International Journal of Engineering Research And Management (IJERM)
ISSN: 2349- 2058, Volume-03, Issue-11, November 2016

Novel CMOS BPF based on Grounded Active Inductor

Mr. Kittipong Tripetch

***Abstract*— Active inductor is a circuit technique which is based on gyrator loop. Gyrator loop is composed of at least two transconductance amplifiers, Usually, frequency response of active inductor have phase shift 90 degree at resonance frequency. This paper propose circuit technique which are based on complementary common source amplifier with drain degeneration resistors (CCSDDR). This paper derive input impedance of the proposed circuit. Bode plot of input impedance of the ground active inductor is plotted in MATLAB with 0.5 micron level1 transistor model which have complete transistor model based on physical constants and parasitic capacitance model. The proposed grounded active inductors is substituted in second order BPF LCR prototype**

***Index Terms*— Grounded Active Inductor , LPF , BPF**

I. Introduction

Gyrator is an architecture which can be a plan for implementation of grounded active inductor which is proposed since 1948 by Tellegen [1]. The most simplest transconductance amplifier which can formed gyrator loop are common source amplifier, common drain amplifier and common gate amplifier. Gyrator loop means feedback output of the first transconductance amplifier input of the second transconductance amplifier, then output of the second transconductance amplifier is fed back to input of the first transconductance amplifier sot it close the gyrator loop. The complimentary input common source is a well known circuit called CMOS inverter which is a digital circuit but it can be used as an analog circuit as well. The propose circuit add four additional resistors between the drain terminal of the NMOS and PMOS of the transconductance amplifier to increase impedance gain at the resonance frequency which is seen in the formulas of symbolic input impedance of the circuit which will be derived in the later section.

Nauta proposed ingenius transconductor since 1992[2]. It is more complicated than basic common source transistor because it can source and sink current at the same time. As a result, it saves silicon area for resistor implementation. The transconductance value can be computed by derivative of offset current which flow out of output nodes of the transconductor.

Manuscript received Nov 20, 2016
Mr. Kittipong Tripetch, Department of Electronic and Electrical engineering Keio University Yokohama, Japan

II. Derivation of Input Impedance of Grounded Inductor Based on CCSDDR

A. The proposed grounded active inductor

It is well known that input impedance of inductance is sL which is ideal formula for input impedance of inductance. For ideal original gyrator, its input impedance which is capacitive terminated by formula L=C/(Gm1*Gm2).

The proposed circuit is depicted in fig.1 as shown below.

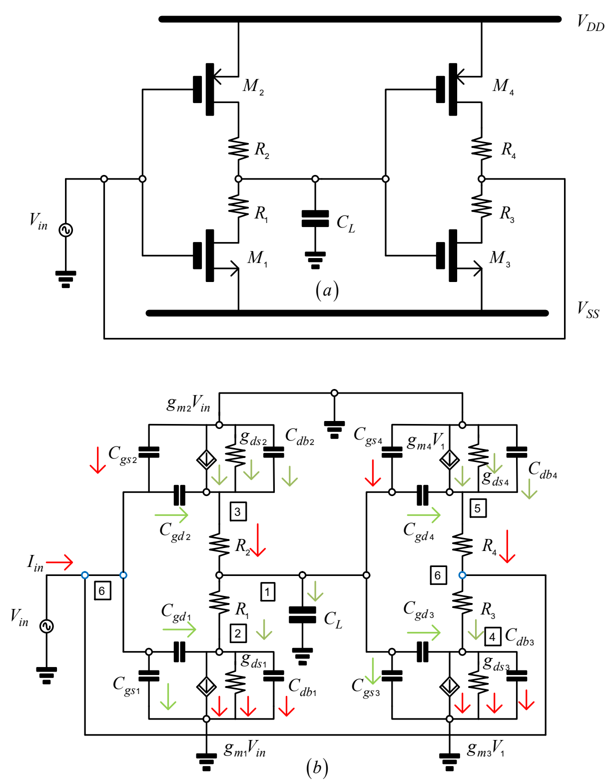

Fig1. (a) Schematic CCSDDR
(b) small signal high frequency equivalent circuit of Fig1. (a)

