

Switched capacitor filter and method of making same

This invention relates, in general, to switched capacitor filters, and more particularly, to high pass switched capacitor filters and method for making same.

Accurate high-order filters are commonly used in various types of electronic systems especially voice-band systems such as telecommunication. Monolithic integrated circuit implementation of these low frequency filters requires the realization of long time constants in small silicon areas, and the realization of transfer functions that are insensitive to parameter variations. It is also desirable to obtain very precise responses without having external trimming components. Conventional active filters implemented with thin-film or hybrid technology do not meet these requirements, and therefore are not suitable for many applications. A recent bipolar/JFET monolithic implementation helped realize these objectives. However, a drawback with this approach is that relatively large chip areas for low frequency applications are required, and the bipolar process is not directly compatible with dense digital logic which is needed for many LSI system applications.

As early as the 1960's, filtering by using switches and capacitors was investigated thoroughly. However, at that time, a suitable integrated circuit technology did not exist which could efficiently realize these filters. More recently, active ladder analog sampled-data recursive filters have been used to implement high-order filters with transfer functions that have very low sensitivity to component variations as compared to cascaded embodiments. When implemented in standard MOS technology these filters achieved a very precise response with wide dynamic range while requiring small chip area, low power dissipation, and relatively low performance operational amplifiers. The low sensitivity of these ladder filters is, to a first order, independent of the sampling frequency. Thus, the anti-aliasing prefilter requirements are greatly reduced when compared to CTD and direct form approaches, by operating the filters at clock frequencies which are many times greater than the pass band frequency. A technique for deriving these active ladder analog sampled-data recursive filters is described in an article entitled "MOS Switched Capacitor Ladder Filters" by D. J. Allstot, R. W. Brodersen, and P. R. Gray, dated 21st April 1978, published by the College of Engineering, University of California, Berkeley, which article is hereby incorporated herein by reference.

Others have postulated a high pass switched capacitor filter using the techniques such as set out in the University of California publication. The technique followed in deriving this filter was to draw the LC prototype signal flow graph and then replace the integrators with switched

capacitors. This filter appears to work, however, it suffers from one major fault. The frequency response of this filter will peak close to the sampling frequency. This peaking effect may not bother a low pass filter sampled at a very high frequency, however, it is not acceptable in a high pass filter used in a PCM codec system. A requirement for the codec system is that the signals must be band limited to half the sampling frequency. Another switched capacitor high pass filter for use in PCM voice applications is described by Gregorian et al in IEEE International Solid State Circuits Conference (Digest of Technical papers), vol. 22, February 1979, pages 28, 29 and 274 "CMOS Switched-Capacitor Filter for a two-chip PCM Voice Coder" which discloses a filter with prewarped frequency characteristics and which uses switched capacitor integrators having operational amplifiers and controllable switches for switching the capacitors, arranged to implement a passive filter prototype by applying a bilinear Z transform to the transfer function of the filter prototype. However, the method proposed by this reference does not readily realize transfer functions which are insensitive to parameter variations as previously mentioned as being necessary.

Accordingly it is an object of the present invention to provide an improved high pass switched capacitor filter having low passband ripple and in which the same sensitivity as the sensitivity of the prototype is substantially maintained.

Another object of the present invention is to provide a CMOS high pass switched capacitor filter having low passband ripple suitable for use in a PCM voice band system.

Yet another object of the present invention is to provide a high pass switched capacitor filter having switched capacitor integrators which are implemented from terms within a bilinear Z transform difference equation.

A further object of the present invention is to provide a new and improved method for making a switched capacitor filter having low passband ripple.

And yet a further object of the present invention is to provide a method for making a high pass switched capacitor filter containing switched capacitor integrators implemented from terms of a bilinear Z transform difference equation.

According to the invention there is provided a high pass filter having a predetermined stop and passband frequency which are prewarped and which uses switched capacitor integrators having operational amplifiers and controllable switches for switching the capacitors arranged to implement a passive filter prototype characterised by implementing difference equations resulting from applying a bilinear Z

transform to S-plane state equations describing the passive prototype equivalent filter which satisfy requirements of a filter having prewarped pertinent frequencies, so that low pass-band ripple for frequencies extending out to substantially one-half of a sampling frequency is provided and the same sensitivity as the sensitivity of the S-plane prototype of said filter is substantially maintained.

In carrying out the above and other objects of the invention, there is provided a switched capacitor filter having low bandpass ripple. A switched capacitor filter is illustrated by a 3-pole Chebyshev high pass switched capacitor filter having switched capacitor integrators which are derived from bilinear Z transform difference equations.

In a preferred embodiment the present invention is implemented as a monolithic CMOS circuit.

Also provided is a method of making a switched capacitor filter having switched capacitor filter having switched capacitor integrators. First the frequency requirements of the filter are prewarped frequency-wise so that during following transformations the derived filter will still meet the required frequency specification. A passive prototype filter is selected using the prewarped frequencies. As an example, the selective passive prototype filter will contain passive LCR components. The state equations for the passive prototype filter are then derived in Laplace transform or s-plane. The s-plane state equations are then changed to bilinear Z transform state equations. In a preferred embodiment the state equations are obtained as difference equations. The difference equations are then implemented using switched capacitor integrators.

The invention will now be described by way of example only with particular reference to the accompanying drawings wherein:

Fig. 1 illustrates diagrammatically a 3-pole Chebyshev switched capacitor filter;

Fig. 2 illustrates a switched capacitor integrator useful as a portion of the circuit of Fig. 2; and

Fig. 3 illustrates a CMOS transmission gate useful as a switching device in Figs. 1 and 2.

Detailed description of the drawings

RC differential integrators useful as audio and other low frequency filters generally have long time constants. If the time constants were realized monolithically, large amounts of silicon chip area would be required. Another disadvantage of the RC differential integrator is that in order to insure reproducibility the absolute values of both the resistors and capacitors must be tightly controlled. This is extremely difficult for typical temperature and processing variations. However, these problems are overcome by using the filter illustrated in Fig. 1, when the ratio of the sampling frequency to the filter break frequency is large. The filter illustrated in

Fig. 1 is a 3-pole Chebyshev switched capacitor filter which readily lends itself to being implemented as a monolithic integrated circuit. One of the advantages of switched capacitor filters is that the capacitors can be expressed as ratios of each other as opposed to each having a discrete value.

