Passive RC-Notch Filter Using Floating Admittance Matrix Approach

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ABSTRACT

A novel approach for realizing the RC notch filter function has been presented using the Floating Admittance Matrix (FAM) technique. The method offers significant advantages in terms of simple implementation and efficient computation. One of the key strengths of the proposed FAM approach is its universal applicability, as it can be employed for the analysis of almost all types of electronic circuits.

The technique utilizes matrix partitioning, which makes the analysis of large and complex networks more manageable. An important feature of the FAM method is that the sum of the elements in every row or column of the matrix becomes zero. This property serves as an immediate check for correctness during formulation and helps in identifying errors at the initial stage itself, thereby reducing both time and effort in circuit analysis.

The FAM method is straightforward and easy to understand. Even a person with basic knowledge of electronics and familiarity with matrix operations can use this technique to analyze circuits and obtain various transfer functions. In addition, the mathematical modeling based on the FAM approach provides great flexibility to circuit designers, enabling them to modify and optimize the design conveniently at different stages of analysis.

Overall, these advantages clearly justify the usefulness and effectiveness of the proposed FAM-based process for electronic circuit analysis and design.

Keywords: Notch filter, Floating Admittance Matrix (FAM), Twin-T Network, Band-pass.filter

INTRODUCTION

Over the past few decades, rapid technological advancement has significantly increased the use of electronics in almost every aspect of human life. As a result, there has been a continuous demand for the improvement of existing electronic systems as well as the development of new and more efficient electronic equipment. Various electronic networks, such as RC bridge-T, twin-T, and lattice equalizer circuits, are extensively used in communication and signal-processing applications. In this work, emphasis is given to the simple realization and analysis of the RC twin-T network using the Floating Admittance Matrix (FAM) technique.

A band-pass filter can be obtained by combining RC low-pass and RC high-pass networks in parallel. Such a filter allows only a specific range of frequencies to pass while attenuating frequencies outside that range. On the other hand, by suitably combining the same low-pass and high-pass sections, a band-reject or band-stop filter can be formed. This type of filter suppresses or greatly reduces signals within a certain frequency range. A notch filter is a special form of band-reject filter that is designed to eliminate a very narrow band of frequencies very effectively.

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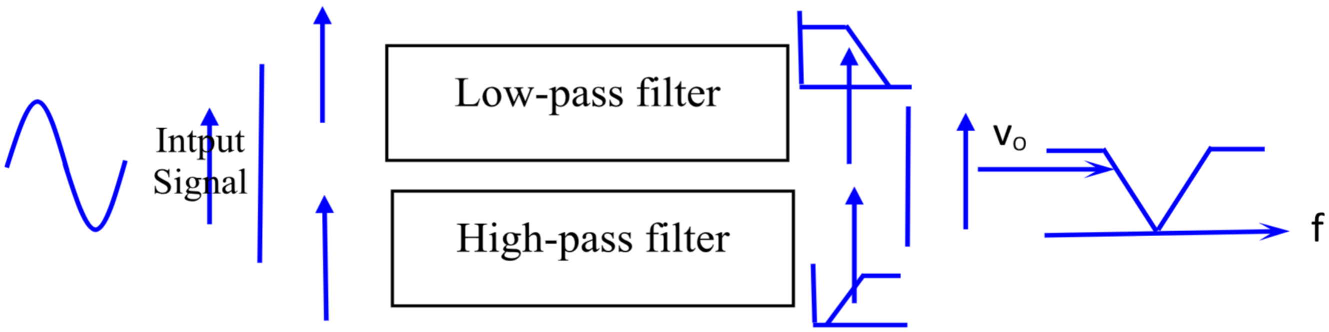

Fig. 1 Band Reject Filter

A twin-T network forms the parallel combination of two-T complementary RC structures. The twin-T network is used as a notch filter for rejecting (offering the highest attenuation) the signal at only one frequency, called the notch frequency (f_o), and passes all frequencies on both sides of the notch frequency. The other names of the band-stop filter are the band-elimination, band-reject, or notch filters. Just like the band-pass design, here we connect the two filter sections in parallel with each other, instead of them in series.

The twin–T network is a handy circuit for the selection of a particular frequency very precisely. One parallel twin-T passes the signals without any attenuation, whereas the other does not function in this frequency range. The other parallel twin-T takes over just after the frequency range; the first twin-T network passed the output signal. This way, for a very narrow range of frequency, neither the first-T nor the second -T network function, and the signal at the twin-T output gets drastically attenuated at only one frequency. For this reason, its name is notch filter because it rejects the magnitude at a notch of frequency only and passes all frequencies on its higher and lower sides.

Notch filters are highly selective because it isa high-Q form of the bandstop filter that can reject a single or very-small band of frequencies rather than a whole bandwidth of a frequency. For instance, it may be necessary to reject or attenuate drastically a specific frequency generating electrical noise (such as mains hum) which comes from the inductive load as that of a motor or ballast lighting, or the removal of harmonics [7-11], etc.

The musicians in sound equipments such as graphic equalizers, synthesizers, and electronic crossovers use a variable type of notch filter to deal with narrow peaks in the systems' acoustic response. So, we see that notch filters behave in much the same way as the combination of low-pass and high-pass filtersin parallel.

Method

Figure 2 shows a general circuit of a RC twin-T network [1-7].The low-pass filter section comprises of $Y_1 = R = Y_2$, and Y_6 =sC_1in a twin-T configuration. Similarly, the other parallel filter is the high-pass section comprisingof Y3 = C = Y4, and Y5 = R1 in the complementary-T configuration. The combined arrangement forms a RC twin-T filter, expected to givea sharp response for the component values in the following ratios. The component values for the RC twin-T band-stop(an extremely small range of frequency) filtercomes out to be;

$G_1 = 2G$

$C_1 = 2C$

For further analysis, we assume that $G_i = Y_L = 0$, i.e., source and load impedances are very high.

