An active R bandpass filter network (10) is formed by four operational amplifier stages interconnected by discrete resistances. One pair of stages (12, 14) synthesizes an equivalent input impedance of an inductance (L_{eq}) in parallel with a discrete resistance (R_0) while the second pair of stages (16, 18) synthesizes an equivalent input impedance of a capacitance (C_{eq}) serially coupled to another discrete resistance (R_i) coupled in parallel with the first two stages. The equivalent input impedances aggregately define a tuned resonant bandpass filter in the roll-off regions of the operational amplifiers.

11 Claims, 3 Drawing Figures
REACTANCELESS SYNTHESIZED IMPEDANCE BANDPASS AMPLIFIER

ORIGIN OF THE INVENTION

The invention described herein was made by an employee of the United States Government and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereof or therefor.

TECHNICAL FIELD

This invention relates generally to bandpass filters and, more particularly, to an active R reactanceless synthesized impedance bandpass amplifier.

BACKGROUND ART

Active electronic filters, particularly bandpass amplifiers, are well known in the art. They are usually constructed with at least one active device and several discrete passive resistive and reactive components. A dual-input differential amplifier, commonly referred to as an “operational amplifier,” is an active device exhibiting a very high, open loop gain, over a wide bandwidth, a very high input impedance, and a very low output impedance. Widespread commercial availability of operational amplifiers and their nearly ideal characteristics make them the preferred active devices for use in active filters. Additionally, operational amplifiers are readily suited to integrated circuit fabrication. To take advantage of the economy, compactness and versatility of integrated circuits, it is desirable to design amplifier circuits which are suitable for integrated circuit fabrication. Amplifier circuits having only passive components are particularly suitable because they may be made as monolithic devices capable of functioning without external passive impedance components. Recent proposals for integrated active amplifier circuits having operational amplifiers include the class of filters called “active R” filters. These filters are constructed with only passive components. Amplifier circuits having only passive components provide two significant advantages. First, resistances can be made to exhibit greater stability than any of the other passive components. Second, resistance components may be made easily adjustable, thereby enabling a circuit to be tuned over a band of frequencies without significantly effecting stability of the circuit. One proposed design relies upon the existence of a resistive-capacitive equivalent in the transfer function of a differential input amplifier to form a bandpass filter with only two passive components, both resistances, and two operational amplifiers. The performance of this particular design provides only minimal improvement over an equivalent circuit constructed with transistors because it relies upon a change of gain with frequency to provide filtering and lacks both the tunability and sharpness of conventional inductive-capacitive tuned filter circuits.

STATEMENT OF INVENTION

Accordingly, it is one object of the present invention to provide an improved active reactanceless synthesized impedance filter network having only passive components. It is another object to provide an active synthesized impedance filter network having only resistive passive components.
octave. While all of the operational amplifiers have roll-off and unity-gain frequencies, the values of those frequencies may differ for different models of operational amplifiers. It should be noted that at the roll-off frequency, the open loop gain of an operational amplifier is typically on the order of thousands of decibels. A gain of this magnitude is extremely difficult to control because, for example, a small variation in the amplitude of an input signal can drive an operational amplifier into saturation, thereby temporarily eliminating the linearity of its responsive characteristics. Stability of an active network having operational amplifiers, therefore, requires the use of one or more resistances in the signal paths of the network to attenuate the gain introduced by the operational amplifiers to more manageable levels.

Stage 12 of the first pair of stages 12, 14, serves as a signal path with the non-inverting port (+) of operational amplifier A1 directly coupled to node 20. Resistances R1 and R2 provide a voltage divider between node 22, the inverting port, and the output port to reduce the open loop gain of operational amplifier A1 to a lower value, thereby assuring a linear response characteristic more consonant with the stability usually desired for a multi-stage network such as network 10. In effect, resistances R1 and R2 form a feedback loop, thereby making the first stage into a conventional non-inverting differential input amplifier stage connected between input node 20 and an output node 24 of the network.

