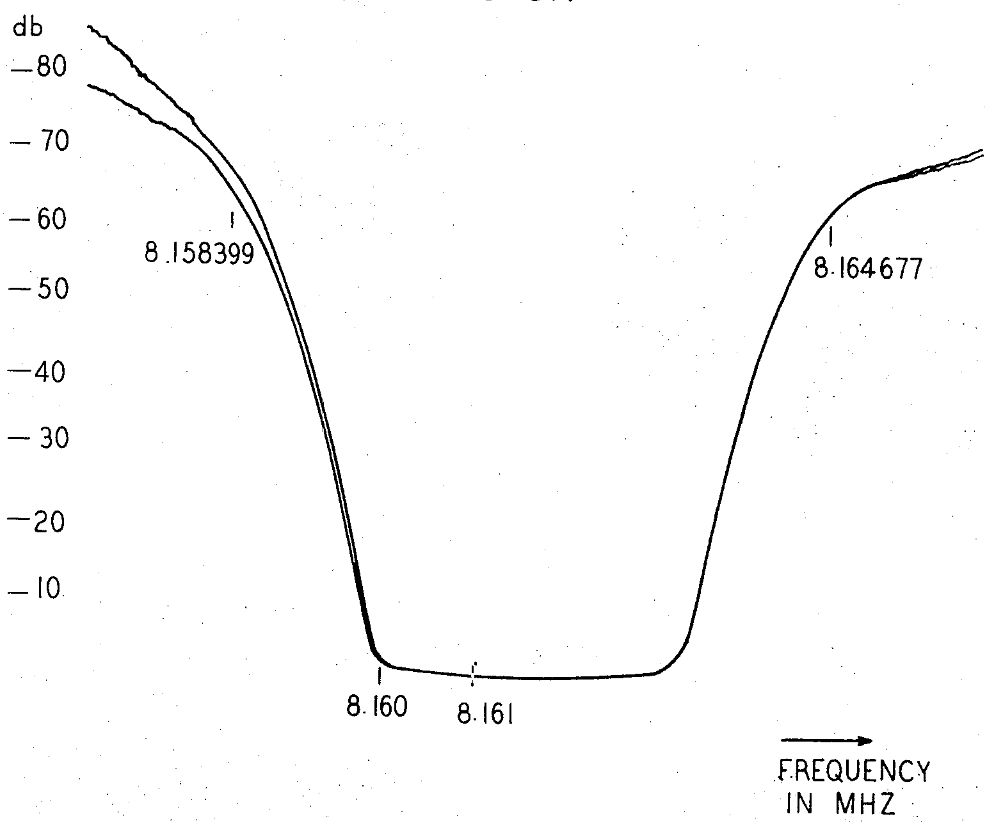
INPUT
OUTPUT

FIG. 3A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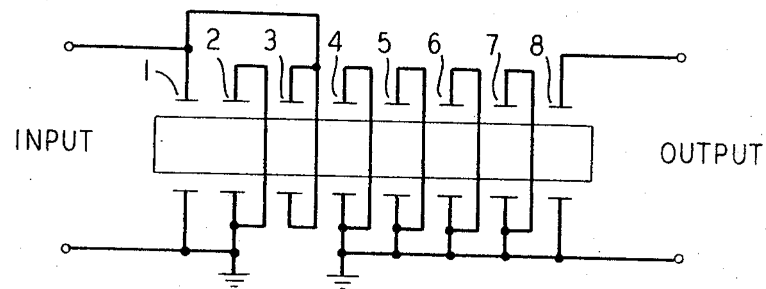
8.158399
8.164677
8.160
8.161
FREQUENCY
IN MHZ

FIG. 4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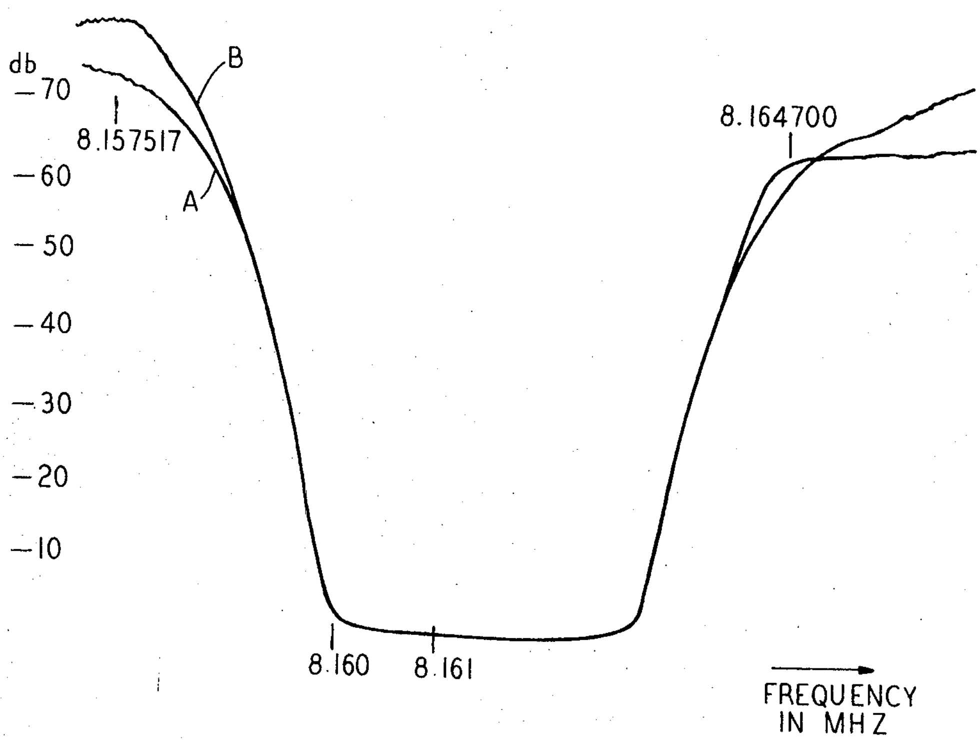
INPUT
OUTPUT