Fig.1a shows the schematic of gyrator or grounded active inductor which composed of four transistors and four resistors and single capacitive load. It can be seen as CCSDDR first stage amplifier in cascade with CCSDDR second stage. Then, output of the second stage can be feedback to input of the first stage as can be depicted in fig.1a

III. Quality Factor of Active Inductor

Quality factor of active inductor can be defined in several ways. The most popular should be imaginary part of input impedance divided by real part of input impedance. Eventhough, the slop is not constant as a function of input frequency because numerator and denominator polynomial has high order, its input frequency is also a function of order of polynomial. After using KCL and Ohm's law for fig.1b, input impedance of this circuit can be derived as following

.

$$Z_{in}=\frac{\begin{bmatrix}-s^{11}k_{114}+s^{10}k_{104}+s^{9}k_{94}+s^{8}k_{84}+s^{7}k_{74}+s^{6}k_{64}\\ +s^{5}k_{54}+s^{4}k_{44}+s^{3}k_{34}+s^{2}k_{24}+sk_{14}-k_{04}\end{bmatrix}\times\left[R_3R_1R_3R_4\right]}{\begin{bmatrix}-s^{12}k_{127}+s^{11}k_{117}+s^{10}k_{107}+s^{9}k_{97}+s^{8}k_{87}+s^{7}k_{77}\\ +s^{6}k_{67}+s^{5}k_{57}+s^{4}k_{47}+s^{3}k_{37}+s^{2}k_{27}+sk_{17}-k_{07}\end{bmatrix}}$$

$$\begin{aligned}
&k_{127}=k_{125}+k_{126},k_{117}=k_{115}-k_{116},k_{107}=k_{105}-k_{106},k_{97}=k_{95}-k_{96}\\
&k_{87}=k_{85}-k_{86},k_{77}=k_{75}-k_{76},k_{67}=k_{65}-k_{66},k_{57}=k_{55}-k_{56}\\
&k_{47}=k_{45}-k_{46},k_{37}=k_{35}-k_{36},k_{27}=k_{25}-k_{26},k_{17}=k_{15}-k_{16},k_{07}=k_{05}+k_{06}
\end{aligned} \tag{1}$$

$$\begin{aligned}
k_{126}&=g_{63}h_{69}\\
k_{116}&=g_{63}h_{59}+g_{53}h_{69}\\
k_{106}&=g_{63}h_{49}+g_{53}h_{59}+g_{43}h_{69}\\
k_{96}&=g_{63}h_{39}+g_{53}h_{49}+g_{43}h_{59}+g_{33}h_{69}\\
k_{86}&=g_{63}h_{29}+g_{53}h_{39}+g_{43}h_{49}+g_{33}h_{59}+g_{23}h_{69}\\
k_{76}&=g_{63}h_{19}+g_{53}h_{29}+g_{43}h_{39}+g_{33}h_{49}+g_{23}h_{59}+g_{13}h_{69}\\
k_{66}&=g_{63}h_{09}+g_{53}h_{19}+g_{43}h_{29}+g_{33}h_{39}+g_{23}h_{49}+g_{13}h_{59}-g_{03}h_{69}\\
k_{56}&=g_{53}h_{09}+g_{43}h_{19}+g_{33}h_{29}+g_{23}h_{39}+g_{13}h_{49}-g_{03}h_{59}\\
k_{46}&=g_{43}h_{09}+g_{33}h_{19}+g_{23}h_{29}+g_{13}h_{39}-g_{03}h_{49}\\
k_{36}&=g_{33}h_{09}+g_{23}h_{19}+g_{13}h_{29}-g_{03}h_{39}\\
k_{26}&=g_{23}h_{09}+g_{13}h_{19}-g_{03}h_{29}\\
k_{16}&=g_{13}h_{09}+g_{03}h_{19}\\
k_{06}&=-g_{03}h_{09}
\end{aligned} \tag{2}$$

