

CHAPTER 4

FOUR TERMINAL FLOATING NULLOR BASED BIQUAD FILTER

This chapter deals with the realization of a multifunction biquad filter using Four Terminal Floating Nullor (FTFN), a new current mode device. Two biquad filters having high input impedance have been realized with single input and two outputs simultaneously. The proposed filter circuits simultaneously implement high-pass and band-pass filtering functions. Each circuit employs two FTFN, two capacitors and two resistors which is the absolute minimum requirement for a biquad filter. By slight modification in the topology of the circuit band-pass and low-pass responses can also be realized at the same outputs. Further, the proposed circuits employ lesser number of passive components than the one reported by Liu and Yung [104].

The following sections introduce the basic FTFN, a four terminal floating nullor device and the current state of its applications as filters. Next the proposed circuits and their performances are discussed.

4.1 FOUR TERMINAL FLOATING NULLOR (FTFN)

Current-mode circuits have been receiving significant attention as they have the potential advantages of accuracy and wide bandwidth over their voltage-mode counterparts [105]. The current-mode circuits may be realized using active devices such as FTFN, DDA, OTA, DDCC, DVCC etc. The noise immunity is of great concern in mixed signal systems that combine analogue as well as digital parts. It is therefore necessary to design analogue circuits which have a fully balanced architecture. The active device such as DDA, OFA, FTFN etc offer fully balanced architecture. Amongst these FTFN, four terminal floating nullor, is more flexible and versatile than others. It provides floating output, which is very useful in some application such as current-amplifiers, voltage to current converters, gyrators, floating impedances etc. [91-112]. Besides being flexible, FTFN is a more all-round building block than the operational amplifier and current conveyor.

In 1954, FTFN was implicitly proposed by Tellegen as an ideal amplifier [88-89]. It was demonstrated that any active circuit can be realized by this active element and passive components. In 1964 Carlin referred this element as a four port **nullor** [90]. The traditional representation of the FTFN as nullor model is shown in Figure 4.1. This figure shows that FTFN may be considered to comprise of an input Nullator and Norator at the output port. It is known as Nullor Model of FTFN or Nullator - Norator pair [92]. In the nullor model of FTFN it is observed that nullator and the norator are isolated from each other, which gives more flexibility in the active network synthesis.

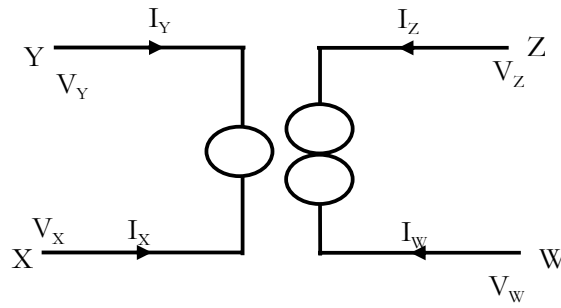


Figure 4.1: Nullor model of FTFN

The symbolic representation of FTFN is shown in Figure 4.2.

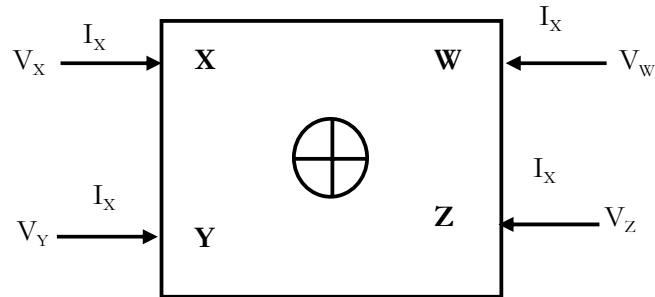


Figure 4.2: A symbolic representation of FTFN

The port characteristics of this active device may be described as:

$$I_y = I_x = 0, \quad V_x = V_y \quad \text{and} \quad I_z = I_w \quad (4.1)$$

The output impedance of W and Z port of an FTFN are arbitrary. In the present analysis that output impedance of W -port has been considered to be very low and that of the Z -port very high.

FTFN based structure provides a number of potential advantage such as complete absence of the passive component matching requirement, minimum number of passive elements [97].

Since its introduction the FTFN has remained as a theoretical element. With the advent of technology and current mode circuit evolution, implementation of FTFN became feasible. Presently FTFN is not commercially available in the chip form. However, there are various techniques for the realization of FTFN using available active devices such as Op-amp, OTA, CCII, etc. The discrete I.C. AD844 can be used for the realization of FTFN as shown in Figure 4.3.

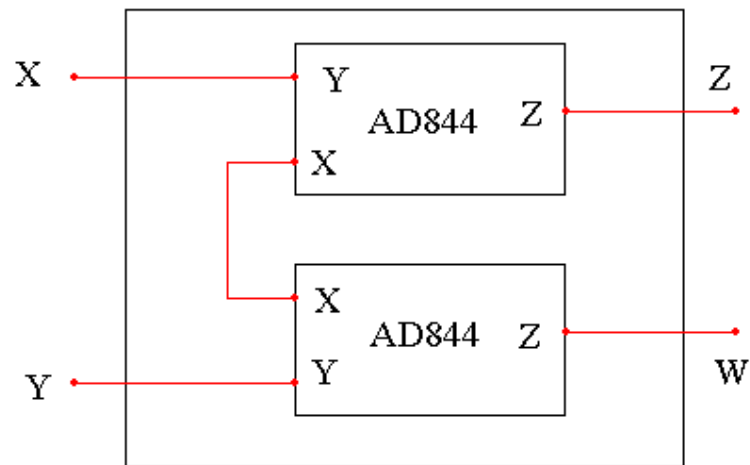


Figure 4.3: Realization of FTFN using AD844

All four basic type amplifiers: Voltage Amplifier, Current Amplifier, Transconductance Amplifier and Transresistance Amplifier may be realized with FTFN as shown in Figure 4.4. FTFN is therefore called a universal amplifier.

