proposed filter, the total harmonic distortion (%THD) at the output of band pass filter for sinusoidal input signal of 1.27 MHz is calculated. The results are plotted in Fig. 3.7. It is observed that the percentage total harmonic distortion (%THD) is low and remains within acceptable limits of 5% [60], [113] till input current of 375 µA.

Fig. 3.6 Simulated (a) low pass, band pass and high pass responses (b) orthogonal tunability of notch responses.

Fig. 3.7 Dependence of total harmonic distortion (%THD) on input signal.
3.1.5 CONCLUSION

A new generalized multi loop feedback current mode biquadratic filter structure using three MOCCII and two grounded capacitors has been introduced that gives explicit current outputs from high impedance nodes. The filter has the following attractive features (i) use of only grounded capacitors makes the structure less sensitive to parasitic and easier to integrate (ii) more versatile - no change in topology is required to implement multiple functions or universal filter (iii) uses same type of CCs (iv) low active and passive sensitivities (v) independent electronic control of \( \omega_0 \) without disturbing bandwidth (vi) electronic and orthogonal control of \( \omega_0 \) and \( Q_0 \) (vii) filter structures 1, 3, 6, 8, 10 and 12 (section 3.1.2) exhibits low input impedance and high output impedance so that filters can easily be cascaded.

3.2 VOLTAGE MODE SISO FILTERS

3.2.1 ALL PASS FILTER

All pass filter (APF) finds wide applications in analog signal processing to shift phase of electrical signal while keeping the amplitude of the input signal constant over the frequency range. Many such APF circuits [114], [115] use op amp as basic building block and large number of passive elements. These circuits suffer from the limited bandwidth performance of the op amp. Most of the current conveyor based circuits [35] - [39], use large active and passive elements along with complex matching constraints. Recently, first order all pass filter structures using only single current conveyor with less
The two types of transfer function of all pass filters can be classified as:

First type: \( T_1(s) = \frac{G - sC}{G + sC} = \frac{1 - sCR}{1 + sCR} \) \hspace{1cm} (3.2.1)

Second type: \( T_2(s) = -\frac{G - sC}{G + sC} = -\frac{1 - sCR}{1 + sCR} \) \hspace{1cm} (3.2.2)

And the corresponding phase responses respectively are

\[ \Phi_1(\omega) = -2 \arctan(\omega CR) \] \hspace{1cm} (3.2.3)

\[ \Phi_2(\omega) = 180^\circ - 2 \arctan(\omega CR) \] \hspace{1cm} (3.2.4)

In this section, we first propose structure of current conveyor (CCII-) based first order all pass filter employing two resistors and a capacitor and extend the circuit to implement the same based on CCCII-, which needs only one each CCCII-, capacitor and resistor. Two generic all pass filters have also been presented in this section. It can be seen is found that some of these CCII- based structures have external resistance connected at x port, therefore, can also be extended to current controlled CCII- (CCCII-) based circuits to access the possibility of electronic control of filter parameters.

### 3.2.1 SINGLE CCII-/CCCII- BASED APF

Here a new structure of APF based on CCII- has been proposed which has subsequently been extended to CCCII- based circuit.
3.2.1.1 CIRCUIT DESCRIPTION

CCII-BASED APF

Using standard notations the port relations of an ideal CCII- can be characterized by

\[ v_x = v_y, \quad i_z = -i_x \quad \text{and} \quad i_y = 0 \]

The proposed CCII- based APF configuration is shown in Fig. 3.8. Its voltage transfer function can be expressed as

\[ \frac{V_{out}}{V_{in}} = \frac{sC - G_1 + G_2}{sC + G_2} \]  \hspace{1cm} (3.2.5)

where \( G_1 = 1/R_1 \) and \( G_2 = 1/R_2 \).

With \( G_2 = G_1/2 \), (3.2.5) reduces to

\[ \frac{V_{out}}{V_{in}} = \frac{s - G_1/2C}{s + G_1/2C} \]  \hspace{1cm} (3.2.6)

Fig. 3.8 All pass filter with single CCII-.

The transfer function in (3.2.6) belongs to second type all pass filter, so phase response of the filter can be expressed as
\[
\varphi(\omega) = 180^\circ - 2 \arctan(2\omega CR_1)
\]  
(3.2.7)

The pole sensitivities of APF are analyzed and found to be

\[
S_{p_i}^{eh} = -1, \quad S_{p_2}^{eh} = -1, \quad S_{c}^{eh} = -1
\]  
(3.2.8)

**CCDII-BASED APF**

Using standard notations the port relations of an ideal CCDII- can be characterized by

\[
v_x = v_y + i_x R_x, \quad i_z = -i_x \quad and \quad i_y = 0
\]

The resistance \(R_x\) at terminal \(x\) is controllable by bias current \(I_0\) and is expressed as

\[
R_x = V_T / 2I_0
\]

where \(V_T\) is the thermal voltage.