$$\begin{aligned}
k_{125}&=g_{69}h_{65}\\
k_{115}&=g_{59}h_{65}-g_{69}h_{55}\\
k_{105}&=g_{49}h_{65}+g_{59}h_{55}-g_{69}h_{45}\\
k_{95}&=g_{39}h_{65}+g_{49}h_{55}+g_{59}h_{45}-g_{69}h_{35}\\
k_{85}&=g_{29}h_{65}+g_{39}h_{55}+g_{49}h_{45}+g_{59}h_{35}-g_{69}h_{25}\\
k_{75}&=g_{19}h_{65}+g_{29}h_{55}+g_{39}h_{45}+g_{49}h_{35}+g_{59}h_{25}-g_{69}h_{15}\\
k_{65}&=-g_{09}h_{65}+g_{19}h_{55}+g_{29}h_{45}+g_{39}h_{35}+g_{49}h_{25}+g_{59}h_{15}-g_{69}h_{05}\\
k_{55}&=-g_{09}h_{55}+g_{19}h_{45}+g_{29}h_{35}+g_{39}h_{25}+g_{49}h_{15}+g_{59}h_{05}\\
k_{45}&=-g_{09}h_{45}+g_{19}h_{35}+g_{29}h_{25}+g_{39}h_{15}+g_{49}h_{05}\\
k_{35}&=-g_{09}h_{35}+g_{19}h_{25}+g_{29}h_{15}+g_{39}h_{05}\\
k_{25}&=-g_{09}h_{25}+g_{19}h_{15}+g_{29}h_{05}\\
k_{15}&=-g_{09}h_{15}+g_{19}h_{05}\\
k_{05}&=-g_{09}h_{05}
\end{aligned} \tag{3}$$

$$\begin{aligned}
&k_{114}=k_{82}k_{33},k_{104}=k_{72}k_{33}-k_{82}k_{23}\\
&k_{94}=k_{62}k_{33}+k_{72}k_{23}-k_{82}k_{13}\\
&k_{84}=k_{52}k_{33}+k_{62}k_{23}+k_{72}k_{13}-k_{82}k_{03}\\
&k_{74}=k_{42}k_{33}+k_{52}k_{23}+k_{62}k_{13}+k_{72}k_{03}\\
&k_{64}=k_{32}k_{33}+k_{42}k_{23}+k_{52}k_{13}+k_{62}k_{03}\\
&k_{54}=-k_{22}k_{33}+k_{32}k_{23}+k_{42}k_{13}+k_{52}k_{03}\\
&k_{44}=k_{12}k_{33}-k_{22}k_{23}+k_{32}k_{13}+k_{42}k_{03}\\
&k_{34}=-k_{02}k_{33}+k_{12}k_{23}-k_{22}k_{13}+k_{32}k_{03}\\
&k_{24}=-k_{02}k_{23}+k_{12}k_{13}-k_{22}k_{03}\\
&k_{14}=-k_{02}k_{13}+k_{12}k_{03}\\
&k_{04}=-k_{02}k_{03}
\end{aligned} \tag{4}$$

$$\begin{aligned}
k_{82}&=k_{71}C_{gd3}\\
k_{72}&=\left(k_{61}C_{gd3}+k_{71}g_{m3}\right)\\
k_{62}&=\left(k_{51}C_{gd3}-k_{61}g_{m3}\right)\\
k_{52}&=\left(k_{41}C_{gd3}-k_{51}g_{m3}\right)\\
k_{42}&=\left(k_{31}C_{gd3}-k_{41}g_{m3}\right)\\
k_{32}&=\left(k_{21}C_{gd3}-k_{31}g_{m3}\right)\\
k_{22}&=\left(k_{11}C_{gd3}+k_{21}g_{m3}\right)\\
k_{12}&=\left(k_{01}C_{gd3}+k_{11}g_{m3}\right)\\
k_{02}&=k_{01}g_{m3}
\end{aligned} \tag{5}$$

$$\begin{aligned}
k_{71}&=g_{69}C_{gd3}\\
k_{61}&=g_{59}C_{gd3}+g_{69}g_{m3}\\
k_{51}&=g_{49}C_{gd3}-g_{59}g_{m3}\\
k_{41}&=g_{39}C_{gd3}-g_{49}g_{m3}\\
k_{31}&=g_{29}C_{gd3}-g_{39}g_{m3}\\
k_{21}&=g_{19}C_{gd3}-g_{29}g_{m3}\\
k_{11}&=g_{09}C_{gd3}+g_{19}g_{m3}\\
k_{01}&=g_{09}g_{m3}\\
k_{33}&=d_{21}\left(C_{gd1}+C_{db1}\right)R_1\\
k_{23}&=d_{21}\left(1+g_{ds1}R_1\right)+d_{11}\left(C_{gd1}+C_{db1}\right)R_1\\
k_{13}&=d_{11}\left(1+g_{ds1}R_1\right)+d_{01}\left(C_{gd1}+C_{db1}\right)R_1\\
k_{03}&=d_{01}\left(1+g_{ds1}R_1\right)
\end{aligned} \tag{6}$$

$$\begin{aligned}
h_{69}&=\left[\left(h_{36}h_{37}\right)R_1R_3-\left(h_{58}C_{gd3}\right)\right]\\
h_{59}&=\left[\left(h_{36}h_{27}-h_{26}h_{37}\right)R_1R_3-\left(-h_{58}g_{m3}+h_{48}C_{gd3}\right)\right]\\
h_{49}&=\left[\left(h_{36}h_{17}-h_{26}h_{27}-h_{16}h_{37}\right)R_1R_3-\left(-h_{48}g_{m3}+h_{38}C_{gd3}\right)\right]\\
h_{39}&=\left[\left(h_{36}h_{07}-h_{26}h_{17}-h_{16}h_{27}+h_{06}h_{37}\right)R_1R_3-\left(-h_{38}g_{m3}+h_{28}C_{gd3}\right)\right]\\
h_{29}&=\left[\left(-h_{26}h_{07}-h_{16}h_{17}+h_{06}h_{27}\right)R_1R_3-\left(-h_{28}g_{m3}+h_{18}C_{gd3}\right)\right]\\
h_{19}&=\left[\left(-h_{16}h_{07}+h_{06}h_{17}\right)R_1R_3+\left(h_{18}g_{m3}+h_{08}C_{gd3}\right)\right]\\
h_{09}&=\left[\left(h_{06}h_{07}\right)R_1R_3-h_{08}g_{m3}\right]
\end{aligned} \tag{7}$$

For compactness of the papers, all equations which shows coefficients of the polynomial are not listed in this paper.

IV. GROUPING THEOREM

A. *Discussion of grouping theorem*

As was described shortly under equation (1). Why do we need grouping theorem

1. Subscript of coefficients has only two meanings, the first number of subscript means order of the polynomial. Its range can be number 1 to 99. The second number of subscript means name of parameters of that coefficients, its range can be number 1 to 9. Such as k127 means it is polynomial order 12, it is the parameter name number7.It does not mean order 127, order 1 and coefficients name 27.

2. Without grouping theorem, one must multiply long term of polynomial, the result of polynomial multiplication or polynomial convolution must be grouped nearly anytime. If

you think coefficient after multiplication is not long enough, please do not use group because the name of variable are limited to alphabet a to z only which have only 26 names multiply by 9 which is variable name of alphabet, thus the total number of variable names should have only 234 variable names.

3. If the total variable names is not enough, you can extend the variable name to 2 alphabet such as aa, ab, ac, ad, …,etc so with this methodology the variable name can be extended to 26 multiply 234 which is equal with 6084 variable names.

4. The maximum variable name should be $26^{26} \times 9 = 6.15 \times 10^{36} \times 9 = 5.540 \times 10^{37}$ which variable name can be extended to 26 alphabet. The variable name can be capital letter or small letter. So the maximum variable name should be $26^{26} \times 9 \times 2 = 1.1081 \times 10^{38}$

V. INPUT IMPEDANCE GRAPH DISCUSSION

It is well known that at low input frequency, it has some constant called dc input impedance. It can be described from fig2 as following. From green line curve, its input impedance has resonance frequency at 435 Hz, at this resonance frequency its circuit consume 20 microampere of current. The peaking magnitude response at this current consumption is 207 dB.

From red line curve, its input impedance has resonance frequency at 1.37 kHz, at this resonance frequency its circuit consume 200 microampere of current. The peaking magnitude response at this current consumption is 189 dB.

From blue line curve, its input impedance has resonance frequency at 1.94 kHz, at this resonance frequency its circuit consume 400 microampere of current. The peaking magnitude response at his current consumption is 182 dB.

VI. TUNING OF BPF CONCEPT

Tuning of BPF concept can be classify into at least two categories. The first is center frequency tuning, it can be tune by design aspect ratio, it can be seen from the graph in fig.2 that as the current consumption higher the center frequency can be tune to higher frequency. The second is quality factor tuning which is defined by center frequency divided by bandwidth at -3dB. It can be tune by adapt the load capacitor.

The last is center frequency tuning which can be seen from graph in fig.4. It can be interpret from graph that the lower the drain degeneration resistance value the higher the resonance frequency. (according to ohm's law, high current mean lower resistor).

VII. Bandpass Filter based on Grounded Active Inductor

It is well known that resonance circuit is the most simplest 2nd order bandpass filter. The problem is it should have resistor connect between input signal source and resonance circuit. Otherwise, the input voltage and output voltage is at the same node. The bandpass filter circuit is shown in fig.5 (a). The passive inductor in fig.5(a) can be replaced by input impedance block which is called resonance impedance block.

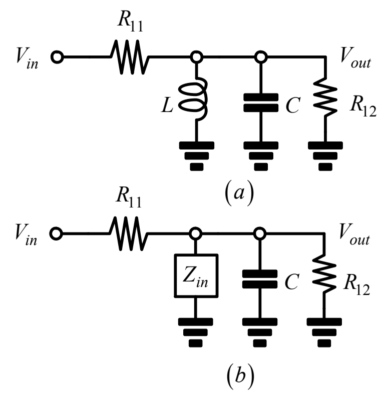

Fig.5 (a) Bandpass Filter Passive Prototype
(b) Bandpass Filter Active Prototype

CONCLUSION

This paper proposed the modification of the Nauta transconductor, its advantage should be higher quality factor of inductor and reduce sensitivity of voltage drop of transistor which may change considerably due to mismatch of the transistors. The disadvantage is exactly the resistor cost of implementation which is the crucial point of investment. This paper also derived the formula of the input impedance of the grounded active inductor based on CCSDDR. Three graphs are plotted to show the trend and rule of thumb of the parameters

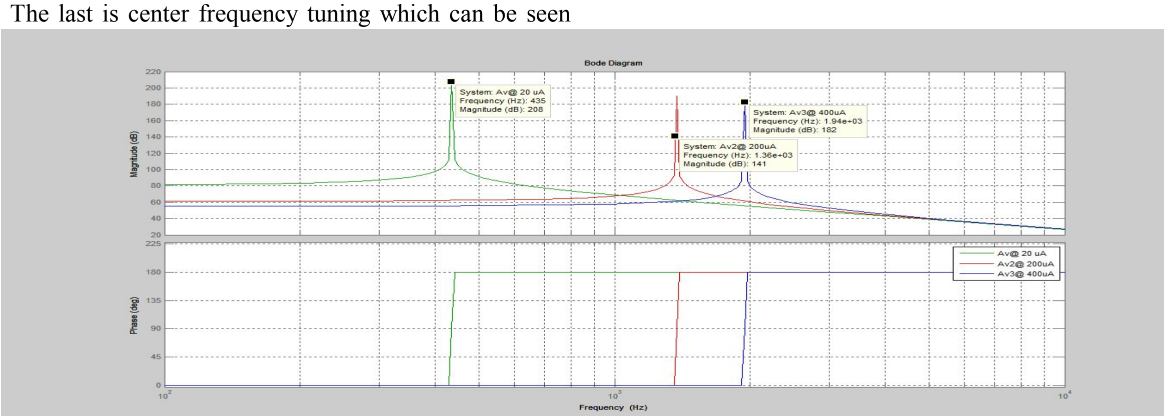

Fig2. Tune Resonance Frequency by current consumption
(a) Magnitude response of grounded active inductor
(b) Phase response of grounded active inductor

