A Grounded Inductance Using an Operational Amplifier Pole and Its Application to Filters

by

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This paper proposes a new simulation circuit of a grounded inductance using an operational amplifier pole. The value of simulated inductance can be varied by a resistance ratio and a gain bandwidth product of the operational amplifier. The proposed structure works well over a wide frequency range and has low sensitivity to active and passive elements. Theoretical and experimental results indicate that the realized circuit is stable over the wide frequency range and can be used effectively for a low-Q active network. The practical examples in a highpass ladder filters are also given together with experimental verifications.

1. Introduction

Recently, operational amplifiers (op amps) are widely used as inductorless filters, oscilators, inductor and capacitor simulations in addition to use as active elements. However, a practical op amp dose not generally ideal because of characteristics of frequency-dependent gain and finite input and output impedances. As the result, the use of op amp is limited by their finite gain bandwidth product. Therefore, many authers have exploited op amp pole in designing active R filter,[1)-3)] inductance and capacitance simulations[4)-6)] etc. In the previous paper,[7)] we also proposed a new integrator using this technique. The utilization of the op amp pole gives the reliable high frequency performance, and eliminates the external capacitances from the circuit. Therefore, it is suitable for monolithic IC implementation.

In this paper, we proposed a new grounded inductance simulation circuit which is composed of two op amps and only resistances without requiring any external capacitances. Since the value of simulated inductance depends primarily on resistance ratios, the proposed circuit is suitable for IC implementation. From the sensitivity analysis, we proved that the circuit has low sensitivities to all the network parameters. It is shown that the cofigulation can be used

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for active network realizing low-Q and the experimental results agree well with the analytic results.

The network analysis based on the single-pole rolloff model of op amp, and stability analysis are also given. Then, the highpass filters are designed using the proposed circuit. The experimental results show that these filters operate successfully as the conventional ones.

2. Theoretical analysis

The new circuit for inductance simulation is shown in Fig. 1. Assuming the sigle-pole rolloff characteristic for the two op amps, the gain is

$$A_i(s)=-\frac{A_{0i}\omega_{pi}}{s+\omega_{pi}}=-\frac{GB_i}{s+\omega_{pi}}, \quad i=1, 2 \qquad \cdots (1)$$

where A_{0i}, ω_{pi} and GB_i are the open loop gain, the 3 dB frequencies and the gain bandwidth product of op amps, respectively, and subscripts i are related to op amp 1 and op amp 2. Assuming a typical case $|s| \gg \omega_{pi}$, the open loop gain $A_i(s)$ is given by

$$A_i(s)=-\frac{GB_i}{s} \qquad \cdots (2)$$

In Fig. 1, the input impedance $Z_{in}(s)$ at the input terminals 1-1′ is obtained as

$$Z_{in}(s)=\frac{A^2 a_1 R_1 R' - A(a_2 R_3 + a_5 R_1 R_f)}{A^2(a_1 a_3 + R_2 R_3 R_f) - A[a_3(a_4 R_3 + a_5 R_f)} *$$

$$* \frac{+a_2 a_5}{R_2 R_f(a_5+R_3)] + a_5 R'[(1+R_1)a_4 + R_2 R_f]} \qquad \cdots (3)$$

where

$$\left.\begin{aligned} a_1 &= R_3 R_f - R_2 R_4 \\ a_2 &= R_1 R_2 + R_2 R_f + R_1 R_f \\ a_3 &= R_1 + R' \\ a_4 &= R_2 + R_f \\ a_5 &= R_3 + R_4 \end{aligned}\right\} \qquad \cdots (4)$$

and it is assumed that $A_1(s)=A_2(s)=A(s)$. Substituting Eq. (2) to Eq. (3), we have

$$Z_{in}(s)=\frac{s^2 R'(U_1 R_1 + U_2) + s\,GB\,R'\,U_3}{s^2[(R'+R_1)U_1 + U_2] + s\,GB(U_3 + U_1 R' U_2)} *$$

$$* \frac{+GB^2(R_3 R_f - R_2 R_4) R_1 R'}{+GB^2[(R_3 R_f - R_2 R_4)(R_1 + R') + R_2 R_3 R_f]} \qquad \cdots (5)$$

where

$$\left.\begin{aligned} U_1 &= R_3 R_f + R_2 R_3 + R_4 R_f + R_2 R_4 \\ U_2 &= (R_3 + R_4) R_2 R_f \\ U_3 &= 2R_1 R_3 R_f + R_2 R_3 R_f + R_1 R_2 R_3 + R_1 R_4 R_f \end{aligned}\right\} \qquad \cdots (6)$$

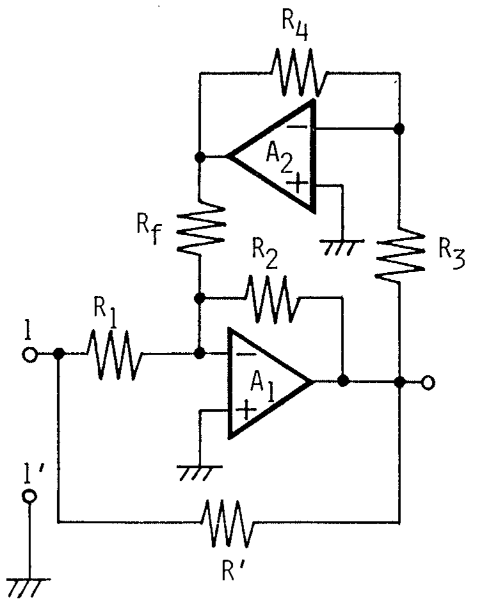

Fig. 1 Circuit for inductance simulation

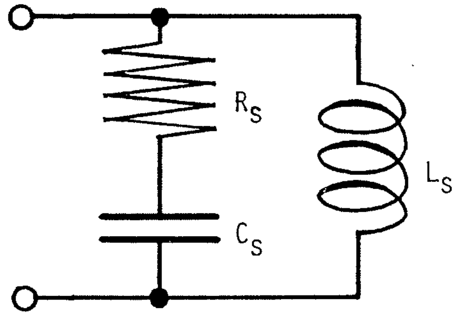

Fig. 2 Equivalent circuit of Fig. 1

The circuit is adjusted so that $(R_2R_4/R_3R_f)=1$ by the suitable choice of resistances R_2, R_3, R_4 and R_f, $Z_{in}(s)$ reduces to

$$Z_{in}(s)=\frac{s^2R'(U_1R_1+U_2)}{s^2[(R'+R_1)U_1+U_2]+sGB(U_3+U_1R'+R_2)} *$$

$$* \frac{+sGBR'U_3}{+GB^2R_2R_3R_f} \quad \cdots\cdots(7)$$

In Eq. (7), it is seen that the circuit of Fig. 1 behaves as an equivalent inductance L_s and a resistance R_s in series with a capacitance C_s as shown in Fig. 2, where the simulated components are

$$L_s=\frac{R'U_3}{GBR_2R_3R_f} \quad \cdots\cdots(8)$$

$$R_s=\frac{(R'+R_1)U_1+U_2}{R'U_3GB} \quad \cdots\cdots(9)$$

$$C_s=\frac{U_3+U_1R'+R_2}{GBR_2R_3R_f} \quad \cdots\cdots(10)$$

The quality factor $Q(\omega)$ of a simulated circuit is given by

$$Q(\omega)=\frac{\omega^2GB(T_1T_4-T_2T_3)+GB^3T_2T_5}{\omega^3T_1T_3+\omega GB^2(T_2T_4-T_1T_5)} \quad \cdots\cdots(11)$$