FIG. 4A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-10
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B
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8.160
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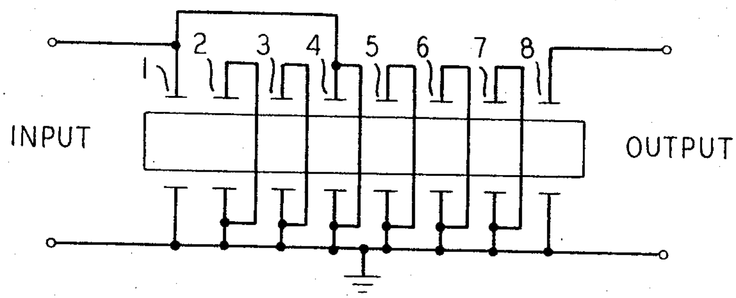
FREQUENCY
IN MHZ

FIG. 5


1
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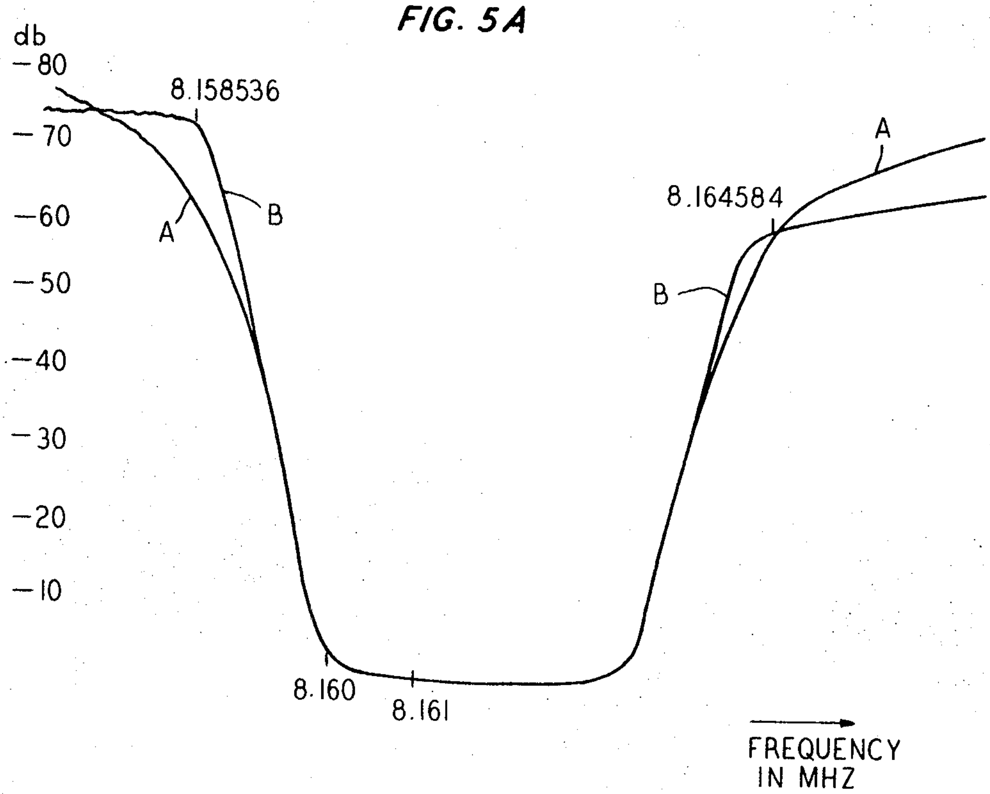
INPUT
OUTPUT

FIG. 5A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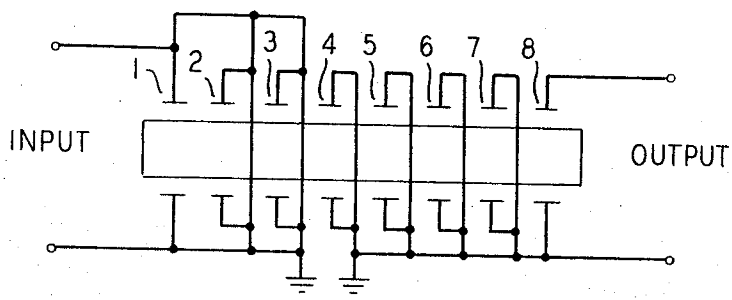
−40
−30
−20
−10
8.158536
A
B
8.164584
A
B
8.160
8.161
FREQUENCY
IN MHZ