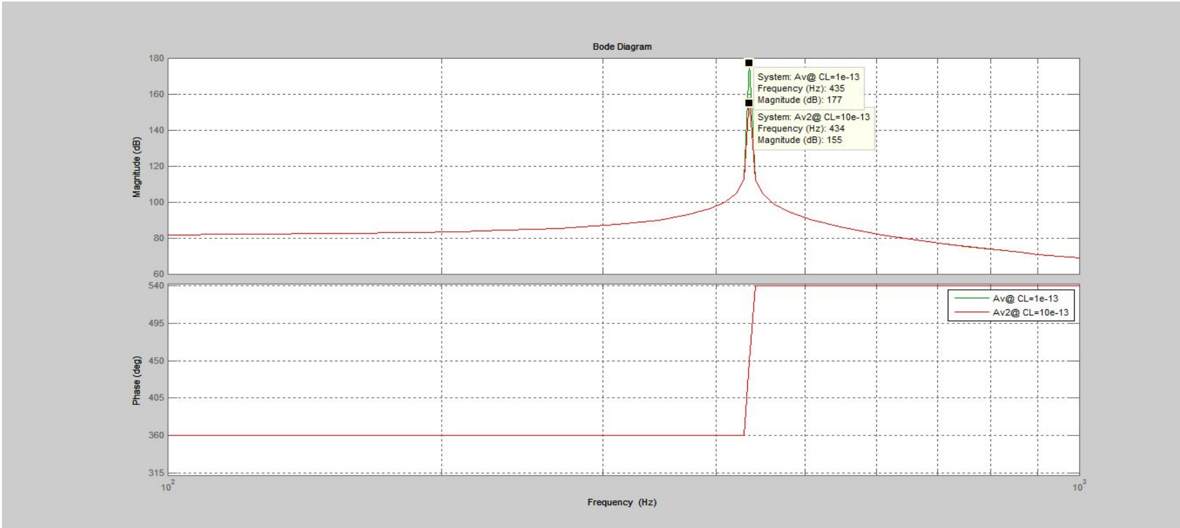

Fig3. Tune Quality Factor by load capacitor
(a) Magnitude response of grounded active inductor
(b) Phase response of grounded active inductor

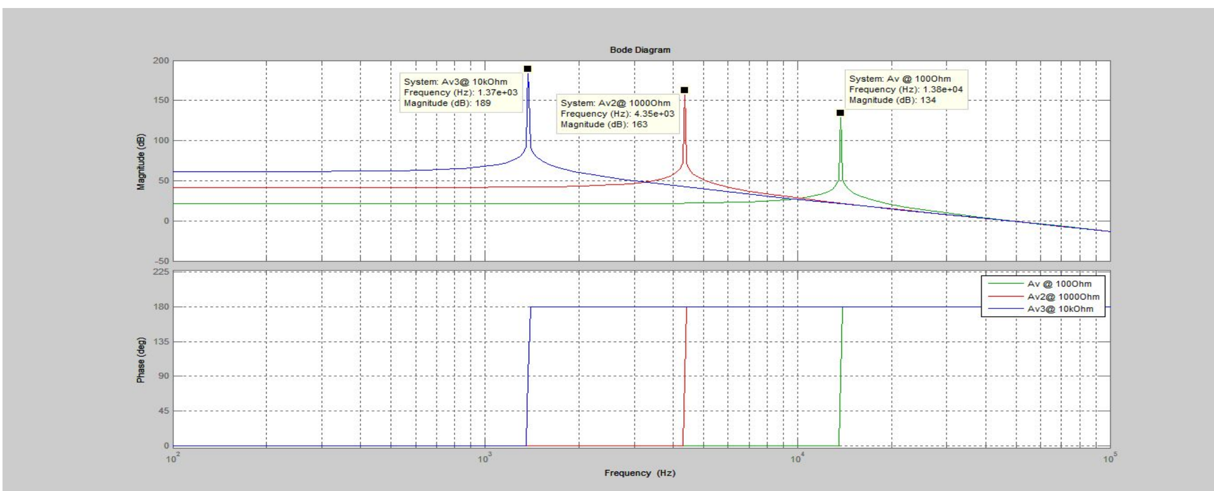

Fig4. Tune resonance Frequency by adapt drain degeneration resistor
(a) Magnitude response of grounded active inductor
(b) Phase response of grounded active inductor

