CHAPTER- 3

NOVEL FIRST ORDER ALL-PASS SECTIONS

All - pass filters are an important class of analogue signal processing circuits that modify the phase response of a signal keeping its amplitude constant at all frequencies. Ever since the introduction of current conveyors, the realization of first order all-pass filters operating in voltage-mode has attracted several researches [42-49]. Some current-mode circuits have also been reported in the literature [50-52]. In the literature, efforts have been made to obtain the function using a single active element, reduce the passive component count, eliminate matching/critical-matching conditions and employing grounded capacitor(s).

In this chapter\(^1\) novel voltage as well as current-mode all-pass sections (APSs) are proposed. The circuits are based on CCII, CCIII and CCCII. Section 3.1 presents a single CCII based all-pass section (APS-1) with three passive components [P4]. Translinear conveyor version employing one CCCII and two passive components named APS-2 is also proposed [P4]. Section 3.2 presents single CCII based circuit (APS-3), its single CCCII based version (APS-4) and a two CCCII based translinear-C version (APS-5). Section 3.3 is devoted to translinear-C all-pass circuits (APS-6, APS-7) that enjoy electronic tuning and an active-C realization [P5]. Section 3.4 presents some single CCIII based circuits that are first of its kind using the relatively new device [19,20]. Two voltage mode circuits (APS-8 and APS-9) and four current-mode circuits (APS-10 to APS-13) are proposed [P6, P7]. All the thirteen APSs are studied for the non-idealities of

\(^1\) The material presented in the chapter is based on Authors' papers [P4], [P5], [P6], [P7].
the used active elements and sensitivity performance. Design and verifications are also
given to confirm the validity of the presented circuits. The chapter concludes with section
3.5, which sums up the presented circuits.

3.1 **Single CCII Based Voltage-mode All-Pass Section (APS-1)**

3.1.1 **Circuit description**

The single CCII based all-pass section (APS-1) employing two passive resistors
($R_1$, $R_2$) and a capacitor ($C$) is shown in Figure 3.1. The circuit is based on an inverting
amplifier comprising a CCII-, and the two resistors with a feedback capacitor. At low
frequencies the circuit has a gain of $-1$ ($C$ looking open), which changes to $+1$ at higher
frequencies ($C$ looking short). Routine analysis of the circuit using the port relation of a
CCII- yields the following voltage transfer function.

$$\frac{V_o}{V_{in}} = \frac{s - \frac{1}{R_1C}}{s + \frac{1}{R_2C}}$$  \hspace{1cm} (3.1)

with $R_1=R_2=R$, the equation (3.1) reduces to

$$\frac{V_o}{V_{in}} = \frac{s - \frac{1}{RC}}{s + \frac{1}{RC}}$$  \hspace{1cm} (3.2)

The above equation gives the standard first order all-pass transfer function with pole
$\omega_o=1/RC$.

3.1.2 **Translinear conveyor version of the circuit (APS-2)**

The proposed APS of the above subsection is easily compatible for realization
using a translinear conveyor [18]. The resulting circuit (APS-2) as shown in Figure 3.2
Figure 3.1 Single CCII-based APS (APS-1)

Figure 3.2 Translinear conveyor based circuit (APS-2)
uses only one resistor and one capacitor besides a translinear conveyor giving rise to a minimal voltage-mode realization of all the available circuits [42-49]. The voltage transfer function using the port relationship for a translinear conveyor is given as

\[
\frac{V_o}{V_{in}} = \frac{s - \frac{1}{RC}}{s + \frac{1}{RC}}
\]  

(3.3)

Where, \( R_x \) is the intrinsic X-terminal resistance of the translinear conveyor that is current controlled as per \( V_T/2I_0 \) [18]. With \( R_x=R \), the equation (3.3) reduces to equation (3.2) realizing a first order APS. The matching required is not difficult as \( R_x \) can be controlled through the bias current of the translinear conveyor.