FIG. 6


1
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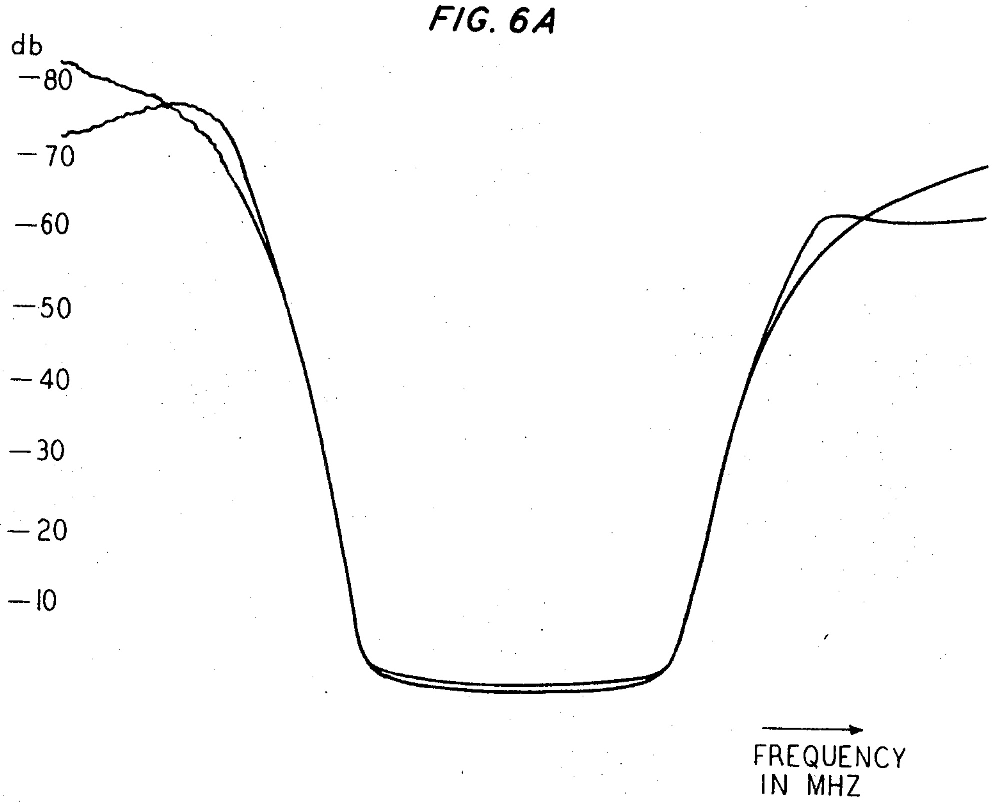
INPUT
OUTPUT

FIG. 6A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—80
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—40
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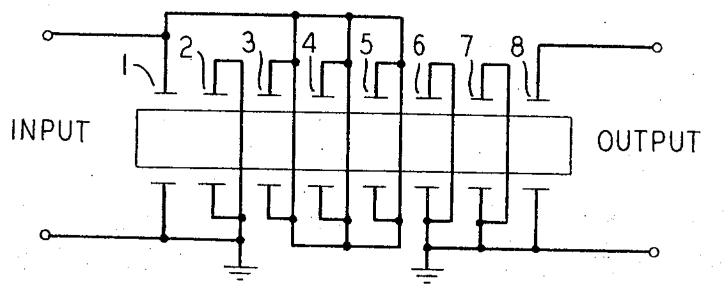
—20
—10
FREQUENCY
IN MHZ

FIG. 7


1
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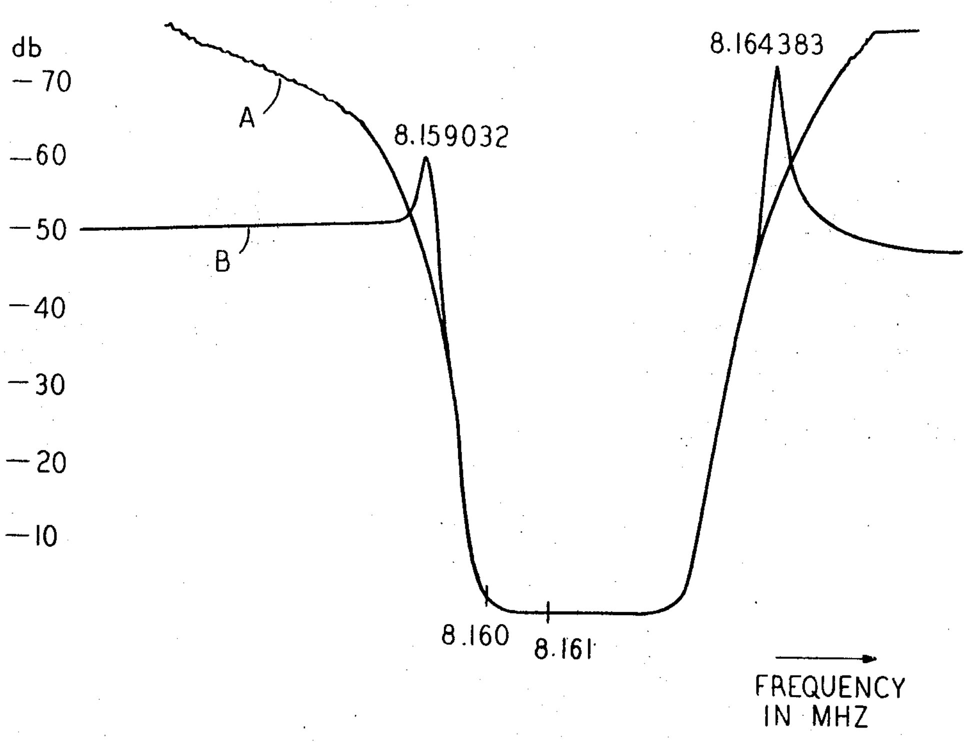
INPUT
OUTPUT