where

Table 1 Calculated values of simulated components and Q-factor

Type	K_{34}	K_{f2}	R_1, R_2 (Ω)	R_3 (Ω)	R_4 (Ω)	R_f (Ω)	Q (1 KHz)	L_s (H)	R_s (Ω)	C_s (pF)
1	.0001	10000	1 M	1 M	100.	100	.148	10.6	$2.12 \cdot 10^{-3}$	10.7
2	.001	1000	100 K	1 M	1 K	100	1.359	1.06	$2.12 \cdot 10^{-4}$	11.6
3			1 M	100 K	100	1 K	1.480	1.06	$2.12 \cdot 10^{-4}$	10.7
4	.01	100	10 K	1 M	10 K	100	7.316	$1.09 \cdot 10^{-1}$	$2.18 \cdot 10^{-5}$	21.1
5			100 K	100 K	1 K	1 K	13.248	$1.09 \cdot 10^{-1}$	$2.18 \cdot 10^{-5}$	11.7
6			1 M	10 K	100	10 K	14.418	$1.09 \cdot 10^{-1}$	$2.18 \cdot 10^{-5}$	10.7
7	.1	10	10 K	100 K	10 K	1 K	59.306	$1.39 \cdot 10^{-2}$	$2.67 \cdot 10^{-6}$	20.5
8			100 K	10 K	1 K	10 K	104.150	$1.39 \cdot 10^{-2}$	$2.67 \cdot 10^{-6}$	11.7
9			1 K	1 M	100 K	100	111.780	$1.39 \cdot 10^{-2}$	$2.67 \cdot 10^{-6}$	108.
10			1 M	1 K	100	100 K	112.670	$1.39 \cdot 10^{-2}$	$2.67 \cdot 10^{-6}$	10.7
11	1.0	1.0	10 K	10 K	10 K	10 K	153.060	$5.31 \cdot 10^{-3}$	$9.55 \cdot 10^{-7}$	21.2
12			100 K	1 K	1 K	100 K	241.940	$5.31 \cdot 10^{-3}$	$9.55 \cdot 10^{-7}$	13.6
13			1 K	100 K	100 K	1 K	32.751	$5.31 \cdot 10^{-3}$	$9.55 \cdot 10^{-7}$	97.6
14			1 M	100	100	1 M	256.850	$5.31 \cdot 10^{-3}$	$9.55 \cdot 10^{-7}$	12.8
15			100	1 M	1 M	100	3.696	$5.31 \cdot 10^{-3}$	$9.55 \cdot 10^{-7}$	862.
16	10.0	.1	10 K	1 K	10 K	100 K	43.558	$1.39 \cdot 10^{-2}$	$2.67 \cdot 10^{-6}$	28.5
17			1 K	10 K	100 K	10 K	10.465	$1.39 \cdot 10^{-2}$	$2.67 \cdot 10^{-6}$	116.
18			100 K	100	1 K	1 M	63.703	$1.39 \cdot 10^{-2}$	$2.67 \cdot 10^{-6}$	19.7
19			100	100 K	1 M	1 K	1.217	$1.39 \cdot 10^{-2}$	$2.67 \cdot 10^{-6}$	999.
20	100	.01	10 K	100	10 K	1 M	4.933	$1.09 \cdot 10^{-1}$	$2.18 \cdot 10^{-5}$	31.4
21			1 K	1 K	100 K	100 K	1.227	$1.09 \cdot 10^{-1}$	$2.18 \cdot 10^{-5}$	125.
22			100	10 K	1 M	10 K	.144	$1.09 \cdot 10^{-1}$	$2.18 \cdot 10^{-5}$	1071.
23	1000	.001	1 K	100	100 K	1 M	.124	1.06	$2.13 \cdot 10^{-4}$	127.
24			100	1 K	1 M	100 K	.014	1.06	$2.13 \cdot 10^{-4}$	1081.
25	10000	.0001	100	100	1 M	1 M	.0014	10.6	$2.12 \cdot 10^{-3}$	1082.

$$\left.\begin{aligned} T_1 &= (U_1 R_1 + U_2) R' \\ T_2 &= U_3 R' \\ T_3 &= (R' + R_1) U_1 + U_2 \\ T_4 &= U_2 + U_3 + (U_1 + R_3 R_f - R_2 R_4) R' \\ T_5 &= R_2 R_3 R_f \end{aligned}\right\} \qquad \cdots\cdots (12)$$

Thus we note that in order to obtain a fixed value of inductance it is necessary to keep the condition $R_3 R_f = R_2 R_4 (= K_{34} K_{f2} = 1)$. Table 1 shows the calculated values of L_s, R_s, C_s and Q for the various cases. The quality factor $Q(\omega)$ indicates a large value in the region of resistance ratio $K_{12} = K_{34} = K_{f2} = 1$.

In order to obtain a pure inductance, the following conditions must be satisfied.

$$\left.\begin{array}{l} |sR'(U_1R_1+U_2)| \ll GB\,U_3 \\ GB^2R_2R_3R_f \gg |s^2[(R'+R_1)U_1+U_2]| \\ GB\,R_2R_3R_f \gg |s(U_3+U_1R'+R_2)| \end{array}\right\} \qquad (13)$$

Then we can be rewritten Eq. (7) in a simple form

$$Z_{in}(s)=\frac{2+K_{12}+K_{34}+K_{f2}}{K_{12}}\cdot\frac{R'}{GB}\cdot s \qquad (14)$$

where $K_{12}=R_2/R_1$, $K_{34}=R_4/R_3$ and $K_{f2}=R_2/R_f$. It is clear that Eq. (14) has the property of an ideal inductance, and the inductance value can be varied by changing the resistance ratios K_{12}, K_{34} and K_{f2}, the gain bandwidth product GB of op amp and element value R'. The value of the ideal inductance L_s is expressed as

$$L_s=\frac{2+K_{12}+K_{34}+K_{f2}}{K_{12}}\cdot\frac{R'}{GB} \qquad (15)$$

It should be noted that exact value of resistance is immaterial but their ratio is important. Calculated values of L_s are shown in Table 1, where the values of R_s and C_s become zero under the conditions Eq. (13).

3. Sensitivity function and stability

The sensitivity is a measure of the displacement in some performance characterstics of a network resulting from a displacement in value of one or.more the element of the network. In this chapter, the sensitivities of the magunitude of the driving point impedance $Z_{in}(s)$, the coefficient for the numerator and denominator polynomial of the $Z_{in}(s)$ and the quality factor $Q(\omega)$ with respect to displacement in R_1, R_2, R_3, R_4, R_f, R' and GB are derived.

The sensitivity of a network function $N(\omega)$ with respect to the element x is defined by[8]

$$S_x^{N(\omega)}=\frac{dN(\omega)}{N(\omega)}\cdot\frac{x}{dx} \qquad (16)$$

We can rewrite Eq. (7) as shown below :

$$Z_{in}(s)=\frac{T_1s^2+T_2GBs}{T_3s^2+T_4GBs+T_5GB^2} \qquad (17)$$

where T_1, T_2, T_3, T_4 and T_5 are the same as Eq. (12). The sensitivity function of the driving point impedance $Z_{in}(s)$ with respect to a element x are given by

$$\mathrm{Re}\,S_x^{Z_{in}(s)}=\frac{R(X_0-X_1)+I(Y_0-Y_1)}{R^2+I^2}\cdot x \qquad (18)$$

$$\mathrm{Im}\,S_x^{Z_{in}(s)}=\frac{R(Y_0-Y_1)-I(X_0-X_1)}{R^2+I^2}\cdot x \qquad (19)$$

where Re $S_x^{Z_{in}(s)}$ and Im $S_x^{Z_{in}(s)}$ stand for the real and imaginary part of $S_x^{Z_{in}(s)}$, respectively, and

$$\left.\begin{aligned}
X_0 &= A_0 T_3 \omega^4 - GB^2(A_0 T_5 + B_0 T_4)\omega^2 \\
Y_0 &= GB[B_0 T_5 GB^2 - (A_0 T_4 + B_0 T_3)\omega^2]\omega \\
X_1 &= A_0 T_3 \omega^4 - GB^2(T_1 G_0 + T_2 F_0)\omega^2 \\
Y_1 &= GB[T_2 G_0 GB^2 - (T_1 F_0 + T_2 E_0)\omega^2]\omega \\
R &= T_1 T_3 \omega^4 - GB^2(T_1 T_5 + T_2 T_4)\omega^2 \\
I &= GB[T_2 T_5 GB^2 - (T_1 T_4 + T_2 T_3)\omega^2]\omega
\end{aligned}\right\} \qquad \cdots\cdots (20)$$