The second stage 14 includes operational amplifier A2 and a variable resistance R0 which providesition serve to create a voltage drop between the output port of operational amplifier A2 and input node 20. A pair of resistances R3, R4 are serially connected between nodes 20 and 24 as a voltage divider. The inverting port (−) of operational amplifier A2 is coupled to the junction between R3 and R4. The non-inverting port (+) of operational amplifier A2 is directly coupled to node 22. Resistance R3 provides a potential drop between the output port of operational amplifier A1 and the inverting input port of operational amplifier A2 while resistance R4 provides a potential difference between the inverting and non-inverting parts of operational amplifier A2. In effect, the second stage 14 forms an inverting feedback loop between the output and input ports of operational amplifier A1 while resistances R3 and R4 cause some attenuation of a signal traveling through this loop, thereby providing a degree of stability to the first pair of coupled stages.

The input admittance, \(Y_{in}\), provided between nodes 20, 22 by the first and second stages 12, 14 may be expressed by the general closed loop feedback equation:

\[
Y_{in} = \frac{(1 - k_o f) Y_{fb}}{1 - k_o f}
\]  

where \(k_o f\) is the voltage gain of the coupled stages as a function of frequency and \(Y_{fb}\) is, in effect, the feedback admittance provided by the combined first and second stages. The voltage gain, \(k_o f\), provided at the output port of operational amplifier A2 of the coupled stages 12, 14 may be expressed as:

\[
k_o f = \frac{-G_2 L}{1 + j \omega L}
\]

where \(k_o\) is the open loop gain introduced through the inverting port of operational amplifier A2, \(G_2\) is the gain provided by first stage 12, \(L\) is the attenuation provided by resistances \(R_3\) and \(R_4\). By reference to FIG. 2, it may be seen that:

\[
f_{-3 \, db} = f_{G}
\]

where \(f_{-3 \, db}\) and \(f_G\) are the minus three decibel frequency and the unity gain frequency, respectively for a typical operational amplifier. Substituting equation (3) into equation (2), it may be seen that for the large values of \(k_o\) typically occurring between \(f_{-3 \, db}\) and \(f_G\) in the commercially available operational amplifiers suitable for use as A1 and A2, the voltage gain function of equation (2) can be expressed as:

\[
K_{L} f = \frac{-G_2 L}{1 + j \omega L} = \frac{j f G L_2 B_2}{j f G}
\]  

The gain provided by stage 12 is determined by the values of resistances \(R_1\) and \(R_2\), and may be expressed as:

\[
G_L = 1 + \frac{R_3}{R_1}
\]

Similarly, the attenuation provided by the second stage 14 is determined by the values of resistances \(R_3\) and \(R_4\), and may be expressed as:

\[
\beta_L = \frac{R_4}{R_3 + R_4}
\]

The closed loop feedback admittance of the combined first and second stages is determined by the value of resistance \(R_o\). Accordingly, by substitution of equations (4), (5) and (6) into equation (1), the input admittance is:

\[
Y_n = \frac{1}{1 - j f G} \left[ \frac{R_1 + R_2}{R_1} \cdot \frac{R_4}{R_3 + R_4} \right] \frac{1}{R_0}
\]

Equation (7) indicates that over the frequency spectrum in the roll-off region of operational amplifier A2, the coupled first and second stages 12, 14 provide an equivalent input admittance between nodes 20 and 22 having a conductance equal in value to the reciprocal of resistance \(R_o\) in series with a negative, single pole susceptance. This is equivalent to a resistance equal in value to \(R_o\) in parallel with an inductance, \(L_{eq}\), between nodes 20 and 22, where:

\[
L_{eq} = \frac{1}{j f G} \left[ \frac{R_1 + R_2}{R_1} \cdot \frac{R_4}{R_3 + R_4} \right] \frac{1}{R_0}
\]