FIG. 7A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-40
-30
-20
-10
A
B
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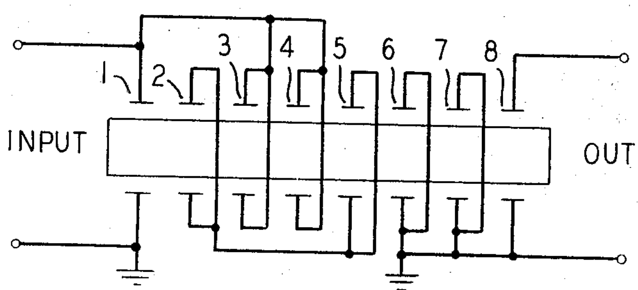
8.164383
8.160
8.161
FREQUENCY
IN MHZ

FIG. 8


1
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6
7
8
INPUT
OUTPUT

FIG. 8A

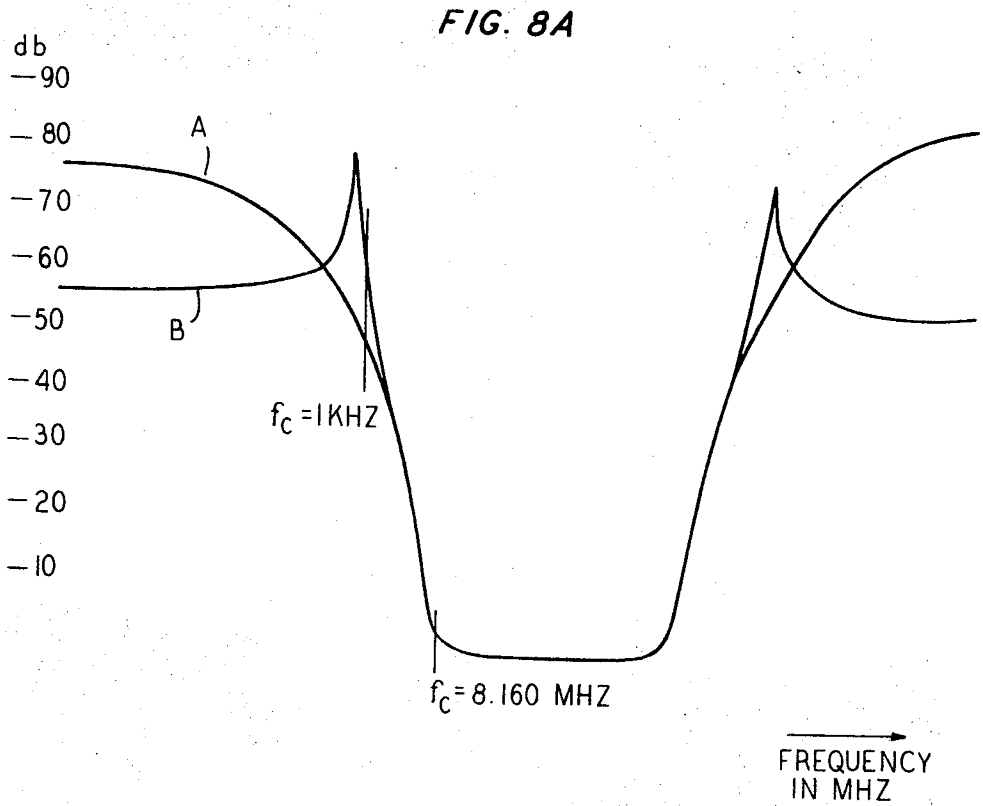
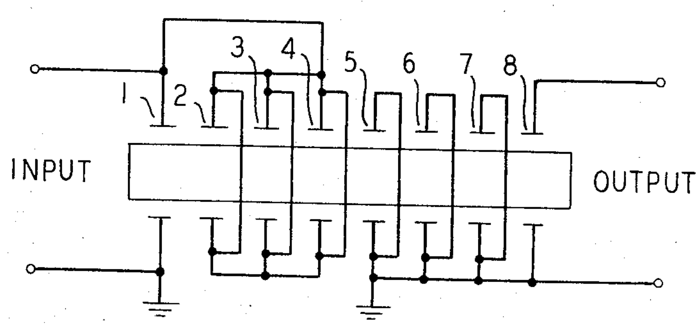

db
—90
— 80
—70
—60
—50
—40
—30
—20
—10
A
B
f_c =1KHZ
f_c= 8.160 MHZ
FREQUENCY
IN MHZ

