United States Patent

Sauerland

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[45] **Oct. 10, 1972**

[54] **EQUAL-RESONATOR PIEZOELECTRIC LADDER FILTERS**

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[73] Assignee: **Clevite Corporation**

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[21] Appl. No.: **730,002**

[52] **U.S. Cl.** .... **333/72,** 333/70 S

[51] **Int. Cl.** **H03h 7/08**

[58] **Field of Search** 333/70, 71, 72, 74; 317/234; 310/8.5, 8.3

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Assistant Examiner—C. Baraff
Attorney—Frederic B. Schramm

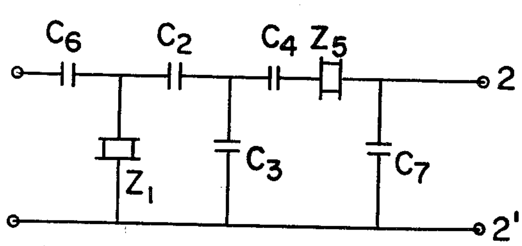
[57] **ABSTRACT**

Piezoelectric ladder filters with the following characteristics are described:

a. The filter selectivity may be changed without changing the resonators and without requiring the frequencies of peak insertion loss to be changed. This type of filter will be referred to as "equal-resonator filter."

b. Except for the restrictions on the series resonant frequency of the shunt resonators and the anti-resonant frequency of the series resonators, the remaining resonator parameters are largely, within a range that will be explained, independent of the filter selectivity. This permits use of predetermined resonators for the design of filters with different selectivity characteristics. It includes filters where all the series resonators and all shunt resonators, respectively, are equal, as well as filters in which all the resonators are identical with each other. The latter type will be called "identical resonator" filters.