In the sensitivity functions for each element, we substitute each of element for x, and the equations as shown below insert in Eq. (20). For example, we deduce the sensitivity function Re $S_x^{Zin(s)}$ for R_1. Substituting Eq. (21) into Eq. (20), and further inserting the resulting Eq. (20) in Eq. (18), then we have the Re $S_x^{Zin(s)}$

R_1;

$$\left.\begin{aligned}
A_0 &= R'(R_3 + R_4)(R_2 + R_f) \\
B_0 &= R'[R_f(2R_3 + R_4) + R_2 R_3] \\
E_0 &= (R_2 + R_f)(R_3 + R_4) \\
F_0 &= R_f(R_3 + R_4) + R_3(R_2 + R_f) \\
G_0 &= 0
\end{aligned}\right\} \qquad \cdots\cdots (21)$$

R_2;

$$\left.\begin{aligned}
A_0 &= R'(R_3 + R_4)(R_1 + R_f) \\
B_0 &= R' R_3(R_1 + R_f) \\
E_0 &= (R_3 + R_4)(R' + R_1 + R_f) \\
F_0 &= R_f(R_3 + R_4) + R_3(R' + R_1 + R_f) \\
G_0 &= 0
\end{aligned}\right\} \qquad \cdots\cdots (22)$$

R_3;

$$\left.\begin{aligned}
A_0 &= R'(R_1 R_f + R_2 R_f + R_1 R_2) \\
B_0 &= R'(2R_1 R_f + R_2 R_f + R_1 R_2) \\
E_0 &= (R' + R_1)(R_2 + R_f) + R_2 R_f \\
F_0 &= (R' + R_1)(R_2 + R_f) + R_2 R_f + R_f(R' + R_1 + R_2) \\
G_0 &= R_2 R_f
\end{aligned}\right\} \qquad \cdots\cdots (23)$$

R_4;

$$\left.\begin{aligned} A_0 &= R'(R_1 R_f + R_2 R_f + R_1 R_2) \\ B_0 &= R' R_1 R_f \\ E_0 &= (R' + R_1)(R_2 + R_f) + R_2 R_f \\ F_0 &= R_f(R' + R_1 + R_2) \\ G_0 &= 0 \end{aligned}\right\} \quad \cdots\cdots (24)$$

R_f;

$$\left.\begin{aligned} A_0 &= R'(R_1 + R_2)(R_3 + R_4) \\ B_0 &= R'(2R_1 R_3 + R_1 R_4 + R_2 R_3) \\ E_0 &= (R_3 + R_4)(R' + R_1 + R_2) \\ F_0 &= (R' + R_1 + R_2)(2R_3 + R_4) \\ G_0 &= R_2 R_3 \end{aligned}\right\} \quad \cdots\cdots (25)$$

R';

$$\left.\begin{aligned} A_0 &= (R_1 R_f + R_2 R_f + R_1 R_2)(R_3 + R_4) \\ B_0 &= R_1 R_f(2R_3 + R_4) + R_2 R_3(R_1 + R_f) \\ E_0 &= (R_f + R_2)(R_3 + R_4) \\ F_0 &= R_f(R_3 + R_4) + R_3(R_2 + R_f) \\ G_0 &= 0 \end{aligned}\right\} \quad \cdots\cdots (26)$$

In the same manner, the sensitivity function with respect to GB is as follows.

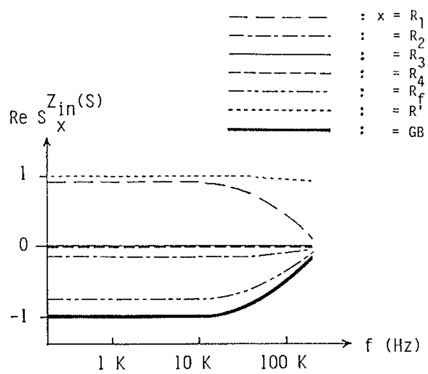

Fig. 3 Calculated values of Re $S_x^{Z_{in}(s)}$ in type 8

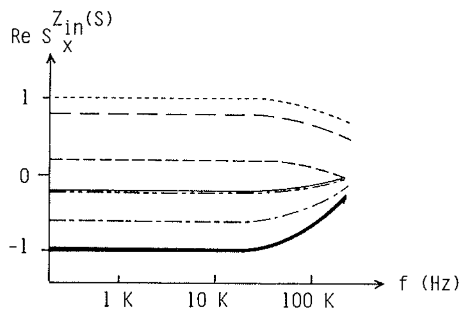

Fig. 4 Calculated values of Re $S_x^{Z_{in}(s)}$ in type 11

$$\mathrm{Re}\ S_{GB}^{Z_{in}(s)}=\frac{(2T_1T_5GB\omega^2)R-[(T_2T_3-T_1T_4)\omega^3+T_2T_5GB^2\omega]I}{R^2+I^2} \qquad \cdots\cdots\cdots\cdots (27)$$

$$\mathrm{Im}\ S_{GB}^{Z_{in}(s)}=\frac{[(T_2T_3-T_1T_4)\omega^3+T_2T_5GB^2\omega]R+2T_1T_5GB\omega^2I}{R^2+I^2} \qquad \cdots\cdots\cdots\cdots (28)$$

When we take typical value listed up in Table 1, each calculated sensitivity factor are shown in Figs. 3, 4 and 5 to real part and Figs. 6, 7 and 8 to imaginary part, respectively.

Next, we deal with the coefficient sensitivity of the driving point impedance $Z_{in}(s)$. We let $N(s)$ be network function as

$$N(s)=\frac{a_0+a_1s+a_2s^2+\cdots\cdots\cdots+a_ms^m}{b_0+b_1s+b_2s^2+\cdots\cdots\cdots+b_ms^m} \qquad \cdots\cdots\cdots\cdots (29)$$

Then, we difine the coefficient sensitivity as follows :

$$S_x^{a_i}=\frac{da_i}{x}\cdot\frac{x}{a_i} \qquad \cdots\cdots\cdots\cdots (30)$$

$$S_x^{b_i}=\frac{db_i}{x}\cdot\frac{x}{b_i} \qquad \cdots\cdots\cdots\cdots (31)$$

where x is any arbituary network element. From Eqs. (17), (30) and (31), the coefficient sensitivity of $Z_{in}(s)$ for each element can be determined as follows :