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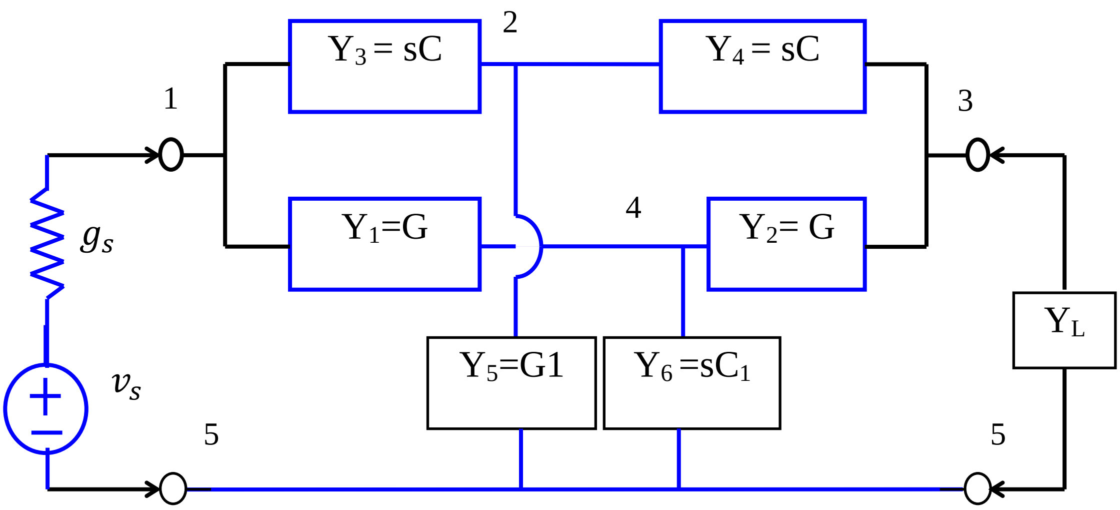

Fig. 2RC Twin -T Network

The design of the RCnotch filtershave a very narrow aswell as very deep stop band at and around their notch frequency. Its selectivity factor Q describes the notch's width precisely the same way the RLC circuit peaks at one frequency. Since, inductor is bulky and lossy component, we avoid it in using in filters.

The most common name of the notch filter design is the RC twin-T-notch filter. In its basic form, the twin-T, is the parallel-teeconsists of two RC branches in two tee sections. Each T-section useseither two resistors and a capacitor or two capacitors and one resistor, as in Fig. 2. We are analyzing the twin-T network shown in Fig. 2 to select a particular frequency using the *floating admittance matrix* approach. For the generalized analysis, we choose either a capacitor or a resistor in the form of admittances such as Y1, Y2, Y3, Y4, Y5 and Y6.

The floating admittance matrix of Fig. 2results [12-18] as;

$$\begin{bmatrix} 1 & 2 & 3 & 4 & 5 \\ g_S + Y_1 + Y_3 & -Y_3 & 0 & -Y_1 & -g_S \\ -Y_3 & Y_3 + Y_4 + Y_5 & -Y_4 & 0 & -Y_5 \\ 0 & -Y_4 & Y_2 + Y_4 + Y_L & -Y_2 & -Y_L \\ -Y_1 & 0 & -Y_2 & Y_1 + Y_2 + Y_6 & -Y_6 \\ -g_S & -Y_5 & -Y_L & -Y_6 & g_S + Y_5 + Y_6 + Y_L \end{bmatrix} \begin{bmatrix} \square \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{bmatrix} \quad (1)$$

Substituting $Y_1 = Y_2 = G$, $Y_3 = Y_4 = sC$, $Y_5 = G_1 = 2G$, $Y_6 = sC_1 = 2sC$, $g_S = 0 = Y_L$, then Eq. (1) yields;

$$\begin{bmatrix} 1 & 2 & 3 & 4 & 5 \\ g_S + G + sC & -sC & 0 & -G & -g_S \\ -sC & 2sC + 2G & -sC & 0 & -2G \\ 0 & -sC & G + sC & -G & 0 \\ -G & 0 & -G & 2G + 2sC & -2sC \\ -g_S & -2G & 0 & -2sC & g_S + 2G + 2sC \end{bmatrix} \begin{bmatrix} \square \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{bmatrix} \quad (2)$$

The voltage transfer function between its terminals 3& 5 and 1&5 in Fig. 2 can be written [12-18] as;

$$A_v|_{15}^{35} = sgn(3-5)sgn(1-5)(-1)^{14}\frac{|Y_{35}^{15}|}{|Y_{15}^{15}|} = \frac{|Y_{35}^{15}|}{|Y_{15}^{15}|} \quad (3)$$

$$|Y_{35}^{15}| = \begin{vmatrix} -sC & 2G + 2sC & 0 \\ 0 & -sC & -G \\ -G & 0 & 2G + 2sC \end{vmatrix} = s^2C^2(2G + 2sC) + (2G + 2sC)G^2$$

$$= 2(G + sC)(s^2C^2 + G^2)$$

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$$\left|Y_{15}^{15}\right| = \begin{vmatrix} 2G+2sC & -sC & 0 \\ -sC & G+sC & -G \\ 0 & -G & 2G+2sC \end{vmatrix} = \begin{vmatrix} 2G+2sC & -sC & 0 \\ 2G+sC & 0 & G+2sC \\ 0 & -G & 2G+2sC \end{vmatrix}$$

$$= 2(G+sC)\{G(G+2sC)+sC(2G+sC)\}$$

$$= 2(G+sC)\{s^2C^2+4sCG+G^2\}$$

$$A_v|_{15}^{35} = \frac{v_{35}}{v_{15}} = \frac{\left|Y_{35}^{15}\right|}{\left|Y_{15}^{15}\right|} = \frac{2(G+sC)(s^2C^2+G^2)}{2(G+sC)\{s^2C^2+4sCG+G^2\}} = \frac{(1+s^2C^2R^2)}{s^2C^2R^2+4sCR+1} \qquad (4)$$

$$\frac{v_{35}}{v_{15}} = -\frac{s^2+\frac{1}{C^2R^2}}{s^2+s\frac{4}{CR}+\frac{1}{C^2R^2}} = -\frac{s^2+\frac{1}{C^2R^2}}{s^2+s\frac{\omega_o}{Q}+\frac{1}{C^2R^2}} = \frac{(s^2+\omega_0^2)}{s^2+s\Delta\omega+\omega_0^2} \qquad (5)$$

$$H_{passive} = \frac{v_{35}}{v_{15}} = \frac{(1-\omega^2C^2R^2)}{1-\omega^2C^2R^2+j4\omega CR+1} = \frac{1-\frac{\omega^2}{\omega_0^2}}{1+j4\frac{\omega}{\omega_0}-\frac{\omega^2}{\omega_0^2}} \qquad (6)$$

Here, notch frequency $=\omega_0 = \frac{1}{RC}$,bandwidth $=\Delta\omega = \frac{\omega_o}{Q}$,and the quality fctor$\frac{4}{CR} = \frac{\omega_o}{Q} = \frac{\omega_o}{4}CR = \frac{1}{4} = 0.25$. For fixed value of R and C, the output voltage isfunction of frequency of input voltage.

The absolute value ofthetransmission coefficient is given as;

$$\left|A_v|_{15}^{35}\right| = H_{passive}(j\omega) = \frac{1-\frac{\omega^2}{\omega_0^2}}{\sqrt{\left(1-\frac{\omega^2}{\omega_0^2}\right)^2+\left(4\frac{\omega}{\omega_0}\right)^2}} \qquad (7)$$

Figure 3 shows the dependence of the output voltage or the voltage gain $\left|A_v|_{15}^{35}\right| = H_{passive}(j\omega)$on frequency.