The proposed CCDII- based APF is shown in Fig. 3.9. It is obtained by replacing CDII- and resistor at terminal \(x\) in Fig. 3.8 by CCDII-. The transfer function can be expressed as

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{sC - G_x + G}{sC + G}
\]  
(3.2.9)

where \(G = 1/R\) and \(G_x = 1/R_x\).

![Diagram](attachment:image.png)

**Fig. 3.9** All pass filter with single CCDII-. 
With \( G = G_0/2 \), (3.2.9) reduces to

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{s - \frac{G_s}{2C}}{s + \frac{G_s}{2C}}
\]  

(3.2.10)

The phase response of the filter can be expressed as

\[
\phi(\omega) = 180^\circ - 2 \arctan(2\omega CR_s)
\]  

(3.2.11)

The pole sensitivities are found to be

\[
S_{R_s}^{\alpha h} = -1, \quad S_{R}^{\alpha h} = -1, \quad S_C^{\alpha h} = -1
\]  

(3.2.12)

It may be observed from (3.2.6) and (3.2.10) that both of the filters have negative unity voltage gain at low frequencies and a positive unity gain at high frequencies. For the later case, the capacitor shorts the input and output nodes, thus realizing a gain of +1. Hence, the active element has no important effect on the high frequency performance [4]. It is evident from (3.2.8) and (3.2.12) that both the filters enjoy attractive sensitivity performance.

### 3.2.1.2 EFFECT OF NONIDEALITIES

With nonidealities, the port relationships of current conveyors modify to

\[ v_x = v_y \beta, \quad i_z = -i_x \alpha \text{ and } i_y = 0 \quad \text{for CCII-} \quad \text{and} \]

\[ v_x = v_y \beta + i_x | R_s(I_0) |, \quad i_z = -i_x \alpha \text{ and } i_y = 0 \quad \text{for CCCII-} \]

where \( \beta = 1 - \varepsilon_x, \quad \alpha = 1 - \varepsilon_y \) with \( |\varepsilon_x| << 1, \quad |\varepsilon_y| << 1 \) and \( \varepsilon_x, \varepsilon_y \) denotes voltage (current) tracking error.
With nonidealities outlined above, the voltage transfer functions, element matching conditions and phase responses of these filters including nonidealities can be expressed for CCII-based configuration as

\[
\frac{V_{\text{out}}}{V_{\text{in}}}|_{s} = \frac{sC - \alpha \beta G_{1} + G_{2}}{sC + G_{2}}, \quad G_{2} = \alpha \beta G_{1} / 2, \quad \varphi(\omega) = 180^\circ - 2\arctan(2\omega CR_{1} / (\alpha \beta))
\]

(3.2.13)

and for CCII-based configuration as

\[
\frac{V_{\text{out}}}{V_{\text{in}}}|_{s} = \frac{sC - \alpha \beta G_{s} + G}{sC + G}, \quad G_{2} = \alpha \beta G_{s} / 2, \quad \varphi(\omega) = 180^\circ - 2\arctan(2\omega CR_{s} / (\alpha \beta))
\]

(3.2.14)

### 3.2.1.3 RESULTS

To validate the theoretical analysis the circuit of Fig. 3.8 is designed for a phase shift of 90° at \( f_{0} = 1 \) kHz. The designed values are \( C = 0.01 \mu F, R_{1} = 10 \text{ k}\Omega, R_{2} = 20 \text{ k}\Omega. \) The active elements used to construct CCII-are commercially available IC AD844 with supply voltages of ±12 V. The experimental and simulation results agree quite well with the theoretical values as shown in Fig. 3.10. Note that the actual gain slightly deviates at lower frequency. This is due to the parasitic resistance at the x terminal of CCII- [40]. It is observed that with higher values of \( R_{1} \) and \( R_{2} \) this deviation reduces. In the case of previously reported works [37], [40] a deviation of actual values at high frequencies was observed because of the limited frequency band of AD844. On the other hand, in the works of [42] and the proposed one, the active element has no important effect on the high frequency performance [116]. The nature of the response is, more or less, same as that of the previously reported works [37], [40], and [42].
3.1.2 SINGLE CCII-/CCII- BASED GENERIC APF CONFIGURATIONS

In this section two new generalized configurations that are capable of realizing eight all pass filter circuits are discussed.