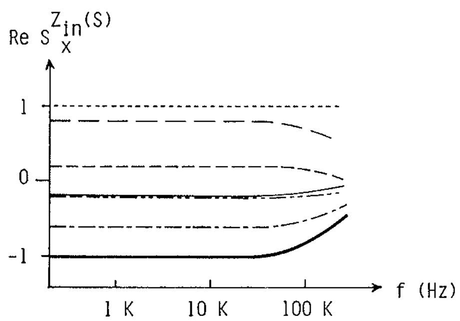

Fig. 5 Calculated values of Re $S_x^{Z_{in}(s)}$ in type 14

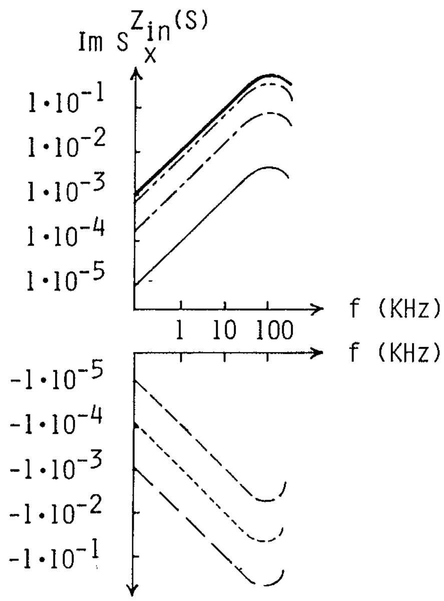

Fig. 6 Calculated values of Im $S_x^{Z_{in}(s)}$ in type 8

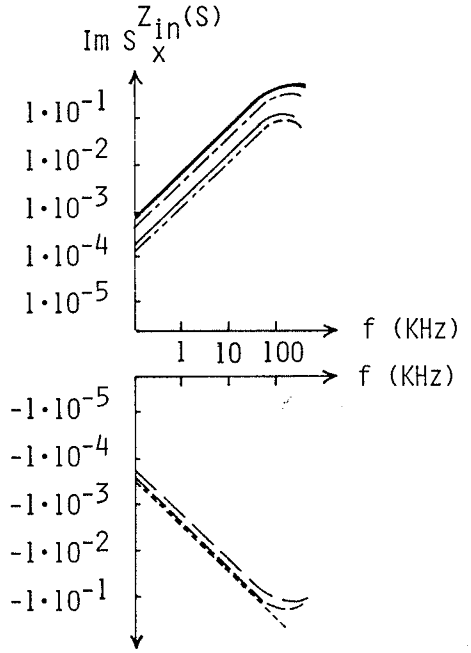

Fig. 7 Calculated values of Im $S_x^{Z_{in}(s)}$ in type 11

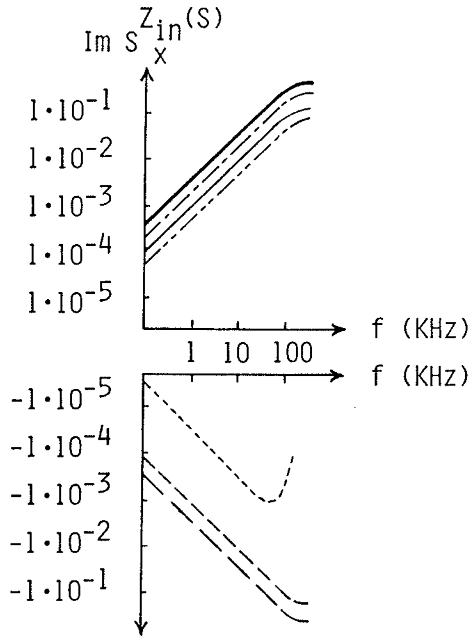

Fig. 8 Calculated values of Im $S_x^{Z_{in}(s)}$ in type 14

$$\left.\begin{aligned}
S_{R_1}^{T_1} &= (R_2+R_f)R_1/[(R_2+R_f)R_1+R_2R_f] \\
S_{R_2}^{T_1} &= (R_1+R_f)R_2/[(R_1+R_f)R_2+R_1R_f] \\
S_{R_3}^{T_1} &= R_3/(R_3+R_4) \\
S_{R_4}^{T_1} &= R_4/(R_3+R_4) \\
S_{R_f}^{T_1} &= (R_1+R_2)R_f/[(R_1+R_f)R_2+R_1R_2] \\
S_{R'}^{T_1} &= 1 \qquad , \quad S_{GB}^{T_1}=0
\end{aligned}\right\} \quad \cdots\cdots (32)$$

$$\left.\begin{aligned}
S_{R_1}^{T_2GB} &= 1-R_2R_3R_fR'/T_2 \\
S_{R_2}^{T_2GB} &= 1-R_1R_fR'(2R_3+R_4)/T_2 \\
S_{R_3}^{T_2GB} &= 1-R_1R_4R_fR'/T_2 \\
S_{R_4}^{T_2GB} &= 1-R_3R'(2R_1R_f+R_2R_f+R_1R_2)/T_2 \\
S_{R_f}^{T_2GB} &= 1-R_1R_2R_3R'/T_2 \\
S_{R'}^{T_2GB} &= 1 \qquad , \quad S_{GB}^{T_2GB}=1
\end{aligned}\right\} \quad \cdots\cdots (33)$$

$$\left.\begin{aligned}
&S^{T_3}_{R_2}=R_1(R_2+R_f)/J_3\\
&S^{T_3}_{R_2}=R_2(R'+R_1+R_f)/J_3\\
&S^{T_3}_{R_3}R_3/(R_3+R_4)\\
&S^{T_3}_{R_4}=R_4/(R_3+R_4)\\
&S^{T_3}_{R_f}=R_f(R'+R_1+R_2)/J_3\\
&S^{T_3}_{R'}=R'(R_2+R_f)/J_3 \qquad , \quad S^{T_3}_{GB}=0
\end{aligned}\right\} \quad \cdots\cdots (34)$$

$$\left.\begin{aligned}
&S^{T_4\cdot GB}_{R_1}=R_1(2R_3R_f+R_2R_3+R_4R_f)/J_4\\
&S^{T_4\cdot GB}_{R_2}=R_2(2R_3R_f+R_2R_3+R_4R_f)/J_4\\
&S^{T_4\cdot GB}_{R_3}=R_3(R_1+R_f+R')(2R_2+R_f)/J_4\\
&S^{T_4\cdot GB}_{R_4}=R_4R_f(R_1+R_f+R')/J_4\\
&S^{T_4\cdot GB}_{R_f}=R_f(R_1+R_f+R')(2R_3+R_4)/J_4\\
&S^{T_4\cdot GB}_{R_1}=R'(2R_3R_f+R_2R_3+R_4R_f)/J_4\\
&S^{T_4\cdot GB}_{GB}=1
\end{aligned}\right\} \quad \cdots\cdots (35)$$

$$\left.\begin{aligned}
&S^{T_5\cdot GB^2}_{R_1}=0 &&, \quad S^{T_5\cdot GB^2}_{R_2}=1\\
&S^{T_5\cdot GB^2}_{R_3}=1 &&, \quad S^{T_5\cdot GB^2}_{R_4}=0\\
&S^{T_5\cdot GB^2}_{R_f}=1 &&, \quad S^{T_5\cdot GB^2}_{R'}=0\\
&S^{T_5\cdot GB^2}_{GB}=2
\end{aligned}\right\} \quad \cdots\cdots (36)$$

where

$$\left.\begin{aligned}
&J_3=(R'+R_1)(R_2+R_f)+R_2R_f\\
&J_4=(2R_3R_f+R_2R_3+R_4R_f)(R_1+R')+R_2R_f(2R_3+R_4)
\end{aligned}\right\} \quad \cdots\cdots (37)$$

Calculated coefficient sensitivity factors of the driving point impedance $Z_{in}(s)$ by using the nominal element values in Table 1 are given in Table 2—5. Here. $S^{T_5}_x$ in not included in the table, as it is obvious from Eq.(36). The variation in any elements are found to be within 1 and 10^{-4} order as is evident from these tables. It is clear that the proposed circuit presents the low-Q sensitivity to all types and to all elements.

In the same manner as before, the values of sensitivity of $Q(\omega)$-factor[8] evaluated using Eq.(11) and Eq.(16) are shown in Table 6.

Finally, we deal with the stability problem. In general, for an network to be stable, a numerator and denominator polynominals of the driving point impedance $Z_{in}(s)$ must be Hurwitz polynominal. From Eq.(7), the driving point impedance $Z_{in}(s)$ is written as a ratio of polynominals $N_0(s)$ and $D_0(s)$. Thus, it is clear that the polynominals $N_0(s)$ and $D_0(s)$ are given as follows :

$$N_0(s)=s^2R'(U_1R_1+U_2)+sGBR'U_3 \qquad \cdots\cdots (38)$$

$$D_0(s)=s^2[(R'+R_1)U_1+U_2]+sGB(U_3+U_1R'+R_2)+GB^2R_2R_3R_f \qquad \cdots\cdots (39)$$