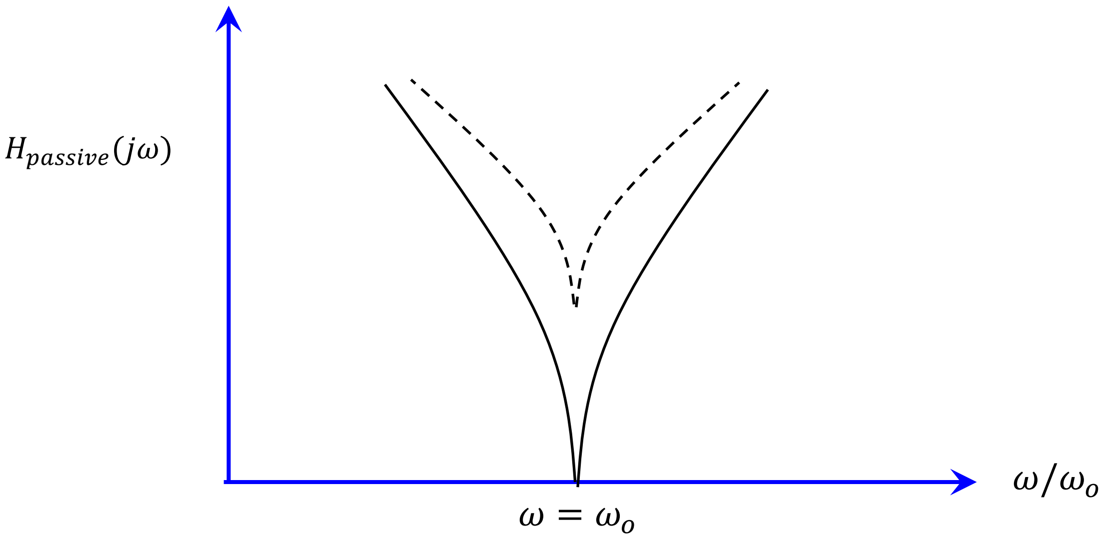

Fig. 3 Plot of absolute value voltage ratio versus frequency

Theplot reveals that the voltage ratio $\left|A_v|_{15}^{35}\right| = H_{passive}(j\omega)$ ceases to zro at only one frequency i.e.,

$$f_0 = \frac{1}{2\pi RC} \qquad (8)$$

The circuit of Fig.1 functions as a resonant network in the close vicinity of this notch frequency,f_0. This type of circuit is, especially, suitable at lowfrequency where the LCR equivalent requires very large value ofL and C.

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Figure 4 is the practical circuit for such a conceived RC notch filter network.

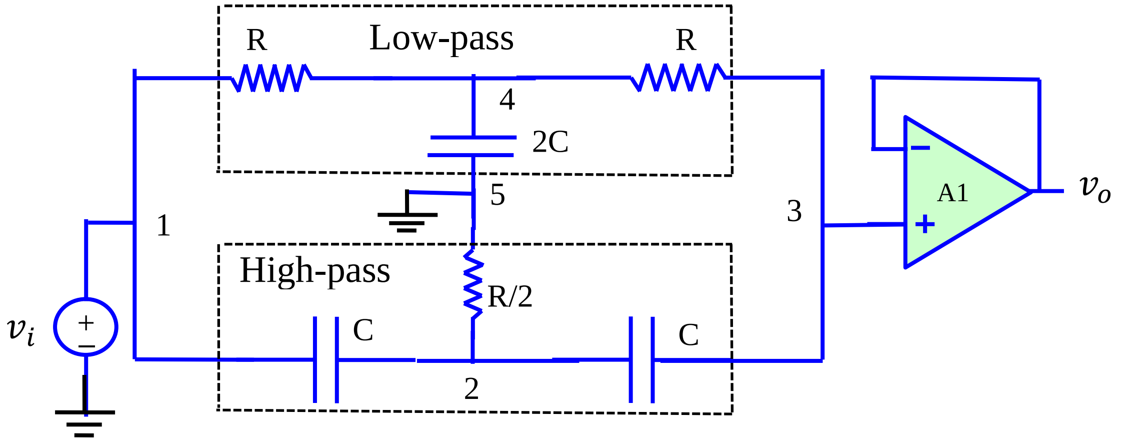

Fig. 4 Twin-T network with inverting Amplifier

One of the shortcomings of this basic twin-T notch filter design is that the maximum value of the output voltage (v_{35}) falls below the notch frequency and is normally less than the maximum value of output voltage w.r.t. that voltage above the notch frequency. This ismainly due to two series resistances (2R) in the low-pass filter section providing higher losses than those of the reactances of the two series capacitors (C) in the high-pass T-section.

Along with the uneven gains ontwo sides of the notch frequency, the other shortcoming of this basic design is that it has a very low and fixed Q value of 0.25, in the order of –12dB. This is because that at the notch frequency, the currents flowing in each series branch in one being 2R and the other being 2C i.e., 180^{o}out of phase.

It is expected that the positive feedback may improve notch filter in making it more selective. Instead of connecting the junction of R/2 and 2C of the other network to ground i.e. 0V, we may connect it to a variable point of the voltage divider network fed from the output voltage as in Fig. 5. The voltage divider network decides the amount of feedback that determines the value of Q that in turn decides the extent of the depth of the notch.

Very frequenctly, the problem arises in the response of the twin-T circuits due to lack of precision value of the passive components used in the network. Also, the quality factor of the circuit is very low as it has only passive components. It has been observed that the circuit reponse increases drastically using active circuits of the twin-T netwrok. Hence, we give a relook for the the selection of precision resistances and capacitances used in the twin-T filter.