The presence of resistance \(R_o\) and of resistances \(R_1\), \(R_2\), \(R_3\) and \(R_4\) in equation (8) establishes that over its roll-off region the feedback loop provided by operational amplifier A2 creates a phase shift of the input admittances of the first and second stages, thereby causing the lumped conductances of \(R_o\), \(R_1\), \(R_2\), \(R_3\) and \(R_4\) to appear as constituent parts of a negative susceptance. At the typical roll-off frequency, \(f_{-3 \, db}\), phase shift is about forty-five degrees while at frequencies near ten times the roll-off frequency this phase shift approaches ninety degrees. Over the band between one hundred times the roll-off
frequency and the unity-gain frequency, the phase shift of the lumped conductances is ninety degrees. If operational amplifier such as an OP-07 manufactured by Precision Monolithics, Incorporated of Santa Clara, Calif., having a roll-off frequency of one Hertz and a unity gain frequency of five hundred mega Hertz, are used for operational amplifiers A1, A2, A3 and A4, the lumped conductances of resistances R5, R1, R2, R3 and R4 will be subjected to a ninety degree phase shift over the band between one hundred Hertz and five hundred mega Hertz by operational amplifier A2 in the second stage, thus presenting an equivalent input inductive susceptance between nodes 20 and 22 of the network.

In the second pair of coupled stages 16, 18, stage 16 serves as a signal path. A variable resistance Rj, is connected across the input ports of operational amplifier A3 of third stage 16. The non-inverting (+) input port of operational amplifier A3 is coupled directly to node 20. Rj provides an input impedance for the second pair of stages while developing a potential difference between the input ports of operational amplifier A3. The output port of operational amplifier A3 is coupled to node 22 via a pair of serially connected resistances R5 and R6 which provide attenuation of any signal passed by the third stage 16 to assure the stability of the third stage. The fourth stage 18 has a single operational amplifier A4 with its non-inverting port (+) coupled to the junction between resistances R5 and R6. The inverting port (-) and output port of operational amplifier A4 are both coupled directly to the inverting port of operational amplifier A3. In effect, operational amplifier A4 is a unity-gain voltage follower coupled between the junction between resistances R5 and R6 and the inverting port of operational amplifier A3, and acts as a feedback loop serving to stabilize the operation of the third stage.

The input impedance, Zin, provided between nodes 20, 22 by the third and fourth stages 16, 18 may be expressed by the general closed loop feedback equation:

\[ Z_{in} = Z_{i}(1 + \frac{C_{j} C_{k} C_{d}}{C_{i}}) \]

(9)

where \( k_{i}(f) \) is the voltage gain of the coupled third and fourth stages as a function of frequency and \( Z_{i} \) is the input impedance of the loop. For the coupled third and fourth stages, the gain-bandwidth function may be expressed as:

\[ k_{d}(f) = \frac{k}{1 + j f} \]

(10)

The fourth stage 18, which acts as a voltage follower for the third stage, provides a gain, \( G_{o} \), of one. The attenuation provided by the coupled third and fourth stages between nodes 20 and 22 is determined by the values of resistances \( R_{5} \) and \( R_{6} \), and may be expressed as:

\[ \beta_{e} = \frac{R_{5}}{R_{5} + R_{6}} \]

(11)

The closed loop feedback impedance of the coupled third and fourth stages is determined by the value of resistance \( R_{e} \). Substitution of these values into equations (9) and (10) gives an input impedance for the coupled third and fourth stages of:
applications, all of the resistances may have fixed values and the entire network may be monolithically constructed by integrated circuit techniques as a single device.

