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_o) 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 aggregate to define a tuned resonant bandpass filter in the roll-off regions of the operational amplifiers.

11 Claims, 3 Drawing Figures
It is yet another object to provide an improved active R reactanceless synthesized impedance bandpass filter network.

It is a further object to provide an active R reactanceless synthesized impedance network synthesizing a tuned bandpass filter network.

It is a still further object to provide a resistively tuned, active reactanceless synthesized impedance bandpass filter network exhibiting stable linear input characteristics over a wide bandwidth.

These and other objects are achieved by a reactanceless synthesized impedance bandpass filter network formed by two pairs of resistance-operational amplifier stages coupled between a common network input terminal and a common reference potential. One pair of stages synthesizes a single pole input equivalent inductance by shifting the phase response of its resistive impedance while the other pair of stages synthesizes a single pole input equivalent capacitance first pair of stages by shifting the phase response of its resistive impedance when the network is tuned to a frequency within the roll-off regions of the operational amplifiers.

BRIEF DESCRIPTION OF DRAWINGS

A more complete appreciation of this invention and, many of the attendant advantages thereof, will be readily apparent as the same becomes better understood by reference to the following detailed description when considered in conjunction with the accompanying drawings in which like number indicate the same or similar components, and wherein:

FIG. 1 is a schematic representation of an embodiment of the invention;

FIG. 2 is a two coordinate graph showing the voltage gain as a function of bandwidth for a representative differential input operational amplifier; and,

FIG. 3 is a schematic representation of an electrical equivalent of the input impedance for the embodiment shown in FIG. 1.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 illustrates an active R, tuned bandpass filter network 10 formed by four active stages 12, 14, 16, 18, each formed around an operational amplifier A1, A2, A3, A4, respectively. The stages are coupled in pairs, in parallel, between a common network input terminal and a common network reference potential at node 22. The first pair of active stages 12, 14 synthesizes an input inductance while the second pair of stages 16, 18 synthesizes an input capacitance. In effect, these two pairs of stages provide an input function equivalent to an inductance coupled in parallel with a capacitance across nodes 20, 22 of the network. A serially connected resistance R1 and capacitance C2 serve as impedance matching components to couple node 20 to an input analog signal source.

FIG. 2 illustrates the gain as a function of frequency for a typical, commercially available single pole operational amplifier of the type suitable for use as operational amplifiers in each of the stages of network 10. The gain for these types of active devices is characterized by a slightly negative slope over the band of frequencies between one Hertz and their minus three decibel (roll-off) frequencies, f rolloff. In the band (the "roll-off region") between their roll-off frequencies and their unity gain frequencies, fU, these devices exhibit a single pole negative slope of approximately six decibels per
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 provides an input conductance serving 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 voltage 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:

\[
Y_{in} = (1 - k L) Y_{fb}
\]  

(1)

where \( k L \) 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, \( k L \), provided at the output port of operational amplifier A2 of the coupled stages 12, 14 may be expressed as:

\[
k L = \frac{-k_0 G_2 B_2}{1 + \frac{s B_2}{k_0 G_2}}
\]  

(3)

where \( k_0 \) 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 R3 and R4. By reference to FIG. 2, it may be seen that:

\[
f_{-3\ dB} = f_G
\]  

(3)

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 \( k_0 \), 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:

\[
k L = \frac{-G_2 B_2}{1} + \frac{f_G G_2 B_2}{f_G - f}
\]  

(4)

The gain provided by stage 12 is determined by the values of resistances R1 and R2, and may be expressed as:

\[
G_L = 1 + R_3/R_1
\]  

(5)

Similarly, the attenuation provided by the second stage 14 is determined by the values of resistances R3 and R4, and may be expressed as:

\[
\beta L = \frac{R_4}{R_3 + R_4}
\]  

(6)

The closed loop feedback admittance of the combined first and second stages is determined by the value of resistance R0. Accordingly, by substitution of equations (4), (5) and (6) into equation (1), the input admittance is:

\[
Y_{in} = \left[ 1 - \frac{1}{f_G} \right] \left[ \frac{R_1 + R_2}{R_1} \cdot \frac{R_4}{R_3 + R_4} \right] \frac{1}{R_0}
\]  

(7)

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 \( R_0 \) in series with a negative, single pole susceptance. This is equivalent to a resistance equal in value to \( R_0 \) in parallel with an inductance, \( L_{eq} \) between nodes 20 and 22, where:

\[
L_{eq} = \frac{1}{\beta L - f_G} \left[ \frac{R_1 + R_2}{R_1} \cdot \frac{R_4}{R_3 + R_4} \right] \frac{1}{R_0}
\]  

(8)

The presence of resistance \( R_0 \) and of resistances R1, R2, R3 and R4 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 \( R_0, R_1, R_2, R_3 \) and \( R_4 \) to appear as constituent parts of a negative susceptance. At the 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 R6 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 R1, 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. R1 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 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:

\[ Z_{in} = Z(j + \frac{G}{fCkA}) \]  (9)

where \( k_1(f) \) is the voltage gain of the coupled third and fourth stages as a function of frequency and \( Z_c \) is the input impedance of the loop. For the coupled third and fourth stages, the gain-bandwidth function may be expressed as:

\[ K(f) = \frac{G_2}{1 + j \omega} \rightarrow -j \frac{G_2G_1C}{f} \]  (10)