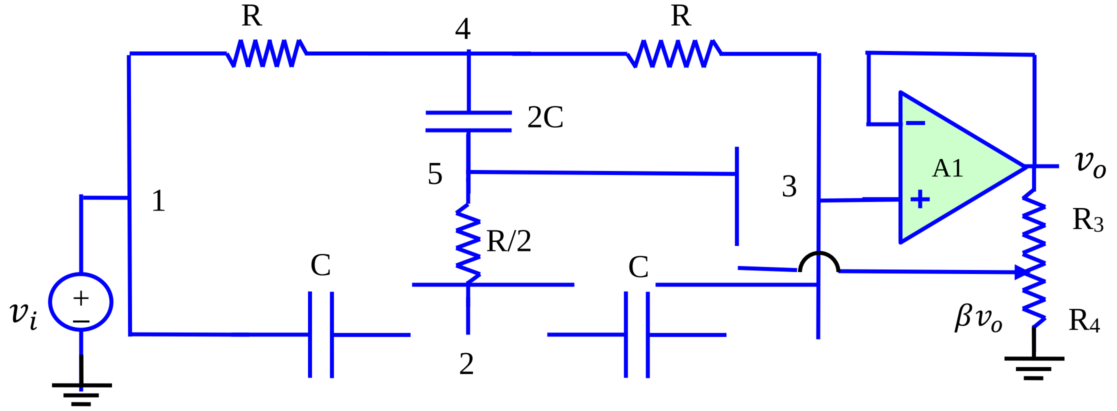

Fig. 5 Twin-T Network with positive feedback

The common point 5 in Fig. 5 is not grounded, instead it is connected to apotentiometer functioning as as a voltage divider composed of R_3 and R_4 to form a positive feedback loop. The fraction of the output voltage $v_o$fed back is given as;

$$v_5 = \beta v_o = \frac{R_4}{R_3+R_4} v_o, \tag{9}$$

The input voltage $v_i - v_5$ and the output voltage $v_o - v_5$ are related by the frequency transfer function $H(j\omega)$ of the twin-T network as;

$$H(j\omega) = \frac{v_o - v_5}{v_i - v_5} \tag{10}$$

$$v_o - v_5 = H(j\omega)(v_i - v_5) = H(j\omega)v_i - H(j\omega)v_5 \tag{11}$$

$$H(j\omega)v_i = v_o + \{H(j\omega) - 1\}v_5 = v_o + \{H(j\omega) - 1\}\frac{R_4}{R_3+R_4} v_o$$

$$H(j\omega)v_i = \frac{R_3 + H(j\omega)R_4}{R_3+R_4} v_o \tag{12}$$

Now, $H_{active}(j\omega) = \frac{v_o}{v_i} = \frac{H(j\omega)(R_3+R_4)}{R_3+H(j\omega)R_4}$ (13)

Now, substituting $H(j\omega)$ from Eq. (5) in Eq. (13) results;

$$H_{passive}(j\omega) = \frac{v_o}{v_i} = \frac{s^2 + \frac{1}{R^2C^2}}{s^2 + \frac{1}{R^2C^2} + js\left(\frac{4}{RC}\right)}$$

$$H_{active}(j\omega) = \frac{v_o}{v_i} = \frac{H(j\omega)(R_3+R_4)}{R_3+H(j\omega)R_4} = \frac{(R_3+R_4)\left(s^2+\frac{1}{R^2C^2}\right)/\left(s^2+s\left(\frac{4}{RC}\right)+\frac{1}{R^2C^2}\right)}{R_3+R_4\left\{\left(s^2+\frac{1}{R^2C^2}\right)/\left(s^2+s\left(\frac{4}{RC}\right)+\frac{1}{R^2C^2}\right)\right\}}$$

$$= \frac{(R_3+R_4)\left(s^2+\frac{1}{R^2C^2}\right)}{R_3\left(s^2+s\left(\frac{4}{RC}\right)+\frac{1}{R^2C^2}\right)+R_4\left(s^2+\frac{1}{R^2C^2}\right)} = \frac{(R_3+R_4)\left(s^2+\frac{1}{R^2C^2}\right)}{(R_3+R_4)\left(s^2+s\left(\frac{4}{RC}\right)+\frac{1}{R^2C^2}\right)R_3}$$

$$= \frac{\left(s^2+\frac{1}{R^2C^2}\right)}{\left(s^2+\frac{1}{R^2C^2}\right)+s\left(\frac{4}{RC}\right)\frac{R_3}{R_3+R_4}} = \frac{\left(s^2+\frac{1}{R^2C^2}\right)}{\left(s^2+\frac{1}{R^2C^2}\right)+s\frac{\omega_o}{Q_{active}}} = \frac{\left(s^2+\frac{1}{R^2C^2}\right)}{\left(s^2+\frac{1}{R^2C^2}\right)+s\Delta\omega_{active}} \tag{14}$$

$$= \frac{s^2+\frac{1}{R^2C^2}}{s^2+\frac{1}{R^2C^2}+s\left(\frac{4}{RC}\right)\left(\frac{R_3}{R_3+R_4}\right)} \tag{15}$$

where, the qualifactor and the bandwidthof the active filter with positive feedback are given as;

$$Q_{active} = \frac{R_3+R_4}{4R_3} = Q_{passive}\left(\frac{R_3+R_4}{R_3}\right), \text{ and } \Delta\omega_{active} = \frac{\omega_o}{Q_{active}} \tag{16}$$

This Eq.(16) suggests that we can adjust the quality factor and the bandwidth of the filter by changing thevalue of R_3 and R_4.

Experimetal Verification

Three circuits of Figs. 6, 8, and 9 have been designed for practical verifications.