FIG. 9


1
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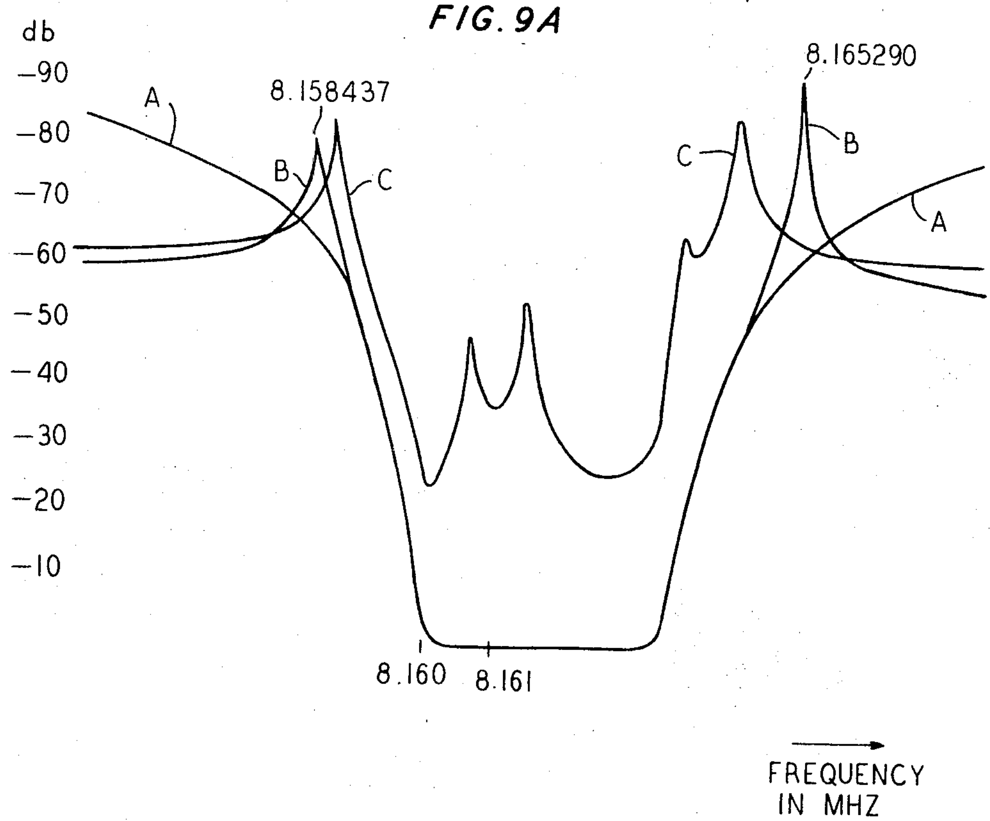
6
7
8
INPUT
OUTPUT

FIG. 9A


db
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-80
-70
-60
-50
-40
-30
-20
-10
A
B
C
8.158437
8.165290
C
B
A
8.160
8.161
FREQUENCY
IN MHZ

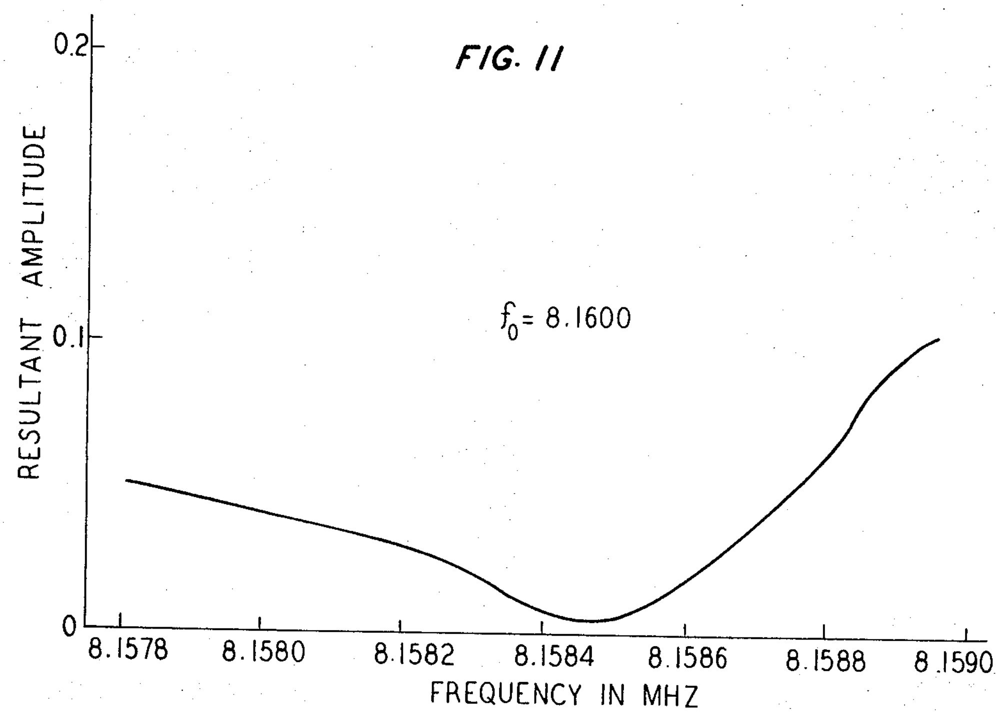

FIG. 11

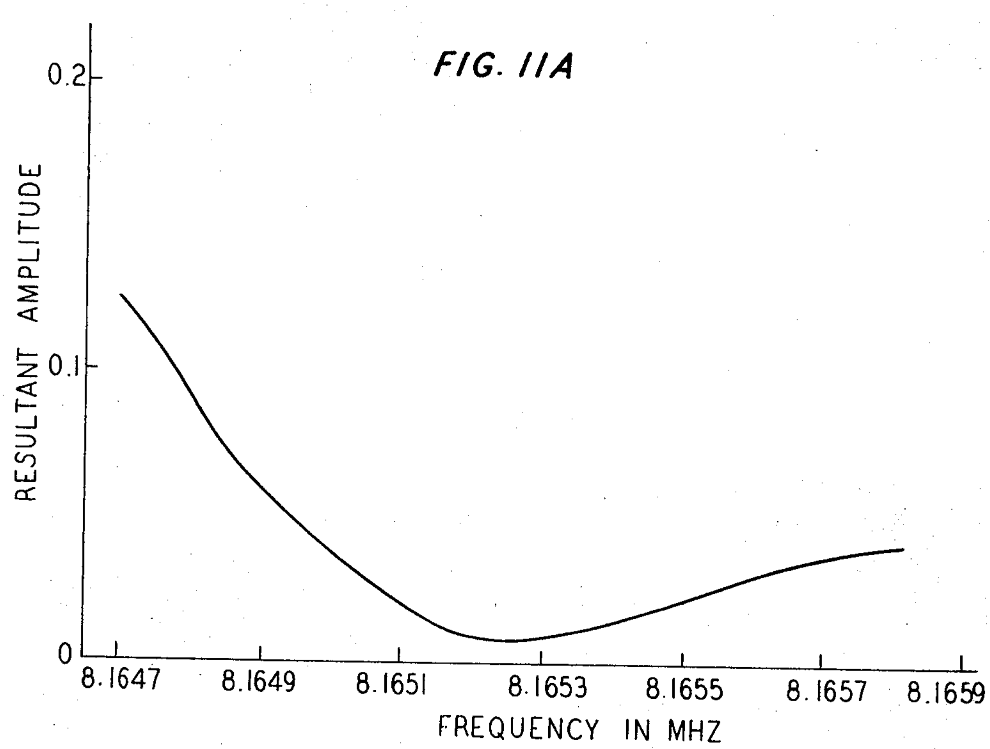

FIG. 11A

CRYSTAL FILTER

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to energy translating devices and, more particularly, to monolithic crystal filters.

2. Description of the Prior Art

The term "monolithic crystal filter" as used herein is meant to define the basic filter structure disclosed by W. D. Beaver and R. A. Sykes in their copending application Ser. No. 558,338, filed June 17, 1966, now U.S. Pat. No. 3,564,463 issued Feb. 16, 1971. In its broadest terms, the Beaver-Sykes apparatus is an energy translating device for translating input oscillatory electrical energy having first characteristics into output oscillatory electrical energy having second characteristics. One specific use to which such a structure may be put is that of a filter. In terms of structure, such a filter involves the use of two or more resonators which share a common piezoelectric body or wafer. The Beaver-Sykes structure is distinguished from other outwardly similar structures by the combination of two features, namely, mass loading and acoustic coupling. The term "mass loading" refers to a particular electrode mass which is determined by the nature of the piezoelectric body and its thickness and by the size and density of the electrodes which make up each of the resonators. Mass loading which conforms to the principles taught by Beaver and Sykes is evidenced by a number of specific conditions. For example, acoustic energy supplied in or near to one of the resonators is essentially confined or trapped within the boundaries of the resonator so that very little escapes to the surrounding piezoelectric body. Also, the relatively limited amount of acoustic energy that does escape from the energy trapping zone of the resonator decreased exponentially in magnitude as the distance from the resonator increases. Further, the contour and dimensions of the outer perimeter of the piezoelectric body have no effect on the nature of the energy transmission accomplished. Finally, with the proper mass loading, there is a substantial difference between the resonant frequency of the resonators and the resonant frequency of the unloaded portions of the piezoelectric body.

Acoustic coupling, the second of the key distinguishing features of a Beaver-Sykes type device, refers to the existence of an energy channel in the piezoelectric body which effects the transmission of acoustic energy between input and output electrodes. Such coupling is evidenced or manifested by a number of conditions which include, for example, the placing of all resonators within the acoustic field of adjacent resonators. Further, the only physical connecting path between the input and output resonators is in the piezoelectric body, and substantially all of the energy transferred from one resonator to another is acoustic energy.

By virtue of the combination of the features of mass loading and acoustic coupling, the image impedance of the structure or circuit as a whole conforms to a specifically defined pattern; and also, the structure or circuit as a whole has an equivalent circuit in the form of a lattice network with resonant and antiresonant frequencies characterized by a specifically defined relation.

In order to ensure the sharpest possible cutoff action and a high degree of selectivity, the transfer characteristics of a filter, including a monolithic crystal filter, should be marked by steep skirts of attenuation and the passband should be bracketed by distinct attenuating peaks. Heretofore, such peaks of attenuation have been achieved in monolithic crystal filters only by the use of electrical coupling which entails the use of an external capacitor to couple two or more resonators or by charge cancellation where portions of split electrodes are coupled directly. Charge cancellation has proved to be effective only in two-pole filters, however, and such filters have a very limited range of practical use.

Accordingly, the general object of this invention is to improve the transfer characteristics of monolithic crystal filters, including multiple pole filters, without employing discrete coupling elements between resonators.

SUMMARY OF THE INVENTION

The stated object and related objects are achieved in accordance with the principles of the invention by a monolithic crystal filter which employs an ungrounded intermediate resonator with the electrodes thereof short circuited, which resonator is positioned between the input and output resonators of the filter. In accordance with the invention, the input wave is applied not only to the input resonator, but also to the intermediate resonator. As the result of energization by the input wave, the input resonator vibrates conventionally in the thickness shear mode to create a first or primary acoustic wave. At the same time a secondary wave, similar in magnitude but displaced in phase, is generated by the intermediate or quasi resonator. The principles of the invention turn to account the relative phase of the two mechanical waves as they travel down the piezoelectric plate or wafer, and at those frequencies at which the waves are equal in magnitude but opposite in phase, a peak of attenuation occurs. In general, the primary and secondary waves cancel each other at at least two frequencies which bracket the filter passband and as a result, the selectivity characteristics of the filter are substantially enhanced.