Table 2 Calculated values of $S_x^{T_1}$

Type	$S_{R'}$	S_{R1}	S_{R2}	S_{R3}	S_{R4}	S_{Rf}	S_{GB}
1	1.0	1.0	1.0	1.0	$1.00\cdot10^{-4}$	$2.00\cdot10^{-4}$	0
2	1.0	.999	.999	.999	$9.90\cdot10^{-4}$	$2.00\cdot10^{-4}$	0
3	1.0	.999	.999	.999	$9.90\cdot10^{-4}$	$2.00\cdot10^{-4}$	0
4	1.0	.990	.990	.990	$9.90\cdot10^{-3}$	$1.96\cdot10^{-2}$	0
5	1.0	.990	.990	.990	$9.90\cdot10^{-3}$	$1.96\cdot10^{-2}$	0
6	1.0	.990	.990	.990	$9.90\cdot10^{-3}$	$1.96\cdot10^{-2}$	0
7	1.0	.917	.917	.909	$9.02\cdot10^{-2}$	.167	0
8	1.0	.917	.917	.909	$9.02\cdot10^{-2}$	.167	0
9	1.0	.917	.917	.909	$9.02\cdot10^{-2}$	.167	0
10	1.0	.917	.917	.909	$9.02\cdot10^{-2}$	.167	0
11	1.0	.667	.667	.500	.500	.667	0
12	1.0	.667	.667	.500	.500	.667	0
13	1.0	.667	.667	.500	.500	.667	0
14	1.0	.667	.667	.500	.500	.667	0
15	1.0	.667	.667	.500	.500	.667	0
16	1.0	.524	.524	$9.09\cdot10^{-2}$	.909	.952	0
17	1.0	.524	.524	$9.09\cdot10^{-2}$	.909	.952	0
18	1.0	.524	.524	$9.09\cdot10^{-2}$	.909	.952	0
19	1.0	.524	.524	$9.09\cdot10^{-2}$	.909	.952	0
20	1.0	.502	.502	$9.90\cdot10^{-2}$	.990	.995	0
21	1.0	.502	.502	$9.90\cdot10^{-3}$	.990	.995	0
22	1.0	.502	.502	$9.90\cdot10^{-3}$	.990	.995	0
23	1.0	.500	.500	$9.99\cdot10^{-4}$	.999	1.0	0
24	1.0	.500	.500	$9.99\cdot10^{-4}$	.999	1.0	0
25	1.0	.500	.500	$1.00\cdot10^{-4}$	1.0	1.0	0

Table 3 Calculated values of $S_x^{T_2GB}$

Type	$S_{R'}$	S_{R1}	S_{R2}	S_{R3}	S_{R4}	S_{Rf}	S_{GB}
1	1.0	1.0	1.0	1.0	$1.00\cdot10^{-8}$	$3.00\cdot10^{-4}$	1.0
2	1.0	.990	.990	1.0	$9.90\cdot10^{-7}$	$2.90\cdot10^{-3}$	1.0
3	1.0	.990	.990	1.0	$9.90\cdot10^{-7}$	$2.90\cdot10^{-3}$	1.0
4	1.0	.990	.980	1.0	$9.71\cdot10^{-7}$	$2.92\cdot10^{-2}$	1.0
5	1.0	.990	.980	1.0	$9.71\cdot10^{-7}$	$2.92\cdot10^{-2}$	1.0
6	1.0	.990	.980	1.0	$9.71\cdot10^{-7}$	$2.92\cdot10^{-2}$	1.0
7	1.0	.924	.840	.992	$7.63\cdot10^{-3}$	.237	1.0
8	1.0	.924	.840	.992	$7.63\cdot10^{-3}$	.237	1.0
9	1.0	.924	.840	.992	$7.63\cdot10^{-3}$	.237	1.0
10	1.0	.924	.840	.992	$7.63\cdot10^{-3}$	.237	1.0
11	1.0	.800	.400	.800	.200	.800	1.0
12	1.0	.800	.400	.800	.200	.800	1.0
13	1.0	.800	.400	.800	.200	.800	1.0
14	1.0	.800	.400	.800	.200	.800	1.0
15	1.0	.800	.400	.800	.200	.800	1.0
16	1.0	.924	$8.40\cdot10^{-2}$	.237	.763	.992	1.0
17	1.0	.924	$8.40\cdot10^{-2}$	.237	.763	.992	1.0
18	1.0	.924	$8.40\cdot10^{-2}$	.237	.763	.992	1.0
19	1.0	.924	$8.40\cdot10^{-2}$	.237	.763	.992	1.0
20	1.0	.990	$9.80\cdot10^{-3}$	$2.92\cdot10^{-2}$	.971	1.0	1.0
21	1.0	.990	$9.80\cdot10^{-3}$	$2.92\cdot10^{-2}$	.971	1.0	1.0
22	1.0	.990	$9.80\cdot10^{-3}$	$2.92\cdot10^{-2}$	.971	1.0	1.0
23	1.0	.999	$9.98\cdot10^{-4}$	$2.99\cdot10^{-3}$	.997	1.0	1.0
24	1.0	.999	$9.98\cdot10^{-4}$	$2.99\cdot10^{-3}$	.997	1.0	1.0
25	1.0	1.0	$1.00\cdot10^{-4}$	$3.00\cdot10^{-3}$	1.0	1.0	1.0

Table 4 Calculated values of $S_x^{T_3}$

Type	$S_{R'}$	S_{R1}	S_{R2}	S_{R3}	S_{R4}	S_{Rf}	S_{GB}
1	$9.90\cdot10^{-3}$	.990	1.0	1.0	$1.00\cdot10^{-4}$	$1.99\cdot10^{-4}$	0
2	$9.08\cdot10^{-2}$	.908	.999	.999	$9.99\cdot10^{-4}$	$1.91\cdot10^{-3}$	0
3	$9.89\cdot10^{-3}$	.989	.999	.999	$9.99\cdot10^{-4}$	$1.99\cdot10^{-3}$	0
4	.498	.498	.990	.990	$9.90\cdot10^{-3}$	$1.48\cdot10^{-2}$	0
5	$9.01\cdot10^{-2}$	.901	.990	.990	$9.90\cdot10^{-3}$	$1.87\cdot10^{-2}$	0
6	$9.80\cdot10^{-3}$	.980	.990	.990	$9.90\cdot10^{-3}$	$1.95\cdot10^{-2}$	0
7	.478	.478	.913	.909	$9.09\cdot10^{-3}$	.130	0
8	$8.40\cdot10^{-2}$	.840	.916	.909	$9.09\cdot10^{-2}$	.160	0
9	.902	$9.02\cdot10^{-2}$	.910	.909	$9.09\cdot10^{-2}$	$9.84\cdot10^{-2}$	0
10	$9.08\cdot10^{-3}$	.908	.917	.909	$9.09\cdot10^{-2}$	.166	0
11	.400	.400	.600	.500	.500	.600	0
12	$6.25\cdot10^{-2}$	.625	.656	.500	.500	.656	0
13	.870	$8.70\cdot10^{-2}$	.522	.500	.500	.522	0
14	$6.62\cdot10^{-3}$	.662	.666	.500	.500	.666	0
15	.985	$9.85\cdot10^{-3}$	.502	.500	.500	.502	0
16	.344	.344	.375	$9.09\cdot10^{-2}$	.909	.938	0
17	.840	$8.40\cdot10^{-2}$	.165	$9.09\cdot10^{-2}$	.909	.916	0
18	$4.98\cdot10^{-2}$	.498	.502	$9.09\cdot10^{-2}$	.909	.950	0
19	.981	$9.81\cdot10^{-3}$	$9.90\cdot10^{-2}$	$9.09\cdot10^{-2}$	.909	.910	0
20	.334	.334	.338	$9.09\cdot10^{-3}$	.990	.993	0
21	.834	$8.42\cdot10^{-2}$	$9.17\cdot10^{-2}$	$9.90\cdot10^{-3}$	.990	.991	0
22	.980	$9.80\cdot10^{-3}$	$1.95\cdot10^{-2}$	$9.90\cdot10^{-3}$	.990	.990	0
23	.833	$8.33\cdot10^{-2}$	$8.42\cdot10^{-2}$	$9.99\cdot10^{-4}$	.999	.999	0
24	.980	$9.80\cdot10^{-3}$	$1.08\cdot10^{-2}$	$9.99\cdot10^{-4}$	.999	.999	0
25	.980	$9.80\cdot10^{-3}$	$9.90\cdot10^{-3}$	$1.00\cdot10^{-4}$	1.0	1.0	0