10 Claims, 9 Drawing Figures



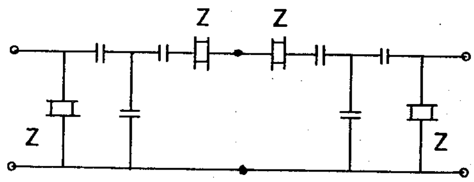


FIG. 1

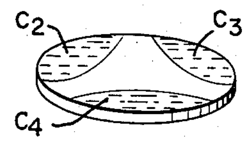


FIG. 7

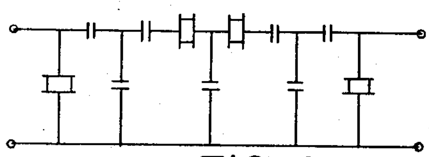


FIG. 2a

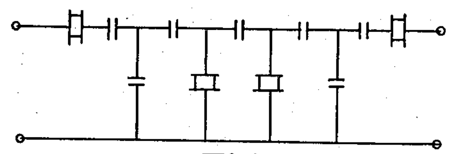


FIG. 2b

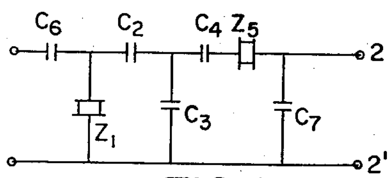


FIG. 3a

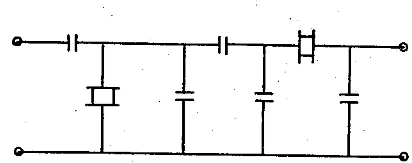


FIG. 3b

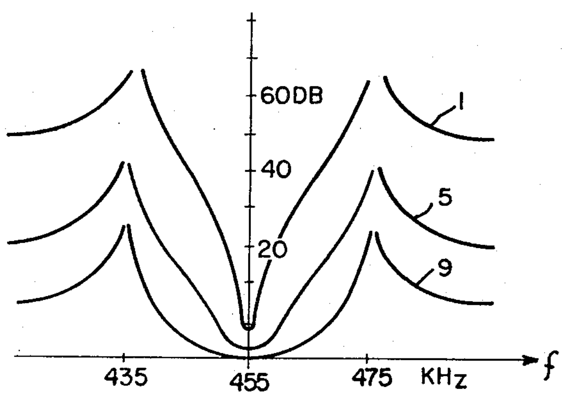


FIG. 4

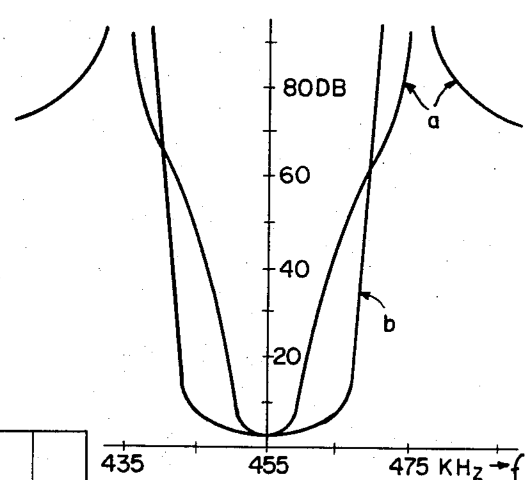


FIG. 5

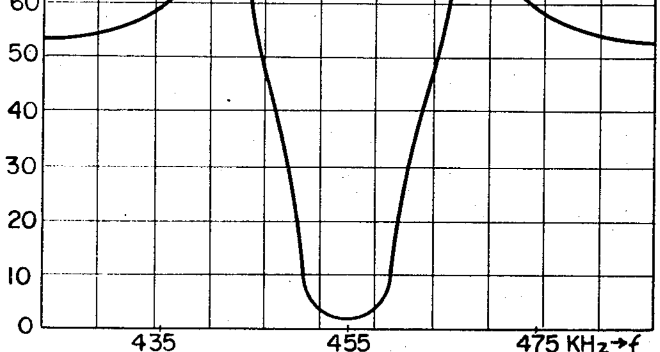


FIG. 6

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EQUAL-RESONATOR PIEZOELECTRIC LADDER FILTERS

DESCRIPTION

In carrying out the invention in accordance with one form thereof, a piezoelectric ladder filter section is made up with two identical piezoelectric resonators, one in a series branch and one in a shunt branch and capacitors are included in the circuit. In one embodiment of the invention, the capacitors include what amounts to a T section or an equivalent pi section between a shunt piezoelectric branch and a series piezoelectric branch. These and other capacitors in the circuit are varied in capacitance in order to obtain the desired bandwidth and skirt ratio (sometimes referred to as selectivity). Starting with the known electrical properties of the piezoelectric resonator chosen as the fundamental "building block" and the desired filter characteristics, a ladder filter is designed by computing the values of capacitors required to produce such characteristics.

A better understanding of the invention will be afforded by the following detailed description considered in conjunction with the accompanying drawing in which:

FIG. 1 is a diagram illustrating the cascading of networks,

FIGS. 2*a* and 2*b* are diagrams of identical resonator cascade networks in accordance with the invention,

FIGS. 3*a* and 3*b* are diagrams of ladder filter sections in accordance with the invention particularly suited to cascading where more than two identical sections are to be cascaded,

FIG. 4 is a graph showing a family of response curves with different bandwidths for ladder filter sections of the type in FIG. 3*a*, with identical resonators ($Z_1 = Z_5$),

FIG. 5 is a diagram of the responses of a cascade of two sections of type 5 of FIG. 4 and five sections of type 9 of FIG. 4, respectively,

FIG. 6 is a graph of a nominal response curve of a cascade of two basic sections of the type shown in FIG. 3*a*,

FIG. 7 is a perspective diagram of the construction which may be employed for the T network of capacitors.

Like reference characters are utilized throughout the drawing to designate like parts.

In order to facilitate explanation of the ladder filters embodying the invention, conventional ladder filters will first be discussed by way of comparison.

I. CONVENTIONAL PIEZOELECTRIC LADDER FILTERS

I–1. Piezoelectric Resonators

To clarify the terminology to be used in subsequent sections, reference is made to the well-known equivalent circuit of a piezoelectric resonator. Its electrical characteristics are commonly specified by either one of the two following sets of parameters:

a. R, L, C. C_o

b. Q, C_o, f_r, Δf, where

f_r = series resonant frequency $= \frac{1}{2\pi}\sqrt{LC}$

f_a = Antiresonant frequency $= f_r\sqrt{1 + C/C_o}$

$\Delta f = f_a = f_r$

$Q = R/2\pi f_r L = 2\pi f_r RC$

R = the series resistance in the equivalent circuit of the piezoelectric resonator

L = the series inductance in the equivalent circuit of a piezoelectric resonator

C = the series capacitance in the equivalent circuit of a piezoelectric resonator

C_o = "Static" capacitance which is represented in the equivalent circuit of the piezoelectric resonator as paralleling the series group L, R and C.