An input signal V_{IN} is coupled to switch 13. Switch 13 serves to couple the input signal to capacitor 14 and then to couple capacitor 14 to the inverting input of amplifier 10. Capacitor 14 is coupled between switch 13 and a reference potential illustrated as circuit ground. The non-inverting input 15 of amplifier 10 is also coupled to ground. A feedback capacitor 16 is coupled between the output of amplifier 10 and its inverting input. The output of amplifier 10 is also coupled to switch 17. Capacitor 18 is coupled between switch 17 and circuit ground. Switch 17 serves to switch capacitor 18 from the output of amplifier 10 to the inverting input of amplifier 10. The output of amplifier 10 is also coupled by capacitor 27 to an inverting input of another operational amplifier 25. The non-inverting input 29 of amplifier 25 is coupled to ground. A feedback capacitor 28 is coupled between the output of amplifier 25 and its inverting input. Capacitor 31 is coupled between switch 32 and ground. Switch 32 serves to couple the output of amplifier 25 to capacitor 31 and then to couple capacitor 31 to the inverting input of amplifier 25. Capacitor 21 is coupled between switch 19 and circuit ground. Switch 19 serves to couple capacitor 21 from the output of amplifier 25 to the input of amplifier 10. The output of amplifier 25 is directly coupled by capacitor 38 to an inverting input of a third operational amplifier 40.

Capacitor 42 is coupled between ground and switch 41. Switch 41 serves to couple capacitor 42 from the output of amplifier 25 to the inverting input of amplifier 40. The non-inverting input 43 of amplifier 40 is coupled to ground. A feedback capacitor 44 is coupled between the output of amplifier 40 and the inverting input of amplifier 40. Capacitor 23 is coupled between switches 22 and 24. Switch 24 serves to couple the output of amplifier 40 to one end of capacitor 23 and then to switch the one end of capacitor 23 to ground. Switch 22 serves to switch the other end of capacitor 23 to ground and then to the inverting input of amplifier 10. Capacitor 34 is coupled between switches 33 and 36. Switch 36 serves to couple the output of amplifier 40 to one end of capacitor 34 and then to switch the one end of capacitor 34 to ground. Switch 33 serves to switch one end of capacitor 34 to ground and then to the inverting input of amplifier 25. Amplifiers 10, 25, and 40 along with their associated capacitors and switches represent three poles of the switched capacitor filter.

An output switched capacitor integrator having an operational amplifier 50 provides output V_O . A feedback capacitor 52 is coupled

13

from the output of amplifier 50 to the inverting input of amplifier 50. Capacitor 46 couples the output of amplifier 40 to the inverting input of amplifier 50. The non-inverting input 51 of amplifier 50 is coupled to ground. Switch 47 is coupled between the inverting input and the output of amplifier 50. Switch 47 resets the integrator having an amplifier 50 implements a difference equation which combines terms of three other state variables to produce the output V_0 . The three other state variables are implemented by the other switched capacitor integrators having amplifiers 10, 25, and 40.

The switches of Fig. 1 are electronically implemented and are switched at the sampling frequency of the filter. The switched capacitors are used to simulate resistors. In the preferred embodiment, the filter of Fig. 1 is implemented as a CMOS structure. Although the filter could be implemented by other than CMOS devices, CMOS devices are preferred because the entire circuit can be implemented on a relatively small area of silicon; and CMOS circuits have low power dissipation. The amplifiers of Fig. 1 can be standard differential or operational amplifiers as is becoming well known in the art of switched capacitor filters. The amplifiers are generally, relative low performance operational amplifiers. At first the filter illustrated in Fig. 1 may appear to be a switched capacitor filter implemented in the ordinary manner. However, upon closer inspection it becomes clear the interconnection and interaction of the individual switched capacitor integrators is different than those heretofore known.

The capacitors of Fig. 1 can be expressed as ratios of each other thereby simplifying a monolithic integrated circuit implementation of the filter. By way of example only, the capacitors can have the following ratios to provide a high pass filter for sixty Hertz rejection in PCM voice channels with a passband of 300 to 4 KHz, passband ripple of 0.02 dB peak-to-peak; 60 Hz rejection greater than fifteen dB, 180 Hz rejection less than 1.5 dB, and a switching rate of 8 KHz:

Capacitor Ratio	
14	1
16	30.822452
18	2
21	2.065893
23	0.96702595
27	15.66957
28	11.28096
31	2.1363366
34	1
37	14.66957
38	1
42	2
44	7.334785
46	15.172
52	1

In selecting the capacitor ratios, preferably,

the switched capacitors are as near unity as possible and then the non-switched capacitors will tend to be large.

Reference to Fig. 2 may provide a better understanding of the implementation of the filter of Fig. 1. Fig. 2 shows a switched capacitor integrator having three input voltages, V_1 , V_2 , V_3 , an output voltage V_4 , and a reference potential illustrated as ground. Operational amplifier 60 has an inverting and a non-inverting input. Non-inverting input 62 is coupled to ground. A feedback capacitor 61 is coupled between the inverting input and the output of amplifier 60. The output of amplifier 60 provides voltage V_4 . Voltage V_3 is coupled to the inverting input of amplifier 50 by capacitor 63. Voltage V_2 is controllably coupled to one end of capacitor 67 by switch 66. Switch 66 can controllably switch the one end of capacitor 67 to input V_2 or to ground. The other end of capacitor 67 is controllably switched by switch 64 to ground or to the inverting input of amplifier 60. Capacitor 69 is coupled from ground to switch 68. Switch 68 can controllably switch one end of capacitor 69 from voltage V_1 to the inverting input of amplifier 60.

The circuit of Fig. 2 is implemented from a difference equation which has been converted to a bilinear Z transform equation. The difference equation is as follows:

$$\Delta V_4 = V_4[(k+1)T] - V_4(kT) =$$

$$-\alpha V_1(kT) + \beta V_2(kT) - \gamma$$

$$[V_3[(k+1)T] - V_3(kT)].$$

This equation can be expressed in the z-plane as follows:

$$(z-1)V_4 = -\alpha V_1 + \beta V_2 - \gamma(z-1)V_3$$

Where V_1 , V_2 , V_3 , V_4 are the input and output voltages for the switched capacitor integrator illustrated in Fig. 2. T is the sampling period and k is an integer. α is equal to the ratio of the capacitance of capacitor 69 divided by the capacitance of capacitor 61. β is equal to the ratio of the capacitance of capacitor 67 divided by the capacitance of capacitor 61. γ is equal to the ratio of the capacitance of capacitor 63 divided by the capacitance of capacitor 61.