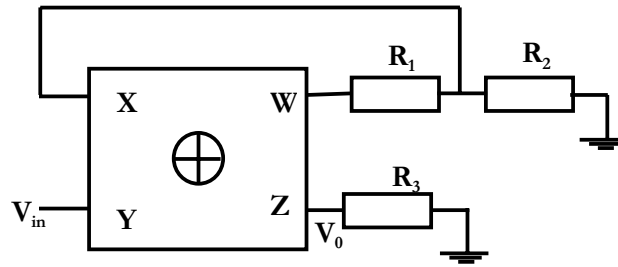


Figure 4.4(a): FTFN as voltage amplifier

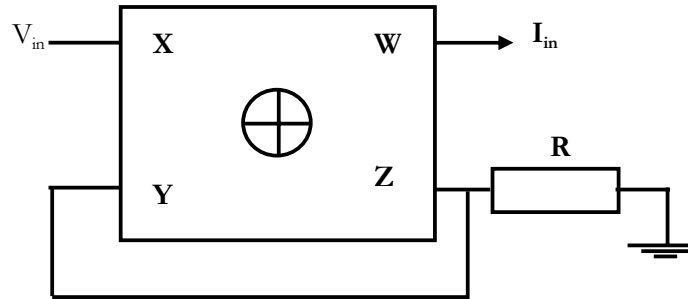


Figure 4.4(b): FTFN as transconductance amplifier

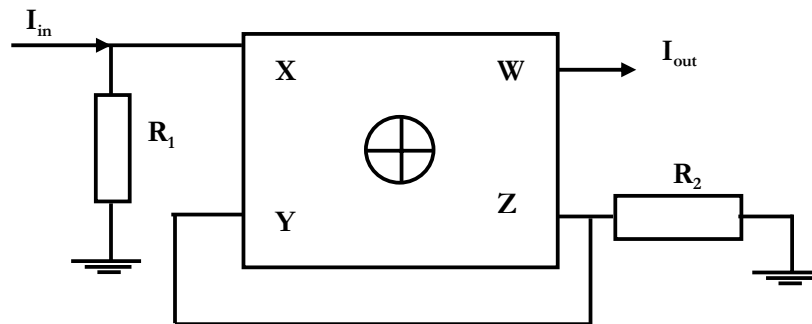


Figure 4.4(c): FTFN as current amplifier

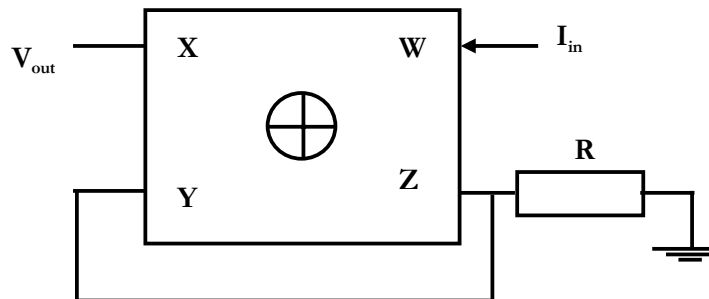


Figure 4.4(d): FTFN transresistance amplifier

4.2 EXISTING REALIZATIONS OF FILTERS USING FTFN

Being a universal active device FTFN has a wide range of applications. It is used in various applications such as oscillators and realization of admittance, filters etc. M. T. Abuelma'atti proposed current mode sinusoidal oscillator using one FTFN and six passive components for low and medium range of frequency [103]. Chipipop also realized current mode FTFN based inverse filter low-pass and high pass filters [106]. These filter circuits provide one filter response at a time. The chaotic circuit has also been realized using FTFN [92,111].

The implementation of higher order filters, using these circuits in cascaded mode, often necessitates the use of additional buffers. Thus there is overwhelming need to develop high input impedance voltage mode (VM) filters to evade the practical difficulties in realizing higher order filters. This high input impedance feature of voltage mode filters permits their use in cascade mode thereby circumventing the need for impedance matching devices. Toward this end some high input impedance VM filter circuits based on FTFN, second generation current conveyors (CCII) and current feedback amplifiers (CFAs) have been reported in the literature [105, 112, 113, 75, 83, 89,]. However, not much work has been reported for the realization of high input impedance filter using FTFN, which is a more flexible and versatile building block than operational amplifier or a CCII [105, 83, 89] to meet the varying and stringent requirements of the circuit designers.

Liu [102] proposed a current mode second order band pass filter using one FTFN and 6 passive components as shown in Figure 4.5. This circuit may be used to realize all filter functions with high sensitivity by changing the passive components only.

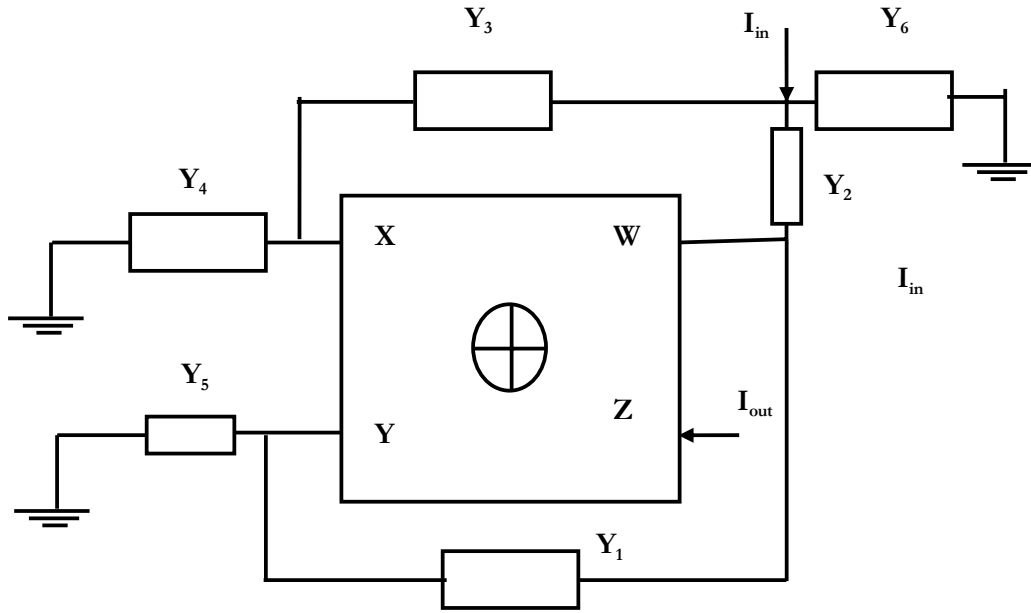


Figure 4.5: Liu's circuit for band-pass filter using FTFN

The transfer function of the Liu's circuit may be obtained as:

$$\frac{I_0}{I_{in}} = \frac{y_5 + y_2 \left(\frac{y_5}{y_1} - \frac{y_4}{y_3} \right)}{y_4 + y_2 \left(\frac{y_4}{y_3} - \frac{y_5}{y_1} \right) + y_6 \left(1 + \frac{y_4}{y_3} \right)} \quad (4.2)$$

Table 4.1 shows the combinations of passive components for realization of various filters.

Table 4.1: Various filter responses from Liu's circuit

	y_1	y_2	y_3	y_4	y_5	y_6
All-pass Filter	$\frac{1}{R_1}$	sC_2	$\frac{1}{R_1}$	$\frac{1}{R}$	$\frac{1}{R_1}$	0
Band-Reject Filter	0	$sC_2 + \frac{1}{R_2}$	$\frac{1}{\left(R_3 + \frac{1}{sC_3} \right)}$	0	0	0

High-pass Filter	$sC_1 + \frac{1}{R_1}$	sC_2	$\frac{1}{R_3}$	$\frac{1}{R_4}$	sC_5	0
Low-pass Filter	$sC_1 + \frac{1}{R_1}$	$\frac{1}{R_2}$	sC_3	sC_4	$\frac{1}{R_5}$	0
Band-pass Filter	$sC_1 + \frac{1}{R_1}$	$\frac{1}{R_2}$	$\frac{1}{R_2}$	sC_4	sC_4	$\frac{1}{R_2}$

The filters realized with these combinations have different quality factors and the cutoff frequencies.

Abuelma'atti proposed a cascadable current mode filter using single FTFN [103] as shown in Figure 4.6. The circuit uses one FTFN and 5 passive components for the realization of low pass, high pass, band pass filter separately, while the realization of the all-pass and notch filter requires the six passive components. It gives low active and passive sensitivities.

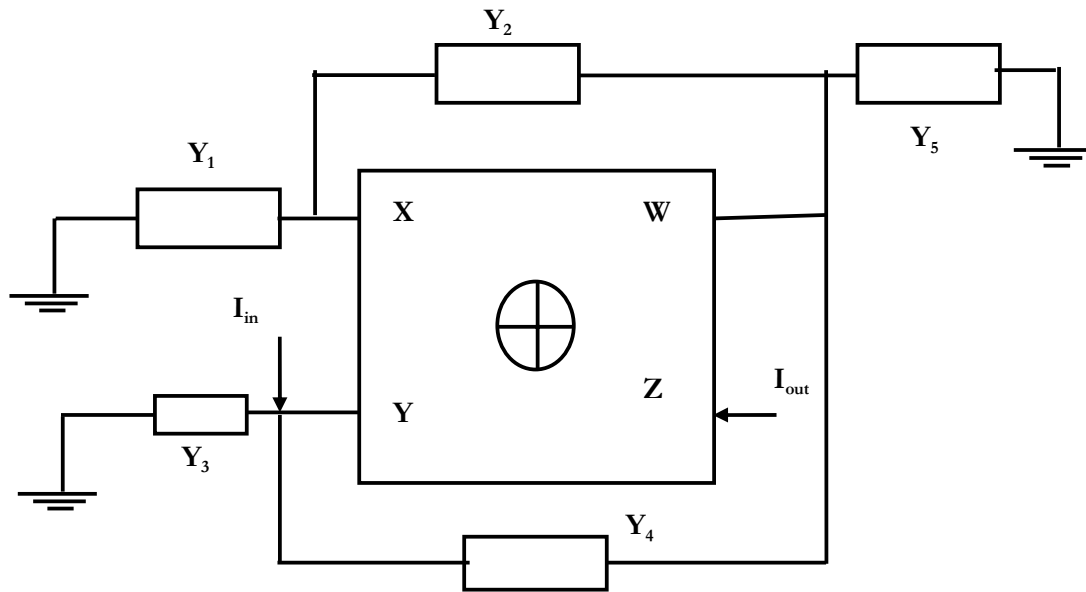


Figure 4.6: Current mode filter by Abuelma'atti using FTFN

The transfer function of the Abuelma'atti circuit may be expressed as I_{in} :

$$\frac{I_{out}}{I_{in}} = \frac{y_2 y_4 + y_2 y_3 - y_1 y_4}{y_1 y_2 + y_2 y_5 + y_1 y_5 - y_2 y_4} \quad (4.3)$$

The circuit realizes different filter responses by proper selection of the component as shown in Table 4.2.

Table 4.2: Various filter realizations from Abuelma'atti circuit

	y_1	y_2	y_3	y_4	y_5
High-pass Filter	$\frac{1}{R_1}$	sC_2	sC_3	0	$\frac{1}{R_5} + sC_5$
Low-pass Filter	$\frac{1}{R_1} + sC_1$	$\frac{1}{R_2}$	$\frac{1}{R_3}$	0	sC_5
Band-pass Filter	$\frac{1}{R_1}$	sC_2	$\frac{1}{R_3}$	0	$\frac{1}{R_5} + sC_5$

Though, same cutoff/center frequency may be obtained for all the realizations with all the capacitors and resistors kept unaltered, the quality factor differ.

Later Liu and Lee [104] proposed voltage mode universal filter employing two FTFNs, three resistances and two capacitors as shown in Figure 4.7. Their circuit realizes two filter responses simultaneously. The band-pass and high-pass filter responses are respectively obtained at output terminal V_{o1} and V_{o2} .

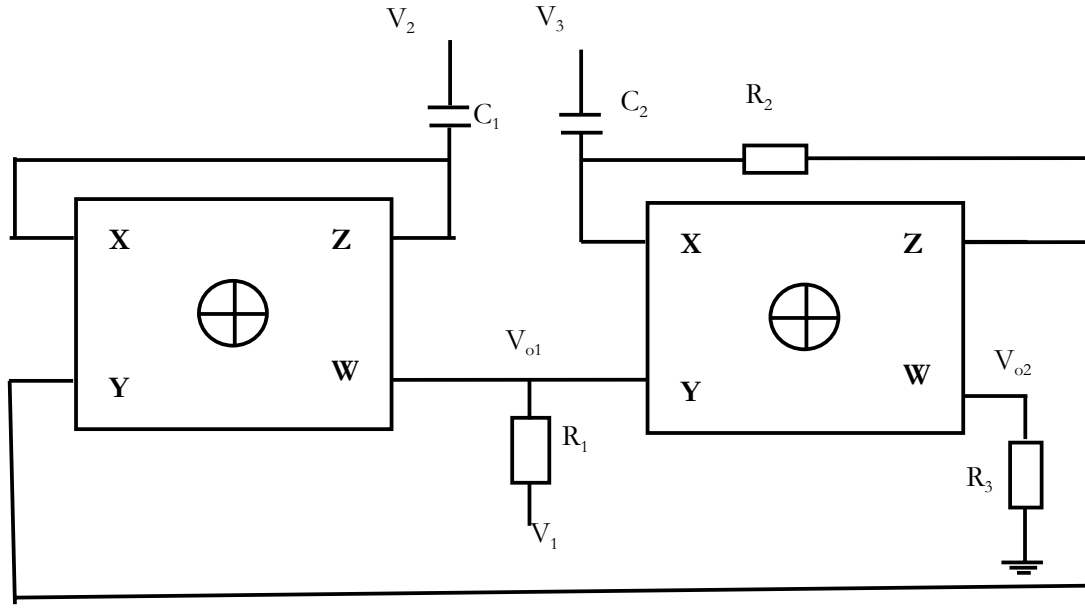


Figure 4.7: Liu and Lee's voltage mode universal filter using FTFN

The transfer function of the universal filter, shown in Figure 4.7 can be expressed as:

$$V_{o1} = \frac{s^2 C_1 C_2 R_1 R_2 V_3 + s C_1 R_1 V_2 + V_1}{1 + s C_1 R_1 + s^2 C_1 C_2 R_1 R_2} \quad (4.4)$$

$$V_{o2} = s C_2 R_3 (V_{o1} - V_3) \quad (4.5)$$

The natural frequency and the quality factor of this filter can be expressed as:

$$\omega_0 = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}} \quad (4.6)$$

and

$$Q = \sqrt{\frac{R_2 C_2}{R_1 C_1}} \quad (4.7)$$

With proper selection of the input in the transfer function, various filter realizations, having same quality factor and the cutoff/central frequency, may be obtained at the output terminal V_{o1} as shown in Table 4.3.

Table 4.3: Various filter realizations from Liu and Lee's circuit

	V_1	V_2	V_3
Low-pass Filter	V_{in}	0	0
Band-pass Filter	0	V_{in}	0
High pass Filter	0	0	V_{in}

The passive and active sensitivities of this filter circuit are very low. This circuit has limited application due to its low input impedance.

Subsequently Liu and Yung [105] realized high input voltage mode filter using FTFN as shown in Figure 4.8.

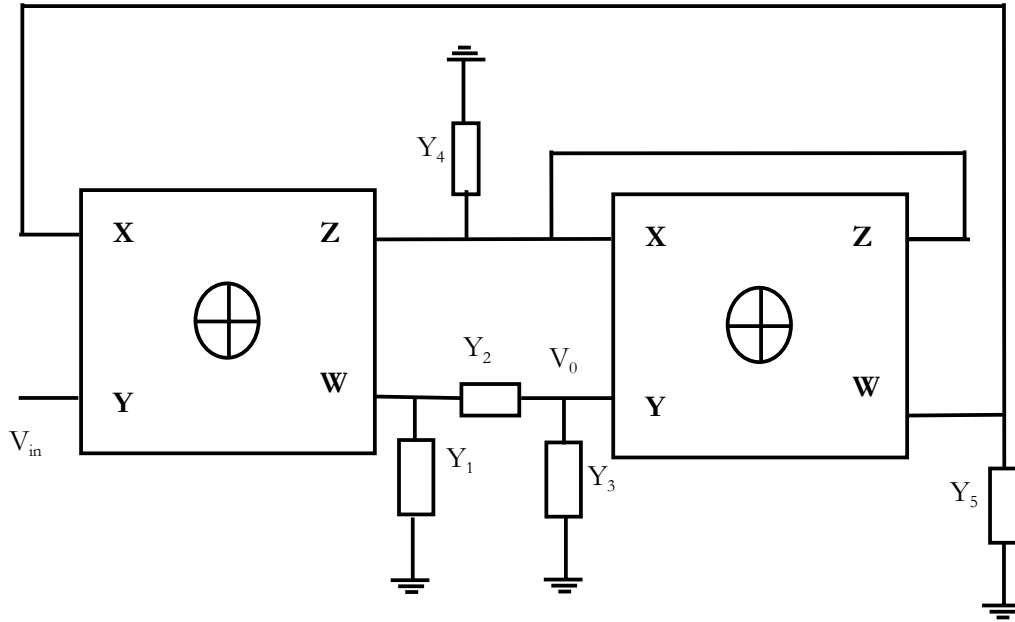


Figure 4.8: Liu and Yung's high input impedance filter using FTFN

The transfer function of this filter circuit may be expressed as follows:

$$\frac{V_0}{V_{in}} = \frac{-y_2 y_5}{y_1(y_2 + y_3) + y_2(y_3 + y_4)} \quad (4.8)$$

By substituting the admittances $y_1 = sC_1$, $y_2 = 1/R_2$, $y_3 = sC_3$, $y_4 = 1/R_4$ and $y_5 = sC_5$ equation (4.8) may be modified as equation (4.9) to realize a band-pass filter as follows:

$$\frac{V_0}{V_{in}} = \frac{-sC_5 R_4}{s^2 C_1 C_3 R_2 R_4 + s(C_1 + C_3)R_4 + 1} \quad (4.9)$$

The center frequency ω_0 and the quality factor Q of the band-pass filter realization are given by equation (4.10) and (4.11):

$$\omega_0 = \frac{1}{\sqrt{R_2 R_4 C_1 C_3}} \quad (4.10)$$

$$Q = \frac{1}{(C_1 + C_3)} \sqrt{\frac{R_2 C_1 C_3}{R_4}} \quad (4.11)$$

This circuit may also be used for realization of high-pass filter response by proper selection of the admittance such as $y_1 = 1/R_1$, $y_2 = sC_2$, $y_3 = 1/R_3$, $y_4 = sC_4$ and $y_5 = sC_5$. The transfer function of the circuit is then obtained as:

$$\frac{V_0}{V_{in}} = \frac{-s^2 C_5 C_2 R_1 R_3}{s^2 C_2 C_4 R_1 R_3 + s(R_1 + R_3)C_2 + 1} \quad (4.12)$$

This realization has low cutoff/center frequency and the quality factor sensitivities with respect to active and passive components. But the circuit realizes only one filter response at a time.

Several circuits have been reported in the literature for the realization of all these filters with high impedance using one FTFN and other active devices [104, 105, 113]. For example, Liu and Yung proposed a high input impedance filter employing one FTFN and positive second generation Current Conveyor (CCII+) having five passive components as shown in Figure 4.9.

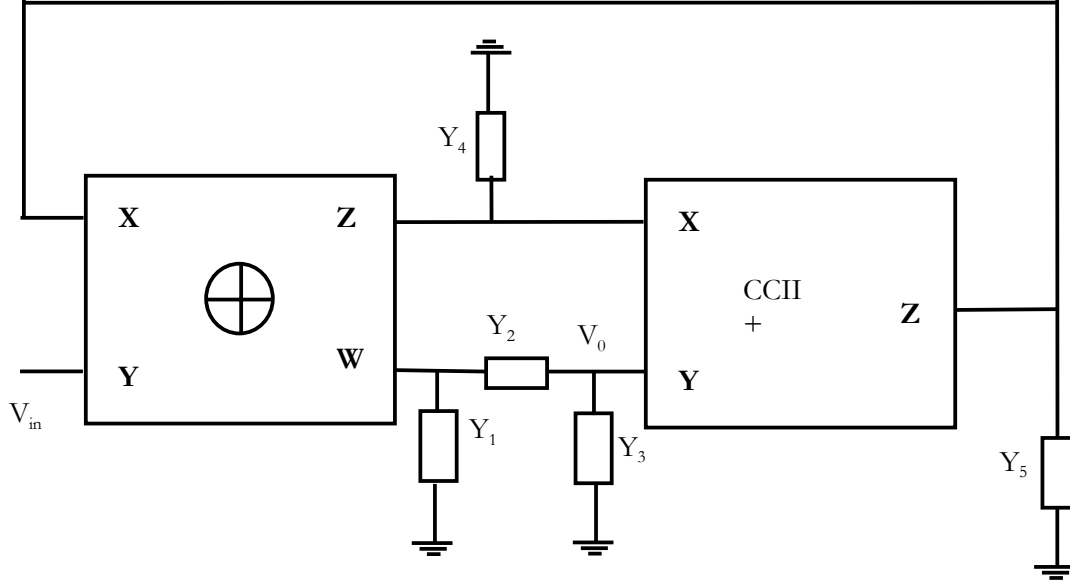


Figure 4.9: High input impedance filters using FTFN and CCII+

The transfer functions of this circuit given by:

$$\frac{V_0}{V_{in}} = -\frac{y_2 y_5}{y_1(y_2 + y_3) + y_2(y_3 + y_4)} \quad (4.13)$$

This circuit realizes low-pass, high-pass and band-pass filter by proper selection of the passive components as shown in Table 4.4.

Table 4.4: Various filter responses from high input impedance filters using FTFN and CCII+

	y_1	y_2	y_3	y_4	y_5
band-pass	sC_1	$\frac{1}{R_2}$	sC_3	$\frac{1}{R_4}$	sC_5
low-pass	sC_1	$\frac{1}{R_2}$	sC_3	$\frac{1}{R_4}$	$\frac{1}{R_5}$
high-pass	$\frac{1}{R_1}$	sC_2	$\frac{1}{R_3}$	sC_4	sC_5

In the following sections we propose two new filter circuits employing two FTFN and four passive components. These circuits realize two filter responses simultaneously. Further, the filter functions obtained with these circuits do not impose any component matching or cancellation constraints. The high input impedance feature of the circuit permits cascading to obtain higher order filters. The resonance frequency ω_0 and bandwidth ω_0/Q are independently controllable. The proposed circuit enjoys low active and passive components parameter variation.