### 3.1.3 Non-ideal effects

A non-ideal CCII or CCCII is characterized by a voltage transfer gain from Y to X as \( \beta \) and current transfer gain from X to Z as \( \alpha \). There are parasitic port impedances as discussed in Chapter 2 at section 2.1.2. Taking into account these non-idealities, the non-ideal voltage transfer function for APS-1 becomes:

\[
\frac{V_o}{V_{in}} = \frac{s - \frac{\alpha \beta}{RRC}}{s + \frac{1}{RRC_p}}
\]  

(3.4)

Here, \( R_p = R_2 R_z / (R_2 + R_z) \) and \( C_p = (C + C_z) \), where, \( R_z \) and \( C_z \) are parasitic resistance and capacitance respectively, between port Z and ground. Next, the non-ideal voltage transfer function for the APS-2 is analyzed and found same as equation (3.4) with the difference that \( R_p=RR_z / (R+R_z) \). It is evident that the pole-\( \omega_0 \) and the filter gain get affected as a result of the non-idealities.
3.1.4 Sensitivity study

The incremental pole-$\omega_0$ and gain sensitivities to active and passive components for both the APS-1 and APS-2 are analyzed and found within unity in magnitude that represents a low value. Thus the circuits enjoy good sensitivity performance.

3.1.5 Design and verification

The APS of Figure 3.2 described in above section was simulated using the CCCII implementation with NR100N and PR100N transistor parameters with a supply voltage of $\pm 2.5$ volts [37,38]. The phase shifter circuit was designed with $C=1\text{nF}$, and $I_o=10\mu\text{A}$. The value of $R$ was taken as 1350ohms. The gain and phase response is shown in Figure 3.3. A phase shift of 90° is obtained at 115KHz, the pole-$\omega_0$. A constant unity gain is obtained at all frequencies whereas; the phase varies from 180° to 0°. Thus the proposed APSs of section 3.1 are verified.

3.2 Versatile All-Pass Sections

A new versatile APS (APS-3) employing a single CCII-, one capacitor and two resistors is proposed that requires a simple resistive matching. Translinear conveyor version of the APS (APS-4) is also given which eliminates one resistor thus requiring one CCII-, one capacitor and one resistor. The matching condition for all-pass realization can be obtained by electronic control of the bias current of CCII-. A fully electronically tunable translinear-C APS is also obtained by replacing the resistor with another CCII-, thus resulting in a circuit (APS-5) with two CCII- and one capacitor with electronic control. CCII based circuit is of special interest because of growing recent popularity of
Figure 3.3 Gain and phase response of APS-2 of Figure 3.2
the device for realization of electronic functions. The proposed circuits can be operated both in voltage mode as well as current mode thus making it more versatile.

3.2.1 Circuit description (APS-3 to 5)

The circuits for the new APS (APS-3) based on single CCII-, its translinear conveyor version (APS-4) and the fully tunable Translinear-C version (APS-5) are shown in Figure 3.4. The CCII- based APS-3 circuit is analyzed for the transfer function (both voltage as well as current) as:

\[ T(s) = \frac{s - \left( \frac{1}{R_2C} - \frac{1}{R_1C} \right)}{s + \frac{1}{R_1C}} \]  

(3.5)

With \( R_2 = R_1/2 \), equation (3.5) reduces to

\[ T(s) = \frac{s - \frac{1}{R_1C}}{s + \frac{1}{R_1C}} \]  

(3.6)

Equation (3.6) is the standard first order all-pass transfer function. If the circuit is operated in voltage mode \( T(s) = V_o/V_i \) and if operated in current mode, \( T(s) = I_{out}/I_{in} \). The APS of Figure 3.4a has its translinear conveyor version as shown in Figure 3.4b. The resulting circuit employs a single translinear conveyor (current controlled conveyor: CCCII-), one capacitor and one resistor. The transfer function of the resulting APS-4 is given as:

\[ T(s) = \frac{s - \left( \frac{1}{R_1C} - \frac{1}{RC} \right)}{s + \frac{1}{RC}} \]  

(3.7)
Figure 3.4 Versatile APS circuits:
(a) APS-3, (b) APS-4, (c) Translinear-C APS-5
Here $R_x$ is the intrinsic resistance of the $X$ terminal of the translinear conveyor that can be controlled by the bias current of the conveyor by the relation $R_x = V_T/2I_0$, $V_T$ being the thermal voltage.