The above equations along with Fig. 2 illustrate a switched capacitor integrator which is implemented from a difference equation, and in the present case, preferably from equations in the z-plane derived by bilinear transform. The method for arriving at the z-plane equations can be achieved by those skilled in the art once the procedure to be followed is learned. As is well known, in order to design a filter the bandpass ripple, passband frequency, stop band frequency, and stop band rejection must be known. The passband ripple frequency and stop band frequencies are prewarped to compen-

14

sate for a frequency warping effect which takes place during a later transformation which is made. The warped frequency, ω , can be obtained (in radians) by multiplying two times the arc tangent of the specified frequency, Ω , (in radians) times T the period of the sampling frequency divided by two which can be written in the following manner:

$$\omega \text{ (new freq.)} = 2 \arctan \frac{\Omega T}{2}$$

Once the prewarped frequencies are known, reference can be made to a standard filter table so that a passive type filter can be derived. As an example, the passive filter equivalent of the filter of Fig. 1 would be a 3-pole Chebyshev high pass prototype doubly terminated ladder filter. State equations for the passive type filter are then reduced to their lowest terms. Through Laplace transformation these equations are then converted to the s -plane. The s -plane equations are then transformed to the z -plane by bilinear Z transform. This transformation is done by the well known technique of changing each s to two times $z-1$ over $z+1$. What the transformation does is it converts the s -plane poles and zeros into an appropriate z -plane pole zero pattern that yields the same frequency magnitude response as the s -plane filter does. A frequency warping effect occurs in the conformal mapping from the s -plane to the z -plane. In other words, the magnitudes would be the same for the frequency response but the frequency is gradually compressed. It is a non-linear compression or arc tangent compression. However, prewarping these frequencies prior to deriving the passive type filter compensates for the conformal transformation warping that occurs. Once the bilinear z transform is performed then the equations are placed in difference equation format. These difference equations can then be implemented as a switched capacitor filter by using switched capacitor integrators as has been shown hereinbefore.

Fig. 3 illustrates the preferred CMOS implementation of the switches shown in Figs. 1 and 2. Transistor 71 is a P-channel transistor in parallel with an N-channel transistor 72. The gate of transistor 72 is shown as being enabled by timing signal ϕ while the gate of transistor 71 is shown enabled by a timing signal $\bar{\phi}$. ϕ and $\bar{\phi}$ are complements of each other. The transmission gate of Fig. 3 could be a direct replacement for switch 47 in Fig. 1. Switch 13 can be two of the transmission gates in series with capacitor 14 connected to the common line between the two transmission gates. Of course, to implement switch 13, the P-channel transistor of the second transmission gate would be enabled by ϕ and the N-channel transistor of the second transmission gate would be enabled by $\bar{\phi}$.

By now it should be appreciated that there has been provided a new and improved filter along with a method for implementing such a filter. The filter of the present invention does not suffer from the peaking problem associated with filters implemented by the prior art technique of deriving the flow graph of a passive filter, and then replacing integrator blocks with switched capacitor integrators. The prior art approach of implementing switched capacitor filters can be described as modeling the passive filter, while the approach of the present invention takes passive filter characteristics and mathematically transforms them into a discrete time plane, the z -plane, and then implements a switched capacitor filter from terms within the mathematical transformation represented by difference equation. This approach eliminates any peaking that may occur near the center of the band pass. The break frequency of the filter should be between 30 and 40 times below the switching frequency. The present filter has particular application to high pass filters.

Claims

1. A high pass filter having a predetermined stop and passband frequency which are prewarped and which uses switched capacitor integrators having operational amplifiers (10, 25, 40) and controllable switches (13, 17, 32, 19, 41, 24, 22, 36, 33) for switching the capacitors (14, 16, 18, 27, 28, 31, 21, 38, 37, 42, 44, 23, 34) arranged to implement a passive filter prototype characterised by implementing difference equations resulting from applying a bilinear Z transform to S -plane state equations describing the passive prototype equivalent filter which satisfy requirements of a filter having prewarped pertinent frequencies, so that low passband ripple for frequencies extending out to substantially one-half of a sampling frequency is provided and the same sensitivity as the S -plane prototype of said filter is substantially maintained.

2. The high pass filter of claim 1 having a plurality of switched capacitor integrators, for providing low passband ripple for frequencies extending out to substantially one-half of a sampling frequency characterised by maintaining substantially the same sensitivity as the sensitivity of the S -plane prototype of said filter, comprising:

- a first switched capacitor integrator, for implementing a first frequency pole of said filter, comprising:
- a first operational amplifier (10) having a first and a second input and an output, the second input being coupled to a reference terminal;
- a first capacitor (14) coupled to the reference terminal;
- a first switch (13) coupled to said first capacitor (14), for switching the first capacitor (14)

14

sate for a frequency warping effect which takes place during a later transformation which is made. The warped frequency, ω , can be obtained (in radians) by multiplying two times the arc tangent of the specified frequency, Ω , (in radians) times T the period of the sampling frequency divided by two which can be written in the following manner:

$$\omega \text{ (new freq.)} = 2 \arctan \frac{\Omega T}{2}$$

Once the prewarped frequencies are known, reference can be made to a standard filter table so that a passive type filter can be derived. As an example, the passive filter equivalent of the filter of Fig. 1 would be a 3-pole Chebyshev high pass prototype doubly terminated ladder filter. State equations for the passive type filter are then reduced to their lowest terms. Through Laplace transformation these equations are then converted to the s-plane. The s-plane equations are then transformed to the z-plane by bilinear Z transform. This transformation is done by the well known technique of changing each s to two times $z-1$ over $z+1$. What the transformation does is it converts the s-plane poles and zeros into an appropriate z-plane pole zero pattern that yields the same frequency magnitude response as the s-plane filter does. A frequency warping effect occurs in the conformal mapping from the s-plane to the z-plane. In other words, the magnitudes would be the same for the frequency response but the frequency is gradually compressed. It is a non-linear compression or arc tangent compression. However, prewarping these frequencies prior to deriving the passive type filter compensates for the conformal transformation warping that occurs. Once the bilinear z transform is performed then the equations are placed in difference equation format. These difference equations can then be implemented as a switched capacitor filter by using switched capacitor integrators as has been shown hereinbefore.