The fourth stage 18, which acts as a voltage follower for the third stage, provides a gain, \( G_1 \), of one. The attenuation provided by the coupled third and fourth stages between nodes 20 and 22 is determined by the values of resistances R5 and R6, and may be expressed as:

\[ \beta_c = \frac{R_6}{R_5 + R_6} \]  (11)

The closed loop feedback impedance of the coupled third and fourth stages is determined by the value of resistance R4. Substitution of these values into equations (9) and (10) gives an input impedance for the coupled third and fourth stages of:  

\[ Z_{in} = R_1 - j \frac{G_1}{f} \frac{R_5}{R_5 + R_6} - R_1 \]  (12)

By observation, it is apparent that the third and fourth stages provide an input impedance across nodes 20 and 22 equivalent to a resistance equal in value to \( R_1 \) in series with a single pole, negative reactance. This reactance effectively provides an equivalent capacitance, \( C_{eq} \), where:

\[ C_{eq} = \frac{1}{2\pi f_0} - \frac{R_5}{R_5 + R_6} - \frac{R_1}{R_1} \]  (13)

Equations (7) and (12) illustrate that over the frequency spectrum in the roll-off region of operational amplifier A3, the combined third and fourth stages 16, 18 provide a positive single pole reactance in the equivalent input circuit of network 10. The presence of resistances R5, R6 and R1 in equation (13) establishes that over its roll-off region, operational amplifier A3 creates a phase shift of the input impedances of the third and fourth stages, thereby causing lumped resistances R5, R6 and R1 to appear as constituent parts of an equivalent input capacitive impedance between nodes 20 and 22.

FIG. 3 schematically illustrates a tuned circuit formed by the electrical equivalent input functions of the four stages 12, 14, 16 and 18. In effect, stages 12 and 14 provide a resistance R2 in parallel with an equivalent inductance, \( R_{eq} \). In turn, stages 16 and 18 provide a resistance R1 in series with an equivalent capacitance \( C_{eq} \) parallel with \( R_{eq} \) and \( C_{eq} \) across input terminal nodes 20, 22. The resonant frequency of the equivalent input circuit is controlled by the values of the synthesized reactances \( L_{eq} \) and \( C_{eq} \). As indicated by equations (8) and (13) where the values of resistances \( R_1 \) through \( R_6 \) are fixed, the resonant frequency may be varied over the roll-off region between \( f_1 \) and \( f_2 \) of operational amplifiers A2 and A3 by adjusting the values of either or both resistances \( R_5 \) and \( R_6 \).

It is apparent from the foregoing that the invention disclosed is a network in which two separate and opposite type single pole reactances are synthesized by two pairs of active R stages to provide a bandpass amplifier tuned to a frequency in the roll-off region between \( f_{-3 dB} \) and \( f_G \) of operational amplifiers A2 and A3. The use of only resistive passive components facilitates fabrication while avoiding the variations in stability due to such causes as differences in the tolerances and ambient temperature sensitivity between resistive and reactive components which plague currently available tuned resonant amplifiers and active filters having lumped reactive components. The resonant frequency, gain, and Q of the network 10 may be broadly controlled by the values of resistances \( R_1 \) and \( R_4 \). The gain is primarily determined by the relative values of resistances \( R_1 \) and \( R_4 \) while the network \( Q \) is primarily set by the values of resistances \( R_3 \), \( R_4 \), \( R_5 \) and \( R_6 \). In practice, the network gain and \( Q \) are design parameters determined by the characteristics of the operational amplifiers and the particular application for which the network is intended. Consequently, the network may be constructed without one or more of the resistances shown in FIG. 1. For example, resistance \( R_1 \) may be eliminated from the network to provide a first stage with a unity gain. Additionally, either resistance \( R_5 \) or \( R_6 \) or both may be made variable to provide a tunable resonant network. In other
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 $L_p$ and $C_p$ 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 predict accurate 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 paraphrase 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; 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, R6) 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 (R3, R5, R6) 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 of said 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 ($f_{-3\,db}$) and the unity gain frequency ($f_c$) 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 (R1, R2) 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 (R4) 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 (R3) 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 a resistor (R6) connected between the non-inverting port of said first operational amplifier (A1) in said first of said pair of circuits and an output 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 (R5) connected across input ports of said first operational amplifier (A3) in said second of said pair of circuits, a pair of resistors (R3, R4) 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 5 wherein said third resistive means of said second feedback loop includes a resistor (R3) connected across the input ports of said first operational amplifier (A3) in said second of said pair of circuits, a pair of resistors (R3, R4) 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 operational amplifier to said reference potential, and

a second active circuit \((14)\) having a second operational amplifier \((A2)\) with a non-inverting input port coupled directly to said receiving means, a third resistance \((R3)\) coupling said output port of said second 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 coupled directly to said receiving means, a sixth resistance \((R6)\) coupling said non-inverting input port to an inverting input port of said third operational amplifier, and seventh and eighth resistances \((R7, R8)\), coupling an output port of said third operational amplifier to said reference potential; and

a fourth active circuit \((18)\) having a fourth operational amplifier \((A4)\) with an inverting input port and an output port coupled directly to said inverting 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 frequency roll-off regions of said second and third operational amplifiers, thereby providing an equivalent 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 frequencies of said second and third operational amplifiers are substantially equal.

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