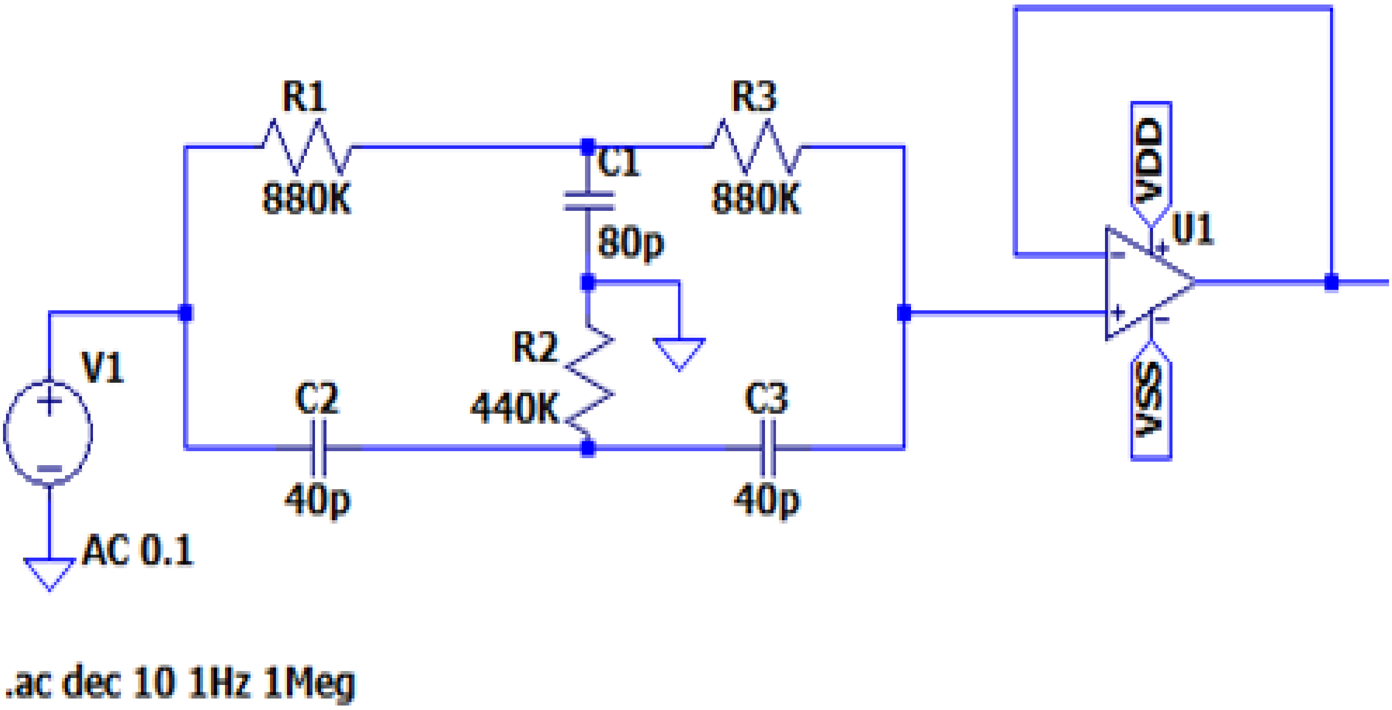

Fig. 6 Twin-T network

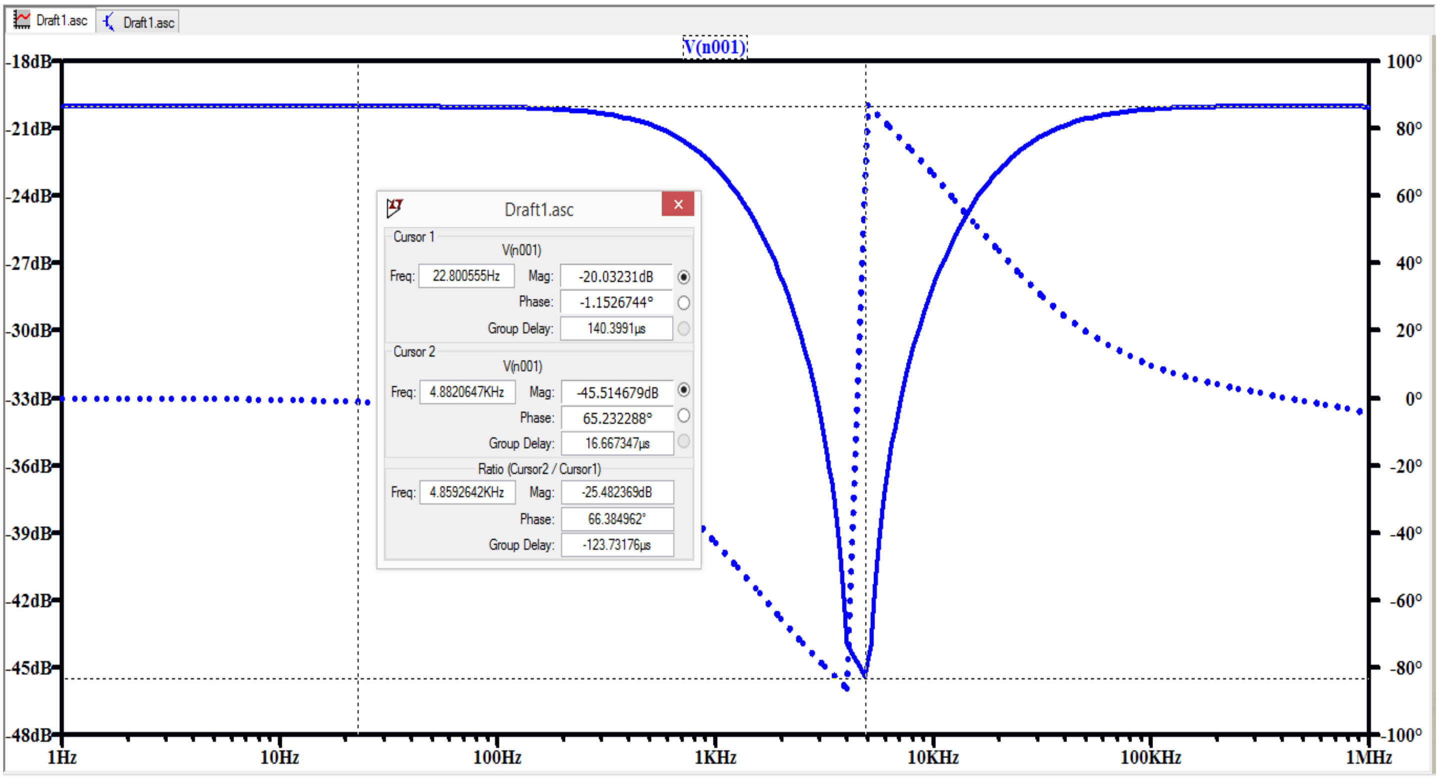

Fig. 7 Indicates notch depth and notch frequency without feedback in the box of the plot

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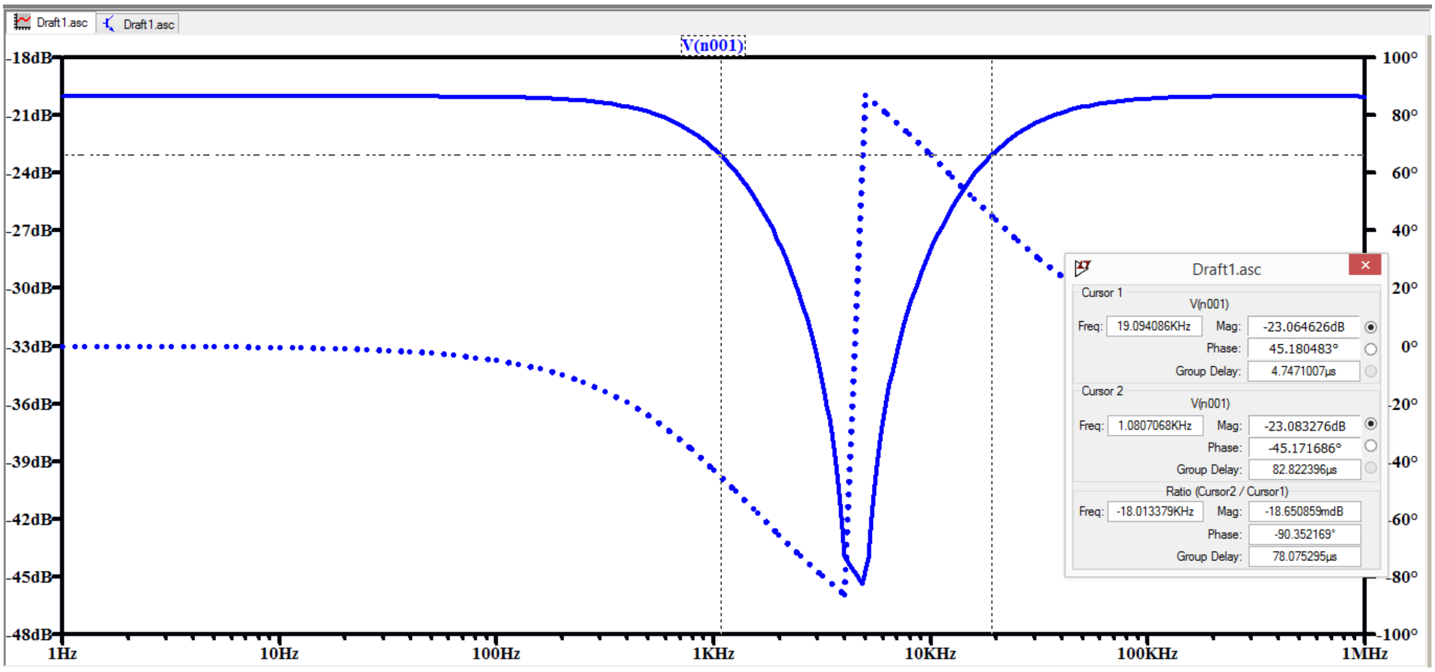