BRIEF DESCRIPTION OF THE DRAWING

FIG. **1** is a schematic circuit diagram of a filter in accordance with the invention;

FIG. **2** is a schematic circuit diagram of a second embodiment of a filter in accordance with the invention;

FIG. **2A** is a plot illustrating the characteristics of the filter of FIG. **2**;

FIG. **3** is a schematic circuit diagram of a third embodiment of a filter in accordance with the invention;

FIG. **3A** is a plot illustrating the characteristics of the filter of FIG. **3**;

FIG. **4** is a schematic circuit diagram of a fourth embodiment of a filter in accordance with the invention;

FIG. **4A** is a plot illustrating the characteristics of the filter of FIG. **4**;

FIG. **5** is a schematic circuit diagram of a fifth embodiment of a filter in accordance with the invention;

FIG. **5A** is a plot illustrating the characteristics of the filter of FIG. **5**;

FIG. **6** is a schematic circuit diagram of a sixth embodiment of a filter in accordance with the invention;

FIG. **6A** is a plot illustrating the characteristics of the filter of FIG. **6**;

FIG. **7** is a schematic circuit diagram of a seventh embodiment of a filter in accordance with the invention;

FIG. **7A** is a plot illustrating the characteristics of the filter of FIG. **7**;

FIG. **8** is a schematic circuit diagram of an eighth embodiment of a filter in accordance with the invention;

FIG. **8A** is a plot illustrating the characteristics of the filter of FIG. **8**;

FIG. **9** is a schematic circuit diagram of a ninth embodiment of a filter in accordance with the invention;

FIG. **9A** is a plot illustrating the characteristics of the filter of FIG. **9**;

FIG. **10** is a schematic circuit diagram of a circuit for measuring certain of the characteristics of a filter in accordance with the invention;

FIG. **10A** is a vector representation of certain of the voltages designated in FIG. **10**; and

FIG. **11** and FIG. **11A** are amplitude frequency plots of the combination of the primary and secondary waves generated within a filter in accordance with the invention.

DETAILED DESCRIPTION

The circuit of FIG. **1** discloses an eight-pole commercial monolithic crystal filter modified in accordance with the principles of the invention. For clarity, the electrodes of the resonators **1–8** are shown as spaced from the piezoelectric body or wafer P although in fact the electrodes are in contact therewith. As indicated, each of the resonators from the input resonator on the left to the output resonator on the right is numbered consecutively **1** through **8**. Resonators **2,4,5,6** and **7** are convention intermediate grounded resonators, intermediate in the sense that they are placed between the input resonator **1** and the output resonator **8**. These intermediate resonators help to shape the passband characteristics as explained in detail in the copending application of R. L. Reynolds and R. A. Sykes, Ser. No. 723,676, filed Apr. 24, 1968. It will be noted, however, that the resonator **3** or the quasi resonator is short circuited and ungrounded and also that it is connected so as to be energized by the input wave. Although FIG. **1** shows the quasi resonator **3** employing a single set of electrodes, the principles of the invention also include coupling together various numbers of intermediate ungrounded resonators or electrode pairs to serve in combination as a single quasi resonator. Such an arrangement is illustrated by the circuit of FIG. **2**.

It has been observed experimentally that, in general, there are at least two frequencies, one above and one below the passband, where the main and secondary waves cancel each other. This effect is shown by the plot B of FIG. **2A**, where attenuation peaks occur at 8.158427 megahertz and at 8.164465 megahertz. The curve A of FIG. **2A**, which is included for comparison purposes, resulted from connecting the filter in conventional fashion, excitation being applied to resonator **1** only, with all other resonators grounded except the output resonator **8** where the signal was detected.

In accordance with one broad feature of the invention, it has been found that the peaks of attenuation occurring in a filter characteristics plot are directly dependent on the particular relative position of the resonator or combination of resonators employed to generate the secondary wave.

Experimentally, it has been observed that as resonators successively farther from the input are employed to generate the secondary wave, the attenuation peaks introduced thereby became sharper and are placed closer to the passband. This effect becomes even more evident when combinations of electrode pairs are employed for the quasi resonator in lieu of a single two-electrode resonator.

In all of the plots **2A** through **8A** the curves labeled A indicate characteristics of a conventionally connected filter, and curve B illustrates the characteristics of a filter connected in accordance with the invention as shown in the correspondingly numbered figure. As shown in FIG. **3A** skirt attenuation is increased somewhat but no strong peaks of attenuation are introduced when the single resonator **2** of FIG. **2** is employed as the quasi resonator. When resonator **3** is connected as shown in FIG. **4** some additional increase in skirt attenuation results, as shown in FIG. **4A**. When resonator **4** is used to generate the secondary wave, as shown in FIG. **5**, relatively strong peaks of attenuation are created with a further increase in skirt attenuation as shown in FIG. **5A**. The effect of employing a combination of electrodes, for example electrodes **2** and **3**, to generate the secondary wave, as shown in FIG. **6** produces the results illustrated by the curves of FIG. **6A**; and the results of employing the combination of resonators **3, 4,** and **5** as shown in FIG. **7** are illustrated by the curves of FIG. **7A**.