I–2 Piezoelectric Ladders

The insertion loss peaks in the lower stopband are caused by series resonance (i.e., short circuit) of the shunt resonators, while the peaks in the upper stopband are due to antiresonance (i.e., open circuit) of the series resonators. One way of describing the selectivity of a bandpass filter is by the "minimum stopband rejection" (the difference between the minimum loss in the band pass and the minimum loss in the band reject regions). and the "skirt ratio" S. For our purposes, we define the latter as $S = P/B$, where P and B are defined respectively as the difference in frequency for the two infinite rejection points which bound the pass band and the difference in frequency of the 3 db loss points in the pass band.

One may change the selectivity i.e., one may obtain a smaller skirt ratio at the expense of lower stopband rejection and vice versa. In a conventional ladder structure (presuming that it is kept the same), each change in selectivity requires a new set of resonators; i.e., to cover for example the entire range of responses would require an infinite number of different resonators. This presents inventory and cost problems in the production of piezoelectric ladder filters. In addition, the maximally obtainable stopband rejection R are limited by the realizable ratio $C_{o\ sh}/C_{o\ ser}$ of the static capacitances of the shunt and series resonators, respectively. In quartz filters, this ratio is usually less than 5; in ceramic filters it is frequently increased by choosing extreme geometries (for example, extremely thin and thick disks) for the shunt and series resonators. As will be discussed in Section IV, this presents problems with regard to spurious resonator responses.

I–3. DRAWBACKS OF CONVENTIONAL PIEZOELECTRIC LADDERS

According to the previous section, the drawbacks may be summarized as follows:

a. Each different filter response requires a different set of resonators.

b. For a given number of resonators in the network, the stopband rejection is limited. For example, for ceramic filters the maximally obtainable stopband rejection for a 2-resonator ladder without additional capacitors is presently about 26 db.

c. High stopband rejection in ladders with a small number of resonators may be obtained by resorting to extreme resonator geometries. This tends to be detrimental to the suppression of spurious resonator responses.

II. EQUAL-RESONATOR PIEZOELECTRIC LADDERS II–1.

Explanation of Terminology

As used in the specification and claims, terms are defined as follows:

a. Piezoelectric ladder filters whose selectivity may be changed without changing the resonators and without requiring the frequencies of peak insertion loss to be changed are called "equal resonator" filters.

b. Equal-resonator filters all of whose resonators are identical are called "identical resonator" filters.

II–2. Basic Principle

The manner in which the ladder filter of the present invention operates may be explained by resort to a theoretical transformation such as is described in elementary circuit textbooks. For example, Simplified Modern Filter Design by Phillip Geffe published by Hayden Book Company, N.Y., 1963. Consider a conventional ladder filter. Let it be assumed that an ideal transformer is inserted between the resonator-capacitor combination in the series arm and the resonator-capacitor combination in the shunt arm of the conventional ladder filter. The turns ratio of such a transformer may be varied to give various filter characteristics with respect to minimum stop band rejection and skirt ratio. Then replace the ideal transformer-capacitor combination (either capacitor may be used here) with either a capacitive II-section or a capacitive T-section. This is an electrical equivalent transformation described in most elementary electrical circuit textbooks, such as that by Geffe. Then the resulting capacitive T or II network may be combined with the other or remaining capacitance to form another capacitive II or T network having different capacitive values. This is also a standard electrical circuit equivalence transformation which is described in most elementary electrical circuit textbooks such as that mentioned. This represents the Principle of Operation since it is already known that one can obtain bandpass filter characteristics from a conventional circuit. An additional advantage of the filter is that it is possible to design a filter which would have non-physically realizable parameters, to transform the circuit and to obtain a circuit having physically realizable parameters.

II–3. Cascaded Sections

The main purpose of the equal-resonator approach is to cover a large number of different filter responses with a small number of different types of resonators. In this regard, the following cases are of special interest:

a. Filters all of whose series resonators and all of whose shunt resonators, respectively, are equal.

b. Identical-resonator filters.

These filter types are obtained as shown below.