Table 5 Calculated values of $S_x^{T_4GB}$

Type	$S_{R'}$	S_{R1}	S_{R2}	S_{R3}	S_{R4}	S_{Rf}	S_{GB}
1	$9.90\cdot10^{-3}$	.990	1.0	1.0	$1.99\cdot10^{-8}$	$3.98\cdot10^{-4}$	1.0
2	$9.07\cdot10^{-2}$	.907	.998	.999	$1.90\cdot10^{-6}$	$3.81\cdot10^{-3}$	1.0
3	$9.88\cdot10^{-3}$	.988	.998	.999	$1.98\cdot10^{-6}$	$3.97\cdot10^{-3}$	1.0
4	.495	.495	.980	.995	$1.46\cdot10^{-4}$	$2.93\cdot10^{-2}$	1.0
5	$8.93\cdot10^{-2}$	.893	.981	.991	$1.84\cdot10^{-4}$	$3.70\cdot10^{-2}$	1.0
6	$9.71\cdot10^{-3}$	.971	.981	.990	$1.91\cdot10^{-4}$	$3.85\cdot10^{-2}$	1.0
7	.460	.460	.840	.958	$1.14\cdot10^{-2}$	.240	1.0
8	$7.85\cdot10^{-2}$	.785	.850	.934	$1.36\cdot10^{-2}$	.286	1.0
9	.895	$8.95\cdot10^{-2}$	.829	.985	$8.88\cdot10^{-3}$	.186	1.0
10	$8.45\cdot10^{-3}$	.845	.852	.930	$1.40\cdot10^{-2}$	.295	1.0
11	.364	.364	.455	.818	.273	.818	1.0
12	$5.41\cdot10^{-2}$	.541	.554	.851	.284	.851	1.0
13	.851	$8.51\cdot10^{-2}$	.298	.766	.255	.766	1.0
14	$5.68\cdot10^{-3}$	.568	.570	.857	.286	.857	1.0
15	.983	$9.85\cdot10^{-3}$	.256	.752	.251	.752	1.0
16	.334	.334	.337	.696	.829	.994	1.0
17	.834	$8.34\cdot10^{-2}$	$9.03\cdot10^{-2}$	.304	.827	.992	1.0
18	$4.78\cdot10^{-2}$	.478	.478	.921	.830	.996	1.0
19	.980	$9.80\cdot10^{-3}$	$1.79\cdot10^{-2}$	.189	.827	.992	1.0
20	.333	.333	.333	.670	.980	1.0	1.0
21	.833	$8.33\cdot10^{-2}$	$8.84\cdot10^{-2}$	.182	.980	1.0	1.0
22	.980	$9.80\cdot10^{-3}$	$9.90\cdot10^{-3}$	$3.88\cdot10^{-2}$	.980	1.0	1.0
23	.833	$8.33\cdot10^{-2}$	$8.33\cdot10^{-2}$	.168	.998	1.0	1.0
24	.980	$9.80\cdot10^{-3}$	$9.80\cdot10^{-3}$	$2.16\cdot10^{-2}$	.998	1.0	1.0
25	.980	$9.80\cdot10^{-3}$	$9.80\cdot10^{-3}$	$1.98\cdot10^{-2}$	1.0	1.0	1.0

In Eqs. (38) and (39), since the resistances and the parameters GB of op amp are possitive, zeros of $N_0(s)$ and $D_0(s)$ are in the left-half S-plane and origin. It is obvious that this proposed circuit is stable.

Table 6 Calculated values of $S_x^{Q(\omega)}$

Type	$S_{R'}$	S_{R1}	S_{R2}	S_{R3}	S_{R4}	S_{Rf}	S_{GB}
1	$-9.90\cdot10^{-3}$	$-9.90\cdot10^{-1}$	$2.00\cdot10^{-4}$	0	$-2.00\cdot10^{-8}$	1.0	1.0
2	$-9.08\cdot10^{-2}$	$-9.08\cdot10^{-1}$	$2.00\cdot10^{-3}$	$4.90\cdot10^{-6}$	$-2.00\cdot10^{-6}$	1.0	1.0
3	$-9.89\cdot10^{-3}$	$-9.89\cdot10^{-1}$	$2.00\cdot10^{-3}$	$5.00\cdot10^{-6}$	$-2.00\cdot10^{-6}$	1.0	1.0
4	$-4.98\cdot10^{-1}$	$-4.98\cdot10^{-1}$	$1.97\cdot10^{-2}$	$4.82\cdot10^{-4}$	$-1.96\cdot10^{-4}$	1.03	1.0
5	$-9.01\cdot10^{-2}$	$-9.01\cdot10^{-1}$	$1.96\cdot10^{-2}$	$4.83\cdot10^{-4}$	$-1.96\cdot10^{-4}$	1.03	1.0
6	$-9.80\cdot10^{-3}$	$-9.80\cdot10^{-1}$	$1.96\cdot10^{-2}$	$4.84\cdot10^{-4}$	$-1.96\cdot10^{-4}$	1.01	1.0
7	$-4.78\cdot10^{-1}$	$-4.79\cdot10^{-1}$	$1.69\cdot10^{-1}$	$3.60\cdot10^{-2}$	$-1.62\cdot10^{-2}$	1.24	1.0
8	$-8.40\cdot10^{-2}$	$-8.40\cdot10^{-1}$	$1.66\cdot10^{-1}$	$3.65\cdot10^{-2}$	$-1.64\cdot10^{-2}$	1.07	1.0
9	$-9.02\cdot10^{-1}$	$-9.02\cdot10^{-2}$	$1.73\cdot10^{-1}$	$3.55\cdot10^{-2}$	$-1.60\cdot10^{-2}$	1.24	1.0
10	$-9.09\cdot10^{-3}$	$-9.09\cdot10^{-1}$	$1.65\cdot10^{-1}$	$3.66\cdot10^{-2}$	$-1.64\cdot10^{-2}$	$-1.52\cdot10^{1}$	1.0
11	$-4.08\cdot10^{-1}$	$-4.24\cdot10^{-1}$	$6.45\cdot10^{-1}$	$6.57\cdot10^{-1}$	$-4.69\cdot10^{-1}$	1.33	1.0
12	$-6.45\cdot10^{-2}$	$-6.71\cdot10^{-1}$	$5.84\cdot10^{-1}$	$6.90\cdot10^{-1}$	$-4.81\cdot10^{-1}$	$-4.63\cdot10^{1}$	1.0
13	$-8.73\cdot10^{-1}$	$-9.08\cdot10^{-2}$	$7.28\cdot10^{-1}$	$6.12\cdot10^{-1}$	$-4.54\cdot10^{-1}$	1.08	1.0
14	$-6.85\cdot10^{-3}$	$-7.12\cdot10^{-1}$	$5.74\cdot10^{-1}$	$6.96\cdot10^{-1}$	$-4.83\cdot10^{-1}$	$-4.82\cdot10^{3}$	1.0
15	$-9.86\cdot10^{-1}$	$-1.03\cdot10^{-2}$	$7.47\cdot10^{-1}$	$6.01\cdot10^{-1}$	$-4.50\cdot10^{-1}$	1.08	1.0
16	$-3.51\cdot10^{-1}$	$-3.72\cdot10^{-1}$	$7.19\cdot10^{-1}$	1.13	-1.63	$-1.43\cdot10^{1}$	1.0
17	$-8.44\cdot10^{-1}$	$-8.94\cdot10^{-2}$	$9.26\cdot10^{-1}$	1.06	-1.60	-1.83	1.0
18	$-5.14\cdot10^{-2}$	$-5.44\cdot10^{-1}$	$5.94\cdot10^{-1}$	1.16	-1.64	$-1.63\cdot10^{3}$	1.0
19	$-9.81\cdot10^{-1}$	$-1.08\cdot10^{-2}$	$9.84\cdot10^{-1}$	1.04	-1.59	1.99	$9.99\cdot10^{-1}$
20	$-3.35\cdot10^{-1}$	$-3.39\cdot10^{-1}$	$6.74\cdot10^{-1}$	1.02	-1.96	$-1.94\cdot10^{1}$	1.0
21	$-8.34\cdot10^{-1}$	$-8.47\cdot10^{-2}$	$9.19\cdot10^{-1}$	1.01	-1.95	$4.73\cdot10^{-2}$	$9.99\cdot10^{-1}$
22	$-9.76\cdot10^{-1}$	$-1.43\cdot10^{-2}$	$9.90\cdot10^{-1}$	1.01	-1.95	1.98	$9.91\cdot10^{-1}$
23	$-8.29\cdot10^{-1}$	$-8.83\cdot10^{-2}$	$9.17\cdot10^{-1}$	$9.96\cdot10^{-1}$	2.00	$-1.80\cdot10^{1}$	$9.89\cdot10^{-1}$
24	$-9.38\cdot10^{-1}$	$-5.27\cdot10^{-2}$	$9.91\cdot10^{-1}$	$9.58\cdot10^{-1}$	-2.00	1.80	$9.13\cdot10^{-1}$
25	$-6.75\cdot10^{-1}$	$-3.19\cdot10^{-1}$	$9.93\cdot10^{-1}$	$6.88\cdot10^{-1}$	-2.00	$4.98\cdot10^{-4}$	$3.76\cdot10^{-1}$