With $R_x = R/2$, equation (3.7) becomes

$$T(s) = \frac{s - \frac{1}{RC}}{s + \frac{1}{RC}}$$  \hspace{1cm} (3.8)

The condition required to obtain equation (3.8) can easily be obtained by controlling the bias current of the conveyor. Next, a fully tunable APS is derived from Figure 3.4b by replacing the resistor $R$ with another CCCII-. The resulting APS-5 circuit as shown in Figure 3.4c, thus requires no resistor and give rise to a translinear-C APS. The condition required for the realization of the all-pass transfer function is $I_{o1} = 2I_{o2}$ that can be easily satisfied by controlling the bias currents of the two CCCII-s. It is to be noted that all the three versions of the APS (Figure 3.4) can be operated either in voltage-mode or current-mode without changing the circuit configuration.

3.2.2 Non-ideal study

The translinear-C APS-5 of Figure 3.4c is analyzed for the non-idealities of CCCII, mentioned in section 3.1.3 to yield the voltage and current transfer functions as

$$\frac{V_o}{V_i} = (1 + \frac{C_p}{C}) \frac{s - \frac{1}{C} (\frac{\alpha_1 \beta_1}{R_{z1}} - \frac{\beta_2}{R_{x2}})}{s + \frac{1}{C + C_p} \left(\frac{1}{R_p} + \frac{1}{R_{x2}}\right)}$$  \hspace{1cm} (3.9)

$$\frac{I_{out}}{I_{in}} = \frac{s - \frac{1}{C} (\frac{\alpha_1 \beta_1}{R_{z1}} - \frac{\beta_2}{R_{x2}})}{s + \frac{\alpha_2 \beta_2}{CR_{x2}}}$$  \hspace{1cm} (3.10)
Here, $R_p$ is the parasitic $Z$-terminal resistance of CCCII (R$_{x1}$) and $C_p$ is $\overline{(C_{x1}+C_{x2})}$. It is to be noted that these parasitics do not appear in current mode transfer function as the $Z$-terminal of CCCII is grounded. The active and passive sensitivities of pole-$\omega_o$ and filter gain (for voltage-mode function) are analyzed and found within unity in magnitude. Thus the APS enjoy good sensitivity performance.

3.2.3 Design and verification

The fully tunable APS-5 of Figure 3.4c was designed for a phase shift of 90° at 110KHz. The designed values were as $C = 0.01\mu F$, $I_{io} = 200\mu A$, $I_{i2} = 100\mu A$. The frequency response for the voltage-mode circuit showing the gain and phase is given in Figure 3.5a and is in conformity with theory. Electronic tuning aspect of the translinear-C APS is shown in Figure 3.5b where the phase response for varying bias current is given. It is to be noted that for the design of a 90° phase shifter as above, the frequency is varied from 58KHz to 200KHz for a variation of $I_{io}$ from 100$\mu$A to 400$\mu$A with a step of 100$\mu$A ($I_{i2}$ vary from 50$\mu$A to 200$\mu$A with a step of 50$\mu$A).

Next, the translinear – C APS-5 was tested by applying a sinusoidal input of 1MHz with $C=1nF$ and the THD measured at the output. The variation of THD (%) with the amplitude of input signal for the APS-5 is shown in Figure 3.6a and 3.6b for both voltage and current-mode operation respectively. The THD is found low (within 1%) for a wide amplitude variation both for the voltage-mode and current-mode operation. This further emphasizes the utility and versatility of the proposed translinear-C all-pass section.
**Figure 3.5a** Frequency response of APS-5