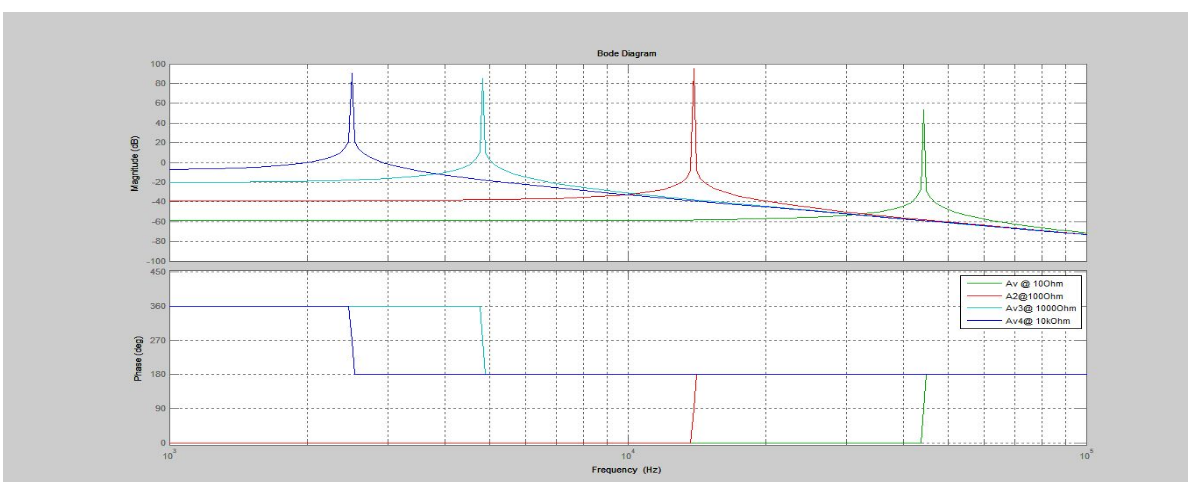

Fig6. Tune Resonance Frequency of Bandpass Filter by drain degeneration resistor
(a) Magnitude Response of Bandpass Active Filter
(b) Phase Response of Bandpass Active Filter

REFERENCES

[1] G. E. Sharpe, " The Pentode Gyrator", IRE Transactions on Circuit Theory", Dec 1957, pp. 321-323

[2] Bram Nauta, " A CMOS Transconductance C Filter technique for Very high frequencies", IEEE Journal of Solid State Circuit, Vol.27, No.2, February 1992, pp. 142-153

[3] H. J. Orchard, " Inductorless Filters", Electronics Letters, June 1966, Vol.2, No.6, pp.224-225

[4] H. J. Orchard, D. F. Sheahan, "Inductorless Bandpass Filter", IEEE Journal of Solid State Circuits, Vol. SC-5, No.3, June 1970, pp. 108-118

[5] M. M. Green, "On Power Transmission of LC ladder filters using active inductor realizations", IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications, Vol.43, No.6, June 1996, pp. 509-511

Kittipong Tripetch have been received Bachelor degree from Mahanakorn University of Technology in Telecommunication engineering since 1996. Master degree from Mahanakorn University of Technology in Microelectronic engineering since 2002. He worked as a lecturer at division of electronic and telecommunication engineering, Faculty of Engineering, Rajamangala University of Technology Suvarnabhumi, Nonthaburi Province since 2004-2014, He have been studying Ph.D in electronic engineering at Keio University, Yokohama, Japan since April 2014.