Fig. 8 Indicates 3 dB frequencies without feedback in the box of the plot

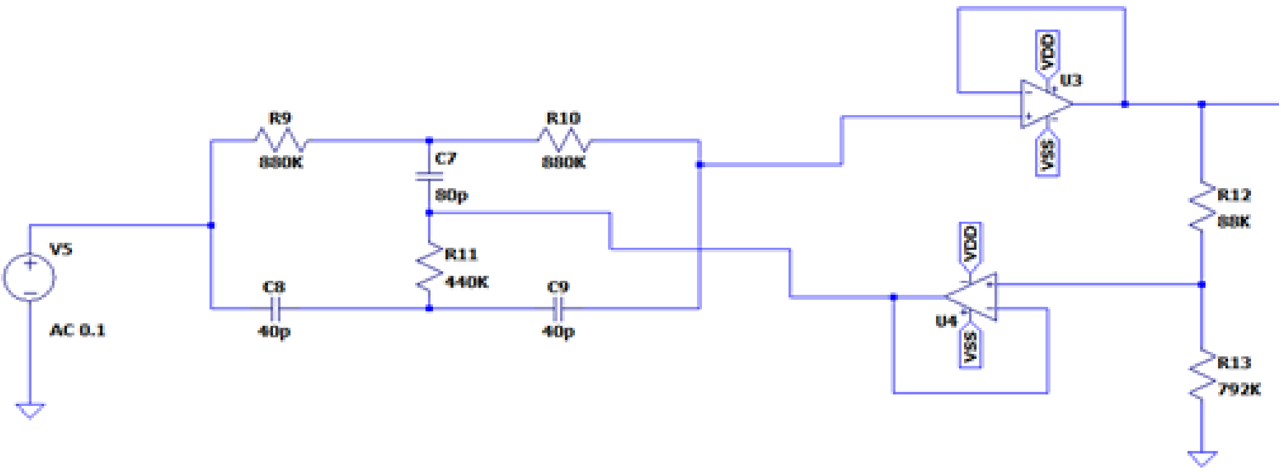


Fig. 9 Twin-T with isolated feedback

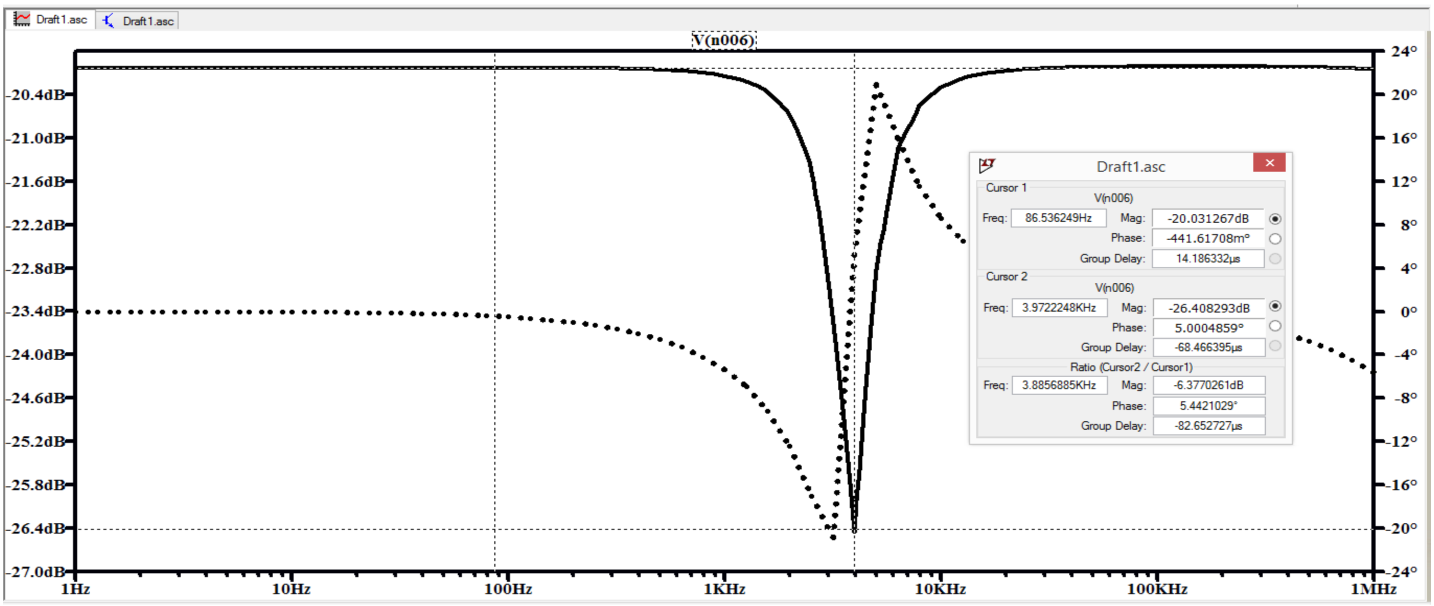


Fig. 10 Indicates Notch frequency and notch depth using one Op am feedback in the box of the plot