4. Experimental results and discussion

The circuit is consisted of six resistances with 1 percent tolerance, one potentiometer and two μA 747 PC-type op amps satisfying the condition of the gain bandwidth products $GB_1 = GB_2 = GB$. The gain bandwidth product of the op amp for a power supply voltage of $\pm 15\ V$ is $GB = 2\pi\ 1.5 \cdot 10^6\ rad/\mathrm{sec}$. The experiment was carried out mainly using the component values in table 1. The values of simulated inductance L and Q-factor were measured by using parallel resonance method and are given by

$$L = 1/2\pi f_0^2 C \qquad \cdots (40)$$

$$Q = f_0/(f_2 - f_1) \qquad \cdots (41)$$

where f_0 is a resonance frequency, and f_1 and f_2 ($f_1 < f_2$) are the frequencies at cut-off frequency.

In Fig. 9, the measured values of the simulated inductance are compared with the theoretical curve for four cases, such as $L = 1.39 \cdot 10^{-2}$ H, $8.7 \cdot 10^{-3}$ H, $5.31 \cdot 10^{-3}$ H and $1.48 \cdot 10^{-3}$ H. As is obvious from this figure, the experimental results agree well with the theoretical ones.

Fig. 10 is an example of a Q-factor against frequency taking the resistance ratio K_{12} as a parameter. It shows how Q varies with frequency depending upon the resistance ratio K_{12}. Four typical resistance ratios of K_{12} are chosen in Fig. 10, such as $K_{12} = 0.5$ ($= 10\,k\Omega/20\,k\Omega$), 0.8 ($= 10\,k\Omega/12.5\,k\Omega$), 1.0 ($= 10\,k\Omega/10\,k\Omega$), 10.0 ($= 100\,k\Omega/10\,k\Omega$) and 100 ($= 100\,k\Omega/1\,k\Omega$).

For the measurements of Q-factor versus frequency, the resonance frequencies were changed by adjusting the external standard capacitance. In order to obtain Q-factor of over 30, the resistance ratio K_{12} must be chosen within $1 \leqq K_{12}$. Furthermore, it is difficult for practical implementation to adjust K_{12} beyond 100.

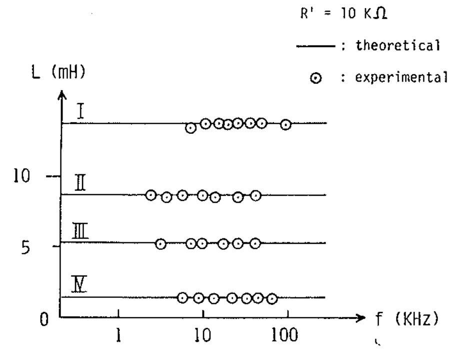

Fig. 9 Theoretical and experimental values of simulated inductance

I : type 10
II : $R_1 = R_2 = 20$ KΩ , $R_3 = 2$ KΩ
$R_4 = 10$ KΩ , $R_f = 100$ KΩ
III : type 11
IV : $R_1 = R_3 = R_4 = 10$ KΩ
$R_2 = R_f = 100$ KΩ

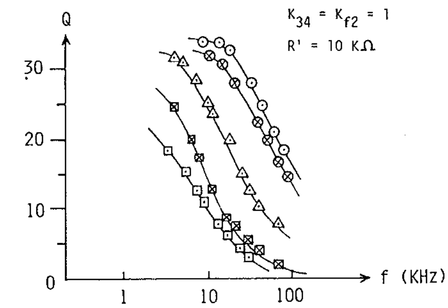

Fig. 10 Experimental Q-factor versus frequency by varing the resistance ratio K_{12}

—⊡— : 0.5 (= 10 KΩ / 20 KΩ)
—⊠— : 0.8 (= 10 KΩ / 12.5 KΩ)
—△— : 1.0 (= 100 KΩ / 100 KΩ)
—⊙— : 10 (= 100 KΩ / 10 KΩ)
—⊗— : 100 (= 100 KΩ / 1 KΩ)

Next, an example of a Q-factor variation with frequency are plotted in Fig. 11 for the case of varing the resistance value for a fixed K_{12} at $R'=R_3=R_4=10$ kΩ, and $K_{f2}=1$. From this figure, it is obvious that the circuit attains a high Q-factor by making R_1, $R_2 \geqq 10$ kΩ. For example, the Q-factor varies from 4 to 25 at 10 KHz depending on the resistance values. This means that Q-factor can be adjusted without changing the inductance value. It is better to choose R_1 and R_2 from 10 kΩ to 100 kΩ in order to be the influence of a op amp's loop gain.

Fig. 12 show how the condition K_{34} $K_{f2}=1$ for realizing the inductance effects the Q-factor.

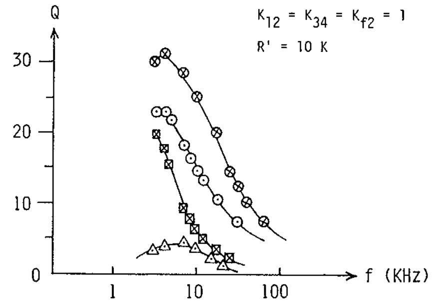

Fig. 11 Experimental Q-factor versus frequency for the various values of R_1 and R_2

—△— : $R_1 = R_2 = 1$ K
—⊠— : = 2 K
—⊙— : = 10 K
—⊗— : = 100 K

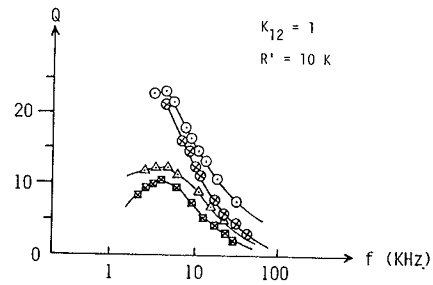

Fig. 12 Experimental Q-factor verszs frequency by varing the resistance ratios K_{34} and K_{f2}

—⊠— : K_{34} = 5.0 , K_{f2} = 0.2
—⊗— : = 2.0 , = 0.5
—⊙— : = 1.0 , = 1.0
—△— : = 0.1 , = 10.0

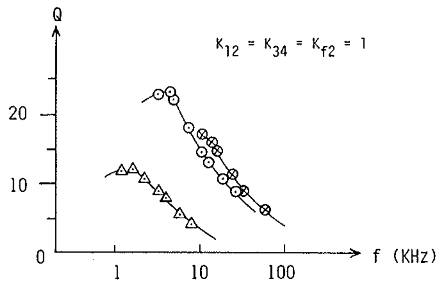

Fig. 13 Experimental Q-factor versus frequency by varing the resistance value R'

It is clear from the figure that values of K_{34} and K_{f2} around unity are recommended to achieve high Q-factor.

Fig. 13 shows the Q vs frequency characteristics for various R's. In order to obtain a high Q-factor it is neccessary to keep the resistance R' around 10 kΩ.

As is clear from above, Q depends on many element values. When we design the inductance with moderate Q at a given frequency, we must select a suitable combination of element values to satisfy the specfications.