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By now it should be appreciated that there has been provided a new and improved filter along with a method for implementing such a filter. The filter of the present invention does not suffer from the peaking problem associated with filters implemented by the prior art technique of deriving the flow graph of a passive filter, and then replacing integrator blocks with switched capacitor integrators. The prior art approach of implementing switched capacitor filters can be described as modeling the passive filter, while the approach of the present invention takes passive filter characteristics and mathematically transforms them into a discrete time plane, the z-plane, and then implements a switched capacitor filter from terms within the mathematical transformation represented by difference equation. This approach eliminates any peaking that may occur near the center of the band pass. The break frequency of the filter should be between 30 and 40 times below the switching frequency. The present filter has particular application to high pass filters.

Claims

1. A high pass filter having a predetermined stop and passband frequency which are prewarped and which uses switched capacitor integrators having operational amplifiers (10, 25, 40) and controllable switches (13, 17, 32, 19, 41, 24, 22, 36, 33) for switching the capacitors (14, 16, 18, 27, 28, 31, 21, 38, 37, 42, 44, 23, 34) arranged to implement a passive filter prototype characterised by implementing difference equations resulting from applying a bilinear Z transform to S-plane state equations describing the passive prototype equivalent filter which satisfy requirements of a filter having prewarped pertinent frequencies, so that low passband ripple for frequencies extending out to substantially one-half of a sampling frequency is provided and the same sensitivity as the S-plane prototype of said filter is substantially maintained.

2. The high pass filter of claim 1 having a plurality of switched capacitor integrators, for providing low passband ripple for frequencies extending out to substantially one-half of a sampling frequency characterised by maintaining substantially the same sensitivity as the sensitivity of the S-plane prototype of said filter, comprising:

- a first switched capacitor integrator, for implementing a first frequency pole of said filter, comprising:
 - a first operational amplifier (10) having a first and a second input and an output, the second input being coupled to a reference terminal;
 - a first capacitor (14) coupled to the reference terminal;
 - a first switch (13) coupled to said first capacitor (14), for switching the first capacitor (14)



to an input (V_{IN}) of the filter and then to the first input of the first amplifier (10);

a second capacitor (16) coupled between the first input and the output of the first amplifier (10), for providing feedback to the first input of the first operational amplifier (10);

a third capacitor (18) coupled to the reference terminal; and

a second switch (17) coupled to said third capacitor (18), for switching the third capacitor (18) to the output of the first amplifier (10) or to the first input;

a second switched capacitor integrator, for implementing a second frequency pole of said filter, comprising:

a second operational amplifier (25) having a first and a second input and an output, the second input being coupled to the reference terminal;

a fourth capacitor (27) coupled between the output of the first amplifier (10) and the first input of the second amplifier (25);

a fifth capacitor (28) coupled between the first input of the second amplifier (25) and the output of the second amplifier (25), for providing feedback to the first input of the second operational amplifier (25);

a sixth capacitor (31) coupled to the reference terminal;

a third switch (32) coupled to said sixth capacitor (31), for switching the sixth capacitor (31) to the output of the second amplifier (25) or to the first input of the second amplifier (25);

a seventh capacitor (21) coupled to the reference terminal; and

a fourth switch (19) coupled to said seventh capacitor (21) for switching the seventh capacitor (21) to the output of the second amplifier (25) or to the first input of the first amplifier (10); and

a third switched capacitor integrator, for implementing a third frequency pole of said filter, comprising: a third operational amplifier (40) having a first and a second input and an output, the second input being coupled to the reference terminal;

an eighth capacitor (38) coupled between the output of the second amplifier (25) and the first input of the third amplifier (40);

a ninth capacitor (37) coupled between the output of the first amplifier (10) and the first input of the third amplifier (40);

a tenth capacitor (42) coupled to the reference terminal;

a fifth switch (41) coupled to said tenth capacitor (42), for switching the tenth capacitor (42) to the output of the second amplifier (25) or to the first input of the third amplifier (40);

an eleventh capacitor (44) coupled between the output of the third amplifier (40) and the first input of the third amplifier (40), for providing feedback to the first input of the first input of the third operational amplifier (40);

a twelfth capacitor (23) having a first and a second terminal;

a sixth switch (24) for switching the first terminal of the twelfth capacitor (23) to the output of the third amplifier (40) or to the reference terminal;

a seventh switch (22) for switching the second terminal of the twelfth capacitor (23) to the first input of the first amplifier (10) or to the reference terminal;

a thirteenth capacitor (34) having a first and a second terminal;

an eighth switch (36) for switching the first terminal of the thirteenth capacitor (34) to the output of the third amplifier (40) or to the reference terminal; and

a ninth switch (33) for switching the second terminal of the thirteenth capacitor (34) to the reference terminal or to the first input of the second amplifier (25).

3. A switched capacitor filter as claimed in claim 2 further characterised by:

a fourth switched capacitor integrator, for implementing a difference equation which combines terms of said first, second and third switched capacitor integrators, comprising:

a fourth operational amplifier (50) having a first input, a second input and an output, the second input being coupled to the reference terminal; a fourteenth capacitor (46) coupled between the first input of the fourth amplifier (50) and the output of the third amplifier (40), for coupling the output of said first, second and third integrators to said fourth integrator;

a fifteenth capacitor (52) coupled between the output of the fourth amplifier (50) and the first input of the fourth amplifier (50), for providing feedback to said first input; and

a tenth switch (47) for resetting the output of the fourth amplifier (50).

4. A switched capacitor filter as claimed in claim 3 characterised in that all of the switches are electronic switches controllable by an input timing signal.

5. A switched capacitor filter as claimed in claim 3 characterised in that the amplifiers are CMOS amplifiers and all the switches other than the tenth switch (47) are CMOS transmission gates, the tenth switch (47) being a field effect transistor.

6. A switched capacitor filter as claimed in claim 2 characterised in that all the capacitors are ratios of each other.

7. A switched capacitor filter as claimed in claim 6 characterised in that the first (14), eighth (38) and thirteenth capacitors (34) are a ratio of one; the third (18) and tenth capacitors (42) are a ratio of two; the second capacitor has a ratio of substantially 30.8; the fourth capacitor has a ratio of substantially 15.6; the fifth capacitor has a ratio of substantially 11.2; the



sixth capacitor has a ratio of substantially 2.1; the seventh capacitor has a ratio of substantially 2.06; the ninth capacitor has a ratio of substantially 14.6; the eleventh capacitor has a ratio of substantially 7.3; and the twelfth capacitor has a ratio of substantially 0.9.

8. A switched capacitor filter as claimed in claim 3 characterised in that all the capacitors are ratios of each other.

9. A switched capacitor filter as claimed in claim 8, characterised in that the fourteenth capacitor (46) is a ratio of substantially 5.1, the fifteenth capacitor (52) is a ratio of substantially one.

10. A switched capacitor filter as claimed in claim 3 characterised in that the first input of each of the operational amplifiers (10, 25, 40) are an inverting input and the second input of each of the operational amplifiers in a non-inverting input.

11. A method for making a high pass switched capacitor filter having a predetermined stop band frequency, comprising the steps of:

prewarping the stop band frequency;
selecting a passive filter prototype, characterised by:
obtaining S-plane state equations for the passive filter prototype;
converting the S-plane state equations to equations in bilinear Z transform format and obtaining difference equations; and
implementing the resulting difference equations using switched capacitor integrator structures so that low passband ripple for frequencies extending out to substantially one half of a sampling frequency is provided and the same sensitivity as the S-plane prototype of said filter is substantially maintained.

12. A method of providing a switched capacitor filter for a desired passband break frequency and stop band frequency, comprising the steps of:

prewarping the passband break frequency and the stop band frequency to obtain prewarped equivalent frequencies;
selecting a passive prototype filter having the prewarped frequencies, characterised by:
obtaining state equations for the passive prototype filter in S-plane domain;
transforming the S-plane state equations to bilinear Z transform state equations in difference equation form; and
implementing the difference equations using switched capacitor integrator structures, so that low pass band ripple for frequencies extending out to substantially one half of a sampling frequency is provided and the same sensitivity as the S-plane prototype of said filter is substantially maintained.

Patentansprüche

1. Hochpaßfilter mit einer vorbestimmten Sperr- und Durchlaßband-Frequenz, die vorverzerrt sind, und das geschaltete Kondensator-Integrator mit Operationsverstärkern (10, 25, 40) und steuerbare Schalter (13, 17, 32, 19, 41, 24, 22, 36, 33) zum Schalten der Kondensatoren (14, 16, 18, 27, 28, 31, 21, 38, 37, 42, 44, 23, 34) verwendet und angeordnet ist, einen passiven Filterprototyp zu realisieren, gekennzeichnet durch Realisieren von Differenzgleichungen, die sich durch Anwenden einer bilinearen Z-Transformation auf S-Ebenen-Zustandsgleichungen ergeben, die das passive äquivalente Prototypfilter beschreiben, das die Anforderungen eines Filters erfüllt, das vorverzerrte entsprechende Frequenzen aufweist, so daß eine niedrige Durchlaßband-Welligkeit für Frequenzen abgegeben wird, die sich im wesentlichen bis zu einem Halben der Abtastfrequenz hinaus erstrecken, und die gleiche Empfindlichkeit wie der S-Ebenen-Prototyp des Filters im wesentlichen erhalten bleibt.

2. Hochpaßfilter nach Anspruch 1 mit einer Vielzahl von geschalteten Kondensator-Integrator zum Abgeben einer niedrigen Durchlaßband-Welligkeit für Frequenzen, die sich im wesentlichen bis zu einem Halben einer Abtastfrequenz hinaus erstrecken, gekennzeichnet durch Aufrechterhalten im wesentlichen der gleichen Empfindlichkeit als die Empfindlichkeit des S-Ebenen-Prototyps des Filters mit:

einem ersten geschalteten Kondensator-Integrator zum Realisieren eines ersten Frequenzpols des Filters mit:

einem ersten Operationsverstärker (10) mit einem ersten und einem zweiten Eingang und einem Ausgang, wobei der zweite Eingang mit einer Bezugsklemme gekoppelt ist;

einem ersten Kondensator (14), der mit der Bezugsklemme gekoppelt ist;

einem ersten Schalter (13), der mit dem ersten Kondensator (14) gekoppelt ist zum Schalten des ersten Kondensators (14) zu einem Eingang (V_{in}) des Filters und dann zu dem ersten Eingang des ersten Verstärkers (10);

einem zweiten Kondensator (16), der mit dem ersten Eingang und dem Ausgang des ersten Verstärkers (10) gekoppelt ist zur Bildung einer Rückkopplung zum ersten Eingang des ersten Operationsverstärkers (10);

einem dritten Kondensator (18), der mit der Bezugsklemme gekoppelt ist; und

einem zweiten Schalter (17), der mit dem dritten Kondensator (18) zum Schalten des dritten Kondensators (18) an den Ausgang des ersten Verstärkers (10) oder an den ersten Eingang gekoppelt ist;

einem zweiten geschalteten Kondensator-Integrator zum Realisieren eines zweiten Frequenzpols des Filters mit:



(17)

einem zweiten Operationsverstärker (25) mit
 einem ersten und einem zweiten Eingang und
 einem Ausgang, wobei der zweite Eingang
 mit der Bezugsklemme gekoppelt ist;
 einem vierten Kondensator (27) der zwischen
 dem Ausgang des ersten Verstärkers (10)
 und dem ersten Eingang des zweiten Ver-
 stärkers (25) gekoppelt ist;
 einem fünften Kondensator (28), der zwischen
 den ersten Eingang des zweiten Verstärkers
 (25) und den Ausgang des zweiten Ver-
 stärkers (25) zur Bildung einer Rückkopplung
 zu dem ersten Eingang des zweiten Opera-
 tionsverstärkers (25) gekoppelt ist;
 einem sechsten Kondensator (31), der mit der
 Bezugsklemme gekoppelt ist;
 einem dritten Schalter (32), der mit dem sech-
 sten Kondensator (31) zum Schalten des sech-
 sten Kondensators (31) an den Ausgang des
 zweiten Verstärkers (25) oder den ersten Ein-
 gang des zweiten Verstärkers (25) gekoppelt
 ist;
 einen siebten Kondensator (21), der mit der
 Bezugsklemme gekoppelt ist; und
 einem vierten Schalter (19), der mit dem sieb-
 ten Kondensator (21) zum Schalten des sieb-
 ten Kondensators (21) an den Ausgang des
 zweiten Verstärkers (25) oder an den ersten
 Eingang des ersten Verstärkers (10)
 gekoppelt ist; und

einem dritten geschalteten Kondensator-Inte-
 grator zum Realisieren eines dritten Frequenz-
 pols des Filters mit:

einem dritten Operationsverstärker (40) mit
 einem ersten und einem zweiten Eingang und
 einem Ausgang, wobei der zweite Eingang
 mit der Bezugsklemme gekoppelt ist;
 einem achten Kondensator (38), der zwischen
 den Ausgang des zweiten Verstärkers (25)
 und den ersten Eingang des dritten Ver-
 stärkers (40) gekoppelt ist;
 einem neunten Kondensator (37), der zwischen
 den Ausgang des ersten Verstärkers (10) und
 den ersten Eingang des dritten Verstärkers
 (40) gekoppelt ist;
 einem zehnten Kondensator (42), der mit der
 Bezugsklemme gekoppelt ist;
 einem fünften Schalter (41), der mit dem zeh-
 nten Kondensator (42) zum Schalten des zeh-
 nten Kondensators (42) an den Ausgang des
 zweiten Verstärkers (25) oder an den ersten
 Eingang des dritten Verstärkers (40)
 gekoppelt ist;
 einem elften Kondensator (44), der zwischen
 den Ausgang des dritten Verstärkers (40) und
 den ersten Eingang des dritten Verstärkers
 (40) zur Bildung einer Rückkopplung zu dem
 ersten Eingang des ersten Eingangs des drit-
 ten Operationsverstärkers (40) gekoppelt ist;
 einem zwölften Kondensator (23) mit einer
 ersten und einer zweiten Klemme;
 einem sechsten Schalter (24) zum Schalten der
 ersten Klemme des zwölften Kondensators

(23) an den Ausgang des dritten Verstärkers
 (40) oder an die Bezugsklemme;
 einem siebten Schalter (22) zum Schalten der
 zweiten Klemme des zwölften Kondensators
 (23) an den ersten Eingang des ersten Ver-
 stärkers (10) oder an die Bezugsklemme;
 einen dreizehnten Kondensator (34) mit einer
 ersten und zweiten Klemme;
 einem achten Schalter (36) zum Schalten der
 ersten Klemme des dreizehnten Kondensa-
 tors (34) an den Ausgang des dritten Ver-
 stärkers (40) oder an die Bezugsklemme; und
 einem neunten Schalter (33) zum Schalten der
 zweiten Klemme des dritten Kondensators
 (34) an die Bezugsklemme oder an den ersten
 Eingang des zweiten Verstärkers (25).

3. Ein geschaltetes Kondensatorfilter, wie in
 Anspruch 2 beansprucht, ferner gekennzeich-
 net, durch

einen vierten geschalteten Kondensator-
 Integrator zum Realisieren einer Differenz-
 gleichung, die die Terme des ersten, zweiten
 und dritten geschalteten Kondensator-Inte-
 grators kombiniert mit:
 einem vierten Operationsverstärker (50) mit
 einem ersten Eingang, einem zweiten Ein-
 gang und einem Ausgang, wobei der zweite
 Eingang mit der Bezugsklemme gekoppelt ist;
 einem vierzehnten Kondensator (46), der
 zwischen den ersten Eingang des vierten Ver-
 stärkers (50) und den Ausgang des dritten
 Verstärkers (40) zum Koppeln des Ausgangs
 des ersten, zweiten und dritten Integrators
 mit dem vierten Integrator gekoppelt ist;
 einem fünfzehnten Kondensator (52), der
 zwischen den Ausgang des vierten Ver-
 stärkers (50) und dem ersten Eingang des
 vierten Verstärkers (50) zur Bildung einer
 Rückkopplung zu dem ersten Eingang
 gekoppelt ist; und
 einem zehnten Schalter (47) zum Rückstellen
 des Ausgangs des vierten Verstärkers (50).

4. Geschaltetes Kondensatorfilter, wie in An-
 spruch 3 beansprucht, dadurch gekennzeich-
 net, daß alle die Schalter elektronische Schal-
 ter sind, die mittels eines Eingangs-Zeit-
 gabsignals steuerbar sind.

5. Geschaltetes Kondensatorfilter, wie in An-
 spruch 3 beansprucht, dadurch gekennzeich-
 net, daß die Verstärker CMOS-Verstärker sind
 und daß alle die Schalter mit Ausnahme des
 Zehnten Schalters (47) CMOS-Übertragungs-
 gatter sind, wobei der zehnte Schalter (47) ein
 Feldeffekttransistor ist.

6. Geschaltetes Kondensatorfilter, wie in
 Anspruch 2 beansprucht, dadurch gekenn-
 zeichnet, daß alle die Kondensatoren Verhält-
 nisanteile voneinander sind.

7. Geschaltetes Kondensatorfilter, wie in An-
 spruch 6 beansprucht, dadurch gekennzeich-
 net, daß der erste (14), achte (38) und
 dreizehnte Kondensator (34) im Verhältnis eins





sind; der dritte (18) und zehnte Kondensator (42) im Verhältnis zwei sind; der zweite Kondensator ein Verhältnis von im wesentlichen 30,8 besitzt; der vierte Kondensator ein Verhältnis von im wesentlichen 15,6 besitzt; der fünfte Kondensator ein Verhältnis von im wesentlichen 11,2 besitzt; der sechste Kondensator ein Verhältnis von im wesentlichen 2,1 besitzt; der siebte Kondensator ein Verhältnis von im wesentlichen 2,06 besitzt; der neunte Kondensator ein Verhältnis von im wesentlichen 14,6 besitzt; der elfte Kondensator ein Verhältnis von im wesentlichen 7,3 besitzt und der zwölfte Kondensator ein Verhältnis von im wesentlichen 0,9 besitzt.

8. Geschaltetes Kondensatorfilter, wie in Anspruch 3 beansprucht, dadurch gekennzeichnet, daß alle die Kondensatoren Verhältnisan-teile voneinander sind.

9. Geschaltetes Kondensatorfilter, wie in Anspruch 8 beansprucht, dadurch gekennzeichnet, daß der vierzehnte Kondensator (46) ein Verhältnis von im wesentlichen 15,1, der fünfzehnte Kondensator (52) ein Verhältnis von im wesentlichen eins besitzt.

10. Geschaltetes Kondensatorfilter, wie in Anspruch 3 beansprucht, dadurch gekennzeichnet, daß der erste Eingang jedes der Operationsverstärker (10, 25, 40) ein invertierender Eingang und der zweite Eingang jedes der Operationsverstärker ein nichtinvertierender Eingang sind.

11. Verfahren zum Herstellen eines Hochpaßfilters mit geschalteten Kondensatoren mit einer vorbestimmten Sperr-/Band-Frequenz umfassend die Schritte:

Vorverzerren der Sperr-/Band-Frequenz, Auswählen eines passiven Filterprototyps, gekennzeichnet, durch:

Erhalten von S-Ebenen-Zustands-Gleichungen für den passiven Filterprototyp;

Umwandeln der S-Ebenen-Zustands-Gleichungen in Gleichungen in dem bilinearen Z-Transformationsformat und Erhalten von Differenzgleichungen; und

Realisieren der sich ergebenden Differenzgleichungen unter Verwendung von Integratorstrukturen mit geschalteten Kondensatoren, so daß sich eine niedrige Durchlaßband-Welligkeit für Frequenzen ergibt, die sich im wesentlichen bis zu einem Halben einer Abtastfrequenz hinaus erstrecken, und die gleiche Empfindlichkeit, wie beim S-Ebenen-Prototyp des Filters im wesentlichen erhalten bleibt.

12. Verfahren zum Erstellen eines Filters mit geschalteten Kondensatoren für eine gewünschte Durchlaßband-Eckfrequenz und Sperrbandfrequenz mit den Schritten:

Vorverzerren der Durchlaßband-Eckfrequenz und der Sperrbandfrequenz, um vorverzernte äquivalente Frequenzen zu erhalten;

Auswählen eines passiven Prototypfilters, das die vorverzernten Frequenzen besitzt, gekennzeichnet durch:

Erhalten von Statusgleichungen für das passive Prototypfilter in dem S-Ebenen-Bereich;

Transformieren der S-Ebenen-Zustands-gleichungen in bilineare Z-Transformations-Zustandsgleichungen in Differenzgleichungsform; und

Realisieren der Differenzgleichungen durch Verwenden von Integratorstrukturen mit geschalteten Kondensatoren, so daß sich eine niedrige Durchlaßband-Welligkeit für Frequenzen ergibt, die sich im wesentlichen bis zu einem Halben einer Abtastfrequenz hinaus erstrecken, und die gleiche Empfindlichkeit wie die Empfindlichkeit des S-Ebenen-Prototyps des Filters im wesentlichen erhalten bleibt.

Revendications

1. Un filtre passe-haut ayant des fréquences de bande atténuée et de bande passante prédéterminées qui sont pré-distordues et qui utilise des intégrateurs à condensateurs commutés ayant des amplificateurs opérationnels (10, 25, 40) et des commutateurs commandés (13, 17, 32, 19, 41, 24, 22, 36, 33) pour commuter les condensateurs (14, 16, 18, 27, 28, 31, 21, 38, 37, 42, 44, 23, 34) conçu de façon à réaliser un prototype de filtre passif, caractérisé en ce qu'on met en oeuvre des équations de différence résultant de l'application d'une transformation en Z bilinéaire à des équations d'état dans le plan S décrivant le filtre équivalent au prototype passif qui satisfont les exigences d'un filtre ayant des fréquences pertinentes pré-distordues, de façon à donner une ondulation faible dans la bande passante pour des fréquences s'étendant pratiquement jusqu'à la moitié d'une fréquence d'échantillonnage, et de façon à maintenir pratiquement la même sensibilité que le prototype dans le plan S de ce filtre.

2. Le filtre passe-haut de la revendication 1 ayant un ensemble d'intégrateurs à condensateurs commutés, pour donner une ondulation faible dans la bande passante pour des fréquences s'étendant pratiquement jusqu'à la moitié d'une fréquence d'échantillonnage, caractérisé par le maintien d'une sensibilité pratiquement identique à la sensibilité du prototype dans le plan S de ce filtre, comprenant: un premier intégrateur à condensateurs commutés, pour réaliser un premier pôle de fréquence de ce filtre, comprenant:

un premier amplificateur opérationnel (10) ayant une première entrée et une seconde entrée et une sortie, la seconde entrée étant connectée à une borne de référence;

un premier condensateur (14) connecté à la borne de référence;

un premier commutateur (13) connecté au



19

premier condensateur (14), pour commuter le premier condensateur (14) sur une entrée (V_{in}) du filtre, puis sur la première entrée du premier amplificateur (10);

un second condensateur (16) connecté entre la première entrée et la sortie du premier amplificateur (10), pour établir une réaction vers la première entrée du premier amplificateur opérationnel (10);

un troisième condensateur (18) connecté à la borne de référence; et

un second commutateur (17) connecté au troisième condensateur (18), pour commuter le troisième condensateur (18) vers la sortie du premier amplificateur (10) ou vers la première entrée;

un second intégrateur à condensateurs commutés, pour réaliser un second pôle de fréquence du filtre, comprenant:

un second amplificateur opérationnel (25) ayant une première entrée et une seconde entrée et une sortie, la seconde entrée étant connectée à la borne de référence;

un quatrième condensateur (27) connecté entre la sortie du premier amplificateur (10) et la première entrée du second amplificateur (25);

un cinquième condensateur (28) connecté entre la première entrée du second amplificateur (25) et la sortie du second amplificateur (25), pour établir une réaction vers la première entrée du second amplificateur opérationnel (25);

un sixième condensateur (31) connecté à la borne de référence;

un troisième commutateur (32) connecté au sixième condensateur (31), pour commuter le sixième condensateur (31), pour commuter le second amplificateur (25) ou sur la première entrée du second amplificateur (25);

un septième condensateur (21) connecté à la borne de référence; et

un quatrième commutateur (19) connecté au septième condensateur (21) pour commuter le septième condensateur (21) vers la sortie du second amplificateur (25) ou vers la première entrée du premier amplificateur (10); et

un troisième intégrateur à condensateurs commutés, pour réaliser un troisième pôle de fréquence du filtre, comprenant:

un troisième amplificateur opérationnel (40) ayant une première entrée et une seconde entrée et une sortie, la seconde entrée étant connectée à la borne de référence;