**Figure 3.5b** Electronic tuning of APS-5
Figure 3.6a THD variation for voltage-mode operation of APS-5

Figure 3.6b THD variation for current-mode operation of APS-5
3.3 Translinear-C Current-mode All-Pass Sections

Translinear conveyors have recently gained popularity because these devices provide electronic tunability to the realizations. Resistor-less realizations can be obtained by employing translinear conveyors (also called current controlled conveyors) as these devices have controllable X-terminal resistance [18, 36, 37, 53]. Translinear-C circuits employ only translinear conveyors and capacitors. Some first order filter sections were reported in technical literature employing translinear conveyors and capacitors [36]. However, as a first attempt (at the time of reporting), translinear-C first order all-pass section is introduced in this section.

3.3.1 Circuit description (APS-6 and APS-7)

The proposed first order current-mode (CM) circuit with two CCCII- and a capacitor (APS-6) is shown in Figure 3.7a. The routine analysis of the circuit yields the following current transfer function.

\[
\frac{I_{\text{out}}}{I_i} = \frac{s - \frac{1}{R_{x2}C}}{s + \frac{1}{R_{x1}C}}
\]

(3.11)

Where \( R_{x1} \) and \( R_{x2} \) are the intrinsic resistance of the conveyors, controllable by the bias currents \( I_{o1} \) and \( I_{o2} \) respectively. With \( I_{o1} = I_{o2} = I_0 \) equation 3.11 becomes

\[
\frac{I_{\text{out}}}{I_i} = \frac{s - \frac{1}{R_xC}}{s + \frac{1}{R_xC}}
\]

(3.12)

Equation (3.12) shows that the circuit of Figure 3.7a realizes a first order current mode all-pass filter. It is to be noted that the CCCII1 in APS of Figure 3.7a is used as
Figure 3.7a Translinear-C current-mode APS-6

Figure 3.7b Translinear-C current mode APS -7
grounded resistor and can be eliminated by using a dual output CCCII-, in place of CCCII1. The resulting circuit (APS-7) as shown in Figure 3.7b requires only one dual output CCCII- and a capacitor, thus giving rise to a canonical APS. The current transfer function for the APS-7 of Figure 3.7b is same as equation (3.12). As only one CCCII is employed, no matching is required as compared to the circuit of Figure 3.7a and the circuit is a canonical structure. Moreover, the circuit APS-7 enjoys the electronic tuning as in APS-6.

3.3.2 Effects of non-ideal CCCII-

The proposed APS-6 and APS-7 are analyzed taking into account the non-idealities of a CCCII-. These are as a result of non-ideal current transfer (from X to Z) and voltage transfer (from Y to X) $\alpha$ and $\beta$ respectively. Moreover, the finite equivalent impedance between port Y and ground ($R_Y / C_Y$) and shunt output impedance on port Z ($R_Z / C_Z$) also contribute to the non-ideal effects [36]. Taking these effects into consideration the non-ideal current transfer function for both the circuits of Figure 3.7a and 3.7b is found as:

$$I_{\text{out}}(s) = \left( \frac{C}{C + C_p} \right) \left( s - \frac{\alpha \beta}{R_p C} \right) \left( s + \frac{\alpha \beta R_y + R_x}{R_p R_x (C + C_p)} \right)$$

$$= \left( \frac{C}{C + C_p} \right) \left( s - \frac{\alpha \beta}{R_p C} \right) \left( s + \frac{\alpha \beta R_y + R_x}{R_p R_x (C + C_p)} \right)$$

(3.13)

Where $C_p = C_Y + C_Z$ and $R_p = R_Y / R_Z$.