Image parameter theory teaches one that one can cascade two filters to obtain a more complex filter as shown in FIG. 1. Image parameter theory is also well known. An example of this explanation is given on pages 176–177 of Transmission Networks and Wave Filters by T. E. Shea published by D. Van Nostrand, N.Y., 1929.

In FIG. 1 a series combination of the two resonators denoted Z acts and contributes as only one resonator of impedance 2Z. Hence, the filter shown in FIG. 1 can provide at most the filtering provided by conventional three-resonator circuits. This drawback can be avoided by using filters which, when cascaded, result in filters shown in FIGS. *2a* and *2b*. The filters shown in FIGS. *2a* and *2b* can provide the filtering provided by conventional four-resonator ladder filters.

II, T or L configurations may be employed. For example, FIGS. *3a* and *3b* typically represent capacitive T sections and II sections, respectively. However, either may be regarded as a combination of two L sections. For example, in FIG. *3a*, the capacitors C_2 and C_3 alone constitute an L section or if the L sections were shown separately, C_2 and a capacitor of half the capacitance of capacitor C_3 would constitute one L section; and capacitor C_4 and a capacitor of half the capacitance of C_3 shunting the other half capacitance would constitute the second L section. It will be observed, for example, in FIG. *3a*, that the resonator Z_1 in the shunt branch is separated from the resonator Z_5 by at least one L branch or at least one T branch capacitive circuit and in FIG. *3b*, the shunt and series resonators are separated by at least one II capacitive circuit.

In other words, an L section would result in the case of the degenerate capacitive circuit in which one of the series capacitors of the T network was short circuited or one of the shunt capacitors of a II network was open circuited or became very large or very small, respectively, so that it could be approximated by a short circuit or an open circuit.

III. SPECIAL FEATURES AND VARIATIONS OF EQUAL-RESONATOR FILTERS

III–1. Filters with more than one insertion loss peak each in the upper and lower stopband at finite frequencies.

The input and output image impedances of section FIG. *3a* are of the form

$$Z_0=\frac{1}{sC'}\sqrt{\frac{s^2+\omega_{01}^2}{s^2+\omega_{02}^2}} \qquad (6)$$

i.e., they are independent of the frequencies of peak insertion loss.

III–2. MATCHING END SECTIONS

The image impedance equ. (6) rises from zero at the lower cut-off frequency to infinity at the upper frequency and is, therefore, not well suited to match to constant termination resistances.

The image impedances Z_o and Z_o' of another similar network, not illustrated, are

$$Z_0=\frac{1}{sC'}\,\frac{s^2+\omega_p^2}{\sqrt{(s^2+\omega_{01}^2)(s^2+\omega_{02}^2)}} \qquad (7)$$

and

$$Z_0'=\frac{1}{sC''}\,\frac{\sqrt{(s^2+\omega_{01}^2)(s^2+\omega_{02}^2)}}{s^2+\omega_p^2} \qquad (8)$$

where ω_p is an insertion loss peak frequency. These image impedances are of higher order (in *s*) than (6) and furthermore have cut-off points of the same type (both poles or both zeros). They consequently provide a better match to constant resistance terminations and may, therefore, be used as matching end sections in cascade filters.

III-3. CHANGE OF INSERTION-LOSS PEAK FREQUENCIES

These frequencies can be changed without changing the resonator parameter. An insertion-loss peak frequency f_{P_U} in the upper stopband may be reduced by shunting a capacitor to the series resonator that produces f_{P_U}. An insertion-loss peak f_{P_L} in the lower stopband may be increased by connecting a capacitor in series with the shunt resonator that produces f_{P_L}. By this method one may obtain equal-resonator filters in which not only the selectivity and bandwidth but also the peak separation may be changed without changing the resonators.

IV. SUPPRESSION OF SPURIOUS RESPONSES IN EQUAL-RESONATOR FILTER

Piezoelectric resonators have spurious responses, i.e., resonances at frequencies other than and in addition to the desired frequency. These spurii may be harmonic, inharmonic or subharmonic responses of the desired mode of vibration. In addition, they may be due to undesired modes of vibration. As a result of spurii, piezoelectric filters exhibit undersired passbands in addition to the desired one.