3.1.2.1 CIRCUIT DESCRIPTION

The proposed two generalized configurations are shown in Fig. 3.11(a) and (b). These configurations use a negative second generation current conveyor (CCII-), and four passive components (three resistors and one capacitor). The proposed generalized configurations are then extended to translinear conveyor [13] by simply replacing CCII- and a resistor at the x port of it by negative second generation current controlled conveyor (CCCII-) as shown in Fig. 3.12(a) and (b).

Considering the generic configurations, the transfer functions for circuits of Figs. 3.11 and 3.12 can respectively be expressed as

$$\frac{V_{out}}{V_{in}} = -\frac{y_2y_1 - (y_2 + y_3)y_4}{(y_2 + y_3)y_4}$$

(3.2.15)
\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{y_2 y_4 - y_1 y_2 - y_1 y_3 - y_1 y_4}{(y_2 + y_3)y_4}
\]  \hspace{1cm} (3.2.16)

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{-y_2 G_x - (y_2 + y_3)y_4}{(y_2 + y_3)y_4}
\]  \hspace{1cm} (3.2.17)

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{y_2 y_4 - G_x y_2 - G_x y_3 - G_x y_4}{(y_2 + y_3)y_4}
\]  \hspace{1cm} (3.2.18)

where \( G_x = 1/R_x \), \( R_x \) is the internal resistance of the conveyer at port \( x \).

(a)  \hspace{5cm} (b)

**Fig. 3.11** CCI- based generic configurations for all pass filter.

(a)  \hspace{5cm} (b)

**Fig. 3.12** CCCII- based generic configurations for all pass filter.
### Table 3.3

Component selection, transfer function and matching condition for the circuits.

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Component Selection</th>
<th>Transfer Function</th>
<th>Matching Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Fig. 3.11(a))</td>
<td>$y_1 = 1/R_1$, $y_2 = 1/R_2$, $y_3 = sC$, $y_4 = 1/R_4$</td>
<td>$\frac{V_{out}}{V_{in}} = \frac{1 - sCR_2}{1 + sCR_2}$</td>
<td>$R_4 = 2R_1$</td>
</tr>
<tr>
<td>2 (Fig. 3.11(a))</td>
<td>$y_1 = 1/R_1$, $y_2 = sC$, $y_3 = 1/R_3$, $y_4 = 1/R_4$</td>
<td>$\frac{V_{out}}{V_{in}} = \frac{1 - sCR_3}{1 + sCR_3}$</td>
<td>$R_4 = 2R_1$</td>
</tr>
<tr>
<td>3 (Fig. 3.11(b))</td>
<td>$y_1 = 1/R_1$, $y_2 = sC$, $y_3 = 1/R_3$, $y_4 = 1/R_4$</td>
<td>$\frac{V_{out}}{V_{in}} = \frac{R_1 - R_4 - 1 - sCR_3}{R_1 + 1 + sCR_3}$</td>
<td>$2R_4 = R_1 - R_3$</td>
</tr>
<tr>
<td>4 (Fig. 3.11(b))</td>
<td>$y_1 = 1/R_1$, $y_2 = 1/R_2$, $y_3 = sC$, $y_4 = 1/R_4$</td>
<td>$\frac{V_{out}}{V_{in}} = \frac{R_4 - 1 - sCR_3}{R_1 + 1 + sCR_3}$</td>
<td>$2R_4 = R_1 - R_3$</td>
</tr>
<tr>
<td>5 (Fig. 3.12(a))</td>
<td>$y_2 = 1/R_2$, $y_3 = sC$, $y_4 = 1/R_4$</td>
<td>$\frac{V_{out}}{V_{in}} = \frac{1 - sCR_2}{1 + sCR_2}$</td>
<td>$R_4 = 2R_x$</td>
</tr>
<tr>
<td>6 (Fig. 3.12(a))</td>
<td>$y_2 = sC$, $y_3 = 1/R_3$, $y_4 = 1/R_4$</td>
<td>$\frac{V_{out}}{V_{in}} = \frac{1 - sCR_3}{1 + sCR_3}$</td>
<td>$R_4 = 2R_x$</td>
</tr>
<tr>
<td>7 (Fig. 3.12(b))</td>
<td>$y_2 = sC$, $y_3 = 1/R_3$, $y_4 = 1/R_4$</td>
<td>$\frac{V_{out}}{V_{in}} = \frac{R_x - R_4 - 1 - sCR_3}{R_x + 1 + sCR_3}$</td>
<td>$2R_4 = R_x - R_3$</td>
</tr>
<tr>
<td>8 (Fig. 3.12(b))</td>
<td>$y_2 = 1/R_2$, $y_3 = sC$, $y_4 = 1/R_4$</td>
<td>$\frac{V_{out}}{V_{in}} = \frac{R_4 - 1 - sCR_3}{R_x + 1 + sCR_3}$</td>
<td>$2R_4 = R_x - R_3$</td>
</tr>
</tbody>
</table>

