3.13 Low pass filter (OPA2604[42] + OPA627BP)

The bandwidth of the amplifiers is restricted to the audio frequency range (below 20kHz). The digital noise, which is far away from 20kHz from the DAC may cause inter-modulation distortion and non-linearity in the pre-amplifier and power amplifier in the next stage. Therefore, a precise low pass filter is constructed at the output stage of the Multi-format Hi-Fi DAC to remove most of the high frequency (>20kHz) signal energy without distortion of the audio signals and nonlinear group delay.

An active Generalized Immittance Converter[43] (GIC) filter is used in the low pass filter design. This is because; an active GIC filter can simulate the transfer characteristic of a passive LC ladder network without using an inductor. In addition, it has a lower sensitivity to component value variations than the other RC active filters, such as Sallen and Key filter. The Sallen and Key filter configuration requires gain greater then unity to derive real resistor values in practice. On the other hand, using a GIC filter configuration can realize a high order filter with a unity gain output stage. It can provide a 3dB increase in signal to noise over a Sallen and Key filter.

Chebyshev and Elliptic filter responses have steep cutoff characteristics, but they are not chosen for audio applications due to their large ripple in the pass band. Bessel filter response has a constant group delay characteristic, which can provide an excellent transient response in audio application, but the cutoff characteristic are less steep than the Butterworth filter response, thus the Bessel filter requires a high order to achieve the stopband attenuation. So, a third order GIC Butterworth low pass filter is used in the Multi-format DAC design to have a steep cutoff characteristic at high frequency (>20kHz) with an allowable phase distortion.

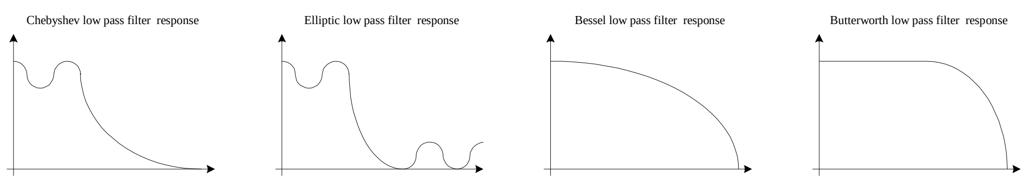


Figure 40: Characteristics of different type of filters[44]

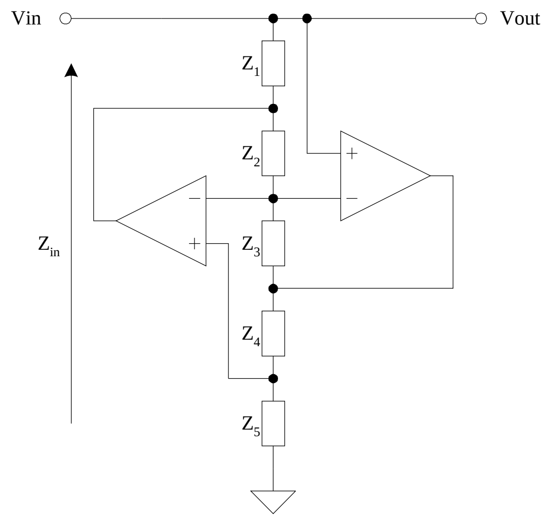
With the implementation of an 8-time digital filtering (DF1704E) in the Multi-format DAC, the major digital noise = 96kHz $\times$ 8 = 768kHz. A 45kHz cutoff frequency is chosen at the following design to have an allowable phase distortion with steep digital noise attenuation.

The cutoff frequency of the GIC low pass filter = 45kHz:

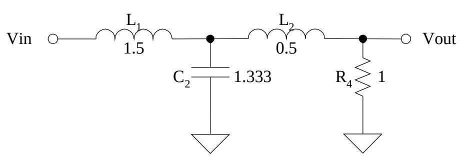
$$Z_{in}(s) = \frac{Z_1(s) \cdot Z_3(s) \cdot Z_5(s)}{Z_2(s) \cdot Z_4(s)}, s = v \ = 2pf$$

$$Z_{in}(s) = \frac{s \cdot R_1 \cdot C_2 \cdot R_3 \cdot R_5}{R_4}$$

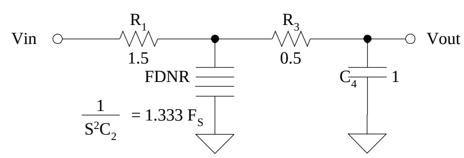
$$Z_{in}(s) = \frac{R_3}{s^2 C_1 R_2 R_4 C_5}$$



The GIC network is transformed from an LC ladder network by multiplying each ladder network element by 1/s. The transformation changes inductors to resistors, capacitors to Frequency Dependent Negative Resistors (FDNRs)[45].