5. Highpass ladder filters

In this chapter, we deal with the design[9),10)] of 5th-order Butterworth highpass filter and 5th-order 1 dB ripple Chebyshev highpass filter. The inductance in highpass ladder filter is replaced by the simulated inductance.

Fig. 14 is conventional the 5th-order Butterworth lowpass filter.[9)] The normalized element values of an equally terminated 5th-order Butterworth lowpass filter are $R_{Sl} = R_{Ll} = 1\ \Omega$, $L_{1l} = L_{51} = 0.168$H $C_{21} = C_{41} = 1.618$F and $L_{31} = 2$H To transform the normalized lowpass filter circuit to a highpass configulation, replace each inductance with capacitance and vice versa using reciprocal element values as shown in Fig. 15. Then, for realizing the corresponding active highpass filter with a cutoff frequency of 20.0 KHz and an impedance level of 300 Ω, the following component values are obtained : $R_{Sh} = R_{Lh} = 300\ \Omega$, $C_{1h} = C_{5h} = 0.043\ \mu$F, $L_{2h} = L_{4h} = 1.48\ m$H, $C_{3h} = 0.013\ \mu$F. For example, the resistance values corresponding to inductance value $L_{2h} = L_{4h}$, using μA 747 PC- type op amp with gain bandwidth product $GB = 2\pi\ 1.5 \cdot 10^6\ rad/$sec for power supply voltage ±15 V,

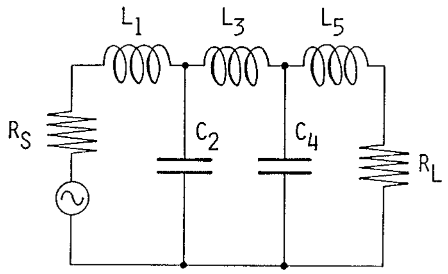

Fig. 14 Normalized lowpass filter

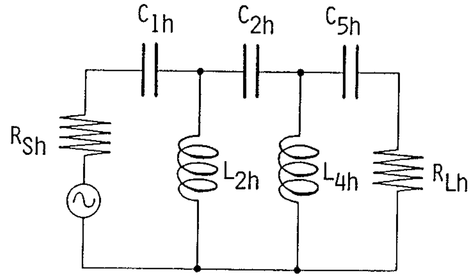

Fig. 15 Transformed highpass filter

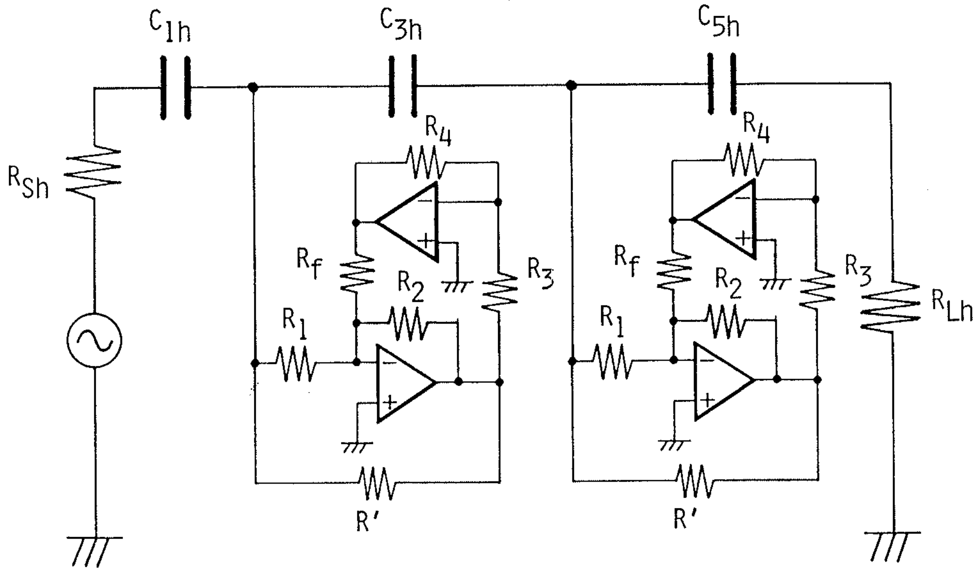

Fig. 16 Experimental circuit of highpass ladder filter

are $R = R_3 = R_4 = R' = 10\ \mathrm{k\Omega}$ and $R_2 = R_f = 100\ \mathrm{k\Omega}$. The final filter circuit is given in fig. 16.

The 5th-order 1 dB ripple Chebyshev filter is relized in the same manner as above. The normalized element values of an equally terminated 5th-order Chebyshev lowpass filter[9] are $R_{S1} = R_{L1} = 1\ \Omega$, $L_{11} = L_{51} = 2.2072$ H, $C_{21} = C_{41} = 1.1279$ F and $L_{31} = 3.1025$ H in Fig. 14. The corresponding active highpass filter with a cutoff frequency of 28.5 KHz and an impedance level of 300 Ω, has the following element values : $R_{Sh} = R_{Lh} = 300\ \Omega$, $C_{1h} = C_{5h} = 0.0084\ \mu$F, $L_{2h} = L_{4h} = 1.48\ m$H and $C_{3h} = 0.006\ \mu$F. The resistance values corresponding to inductance values L_{2h} and L_{4h} are the same as in the example adove. Then, the final filter circuit is

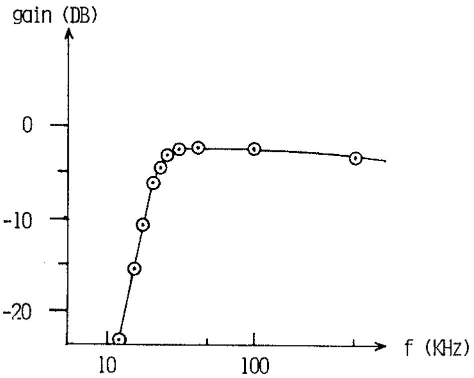

Fig. 17 Experimental frequency response of 5th-order Butterworth highpass filter

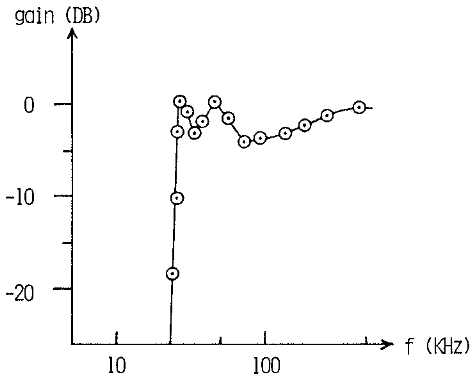

Fig. 18 Experimental frequency response of 5th-order 1 dB ripple Chebyschev highpass filter

shown in Fig. 16.

These highpass filters were composed of μA 747 *PC*-type op amps with bain gandwidth product $GB = 2\pi 1.5 \cdot 10^6$ *rad/*sec and 1 percent tolerance resistors and capacitances. The power supply voltage is$\pm$15V. It is seen that the experimental results agree approximately with theoretical as is evident from the Figs. 17 and 18. We can conclude from the experimenatl described above that the inductance simulation circuit shown in Fig. 1 operates succesfully as a inductance.

6. Conclusion

We have described the grounded inductance using op amp pole. The structure simulates as inductance and a resistance in series with a capacitance and can be operated at much higher frequencies than classical active network. The circuit is suitable for microcircuit fabrication of the network. Furthermore, it has been obvious that the realized circuit has low sensitivity to active and passive elements from the sensitivity analysis, and the inductance value can be changed with the resistance ratios K_{12}, K_{34} and K_{f2}, which assures better temperature performance. The proposed circuit is suitable for realizing inductance with relatively low Q-factor. The Q-factor can be adjusted by either the resistance ratios or values. As examples of application of such simulated inductance, the 5th-order Butterworth and 5th-order 1 dB ripple Chebyschev highpass ladder filter were presented. It has been obvious that these filter configulations work succesfully over the wide frequency.

We expect that this proposed scheme can be readily applied to other filter realizations, FDNR and GIC i.e.

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