un huitième condensateur (38) connecté entre la sortie du second amplificateur (25) et la première entrée du troisième amplificateur (40);

un neuvième condensateur (37) connecté entre la sortie du premier amplificateur (10) et la

première entrée du troisième amplificateur (40);

un dixième condensateur (42) connecté à la borne de référence;

un cinquième commutateur (41) connecté au dixième condensateur (42), pour commuter le dixième condensateur (42) vers la sortie du second amplificateur (25) ou vers la première entrée du troisième amplificateur (40);

un onzième condensateur (44) connecté entre la sortie du troisième amplificateur (40) et la première entrée du troisième amplificateur (40), pour établir une réaction vers la première entrée du troisième amplificateur opérationnel (40);

un douzième condensateur (23) ayant une première borne et une seconde borne;

un sixième condensateur (24) destiné à commuter la première borne du douzième condensateur (23) vers la sortie du troisième amplificateur (40) ou vers la borne de référence;

un septième commutateur (22) destiné à commuter la seconde borne du douzième condensateur (23) vers la première entrée du premier amplificateur (10) ou vers la borne de référence;

un treizième condensateur (34) ayant une première borne et une seconde borne;

un huitième commutateur (36) destiné à commuter la première borne du treizième condensateur (34) vers la sortie du troisième amplificateur (40) ou vers la borne de référence; et

un neuvième commutateur (33) destiné à commuter la seconde borne du treizième condensateur (34) vers la borne de référence ou vers la première entrée du second amplificateur (25).

3. Un filtre à condensateurs commutés selon la revendication 2, caractérisé en outre par:

un quatrième intégrateur à condensateurs commutés, pour mettre en oeuvre une équation de différence qui combine des termes des premier, second et troisième intégrateurs à condensateurs commutés, comprenant:

un quatrième amplificateur opérationnel (50) ayant une première entrée, une seconde entrée et une sortie, la seconde entrée étant connectée à la borne de référence;

un quatorzième condensateur (46) connecté entre la première entrée du quatrième amplificateur (50) et la sortie du troisième amplificateur (40), pour connecter au quatrième intégrateur la sortie des premier, second et troisième intégrateurs;

un quinzième condensateur (52) connecté entre la sortie du quatrième amplificateur (50) et la première entrée du quatrième amplificateur (50), pour établir une réaction vers cette première entrée; et

une dixième commutateur (47) pour restaurer la sortie du quatrième amplificateur (50).



20

4. Un filtre à condensateurs commutés selon la revendication 3, caractérisé en ce que tous les commutateurs sont des commutateurs électroniques qui peuvent être commandés par un signal d'horloge d'entrée.

5. Un filtre à condensateurs commutés selon la revendication 3, caractérisé en ce que les amplificateurs sont des amplificateurs CMOS et tous les commutateurs autres que le dixième commutateur (47) sont des portes de transmission CMOS, tandis que le dixième commutateur (47) est un transistor à effet de champ.

6. Un filtre à condensateurs commutés selon la revendication 2, caractérisé en ce que tous les condensateurs sont définis par des rapports mutuels.

7. Un filtre à condensateurs commutés selon la revendication 6, caractérisé en ce que les premier (14), huitième (38) et treizième condensateurs (34) sont dans un rapport de un; le troisième (18) et le dixième condensateurs (42) sont dans un rapport de deux; le second condensateur a un rapport pratiquement égal à 30,8; le quatrième condensateur a un rapport pratiquement égal à 15,6; le cinquième condensateur a un rapport pratiquement égal à 11,2; le sixième condensateur a un rapport pratiquement égal à 2,1; le septième condensateur a un rapport pratiquement égal à 2,06; le neuvième condensateur a un rapport pratiquement égal à 14,6; le onzième condensateur a un rapport pratiquement égal à 7,3; et le douzième condensateur a un rapport pratiquement égal à 0,9.

8. Un filtre à condensateurs commutés selon la revendication 3, caractérisé en ce que tous les condensateurs sont définis par des rapports mutuels.

9. Un filtre à condensateurs commutés selon la revendication 8, caractérisé en ce que le quatorzième condensateur (46) a un rapport pratiquement égal à 15,1, et le quinzième condensateur (52) a un rapport pratiquement égal à un.

10. Un filtre à condensateurs commutés selon la revendication 3, caractérisé en ce que la première entrée de chaque amplificateur opérationnel (10, 25, 40) est une entrée inverseuse et la seconde entrée de chaque amplificateur opérationnel est une entrée non inverseuse.

11. Une procédé pour réaliser un filtre à condensateurs commutés passe-haut ayant une

fréquence de bande atténuée prédéterminée, comprenant les opérations suivantes:

on pré-distord la fréquence de la bande atténuée;

on sélectionne un prototype de filtre passif, caractérisé en ce que:

on détermine des équations d'état dans le plan S pour le prototype de filtre passif;

on convertit les équations d'état dans le plan S en équations dans un format de transformation en Z bilinéaire et on détermine des équations de différence; et

on met en oeuvre les équations de différence résultantes en utilisant des structures d'intégrateurs à condensateurs commutés, de façon à obtenir une faible ondulation dans la bande passante pour des fréquences s'étendant pratiquement jusqu'à la moitié d'une fréquence d'échantillonnage, et de façon à maintenir pratiquement la même sensibilité que le prototype du filtre relatif au plan S.

12. Un procédé pour réaliser un filtre à condensateurs commutés pour une fréquence de coupure de bande passante désirée et pour une fréquence de bande atténuée désirée, comprenant les opérations suivantes:

on pré-distord la fréquence de coupure de la bande passante et la fréquence de la bande atténuée pour obtenir des fréquences équivalentes pré-distordues;

on sélectionne un filtre prototype passif ayant les fréquences pré-distordues, caractérisé en ce que:

on détermine des équations d'état pour le filtre prototype passif dans le domaine du plan S;

on transforme les équations d'état dans le plan S en équations d'état de transformation en Z bilinéaire sous forme d'équations de différence; et

on met en oeuvre les équations de différence en utilisant des structures d'intégrateurs à condensateurs commutés, de façon à obtenir une ondulation faible dans la bande passante pour des fréquences s'étendant pratiquement jusqu'à la moitié d'une fréquence d'échantillonnage, et de façon à maintenir pratiquement une sensibilité identique à la sensibilité du prototype du filtre relatif au plan S.