An output signal from network 10 may be taken directly from the output port of operational amplifier A1 at node 24. In such an application, network 10 will act as a bandpass filter if the center frequency determined by the relative values of the synthesized L<sub>eq</sub> and C<sub>eq</sub> is designed to be within the roll-off regions of operational amplifiers A2 and A3. Preferably to avoid phase distortion, the center frequency should be set to fall within a band between ten times the roll-off frequency and the unity gain frequency of operational amplifiers A2 and A3. To assure predictable performance of the network, in any application the operational amplifiers A2 and A3 should be selected to exhibit nearly equal gain-bandwidth products (i.e., nearly equal roll-off frequencies). Preferably, the gain-bandwidth products and roll-off frequencies of operational amplifiers A1 and A4 are well beyond the gain-bandwidth products and roll-off frequencies of operated amplifiers A2 and A3.

For a different application, e.g., phase detection, separate output signals taken from nodes 26 and 28 will exhibit phase shifts of plus and minus ninety degrees, respectively, from an input signal applied to input terminal node 20, thereby providing paraphase amplification of the input signal.

1. An active filter network, comprising:
   a pair of active circuits (12-14, 16-18) each having first (A1, A3) and second (A2, A4) operational amplifiers coupled together to provide multiple feedback loops therein;
   means (20) for applying an input signal directly to a non-inverting input port of each of said first operational amplifiers in each of said pair of circuits;
   first resistive means (R1, R2) included within a first of said feedback loops for attenuating the amplitude of signals between an output port and inverting input port of said first operational amplifiers (A1) in a first of said pair of circuits (12-14);
   second resistive means (R3, R4, R<sub>0</sub>) included within said first of said feedback loops in conjunction with said second operational amplifier (A2) in said first of said pair of circuits (12-14) for attenuating and inverting the amplitude of signals between said output port and non-inverting input port of said first operational amplifier in said first of said pair of circuits; and
   third resistive means (R<sub>0</sub>, R<sub>1</sub>, R<sub>2</sub>) included within a second of said feedback loops in conjunction with said second operational amplifier (A4) in a second of said pair of circuits (16-18) coupled in a voltage follower configuration for attenuating the amplitude of signals between the output port and said non-inverting input port of said first operational amplifier in said first of said pair of circuits; wherein said resistive means are of a magnitude to tune each of said circuits to operate in the gain versus frequency roll-off region of said second operational amplifier (A2) in said first of said pair of circuits (12-14) and said first operational amplifier (A3) in said second of said pair of circuits (16-18), thereby providing an equivalent inductive reactance by said first of said pair of circuits and an equivalent capacitive reactance by said second of said pair of circuits to said input signal at frequencies in said roll-off region.

2. The active filter network of claim 1 wherein said second operational amplifier (A2) in said first of said pair of circuits (12-14) and said first operational amplifier (A3) in said second of said pair of circuits (16-18) exhibit near equal roll-off characteristics.

3. The active filter network of claim 2 wherein said second operational amplifier (A4) in said second of said pair of circuits (16-18) and said first operational amplifier (A1) in said first of said pair of circuits (12-14) exhibit roll-off characteristics at substantially higher frequencies than said second operational amplifier (A2) in said first pair of circuits and said first operational amplifier (A3) in said second of said pair of circuits.

4. The active filter network of claim 3 wherein said resistive means are of a magnitude to tune each of said pair of circuits to a frequency range between ten times the roll-off frequency (f-3) and the unity gain frequency (f<sub>G</sub>) of said second operational amplifier (A2) in said first of said pair of circuits (12-14) and said first operational amplifier (A3) in said second of said pair of circuits (16-18).

5. The active filter network of claim 1 wherein said first and second resistive means of said first feedback loop includes a pair of resistors (R<sub>1</sub>, R<sub>2</sub>) both having one end connected to the inverting port of said first operational amplifier (A1) in said first of said pair of circuits and their other ends connected, respectively, to ground and to the output port of said first operational amplifier (A1) in said first of said pair of circuits, a resistor (R<sub>0</sub>) connected across input ports of said second operational amplifier (A2) in said first of said pair of circuits and having one end thereof connected to ground, a resistor (R<sub>3</sub>) connected between the output port of said first operational amplifier (A1) in said first of said pair of circuits and an inverting port of said second operational amplifier (A2) in said first of said pair of circuits and having one end thereof connected to ground, a resistor (R<sub>4</sub>) connected between the output port of said second operational amplifier (A2) in said first of said pair of circuits and having one end thereof connected to an inverting port of said second operational amplifier (A2) in said first of said pair of circuits.

