# Current Mode Programmable Analog Modules using Low voltage Digitally Controlled CMOS CCII

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## ABSTRACT

The current mode programmable analog modules are realized using digitally controlled low voltage CMOS current conveyors. These programmable modules include current mode amplifiers, integrators, differentiators, first order multifunctional filter and second order multifunctional filters. The realized current mode programmable analog modules can provide digital control to the parameters through an n-bit control word with high resolution capability and reconfigurability. These programmable analog modules are suitable for realizing current mode field programmable analog array. The realized programmable analog modules are designed and verified using PSPICE and the results thus obtained justify the theory.

## General Terms

Digitally programmable analog modules.

## Keywords

Current conveyors, current mode amplifiers, filters.

## 1. INTRODUCTION

Recently, the introduction of digital control to the current conveyor (CCII) has boosted its functional capability and versatility in addition to its higher signal bandwidth, greater linearity and large signal bandwidth [1-14]. This digital control has eased the on chip control of continuous time systems with high resolution capability and reconfigurability [1-8].

This paper basically deals with the realization of reconfigurable current mode programmable analog modules (CMPAMs) using digitally controlled low voltage CMOS CCII [1-4], [6-8]. The realized CMPAMs include the current mode amplifiers, integrators, differentiators, first order and second order multifunctional filters using Low voltage digitally programmable CMOS CCII (DPCCII). All the realized CMPAMs provide digitally programmable module parameters through an n-bit control word. These CMPAMs can be used as a programmable module of a field programmable analog array (FPAA) [15], [16]. To verify the theory, the realized CMPAMs are designed and verified using PSPICE and the results thus obtained justify the theory.

## 2. THE CMOS DPCCII

The digitally programmable CCII (DPCCII) symbol is shown in “Figure 1(a)” and its CMOS implementation with 4-bit control word is shown in “Figure 1(b)” [4], [8]. The current summing network (CSN) is included at port-X. The transfer matrix can be expressed as

$$\begin{bmatrix} I_Y \\ V_X \\ I_Z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ \alpha & 0 & 0 \\ 0 & \pm\beta N^m & 0 \end{bmatrix} \begin{bmatrix} V_Y \\ I_X \\ V_Z \end{bmatrix} \quad (1)$$

Thus the port voltages and currents for DPCCII can be expressed as

$$\begin{aligned} I_Y &= 0, \\ V_X &= \alpha V_Y, \\ I_Z &= \pm\beta N^m I_X \end{aligned} \quad (2)$$

In equation (2) α is the voltage transfer gain from terminal-Y to terminal-X and β is the current transfer gain from X to Z. Both the voltage gain (α) and the current gain (β) are ideally unity. N is an n-bit digital control word, the plus sign(+) is for $I_{Z+}$ and minus sign(-) is for $I_{Z-}$. The power integer m = 1 for current summing network (CSN) at port-Z and m = -1 for current summing network (CSN) at port-X of the DPCCII [1], [4-8]. The additional number of Z+ or Z- outputs may be added as per requirement just by connecting in parallel a set of PMOS and NMOS for each output as shown in “Figure 1(b)”.