4.3 PROPOSED CIRCUIT

The two proposed circuits provide combination of two filter responses. First circuit gives band pass and high pass filter, while second circuit provides band pass and low passes filter responses. These circuits are realized by the positive FTFN and passive components. The analysis of the circuit of Figure 4.9 yields the high pass and band pass filter responses.

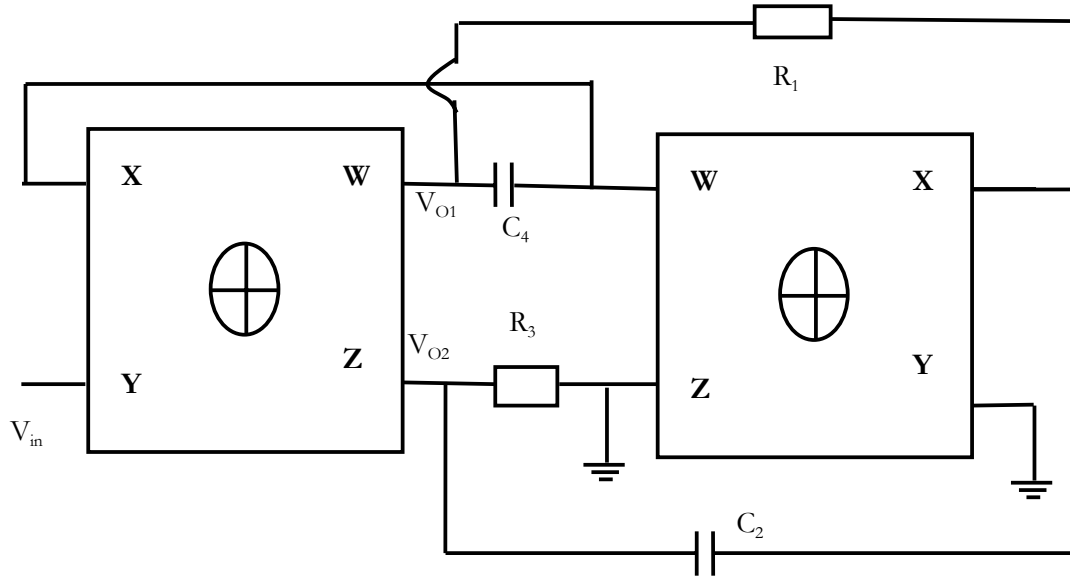


Figure 4.10: Proposed band pass- high pass (BP-HP) filter circuit using FTFN

The two transfer function of the filter circuit shown in Figure 4.10 is given by equations (4.13) and (4.14):

$$\frac{V_{o1}}{V_{in}} = \frac{s^2 C_2 C_4 R_1 R_3}{s^2 R_1 R_3 C_2 C_4 + 2s R_3 C_2 + 1} \quad (4.13)$$

$$\frac{V_{o2}}{V_{in}} = -\frac{s R_3 C_4}{s^2 R_1 R_3 C_2 C_4 + 2s R_3 C_2 + 1} \quad (4.14)$$

The circuit provides the same characteristic equations (4.13) and (4.14). Thus, parameter ω_0 , ω_0/Q and Q are same for these two filters and are given by equation (4.15), (4.16) and (4.17) respectively:

$$\omega_0 = \sqrt{\frac{1}{C_2 C_4 R_1 R_3}} \quad (4.15)$$

$$\frac{\omega_0}{Q} = \frac{2}{R_1 C_4} \quad (4.16)$$

$$Q = \frac{1}{2} \sqrt{\frac{C_4 R_1}{C_2 R_3}} \quad (4.17)$$

ANALYSIS WITH NON IDEAL FTFN: Analysis of the circuit considering non-ideal behavior of FTFN may be carried out by using following relations

$$V_x = \alpha V_y \quad \text{and} \quad I_z = \beta I_w \quad (4.18)$$

where $\alpha = 1 - \varepsilon_1$ and $\varepsilon_1 (\varepsilon_1 \ll 1)$ denotes the voltage trekking error of FTFN; and $\beta = 1 - \varepsilon_2$ and $\varepsilon_2 (\varepsilon_2 \ll 1)$ is the current trekking error. The transfer functions of the filter circuits shown in Figure 4.10 may be therefore written as:

$$\frac{V_{o1}}{V_{in}} = \frac{\alpha_1 \beta_1 s^2 C_2 C_4 R_1 R_3}{s^2 \beta_1 R_1 R_3 C_2 C_4 + (1 + \beta_1) s R_3 C_2 + 1} \quad (4.19)$$

$$\frac{V_{o2}}{V_{in}} = -\frac{s \alpha_1 \beta_1 R_3 C_4}{s^2 \beta_1 R_1 R_3 C_2 C_4 + (1 + \beta_1) s R_3 C_2 + 1} \quad (4.20)$$

The active and passive sensitivities of the cutoff/center frequency ω_0 and the quality factor are small and are given by:

$$S_{C_2, C_4, R_1, R_3, \beta_1}^{\omega_0} = -\frac{1}{2} \quad (4.21)$$

$$S_{C_4, R_3}^Q = \frac{1}{4} \quad (4.22)$$

$$S_{C_2, R_3}^Q = -\frac{1}{4} \quad (4.23)$$

$$S_{\beta_1}^Q = \frac{1 - 2\beta_1}{\beta_1(1 + \beta_1)} \quad (4.24)$$

$$S_{\alpha_1, \alpha_2, \beta_2}^{\omega_0} = S_{\alpha_1, \alpha_2, \beta_2}^Q = 0 \quad (4.25)$$

Thus the active and passive sensitivities are not more than one. The magnitude and phase responses of the high-pass and band-pass filters are shown in Figure 4.11 respectively, match with the theoretical results.

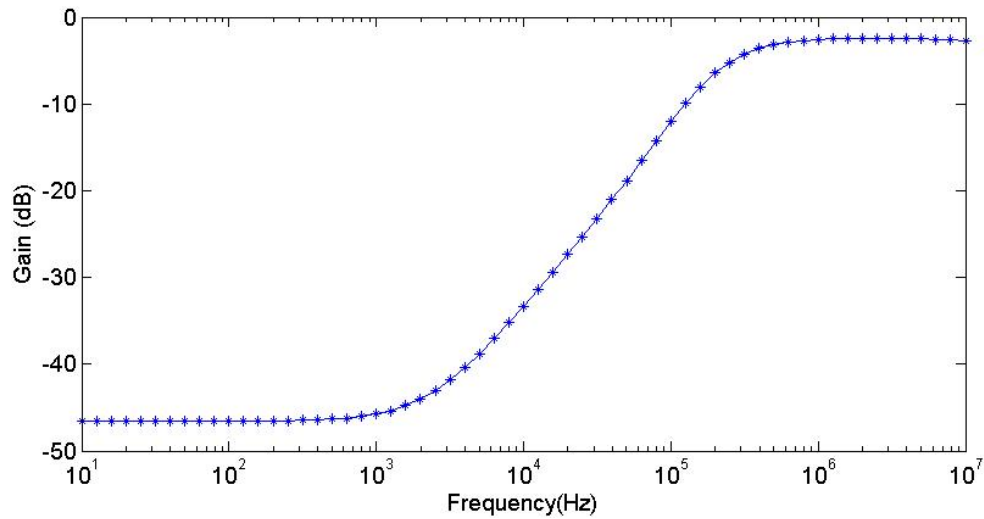


Figure 4.11(a): High pass filter magnitude response of BP-HP filter circuit using FTFN

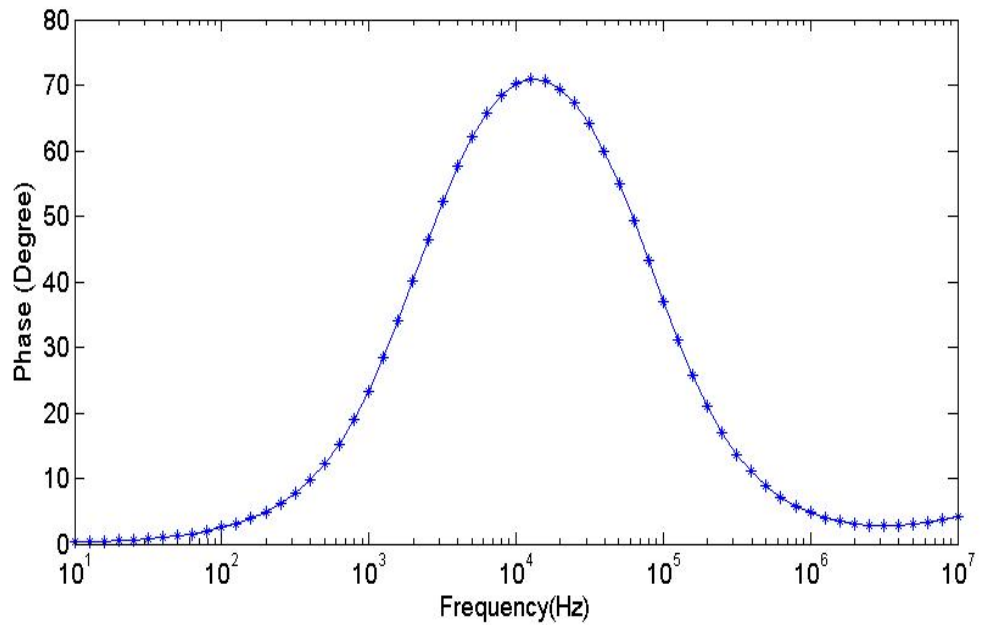


Figure 4.11(b): High pass filter phase response of BP-HP filter circuit using FTFN

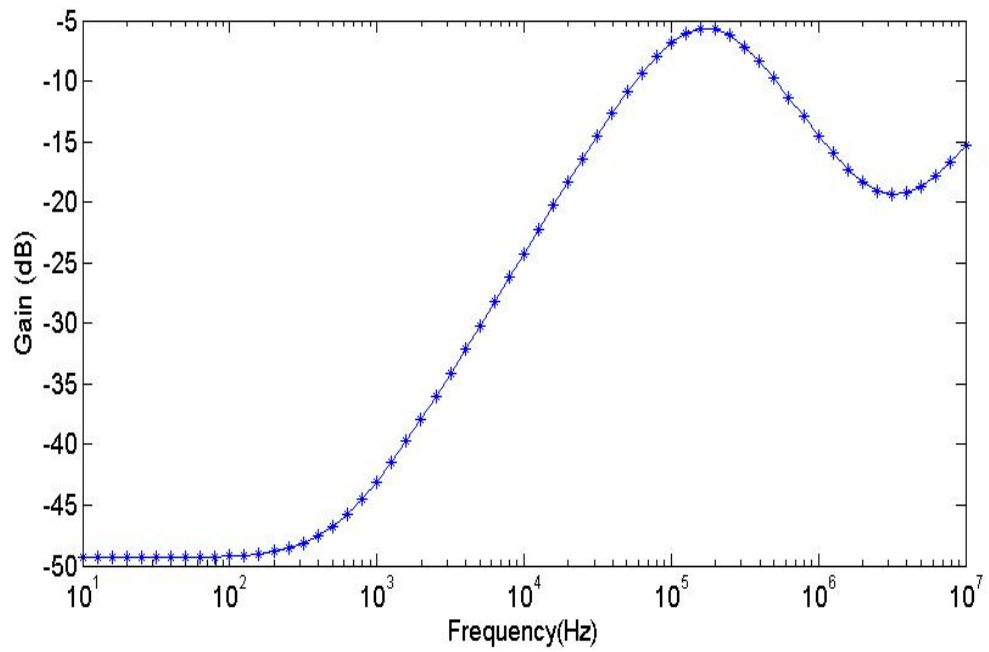


Figure 4.11(c): Band pass filter magnitude response of BP-HP filter circuit using FTFN

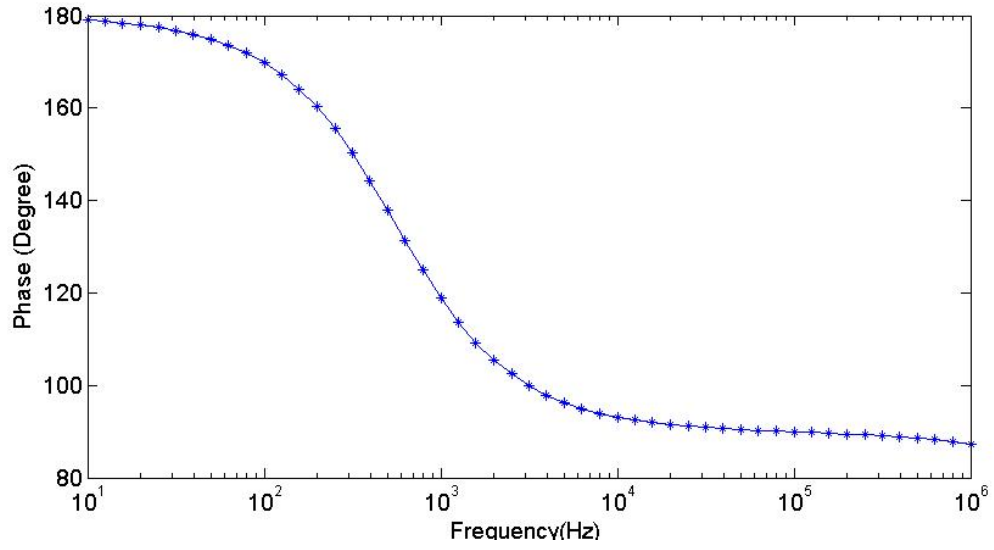


Figure 4.11(d): Band pass filter phase response of BP-HP filter circuit using FTFN

SECOND CIRCUIT

The second proposed circuit is a modification of the first circuit for the realization of voltage-mode low pass and band pass filter, shown in Figure 4.12.

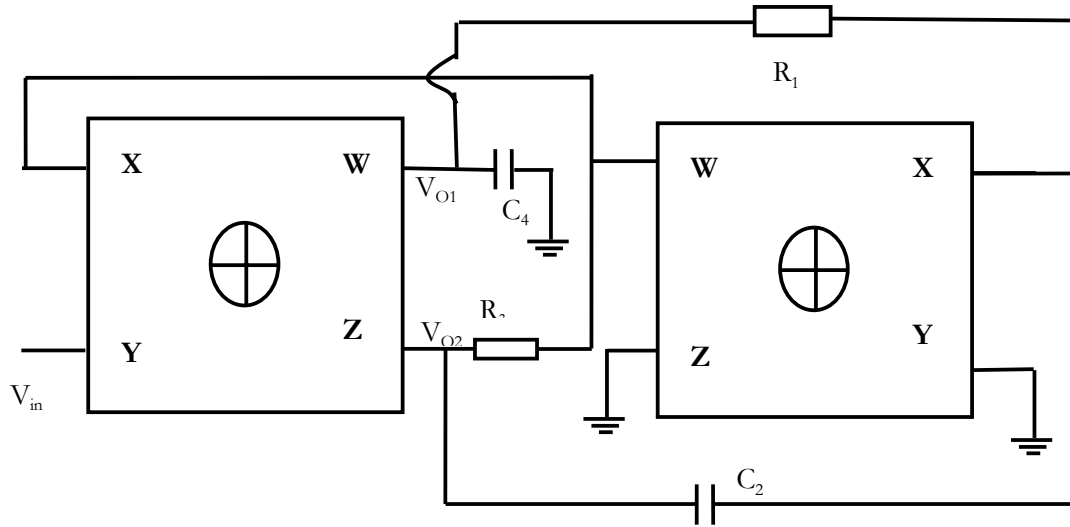


Figure 4.12: Band pass-low pass (BP-LP) filter circuit using FTFN

The transfer functions of the modified circuit of Figure 4.12 are given as:

$$\frac{V_{o1}}{V_{in}} = \frac{sR_1C_2}{s^2R_1R_3C_2C_4 + 2sR_3C_2 + 1} \quad (4.26)$$

$$\frac{V_{o2}}{V_{in}} = -\frac{1}{s^2R_1R_3C_2C_4 + 2sR_3C_2 + 1} \quad (4.27)$$

It may be observed that characteristic equation for the both filter realization are same. Thus the parameter $\omega_0, \omega_0/Q$ and Q are the same for two filter realizations and are given by equations (4.28) to (4.30).

$$\omega_0 = \sqrt{\frac{1}{C_2C_4R_1R_3}} \quad (4.28)$$

$$\frac{\omega_0}{Q} = \frac{2}{R_1C_4} \quad (4.29)$$

$$Q = \frac{1}{2} \sqrt{\frac{C_4R_1}{C_2R_3}} \quad (4.30)$$

The characteristic equations (4.13)-(4.14) are same as (4.26)-(4.27). From equation (4.28) and (4.29) it can be seen that band pass gain in the two circuits can be controlled by the ratios $C_4/2C_2$ and $R_1/2R_3$ respectively however this will change the cutoff/central frequency ω_0 . If the adjustment is made by C_2 and the bandwidth remains unaffected but the cutoff/central frequency ω_0 changes. An examination of (4.15) and (4.16) shows that non-interacting tuning of ω_0/Q and ω_0 can be obtained by adjusting former parameter of interest through the components C_4 and/or R_1 and the latter through C_2 and/or R_3 .

The frequency responses of the band-pass and low-pass filter realizations using modified circuit of in Figure 4.12 are shown in Figure 4.13 match with ideal response.

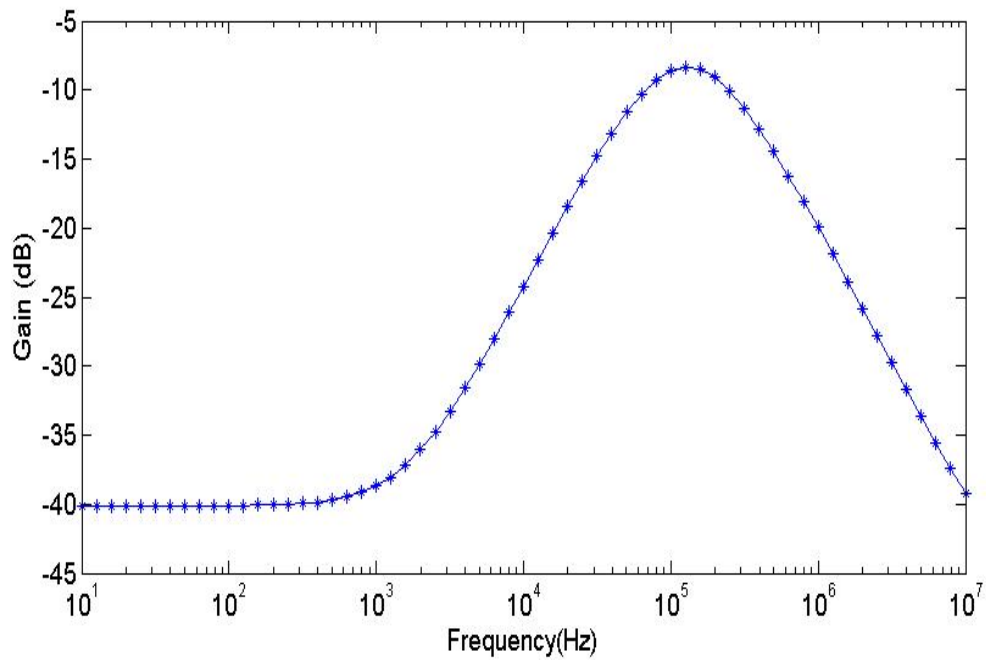


Figure 4.13(a): Band pass magnitude response of BP-LP filter circuit using FTFN

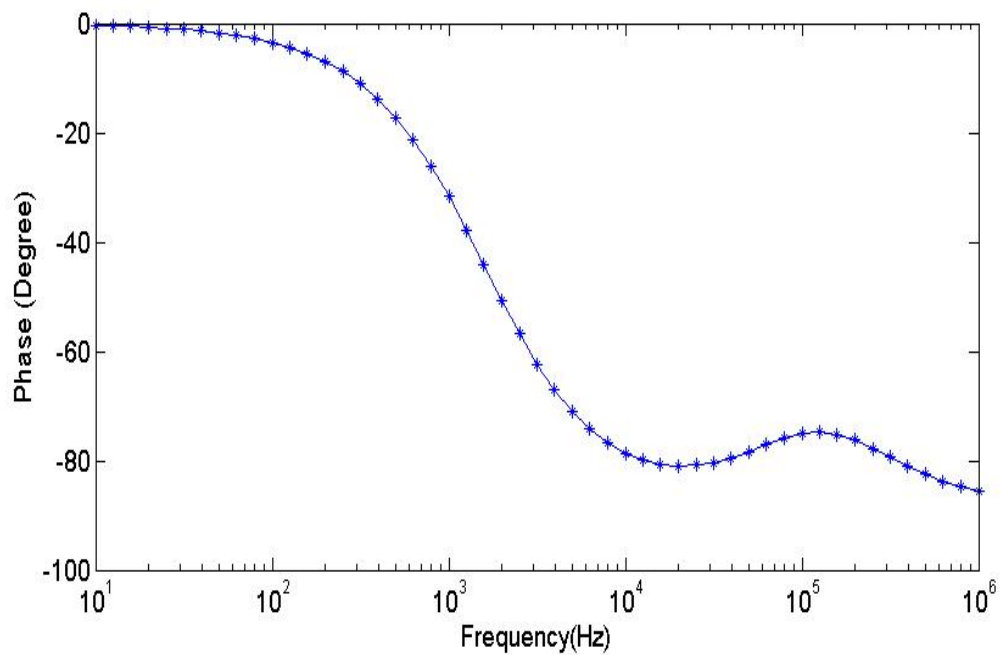


Figure 4.13(b): Band pass phase response of BP-LP filter circuit using FTFN

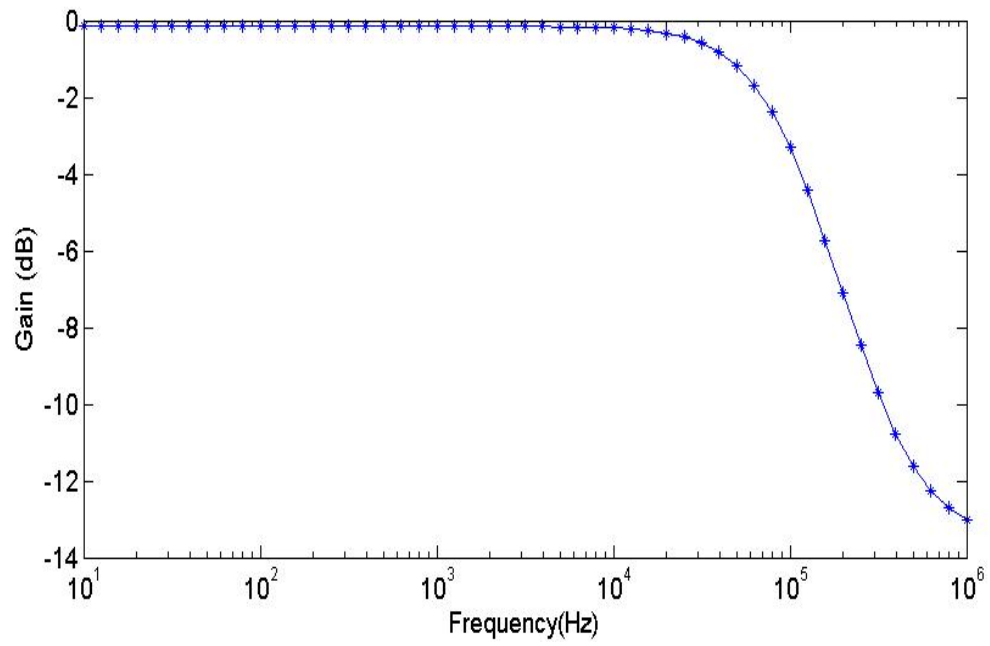


Figure 4.13(c): Low pass magnitude response of BP-LP filter circuit using FTFN

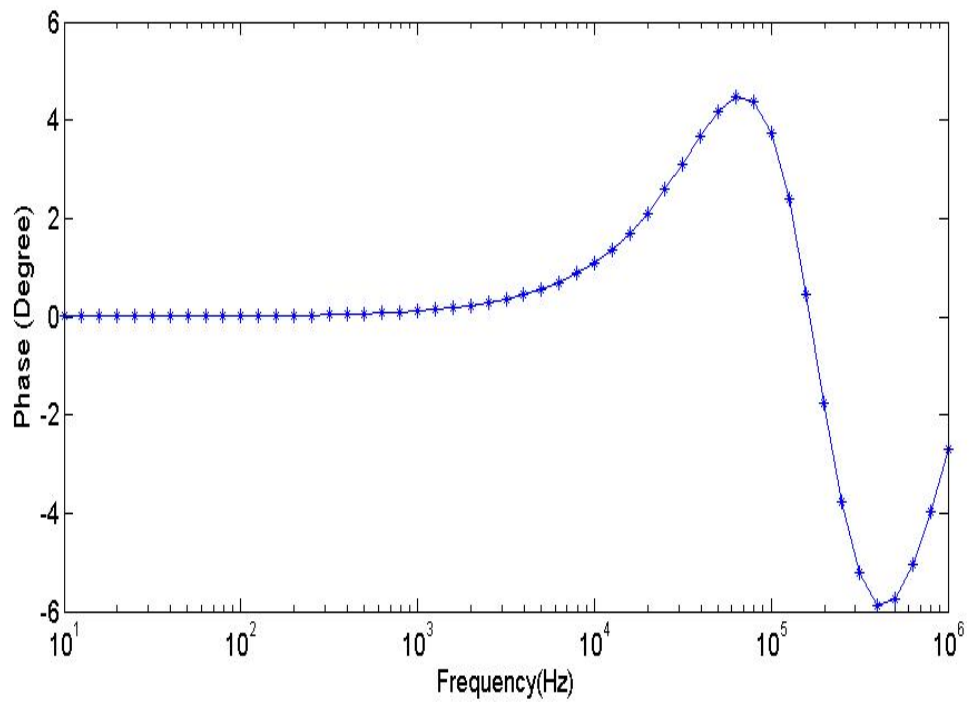


Figure 4.13(d): Low pass phase response of BP-LP filter circuit using FTFN

4.4 SIMULATION AND RESULT

Bread board realizations were done to verify the response of the circuit. The positive FTFN can be implemented by cascading two AD844 of Analog Devices, to realize high pass and band pass responses with the passive components chosen as $R_1=1\text{k}\Omega$, $R_3=1\text{k}\Omega$, $C_2=1\text{nF}$ and $C_4=1\text{nF}$. The band pass and low pass realizations may be obtained with passive components chosen as $R_1=1\text{k}\Omega$, $R_3=1\text{k}\Omega$, $C_2=1\text{nF}$ and $C_4=1\text{nF}$. Figure 4.11 show magnitude and phase responses of the high-pass and band-pass filter, where Figure 4.13 shows the magnitude and phase responses of band-pass and low-pass filters respectively. Both the choices give the same frequency resonant frequency $\omega_0=159.15\text{ kHz}$ at $Q=0.5$. The results shown in figures agree with the analysis.

4.5 CONCLUSION

This chapter first considers the concept of FTFN as a combination of nullator and the norator. Subsequently realizations of all four types of amplifier, employing FTFN are discussed. Next the available circuits employing FTFN are presented.

In the subsequent sections of the chapters two voltage-mode circuits employing two FTFN are proposed. These circuits have high input impedance and low passive components as compared to existing one reported in the literature. The proposed circuit provides two filter realizations simultaneously. First circuit offers high-pass and band-pass filter realizations, where as band-pass and low-pass are obtained from the second circuit. The proposed circuits do not impose any component matching constraints. The proposed circuits have low sensitivity figures. The proposed circuit offers linear phase responses which are not generally available in the filters realized with minimum number of active elements. These circuits may be used in the video signal processing where phase has very significant role to play.