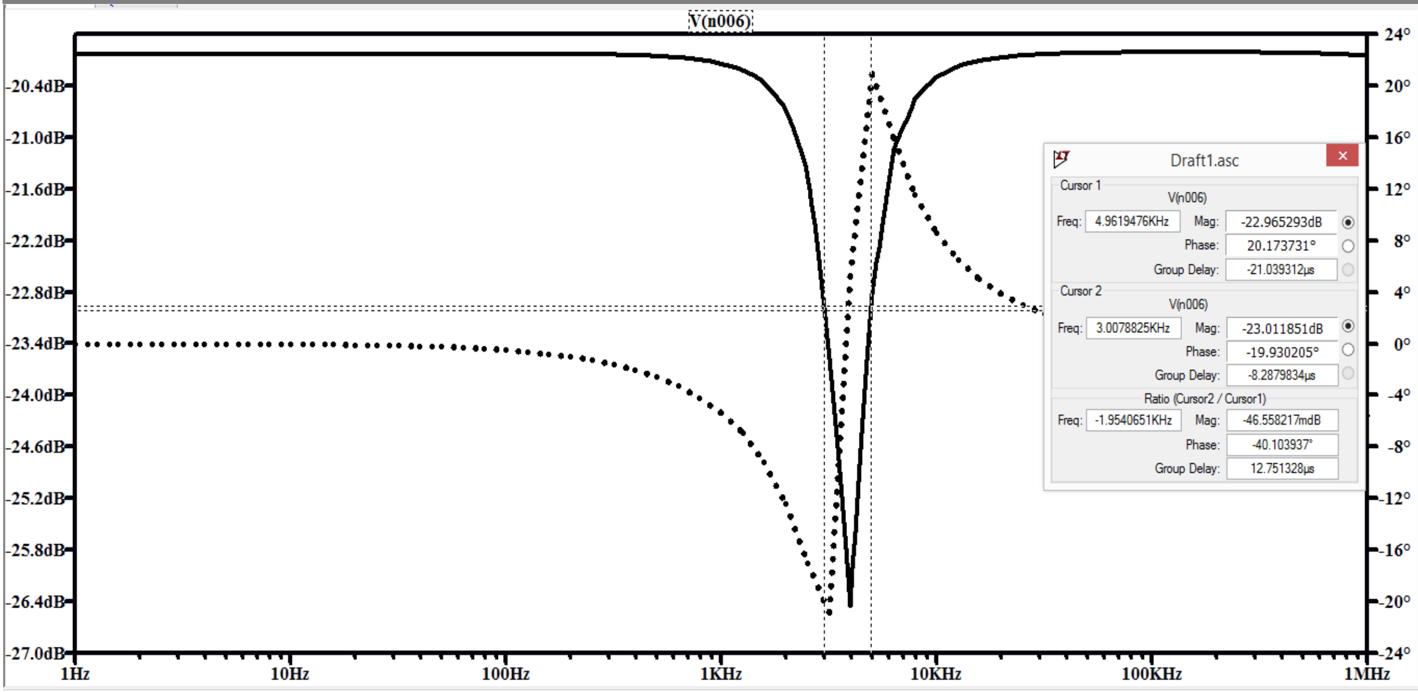
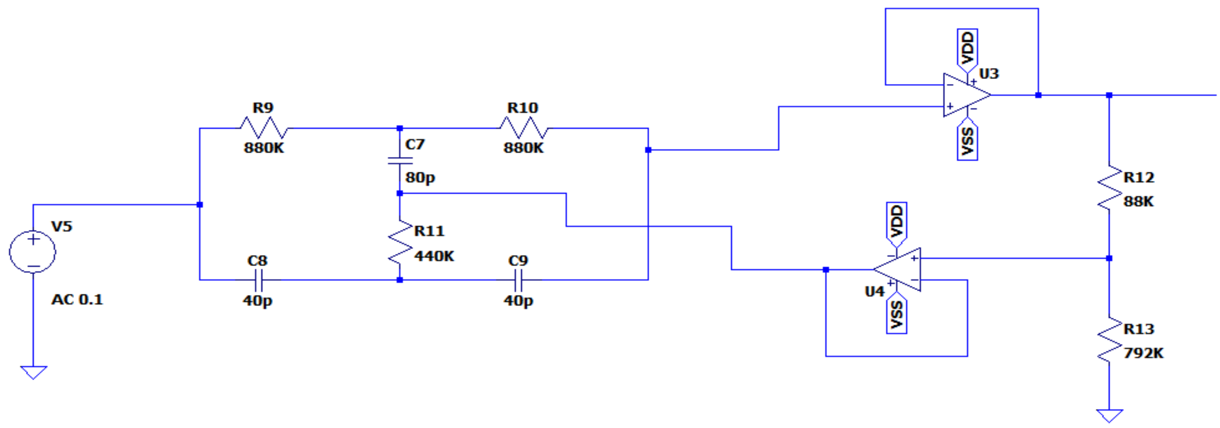


Fig. 11 Indicates 3dB frequencies using one Op Amp feedback in the box of the plot



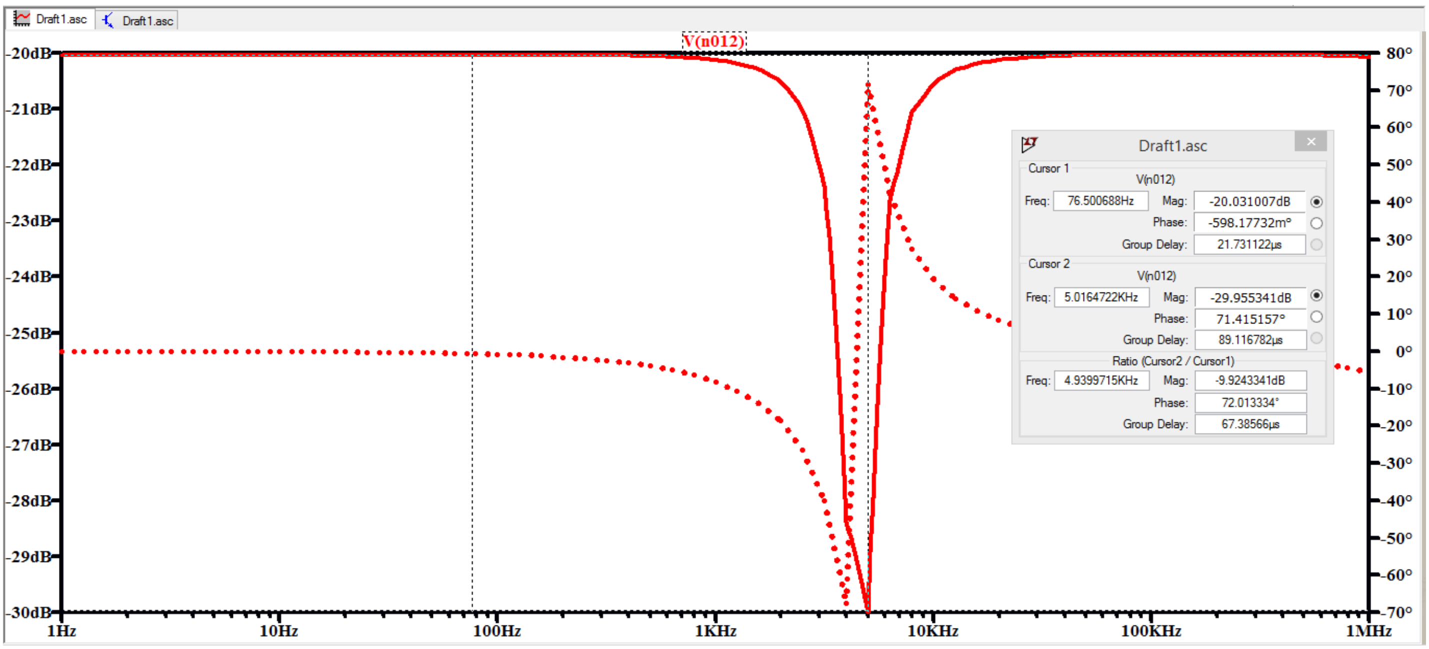


Fig. Indicates Notch frequency and notch depth using two Op Amp feedback in the box of the plot

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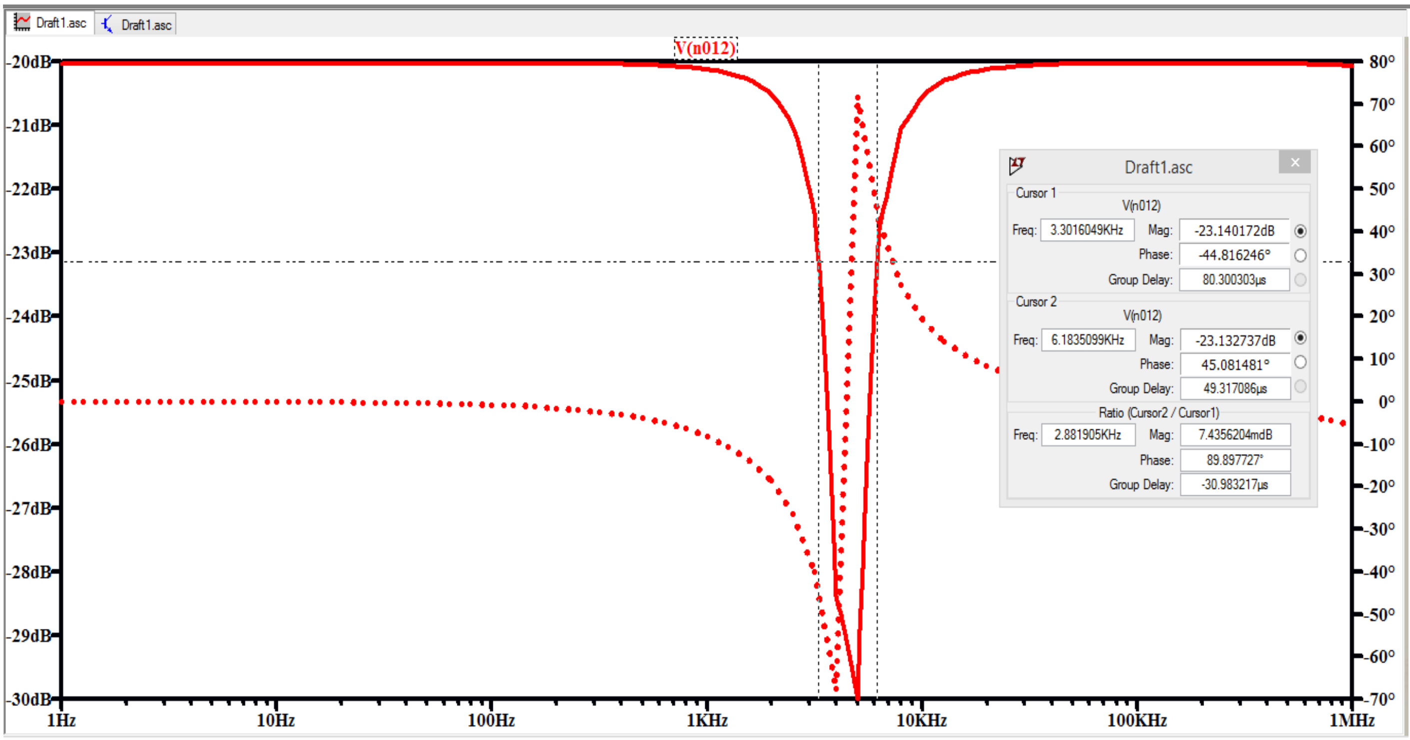

Fig. Indicates 3dB frequencies using two Op Amp feedback in the box of the plot

$$\omega_o = 2\pi f_0 = 6.286\ x60 = 377\ rad/s$$

$f_0 = \frac{1}{2\pi RC}, C = \frac{1}{2\pi R f_0 R} = \frac{1}{377x100\ k} = \frac{10x10^{-6}}{3.77} = 2.65\ \mu F$

RESULT AND DISCUSSIONS

The magnitude and phase plots of twin-T network of Figs. 6 and 7 reveals a close corroboration of the theoretical results. Resistancesand capacitances also play important roles in producing very closely related output functions. For that, precision resistances and capacitances must be considered.

Generally, the resistors are available with tolerances of ±1%, ±2%, ±5% and are adequate in less critical circuits. But, for the twin-T notch filter, tolerances less than these values may be required. Carbon track resistor may be sutable if it is measured values on Wayne-Kerr bridge is taken. The other type of suitable resistor for such circuit could be Cermet track variable resistor that give better reliability. However, a bridge for exact value of resistor could be used.

TheSilver Mica capacitors have tolerances of ±1%, but the maximum value available is limited to only 4.7 nF. They have good temperature stability. Hence, such capacitors are suitable where the filter has to operate in the environment of wide temperature arrange of variation. The Polystyrenecapacitors are most suitable for fiters on accont of their close tolerances and available in large capacitance range. They also have excellent tempearute stability. The ceramic capacitances come in three forms; namely, metallized, resin dipped and disck types. The metallized ceramic capacitor has good tolerance (±2%) and temperature stability. The rasin type of ceramic capacitor has ±5% tolerance. The disk type ceramic capacitor has very poor tolerance, making them unsuitable for filter use.

For large valus of capacitor, thePolyster type may be of the choice. Their tolerances is between ±5% to ±10%. Also, their temperature stability is also very poor. TheElectrolytic type of capacitors have tolerances of± 20% or more and its values is likely to change with uses. Apart from these reasons they are polarized, makes them unsuitable for filters.

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