The sharpest attenuation peaks and the maximum steepening of the skirts and the least amount of inband distortion occurred, as shown by the curves of FIG. **8**, when resonators **2, 3, 4** and **5** were connected in the configuration shown in FIG. **8A**. The peaks introduced by this arrangement not only increase the attenuation at the carrier frequency minus 1 KHz. by 10 db. but also the out-of-band attenuation is left virtually undisturbed.

In FIG. **9A**, curve A is the plot of the filter with all intermediate resonators conventionally grounded; curve C results from connecting the filter as shown in FIG. **9** but with the generation of a secondary wave only; and curve B is the plot of the filter connected as shown in FIG. **9** in which both the main and secondary waves are generated.

Experiments have been conducted to evaluate and demonstrate qualitatively the effect of the secondary wave and in the course of these experiments, the amplitude and phase of the voltages of both the main and secondary waves have actually been measured. These measurements have been conducted employing a circuit connected in the manner illustrated in FIG. **10**. Terminating resistors **R1** and **R2** with a magnitude of 422 ohms were found to be suitable, and the resistor R at 75 ohms reflects the source resistance of the generator G. The reference voltage was measured at point A with its phase at 0°, and the voltages V_1 and V_2 were measured at the points indicated with their respective phases $\phi 1$ and $\phi 2$ having the relation to the reference voltage as illustrated in FIG. **10A**.

The equation for computing the resultant amplitude of the two waves is as follows:

$$\text{Resultant Amplitude} = \sqrt{(V_{1x} + V_{2x})^2 + (V_{1y} + V_{2y})^2},$$

where

$$V_{1x} = V_1 \cos \phi_1 \qquad V_{1y} = V_1 \sin \phi_1$$
$$V_{2x} = V_2 \cos \phi_2 \qquad V_{2y} = V_2 \sin \phi_2 .$$

It is clear that the vector sum of the two voltages V_1 and V_2 is the filter's desired input, and accordingly the peaks should occur at the frequencies where the two voltages are equal in magnitude and opposite in phase. FIG. **11** and FIG. **11A** are graphical representations of the resultant amplitude versus frequency. These peaks and the frequencies at which they occur are illustrated by curve B in FIG. **9A**. It will be noted that in FIGS. **11A** and **11B** the minimum occurs at these frequencies, thus corroborating the existence of the transmission zeros and the existence of a secondary wave.

It is to be understood that the embodiment described herein is merely illustrative of the principles of the invention. Various modifications thereto may be effected by persons skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A monolithic crystal filter comprising, in combination, a plurality of resonators each including a respective portion of a common piezoelectric body sandwiched between a respective pair of electrodes, said resonators including an input resonator, an output resonator and intermediate resonator means positioned therebetween, at least one opposing pair of said electrodes of said intermediate resonator means being short circuited and ungrounded, means for applying a common input signal simultaneously to said input resonator and to said last named electrodes, whereupon a primary acoustic wave and a secondary acoustic wave substantially equal in magnitude but different in phase are generated in said body, thereby enhancing the degree of selectivity of said filter.

2. Apparatus in accordance with claim **1** wherein said intermediate resonator means includes at least one grounded resonator.

3. Apparatus in accordance with claim **1** wherein said intermediate resonator means includes at least one grounded resonator on either side of said short-circuited and ungrounded electrodes.

4. Apparatus in accordance with claim **1** wherein said intermediate resonator means includes a plurality of ungrounded, short-circuited resonators to which said input signal is applied and a plurality of grounded resonators.

5. Apparatus in accordance with claim **4** further including at least one short-circuited ungrounded resonator having no means for the direct application of an external signal thereto.

6. Apparatus in accordance with claim **4** further including at least one short-circuited ungrounded resonator having no means for the direct application of an external signal thereto positioned on either side of said ungrounded short-circuited resonators to which said input signal is applied.

7. Apparatus in accordance with claim **6** including conducting means interconnecting said ungrounded short-circuited resonators to which no input signal is applied.

8. A monolithic crystal filter comprising, in combination, a plurality of resonators each including a respective portion of a common piezoelectric body sandwiched between a respective pair of said electrodes, said resonators including an input resonator, an output resonator and intermediate resonator means positioned therebetween, said intermediate resonator means including at least one ungrounded short-circuited resonator, means for applying a common input signal simultaneously to said input resonator and to said ungrounded short-circuited resonator, and means for deriving an output signal from said output resonator.

9. Apparatus in accordance with claim **8** wherein said intermediate resonator means further includes at least one grounded resonator.

10. Apparatus in accordance with claim **8** wherein said intermediate resonator means further includes at least one grounded resonator and at least one ungrounded short-circuited resonator having no means for the direct application of an input signal thereto.

11. Apparatus in accordance with claim **8** wherein the energy transferred to said output resonator during operation is substantially entirely acoustic.

12. Apparatus in accordance with claim **8** wherein said intermediate resonator means includes a first plurality of ungrounded short-circuited interconnected resonators thereby to enable simultaneous application of said input signal to said input resonator and to said plurality of resonators, at least two additional ungrounded short-circuited interconnected resonators bracketing said plurality of resonators, and a second plurality of grounded resonators, whereby the phase cancellation that occurs as the result of the interaction between the primary acoustic wave generated by said input resonator and the second acoustic wave generated by said first plurality of resonators creates peaks of attenuation bracketing the bandpass of said filter.

* * * * *