Presently, most piezoelectric filters are used in conjunction with LC circuits tuned to the filter's center frequency. In these cases, spurious responses present no serious handicap if they are removed far enough from the center frequency to be attenuated sufficiently by the selectivity of the tuned LC circuits. However, with the modern trend toward inductorless IF filters, the suppression of spurii becomes an important problem. The effect of spurious responses in piezoelectric filters may be reduced or eliminated by proper resonator and/or filter design as described in the following.

IV-1. RESONATOR DESIGN

By proper choice of the resonator geometry as is well known by those familiar with the art, particular spurious responses can be reduced, eliminated or shifted to frequencies where they are less harmful. The geometry, however, affects the electrical properties of the resonator. Consequently, a geometry that is optimal with regard to spurious responses may not be optimal in meeting the requirements of a specific filter.

In a simple ladder filter a large stopband rejection R requires a large ratio $C_{o\ sh}/C_{o\ ser}$ of the static capacitances of shunt and series resonators, respectively. In ceramic filters with radial-mode resonators, this can for example be achieved by using a thin shunt resonator and a thick and possibly partially electroded series resonator, i.e., by resorting to extreme resonator geometries and without regard for the geometry that would enhance the suppression of spurii.

If the filter terminations are not predetermined, then the resonators may be predetermined, and the static capacitances of the shunt and series resonator may be chosen to conform to the resonator geometry that is optimum with regard to suppression of spurii. The equal-resonator ladder, therefore, allows use of resonators designed for minimum spurious response.

V. PERFORMANCE DATA FOR IDENTICAL-RESONATOR LADDER FILTERS

V-1. Basic Sections

Starting with a single type ceramic resonator with the following parameters: $C_o = 500$ pF; $f_r = 435$ kHz; $f_a = 475$ kHz; Q = 500. Table I gives capacitive values and termination resistance values for several different identical resonator filter characteristics where the filter network is as shown in FIG. 2*a*. FIG. 4 shows the filter responses for three of those.

Table II shows analogous results for another identical resonator filter.

V-2. CASCADED SECTIONS

Any number of basic and identical equal-resonator sections may be cascaded to obtain more complex filters.

FIG. 5, in curve a, shows the response of a cascade of two sections of the type No. 5 of FIG. 4 and in curve b, shows the response of a cascade of five sections of the type No. 9 of FIG. 4.

VI. CONCLUSIONS

The main advantages of equal-resonator filters may be summarized as follows:

a. Flexibility with regard to obtaining a large range of responses with a small number of different resonator types.

b. Optimum spurious suppression with regard to both resonators and network design.

c. Wider range of performance if compared to conventional piezoelectric ladders with equal number of resonators. For example, the ultimate stopband rejection of curve 1 of FIG. 4 is approximately 50 db while that of the equivalent conventional two-resonator ladder is at most about 30 db because of the practical limitations in realizing a large capacitance ratio $C_{o\ sh}/C_{o\ ser}$.

Although equal resonator ladders require a larger number of capacitors than the conventional ladders, they are advantageous for the large number of smaller volume applications with different filter specifications. For example, if a resonator manufacturer were to offer several different resonators centered about 455 kHz and collections of tables

TABLE I

no.	ins: loss DB	6 CB B/W kHz	Stop. Rejec. DB	C_6 pf	C_2 pf	C_3 pf	C_4 pf	C_7 pf	R_{in}	R_{out}
1	5	3	52	52	520	10000	570	5200	7000	64
2	2.5	6	38	160	540	3000	720	1600	2500	
3	1.5	10	30	280	560	1600	1000	940	1750	300
4	1.2	11	27	340	580	1280	1080	790	1400	320
5	.9	17	20	590	720	710	1600	460	950	460
6	.7	22	13	980	1300	440	1600	280	700	630

TABLE II

1a	8	4	44	52	540	7000	560		7000	350
3a	1.2	11	25	280	660	1140	730		1600	390
5a	.9	20	16	580	1250	510	740		900	400
7a	.8	24	13	900	60000	340	530		650	390
8a	.8	24	13	900	760000	330	520		650	390

similar to Tables I and II, a customer could build his own filters to most of the specifications that are possible with present piezoelectric ladder filters at 455 kHz.