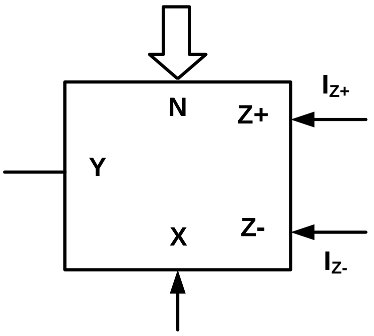

**Fig 1(a): Symbol for 4-bit DPCCII**

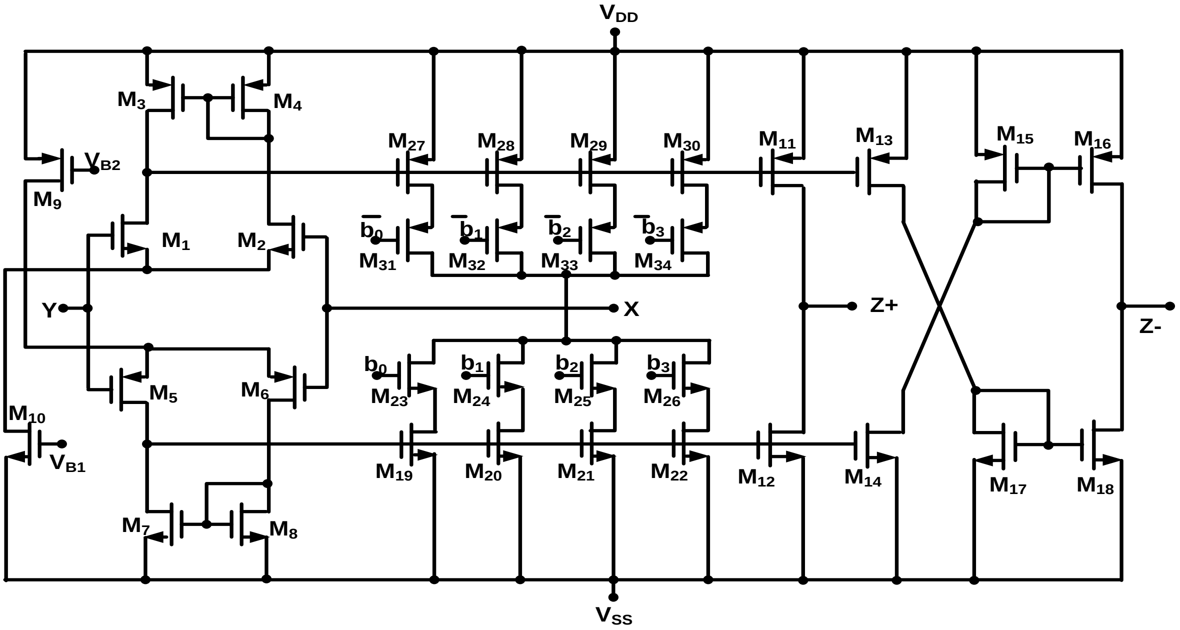

**Fig 1(b): The CMOS implementation of a 4-bit DPCCII with CSN at port X**

# 3. THE CMPAM CIRCUITS

Three current mode programmable analog module circuits are given, viz., CMPAM-1, CMPAM-2, and CMPAM-3.

## 3.1 CMPAM-1: Digitally Progrmmable Current Amplifiers

The CMPAM-1 is the digitally programmable current amplifier using CMOS DPCCII is shown in “Figure 2”. The circuit uses one DPCCII along with grounded resistors $R_1$ and $R_2$.

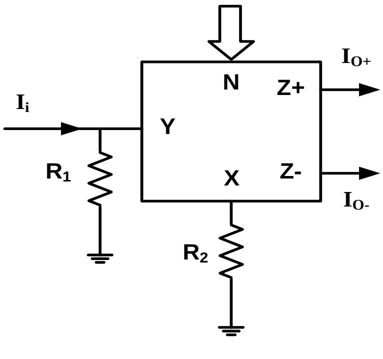

**Fig 2: CMPAM-1: Digitally Progrmmable Current Amplifiers**

The routine analysis yields its non-inverting and inverting current gains respectively $G_+$ and $G_-$ as follows.

$$G_+ = \frac{I_{O+}}{Ii} = \alpha\beta N^m \frac{R_1}{R_2}$$

and (3)

$$G_- = \frac{I_{O-}}{Ii} = -\alpha\beta N^m \frac{R_1}{R_2}$$

From equation (3) it is clear that the current gains can be set directly or inversely proportional to n-bit digital control word N by choosing the DPCCII with m = +1 or -1, respectively as described in Section-II. It is to be noted that both the resistors can be set equal to minimize the component spread which is desirable for IC implementation. The non-ideal gains α and β may slightly affect the gain which can be adjusted through resistors ratio $R_2 / R_1$.

It is also to be noted that by replacing $R_1$ with a capacitor in “Figure 2”, the CMPAM-1 results a digitally programmable integrator with inverting and non-inverting outputs. Similarly, by replacing $R_2$ with a capacitor the CMPAM-1results a digitally programmable differentiator with inverting and non-inverting outputs.

## 3.2 CMPAM-2: Digitally Programmable Current Mode First-Order Multifunctional Filters

The CMPAM-2 is the digitally programmable current mode first order multifunctional filter using CMOS DPCCII is shown in “Figure 3” [7]. The circuit uses one CCII and one DPCCII, each one with three outputs along with grounded R and C components. The DPCCII uses the CSN at port-X as shown in “Figure 1(b)”. The routine analysis yields its current transfer functions respectively for low pass, high pass and all pass filters as

$$\frac{I_{LP}}{I_{IN}} = \frac{\frac{N}{RC}}{s + \frac{N}{RC}} \qquad 4(a)$$

$$\frac{I_{HP}}{I_{IN}} = \frac{s}{s + \frac{N}{RC}} \qquad 4(b)$$

$$\frac{I_{AP}}{I_{IN}} = -\frac{s - \frac{N}{RC}}{s + \frac{N}{RC}} \qquad 4(c)$$

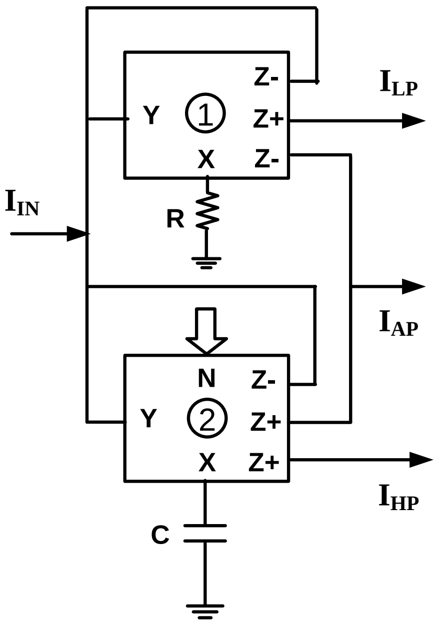

**Fig 3: The CMPAM-2: Digitally Programmable Current Mode First order Multifunctional filter**

The pole frequency ($\omega_0$) and the phase angle ($\phi$) for the APF can be expressed as follows.

$$\omega_0 = \frac{N}{RC}$$
$$\Phi = -2\tan^{-1}\left(\frac{\omega RC}{N}\right) \qquad (5)$$

From equation (4) it is evident that the pole frequency $\omega_0$ is directly proportional to the digital control word N. Also the phase can be controlled through N at any constant pole-$\omega_0$. The control through external digital control word N, facilitate the on chip system control. Thus the multifunctional filter of "Figure 2" can be used as a programmable module of a field programmable analog array (FPAA)[15].

Taking the non-idealities of CCIIs into account as given in equation((2), with $\alpha_1$ and $\beta_1$ for CCII-1 and $\alpha_2$ and $\beta_2$ for CCII-2, the ideal transfer functions given in equation (4) yield the non-ideal transfer functions as follows.

$$\frac{I_{LP}}{I_{IN}} = \frac{\frac{\alpha_1\beta_1 N}{\alpha_2\beta_2 RC}}{s + \frac{\alpha_1\beta_1 N}{\alpha_2\beta_2 RC}} \qquad 6(a)$$

$$\frac{I_{HP}}{I_{IN}} = \frac{s}{s + \frac{\alpha_1\beta_1 N}{\alpha_2\beta_2 RC}} \qquad 6(b)$$

$$\frac{I_{AP}}{I_{IN}} = -\frac{s - \frac{\alpha_1\beta_1 N}{\alpha_2\beta_2 RC}}{s + \frac{\alpha_1\beta_1 N}{\alpha_2\beta_2 RC}} \qquad 6(c)$$

Also the equation (5) reduces to

$$\omega_0 = \frac{\alpha_1\beta_1 N}{\alpha_2\beta_2 RC}$$
$$\Phi = -2\tan^{-1}\left(\frac{\omega\alpha_2\beta_2 RC}{\alpha_1\beta_1 N}\right) \qquad (7)$$

The equations (6) and (7) show that with $\alpha_1 = \alpha_2$ and $\beta_1 = \beta_2$, the pole-frequency for first order multifunctional filter and the phase angle $\phi$ for the all pass section are unaffected due to non-idealities.

## 3.3 CMPAM-3: Digitally Programmable Current Mode Second-Order Multifunctional Filters

The CMPAM-3 is the digitally programmable current mode second order multifunctional filter using low voltage digitally controlled CMOS DPCCII with m=1, is shown in "Figure 4". The circuit uses three DPCCII, each one with two outputs along with grounded R and C elements.

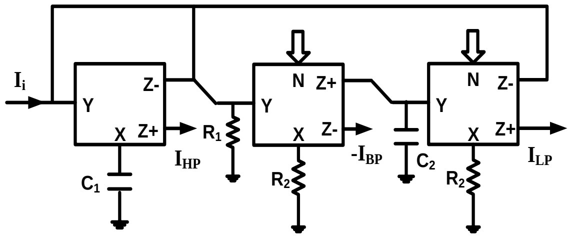

**Fig 4: The CMPAM-3: Digitally Programmable Current Mode Second order Multifunctional filter**

The routine analysis yields its current transfers functions respectively for low pass filter (LPF), band pass filter (BPF) and high pass filter (HPF) as follows.

$$\frac{I_{LP}}{I_{IN}} = \frac{\frac{N^2}{R_2R_3C_1C_2}}{s^2 + s\frac{1}{R_1C_1} + \frac{N^2}{R_2R_3C_1C_2}} \qquad 8(a)$$

$$\frac{I_{BP}}{I_{IN}} = \frac{-s\frac{N}{R_2C_1}}{s^2 + s\frac{1}{R_1C_1} + \frac{N^2}{R_2R_3C_1C_2}} \qquad 8(b)$$

$$\frac{I_{HP}}{I_{IN}} = \frac{s^2}{s^2 + s\frac{1}{R_1C_1} + \frac{N^2}{R_2R_3C_1C_2}} \tag{8(c)}$$

By just directly adding $I_{HP}$ and $I_{LP}$ the Band Reject (BR) output ($I_{BR}$) response can easily be obtained and the resulting transfer function can be expressed as follows.

$$\frac{I_{BR}}{I_{IN}} = \frac{s^2 + \frac{N^2}{R_2R_3C_1C_2}}{s^2 + s\frac{1}{R_1C_1} + \frac{N^2}{R_2R_3C_1C_2}} \tag{8(d)}$$

And by directly adding $I_{HP}$, $I_{BP}$ and $I_{LP}$ with $R_1=R_2$, the All-Pass output ($I_{AP}$) response can easily be obtained and the resulting transfer function can be expressed as follows.

$$\frac{I_{AP}}{I_{IN}} = \frac{s^2 - s\frac{N}{R_1C_1} + \frac{N^2}{R_2R_3C_1C_2}}{s^2 + s\frac{1}{R_1C_1} + \frac{N^2}{R_2R_3C_1C_2}} \tag{8(e)}$$

From equation (4) the filter parameters can be expressed as follows.

The pole frequency

$$\omega_0 = \frac{N}{\sqrt{C_1C_2R_2R_3}} \tag{9(a)}$$

The pole-Q

$$Q = R_1N\sqrt{\frac{C_1}{C_2R_2R_3}} \tag{9(b)}$$

If resistance $R_1$ is replaced by an equivalent digitally programmable resistor (DPR) as shown in "Figure 5", and

$$R_1 = \frac{R}{N_0} \tag{10}$$

with $R = R_2 = R_3$, and $C_1 = C_2 = C$, the pole-$\omega_0$ and pole-Q from equation (5) reduces to

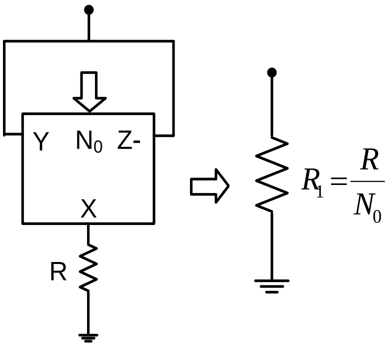

**Fig 5: The digitally programmable resistor (DPR) using CMOS DPCCII with m=1**

$$\omega_0 = \frac{N}{RC}$$

$$Q = \frac{N}{N_0} \tag{11}$$

The filter gains are

$H_{LP} = H_{HP} = 1$, and the $H_{BP} = Q$

From equation (6) it is evident that the pole frequency $\omega_0$ is directly proportional to digital control word N. The pole-Q can be independently controlled through the digital control word $N_Q$. The minimum $N_0 = 1$, and thus maximum Q = N. However, by selecting the DPCCII with m = -1, for the DPR of "Figure 5", with $R_1 = RN_0$, results the pole-Q as

$$Q = NN_0 \tag{12}$$

Thus from equation (7), it is obvious that the pole-Q can be independently and directly controlled through the digital control word $N_0$. Now with $N_0 = 1$ the minimum Q = N. The maximum $Q = NN_0$ and the choice is suited for designing high-Q filter.

Taking the non-idealities of CCIIs into account as given in equation (2), for the CMPAM-2 of "Figure 4", with identical α and β for all the CCIIs, the ideal relationship of pole-$\omega_0$, filter gains and pole-Q given in equation(11) and (12) respectively, yields the non-ideal pole-$\omega_0$, filter gains and pole-Q as follows.

$$\omega_0 = \frac{N}{RC}\sqrt{\alpha\beta}$$

$$Q = \frac{N}{N_0}\sqrt{\alpha\beta} \tag{13}$$

The filter gains are

$H_{LP} = H_{HP} = 1$, and the $H_{BP} = Q$

$$Q = NN_0\sqrt{\alpha\beta} \tag{14}$$

It is evident from equation (13) and (14) that the non-idealities slightly affect the pole-$\omega_0$ and pole-Q.

## 4. DESIGN AND VERIFICATION

All the realized digitally controlled current mode programmable analog modules of Section-1 were designed and verified by performing PSPICE simulation with supply voltage ± 0.75V using CMOS TSMC 0.25µm technology parameters. The CMOS DPCCII with 4-bit current summing network at port-X (i.e. m = -1) of Fig. 1(b) was used for CMPAM-1 and CMPAM-2. The aspect ratios used are given in the Table 1. The CMPAM-3 was verified using the DPCCII with the CSN at port-Z (i.e. m=1). The CMPAM-1 i.e. the current amplifier was initially designed for a current gain of unity with $R_1=R_2=3.3K\Omega$ and the then the gain was tuned through digital control word N. The observed wave shapes at different N are shown in "Figure 6" at 100KHz frequency. The CMPAM-2 was initially designed for a cut frequency of 16 kHz with N = 1, R = 3.3kΩ and C = 3nF. Then the pole frequency was controlled through digital control word N. The observed frequency responses of the filter for different control words are given in "Figure 7".

**Table 1: The aspect ratios of the MOSFETs of the DPCCII**

| MOSFETs | W µm | L µm |
|---|---|---|
| $M_1$, $M_2$, $M_5$, $M_6$ | 5 | 0.25 |
| $M_3$, $M_4$, $M_7$, $M_8$ | 0.5 | 0.5 |
| $M_9$, $M_{10}$ | 0.5 | 0.25 |
| $M_{11}$, $M_{12}$, $M_{13}$, $M_{14}$, $M_{15}$, $M_{16}$, $M_{17}$, $M_{18}$, $M_{19}$, $M_{23}$, $M_{27}$, $M_{31}$ | 25 | 0.25 |
| $M_{20}$, $M_{24}$, $M_{28}$, $M_{32}$ | 50 | 0.25 |
| $M_{21}$, $M_{25}$, $M_{29}$, $M_{33}$ | 100 | 0.25 |
| $M_{22}$, $M_{26}$, $M_{30}$, $M_{34}$ | 200 | 0.25 |

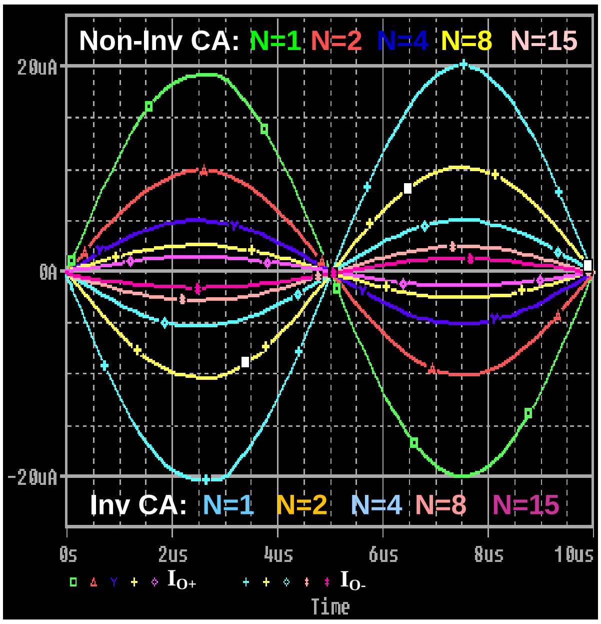

**Fig 6: The output wave shapes at different control word N of the inverting and non-inverting current amplifier (CA) at 100KHz.**

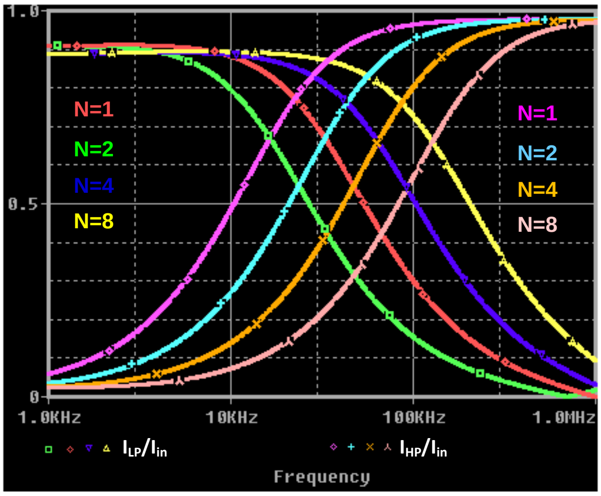

**Fig 7(a): Frequency response of LP and HP first order current mode filters at different control word N**

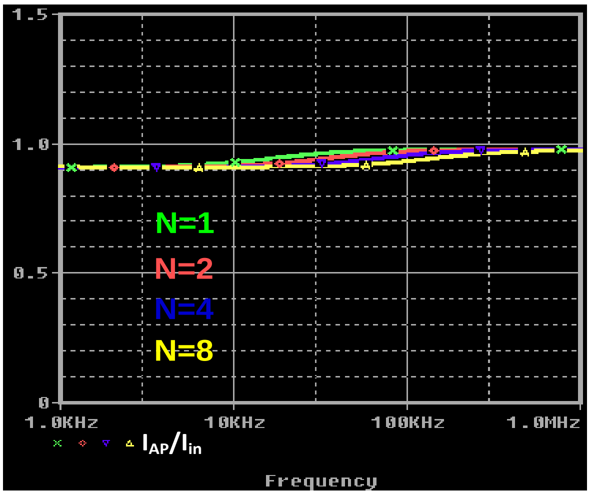

**Fig 7(b): Frequency response of the first order current mode AP filter at different control word N**

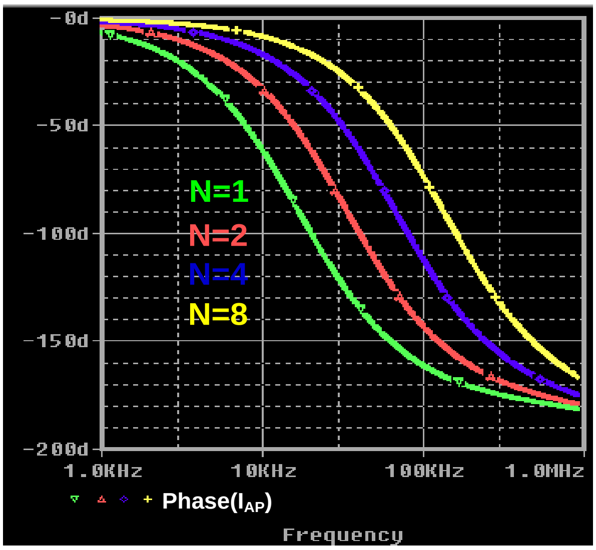

**Fig 7(c): Variation of phase angle of the first order current mode AP filter at different control word N**

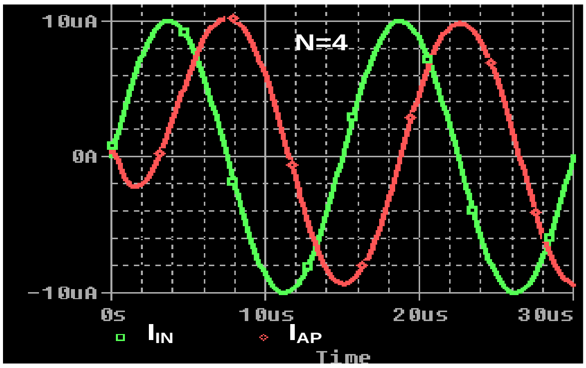

**Fig 7(d): The input and output wave shapes of the first order all pass filter at $\phi = 90^0$**

The CMPAM-3 was initially designed for a pole frequency of $f_0$ =46.8kHz and pole-Q = 1 with N =N$_0$ = 1, R = 13.6kΩ and C = 0.25nF. Then the pole frequency was controlled through digital control word N. The observed frequency responses of the filter for different control words are given in “Figure 8”. All the results observed in “Figure 6” through “Figure 8” show the close conformity with the design.

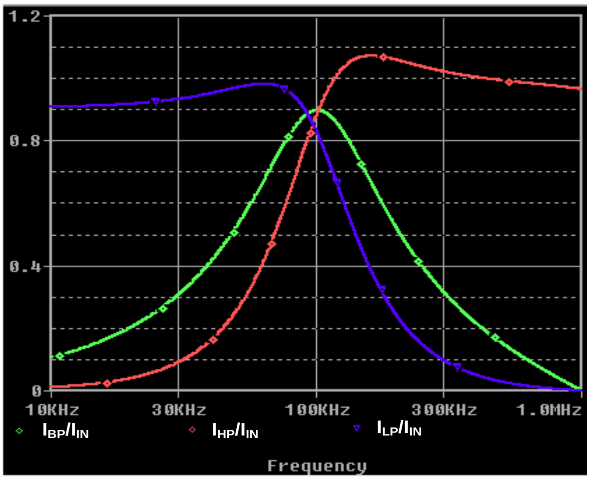

**Fig 8(a): ): Frequency response of LP, HP and BP second order current mode filter at control word N = 2**

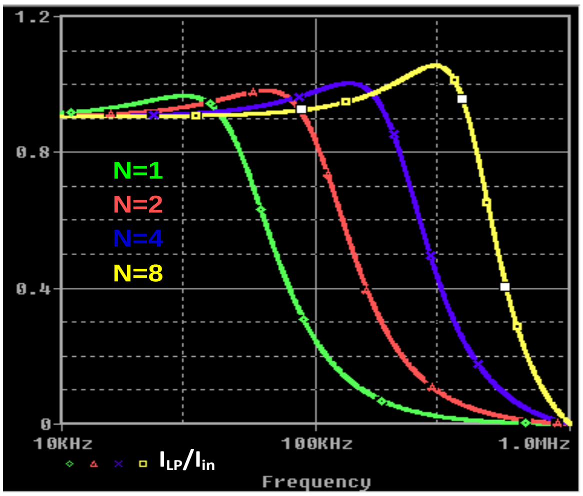

**Fig 8(b): Frequency response of LP second order current mode filter at different control word N**

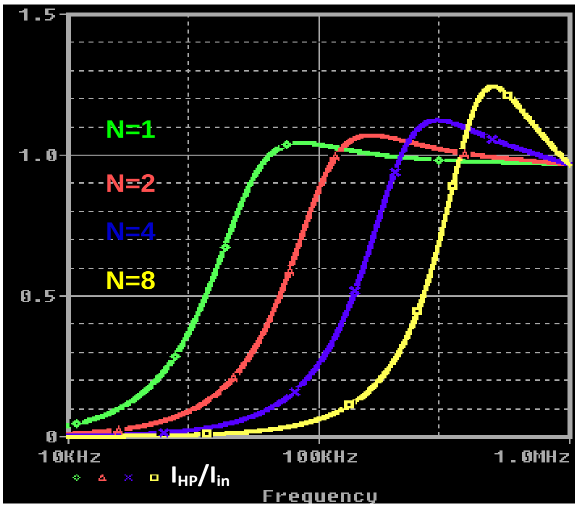

**Fig 8(c): Frequency response of HP second order current mode filter at different control word N**

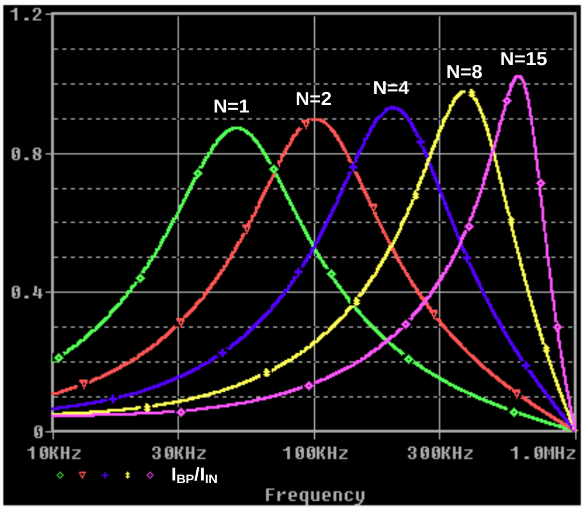

**Fig 8(d): Frequency response of the BP second order current mode filter at different control word N**

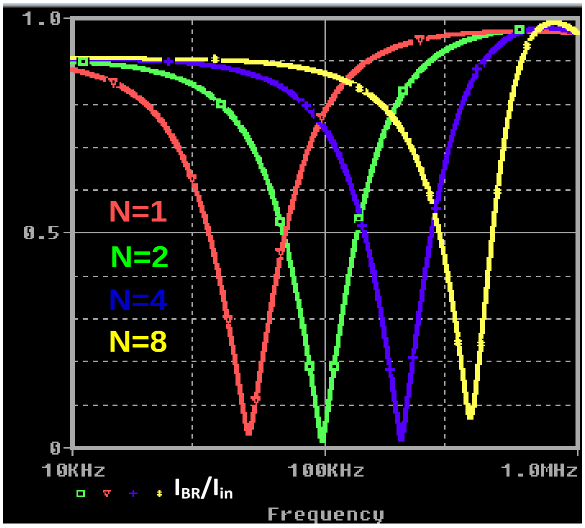

**Fig 8(e): Frequency response of BR second order current mode filter at different control word N**

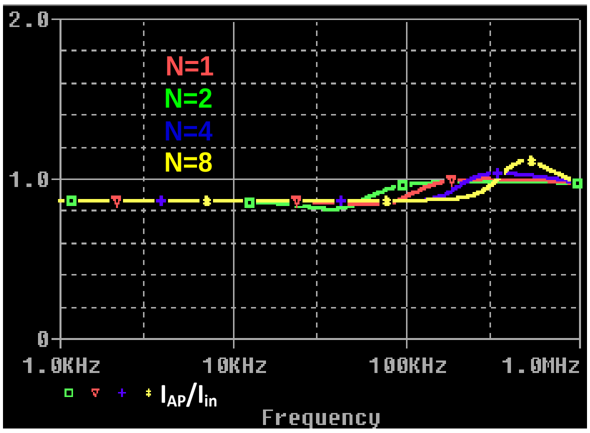

**Fig 8(f): Frequency response of AP second order current mode filter at different control word N**

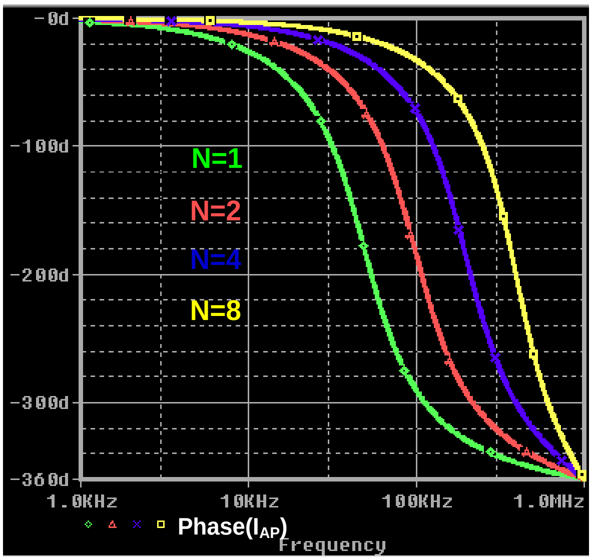

**Fig 8(g): Variation of phase angle of the second order current mode AP filter at different control word N**

## 5. CONCLUSION

Three current mode programmable analog modules are realized using digitally controlled low voltage CMOS current conveyors. These programmable modules include current mode amplifiers with inverting and non-inverting outputs, integrators, differentiators, first order multifunctional filter wit low pass, high pass, and all pass filter sections. The third programmable analog module realized is second order current mode multifunctional filter which provides low pass, high pass, band pass, band reject and all pass responses. All the realized current mode programmable analog module parameters are digitally programmable through an n-bit control word with high resolution capability and reconfigurability. These programmable analog modules are suitable for realizing current mode field programmable analog array. All the three realized programmable analog modules were designed with minimal passive components' spread and verified using PSPICE. All the results thus obtained justify the theory.

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