A normalized third-order Butterworth filter



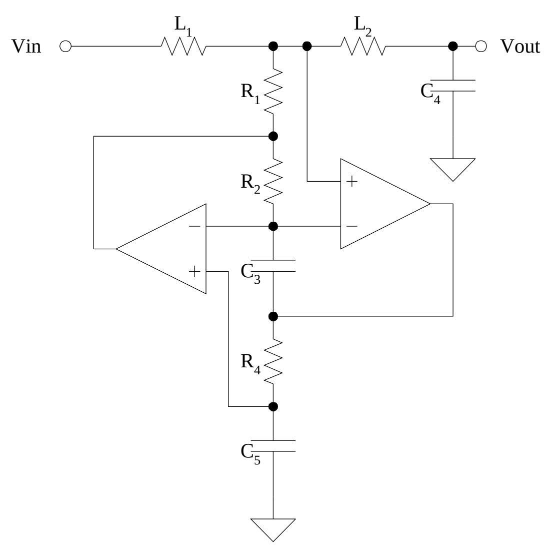
A normalized GIC filter by multiplying each normalized element value by 1/s

$\therefore$ $Z_1 = R_1$, $Z_2 = R_2$ and $R_1 = R_2 = 1$

$Z_3 = C_3$, $Z_5 = C_5$ and $C_3 = C_5 = 1/s$

$Z_4 = R_4 = 1.333\Omega$

If Z_1 is a capacitor, and the filter is ac coupled, the op-amp will not have a bias-current return path, which will affect the filter's operation. Therefore, make Z_3 and Z_5 capacitive to give the op-amp a bias-current return path in the GIC filter. Set $R_2 = R_3$ ($Z_2 = Z_3$) to minimize the effect of op-amp gain-bandwidth mismatch. Set $R_1 = R_2$ and $C_3 = C_5$, then R_4 can be used to trim the filter.



$$L_1 = \frac{1.5}{s} = \frac{1.5}{2p \times (45kHz)} = 5.305 \times 10^{-6}\,\Omega$$

$$L_2 = \frac{0.5}{s} = \frac{0.5}{2p \times (45kHz)} = 1.768 \times 10^{-6}\,\Omega$$

$$R_1 = \frac{1}{s} = \frac{1}{2p \times (45kHz)} = 3.537 \times 10^{-6}\,\Omega$$

$$R_2 = R_1 = 3.537 \times 10^{-6}\,\Omega$$

$$R_4 = \frac{1.333}{s} = \frac{1.333}{2p \times (45kHz)} = 4.716 \times 10^{-6}\,\Omega$$

$$C_3 = C_4 = C_5 = 1F$$

Then, scale the capacitor and resistor values to realize practical circuit elements by multiplying the scale factor.

Choose 1000pF as the capacitor value, so $C_3 = C_4 = C_5 = 1000\,pF$

Scale factor = $\dfrac{1F}{1000\,pF} = 1 \times 10^9$

$$\therefore \quad L_1 = 5.305 \times 10^{-6}\,\Omega \times (1 \times 10^9) = 5305\Omega \approx 5.36k\Omega$$

$$L_2 = 1.768 \times 10^{-6}\,\Omega \times (1 \times 10^9) = 1768\Omega \approx 1.78k\Omega$$

$$R_1 = 3.537 \times 10^{-6}\,\Omega \times (1 \times 10^9) = 3537\Omega \approx 3.57k\Omega$$

$$R_2 = R_1 = 3.537 \times 10^{-6}\,\Omega \approx 3.57k\Omega$$

$$R_4 = 4.716 \times 10^{-6}\,\Omega \times (1 \times 10^9) = 4716\Omega \approx 4.75k\Omega$$

An op-amp (OPA627BP) is added as a unity-gain buffer to achieve a high input impedance and low output impedance characteristic[46]. Finally, a 51.1Ω resistor is connected to the output of the op-amp (output impedance of OPA627BP = 55Ω) for accidental short circuit protection.