6. The active filter of claim 1 wherein said third resistive means of said second feedback loop includes a resistor (R<sub>0</sub>) connected across input ports of said first operational amplifier (A3) in said second of said pair of circuits, a pair of resistors (R<sub>3</sub>, R<sub>4</sub>) both having one end connected to a non-inverting port of said second operational amplifier (A4) in said second of said pair of circuits and their other ends respectively connected to ground and to an output port of said first operational amplifier (A3) in said second of said pair of circuits, and an inverting port and an output port of said second operational amplifier (A4) in said second of said pair of circuits being commonly connected.

7. The active filter of claim 3 wherein said third resistive means of said second feedback loop includes a resistor (R<sub>0</sub>) connected across the input ports of said first operational amplifier (A3) in said second of said pair of circuits, a pair of resistors (R<sub>3</sub>, R<sub>4</sub>) both having one end connected to the non-inverting port of said second operational amplifier (A4) in said second of said pair of circuits and their other ends respectively connected to ground and to the output port of said first operational amplifier (A3) of said second of said pair of circuits, and the inverting port and output port of said
second operational amplifier (A4) of said second of said
pair of circuits being commonly connected.

8. An active filter network, comprising:
means (20) for receiving an input signal;
a first active circuit (12) having a first operational 5
amplifier (A1) with a non-inverting input port cou-
pled directly to said receiving means, a first resis-
tance (R1) coupling an inverting input port of said
first operational amplifier to a reference potential,
and a second resistance (R2) coupling said invert-
ing input port to an output port of said first opera-
tional amplifier;
a second active circuit (14) having a second opera-
tional amplifier (A2) with a non-inverting input
port coupled to said reference potential, a third 15
resistance (R3) serially coupling said output port of
said first operational amplifier to an inverting input
port of said second operational amplifier, a fourth
resistance (R4) coupling said non-inverting and
inverting input ports of said second operational
amplifier, and a fifth resistance (R5) coupling an
output port of said second operational amplifier to
said receiving means;
a third active circuit (16) having a third operational
amplifier (A3) with a non-inverting input port cou-
ped directly to said receiving means, a sixth resis-
tance (R6) coupling said non-inverting input port to
an inverting input port of said third operational
amplifier, and seventh and eight resistances (R7,
R8,) coupling an output port of said third opera-
tional amplifier to said reference potential; and
a fourth active circuit (18) having a fourth opera-
tional amplifier (A4) with an inverting input port
and an output port coupled directly to said inver-
ting port of said third operational amplifier and a
non-inverting port coupled between said seventh
and eighth resistances, wherein said resistances are
of magnitudes to tune said first and second active
circuits and said third and fourth active circuits,
respectively, to operate in the gain versus fre-
quency roll-off regions of said second and third
operational amplifiers, thereby providing an equiv-
alent inductive reactance by said first and second
circuits and an equivalent capacitive reactance by
said third and fourth circuits to said input signal at
frequencies in said roll-off region.

9. The network of claim 8 wherein said roll-off fre-
quencies of said second and third operational amplifiers
are substantially equal.

10. The network of claim 8 wherein said roll-off fre-
quencies of said first and fourth operational amplifiers
are substantially greater than the roll-off frequencies of
said second and third operational amplifiers.

11. The network of claim 9 wherein said roll-off fre-
quencies of said first and fourth operational amplifiers
are substantially greater than the roll-off frequencies of
said second and third operational amplifiers.

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