Two alternative circuits can be obtained from each of the generic configurations by appropriate selection of the admittances as is given in Table 3.3. Therefore a total of eight topologies have been derived. Four of the derived topologies belong to first type transfer function and remaining configurations are representative of the second type.

It may be noted that the sensitivity of pole at $\omega_0$ is within 1 in magnitude for all the filters (circuit 1 to circuit 8 in Table 3.3). Thus all circuits enjoy the attractive sensitivity performance. It is evident that the proposed selection of the admittances
allows the poles for all the eight filter circuits to lie in the left half of the s plane and even the matching condition does not alter the quadrant of the poles. Thus all the eight filters described here are unconditionally stable.

32.2 RESULTS

The functionality of the proposed approach is tested through various PSPICE simulations. The simulations for circuits 5 to 8 (Table 3.3) have been carried out by replacing CCCII- with schematic represented in Fig. 2.5(b) of section 2.3 with supply voltage of ±2.5 V. The filter characteristics are determined using transistor models PR 100N (PNP) and NR 100N (NPN) of bipolar ALA arrays [112]. The circuits are designed for 90° phase shift at f₀ = 318 kHz. The designed values are C = 1 nF, I₀ = 10 μA, (i) R₂ = 500 Ω, R₄ = 2500 Ω for circuit 5 (Table 3.3); (ii) R₂ = 500 Ω, R₄ = 2500 Ω for circuit 6 (Table 3.3); (iii) R₂ = 500 Ω, R₄ = 375 Ω for circuit 7 (Table 3.3); (iv) R₂ = 500 Ω, R₄ = 375 Ω for circuit 8 (Table 3.3). The theoretical and simulated results for gain and phase are plotted in Fig. 3.13(a) to Fig. 3.13(d) for topologies described by circuits 5 to 8 (Table 3.3) respectively.

To demonstrate tuning of phase characteristic with R₂, the circuit 5 (Table 3.3) has been simulated with R₂ = 500 Ω, 750 Ω, 1000 Ω, 1500 Ω and 2000 Ω and the results obtained are shown in Fig. 3.14. The simulated results show well agreement with the theoretical predictions.
Fig. 3.13  Phase and gain plots of selected circuits from Table 3.3
(a) circuit 5, (b) circuit 6, (c) circuit 7, (d) circuit 8.

Fig. 3.14  Phase response variation for circuit 5 with $R_2$ (Table 3.3)

$\Diamond R_2 = 2000 \, \Omega$, $\heartsuit R_2 = 1500 \, \Omega$, $\circ R_2 = 1000 \, \Omega$, $\star R_2 = 750 \, \Omega$, $\times R_2 = 500 \, \Omega$. 
3.1.3 CONCLUSION

In sections 3.2.1.1 and 3.2.1.2 respectively one and four first order APF topologies using CCII- have been presented and extended to CCCII-. The former CCII-based circuit provides first type APF whereas the later are capable of generating both types of APF responses. All the circuits use one capacitor for their realization. The circuits use simple matching conditions and realization with same type of active elements makes them more attractive from mass production point of view. Although the circuit of Fig. 3.8 uses same number of active and passive components and gives almost same nature of responses as that of previously reported works [37], [40], [42], it is a new circuit which has been reported by the author. The circuit of Fig. 3.8 is verified with both experiments and simulations whereas the later one (Fig. 3.12) is verified with simulation. All the results are in close agreement with the theoretical predictions.

3.2 CHANNEL SELECT FILTER

In the preceding section we have presented all pass filter structures. We now consider a specific problem of realization of channel select filter. Firstly, the background for the problem is discussed and then current conveyor based realization is presented.

The recent evolution in wireless communication has led to the development of different standards to provide broadband multimedia services. For 2G cellular systems several standards namely Personal Digital Cellphone (PDC), the European Global System Mobile (GSM) or the North American Digital Cellphone (IS-95) are used. The next generation of mobile communication (3G) will use wideband CDMA signals. To effectively utilize the different available wireless services there is a need of a single