For a practical CCCII $R_p \gg R_x$, $C_p << C$, and the transfer ratios ($\alpha$ and $\beta$) are unity for frequencies till tens of MHz, thus equation (3.13) reduces to the ideal current transfer function of equation (3.12).
3.3.3 Sensitivity study

The incremental sensitivities of pole-ω₀ to active and passive components for the two APSs described by the non-ideal transfer function of equation (3.13) are analyzed and found as:

\[
S_{\alpha,\beta}^{\omega_0} = \frac{-\alpha \beta R_p}{\alpha \beta R_p + R_v} \quad S_{\beta}^{\omega_0} = \frac{R_v}{\alpha \beta R_p + R_v} \quad S_{\epsilon,\xi,\rho}^{\omega_0} = \frac{-C}{C + C_p}
\]  

(3.14)

Similarly the sensitivity of filter gain H=C/(C+Cₚ) to active and passive components is given as:

\[
S_{\epsilon,\xi,\rho}^{H} = \frac{C_p}{C + C_p} \quad S_{\alpha,\beta,\rho}^{H} = 0
\]  

(3.15)

It is evident from equations (3.14) and (3.15) that all sensitivity values are within unity in magnitude hence the proposed current mode all pass circuits enjoy attractive sensitivity performance.

3.3.4 Design and verification

The CM APS-6 and APS-7 were verified using PSPICE simulation. CCCII is simulated using NR100N and PR100N transistors with a supply of ±2.5volts [37,38]. The APS-7 of Figure 3.7b was designed for a phase shift of 90° at 100KHz. The designed values were as C = 12nF and Iₒ = 100μA. The simulation results for the frequency response are shown in Figure 3.8. The output current of the APS differs from the input ac current (Iᵢ = 100μA) no more than 1% for all frequencies. The phase at the designed frequency (90° at 100KHz) is in error by the designed value by 1%. Time domain waveforms of the input and output currents are also shown in Figure 3.9 for the above

* Incremental Sensitivity defined in Appendix A2
Figure 3.8 Output current and phase of Translinear-C APS-7
Figure 3.9 Input and output waveforms for APS-7
at the output. Figure 3.10 shows the dependence of THD (dB) on the input current signal level for the designed values as given above ($I_o = 100\mu A$). The THD is found low, i.e. within $-40$ dBs (1%) for input currents (peak to peak) as high as 2.6 times the bias current of the conveyor. However, the THD increases to a value of $-23$ dBs (7%) for an input current 1mA peak to peak (10 times the bias current). Figure 3.11 next shows the pole-zero tuning with $I_o$. The shown variation of $f_o$, (the pole frequency) is the one at which the APS shifts the phase of the input signal by 90deg. It can be seen from the Figure 3.11 that a wide variation (1KHz to 1MHz) with the bias current (1\mu a to 1000\mu a) is obtained for $C=12nF$. Thus the APS can be electronically controlled over a wide frequency range just by varying the bias current of the translinear conveyor. It is to be concluded that the new canonical current-mode APS (APS-7) enjoys attractive frequency response, transient response, low distortions and wide tunability with the bias current.

3.4 Single CCIII Based All-Pass Sections

3.4.1 Voltage-mode circuits (APS-8 and APS-9)

The first of the proposed voltage-mode all-pass section using CCIII is shown in Figure 3.12. The circuit (APS-8) uses a single CCIII, one capacitor and three resistors. Routine analysis of the circuit using the port relationship of CCIII (given in Chapter-1) yields the following voltage transfer function.

$$\frac{V_o}{V_i} = K \frac{s - \frac{1}{R_C}}{s + \frac{a}{R_C}}$$

(3.16)

Where, $K=R_2/(R_2+R_3)$, and $a = (R_1+R_3)/(R_2+R_3)$. With $R_1=R_2=R$, equation (3.16) reduces to
Figure 3.10 THD variation of APS-7 with signal amplitude

Figure 3.11 Pole frequency tuning with bias current for C=12nF
Figure 3.12 Single CCIII-based APS-8

Figure 3.13 Single CCIII-based APS-9
From equation (3.17), it is evident that the circuit realizes a first order all-pass section with gain $K (<1)$.

Another all-pass section (APS-9) is next given in Figure 3.13. The circuit can be derived from the APS-8 by reducing $R_3=0$, which results in $K=1$. The APS-9 thus employs only one capacitor and two equal value resistors. Circuit analysis yields the following first order all-pass transfer function as:

$$\frac{V_o}{V_i} = K \frac{s - \frac{1}{RC}}{s + \frac{1}{RC}}$$

Equation (3.18) shows that the circuit APS-9 realizes first order all-pass filter with unity gain under the condition $R_1=R_2=R$.

3.4.2 Current-mode circuits (APS-10 to APS-13)

Some current-mode first order all-pass filters have been reported in technical literature employing current conveyors and FTFNs [50-52]. Here, two current-mode novel general structures employing a single CCIII (+ or -) and two passive elements are proposed. The novel circuits with one active and two passive elements represent minimal all-pass structures. Each general structure can realize two different APSs with appropriate selection of passive elements. The general APS structures are shown in Figure 3.14a and b. Routine analysis of the structures yield the same current transfer function as:
Figure 3.14 (a) All-pass filter configuration using CCIII+

Figure 3.14 (b) All-pass filter configuration using CCIII-
\[ \frac{I_o}{I_m} = \frac{Y_2 - Y_1}{Y_2 + Y_1} \tag{3.19} \]

Appropriate choice of \( Y_1 \) and \( Y_2 \) yields the following:

Choice 1: \( Y_1 = sC, \ Y_2 = 1/R \):

\[ \frac{I_o}{I_m} = \frac{s - \frac{1}{RC}}{s + \frac{1}{RC}} \tag{3.20} \]

Choice 2: \( Y_1 = 1/R, \ Y_2 = sC \):

\[ \frac{I_o}{I_m} = \frac{\frac{s - \frac{1}{RC}}{1}}{\frac{s + \frac{1}{RC}}{1}} \tag{3.21} \]

Equations (3.20) and (3.21) show, that different choices give APS with different phase response. Thus four distinct APSs (APS 10-13) are realized, two from each configuration, and are shown in Figures 3.15 and 3.16. Current-mode APS-10 and APS-12 are described by eqn. (3.20), whereas CM APS-11 and APS-13 by eqn. (3.21).

3.4.3 Effects of non-ideal CCIII

The defining equation of a non-ideal CCIII is as:

\[ i_y = -\gamma i_x, \ V_x = \alpha V_y, \ i_z = (p\beta)i_x \tag{3.22} \]

where, \( p=1 \) for CCIII+, and \( p=-1 \) for CCIII- and \( \gamma = (1-k_1), \ \alpha = (1-k_2), \ \beta = (1-k_3). \ k_i, \ i=1-3 \) are the transfer errors. The voltage transfer gain ‘\( \alpha \)’, the current transfer gains \( \gamma \) and \( \beta \) differ from unity by their transfer errors. The voltage-mode circuit of Figure 3.13 is analyzed for the non-ideal transfer function as:
Figure 3.15a Current-mode APS-10

Figure 3.15b Current-mode APS-11
Figure 3.16a Current-mode APS-12

Figure 3.16b Current-mode APS-13
Next, the current-mode APSs of Figures 3.15 and 3.16 are analyzed for the non-ideal transfer functions as

\[ \frac{V_o}{V_i} = -\frac{s-\frac{\alpha \beta}{RC}}{s + \frac{1}{RC}} \]  
(3.23a)

\[ APS - 10: \quad \frac{I_o}{I_m} = -\beta \frac{s-(\alpha \gamma / \beta) \frac{1}{RC}}{s+(\alpha \gamma) \frac{1}{RC}} \]  
(3.23b)

\[ APS - 11: \quad \frac{I_o}{I_m} = \frac{s-(\beta / \alpha \gamma) \frac{1}{RC}}{s+(1/\alpha \gamma) \frac{1}{RC}} \]  
(3.23c)

\[ APS - 12: \quad \frac{I_o}{I_m} = -(\beta \frac{1}{\gamma}) \frac{s-(1/\alpha \beta) \frac{1}{RC}}{s+(1/\alpha \gamma) \frac{1}{RC}} \]  
(3.23d)

\[ APS - 13: \quad \frac{I_o}{I_m} = \frac{s-(\alpha \beta) \frac{1}{RC}}{s+(\alpha \gamma) \frac{1}{RC}} \]  
(3.23e)

3.4.4 Sensitivity study

The incremental sensitivities of the pole-\( \omega_0 \) to active and passive elements for the VM-APSs are analyzed and found within unity in magnitude that represents a low value. The same for the four CM-APSs are also analyzed and given in Table 3.1. From the above table it is concluded that all active and passive sensitivities are within unity in magnitude for all the CM-APSs. Thus the circuits enjoy attractive sensitivity performance. Moreover, the ideal as well as non-ideal transfers functions show that the poles of all the APSs always lie in the left half of s-plane thus making the circuit unconditionally stable.
Table: 3.1 Sensitivity figures for CM APSs

<table>
<thead>
<tr>
<th>Circuit</th>
<th>$S_\alpha^a$</th>
<th>$S_\alpha^b$</th>
<th>$S_\beta^a$</th>
<th>$S_\beta^b$</th>
<th>$S_{R,C}^H$</th>
<th>$S_R^H$</th>
<th>$S_{R,C}^H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>APS-10</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>APS-11</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>APS-12</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>APS-13</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

3.4.5 Design and verification

The proposed APSs were verified using SPICE simulations. The CMOS implementation of CCIII was used in simulation with ±5 volts supply and 2μ CMOS parameters [20]. The circuit of APS-10 was designed for a -90° phase-shift at 100KHz. The designed values were as $C = 1nF$ and $R = 1.59K$. The simulated results for the frequency response are given in Figure 3.17a and verify the circuit. Similarly a phase shifter was designed using the APS-11 for a 90° phase-shift at 100KHz. The designed values of components used were same as above. The frequency response showing gain and phase plots are shown in Figure 3.17b and verify the circuit.

Next, the transient response of APS-11 designed as a phase shifter was studied. The designed values were as $C = 1nF$ and $R = 1.59K$. A sinusoidal current input of 0.1mA peak at 100KHz was applied to the CM APS-6 and the output current obtained with the desired phase shift of 90°. The results for the transient response are shown in Figure 3.18. The practical utility of the circuit is further studied by measuring the total harmonic distortions (THD) as a function of input amplitude. The THD results for the APS-6 with the above designed values are given in Figure 3.19 and shows that the low level input currents of amplitude till 110μA (220μA peak to peak) results in THD values...
Figure 3.17a Gain and phase plots of CM-APS-10

Figure 3.17b Gain and phase plots of CM-APS-11
Figure 3.18 Time domain waveforms for the CM APS-11

Figure 3.19 THD variation with signal amplitude for APS-11
less than 1%. Thus the transient response and low THD results confirm the practical utility of the proposed circuits.

3.5 Concluding Remarks

The chapter introduced thirteen novel first order all-pass filters (APS 1 – 13) employing different active elements. One single CCII based voltage-mode circuit with three passive components was introduced and also realized with a CCCII with only two passive components. A versatile all-pass filter circuit with one CCII and three passive components was presented which could be operated either in voltage-mode or current-mode without changing the circuit configuration. It was also shown realized with one CCCII and two passive components with electronic tunability. The same was next reduced to a fully tunable translinear-C circuit with two CCCIIIs and one capacitor. Next, one current-mode translinear-C circuit using two CCCIIIs and one capacitor and another circuit with only one dual output CCCII and a capacitor were introduced that enjoyed electronic tunability. Translinear-C circuits for first order all-pass filters were also first of its kind not attempted earlier in otherwise valuable literature [36, 42-52]. Two voltage-mode and four canonical current-mode all-pass filters using single CCIII were proposed. Voltage-mode circuits employed three/four passive components whereas, the current-mode circuits with only two passive components were canonical. CCIII based APSs were first of its kind using this active element [19-20, 42-52]. The proposed first order all-pass circuits were verified using the simulations. These first order all-pass sections are expected to be useful as phase shifters, phase equalizers, and in realizing quadrature oscillators in communications and analogue signal processing applications.