Moreover, the equal-resonator ladder may even become desirable for some large volume applications because of its advantages regarding spurious response. In this case, a number of means could be used to reduce the cost and size of the additional capacitors. For example, capacitors C_2, C_3 and C_4 of FIG. 3*a* could be made in one piece as suggested in FIG. 7, with one common electrode on the opposite face of the disk.

Further, the electrodes and interconnections for all capacitors of one or more basic section(s) could be combined on a ceramic substrate that could at the same time serve as "circuit board" for the resonators.

The capacitors C_2, C_3, C_4, C_6, C_7 may be made either adjustable in capacitance or continuously variable in order that a selected bandwidth and skirt ratio may be obtained while the filter is in circuit.

Certain embodiments of the invention and certain methods of operation embraced therein have been shown and particularly described for the purpose of explaining the principle of operation of the invention and showings its application, but it will be obvious to those skilled in the art that many modifications and variations are possible, and it is intended, therefore, to cover all such modifications and variations as fall within the scope of the invention.

What is claimed is:

1. A bandpass electric wave filter having ladder structure with shunt and series branches, a piezoelectric resonator in a shunt branch, a piezoelectric resonator in a series branch, and a capacitive circuit separating the resonators, the capacitive circuits being selected from a group consisting of Π, T and L circuits, in the case of an L circuit a capacitor in a series branch being connected to the shunt branch resonator and a capacitor in a shunt branch being connected to a series branch capacitor, the capacitive circuit providing high stop band rejection corresponding to stop band rejection of resonators with larger ratios of static capacitance of shunt resonators to static capacitance of series resonators and no separating capacitive circuit, the values of capacitances in the capacitive circuit being such as result from a transformation to a capacitive, Π, T or L network, of a capacitor-transformer coupling between resonators to give the equivalent of large ratios of static capacitance of the resonators needed for desired high stop band rejection.

2. A bandpass electric wave filter having ladder structure with shunt and series branches comprising capacitors and at least three piezoelectric resonators in combination, each resonator being connected in either a series branch or a shunt branch with at least one resonator in a shunt branch, and at least one resonator in a series branch, with at least one capacitive circuit separating a resonator in a series branch from a resonator in a shunt branch, the capacitive circuits being selected from a group consisting of Π, T and L circuits, in the case of an L circuit the separation being such that a resonator in a shunt branch is connected to a capacitor in a series branch, which is connected to a capacitor in a shunt branch, which in turn, is connected to a resonator in a series branch, the capacitive circuit providing high stop band rejection corresponding to stop band rejection of to with larger ratios of static capacitance of shunt resonators to static capacitance of series resonators and no separating capacitive circuit, the values of capacitances in the capacitive circuit being such as result from a transformation to a capacitive, Π, T or L network, of a capacitor-transformer coupling between resonators to give the equivalent of large ratios of static capacitance of the resonators needed for desired high stop band rejection.

3. A ladder filter as described in claim 2 having at least three resonators with all of the resonators in series branches being substantially identical and all of the resonators in shunt branches being substantially identical.

4. A ladder filter as described in claim 3 with the resonator in shunt branch and the resonator in the series branch separated by a capacitive L section.

5. A ladder filter as described in claim 3 with a resonator in a shunt branch and a resonator in a series branch separated by capacitive Π circuit.

6. A ladder filter as described in claim 3, such that a resonator in a shunt branch and a resonator in a series branch are separated by capacitive T section.

7. A ladder filter as described in claim 3 in which all resonators are substantially identical.

8. A ladder filter as described in claim 7 with a resonator in a shunt branch and a resonator in a series branch separated by capacitive L section.

9. A ladder filter as described in claim 7 with a resonator in a shunt branch and a resonator in a series branch separated by a capacitive Π section.

10. A ladder filter as described in claim 7 with a resonator in a shunt branch and a resonator in a series branch separated by a capacitive T section.

* * * * *

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,697,903 Dated October 10, 1972

Inventor(s) Franz L. Sauerland

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

In the specification:
Column 1, line 67 reading " $f=f_a=f_r$" should read -- $f=f_a-f_r$--;

Column 8, Claim 2, line 16, reading "stop band rejection of to with larger ratios of static" should read --stop band rejection of resonators with larger ratios of static--.

Signed and sealed this 1st day of May 1973.

(SEAL)
Attest:

EDWARD M. FLETCHER, JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents