Replacing op-amps with BJTs as voltage buffers

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1 Background and motivation

Often when designing simple audio-related circuits it seems such a waste to put in an IC circuit such as a basic op-amp is. In many cases it is more elegant to stick with a simple BJT design all the way. Often it is more than possible to use BJTs instead of op-amps if an ideal solution is not necessary. Using BJTs also saves the trouble of generating a split voltage source for the op-amp.

2 Sallen and Key filters

The Sallen and Key filter topology consists of a resistor-capacitor network, which is tied in with a unity gain non-inverting op-amp buffer. The Sallen and Key topology implements the Butterworth filter-type and the order is determined by the number of RC pairs used in the filter. To present an example analysis, a second-order Sallen and Key high-pass filter is shown in Figure 1.

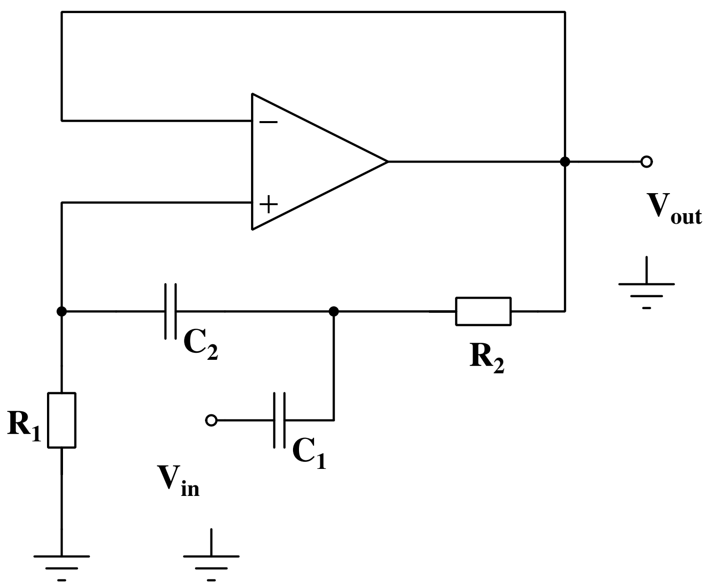

Figure 1: A high-pass Sallen and Key filter using an op-amp

The transfer function of this filter is easily found from related literature and it is stated here without derivation. The transfer function of the second-order Sallen and Key high-pass filter is

$$\frac{V_{in}}{V_{out}} = \frac{s^2}{s^2 + s\left(\frac{1}{R_2C_1} + \frac{1}{R_2C_2}\right) + \frac{1}{R_1C_1R_2C_2}}. \tag{1}$$

The resonance (or angular) frequency is calculated from the equation

$$f_r = \frac{1}{2\pi\sqrt{R_1C_1R_2C_2}}, \tag{2}$$

and the quality factor is

$$Q = \frac{R_2C_1 + R_2C_2}{\sqrt{R_1C_1R_2C_2}}. \tag{3}$$

Since the op-amp is used as a non-inverting unity gain buffer, it can be replaced by a BJT emitter follower, which is non-inverting and almost reaching the unity gain. The only thing missing is a decently high input impedance, but when using a high gain transistor with large emitter resistor (about 10 kilohms or more), the input impedance gets close to 10 megohms. The BJT version of the Sallen and Key high-pass filter is shown in Figure 2.

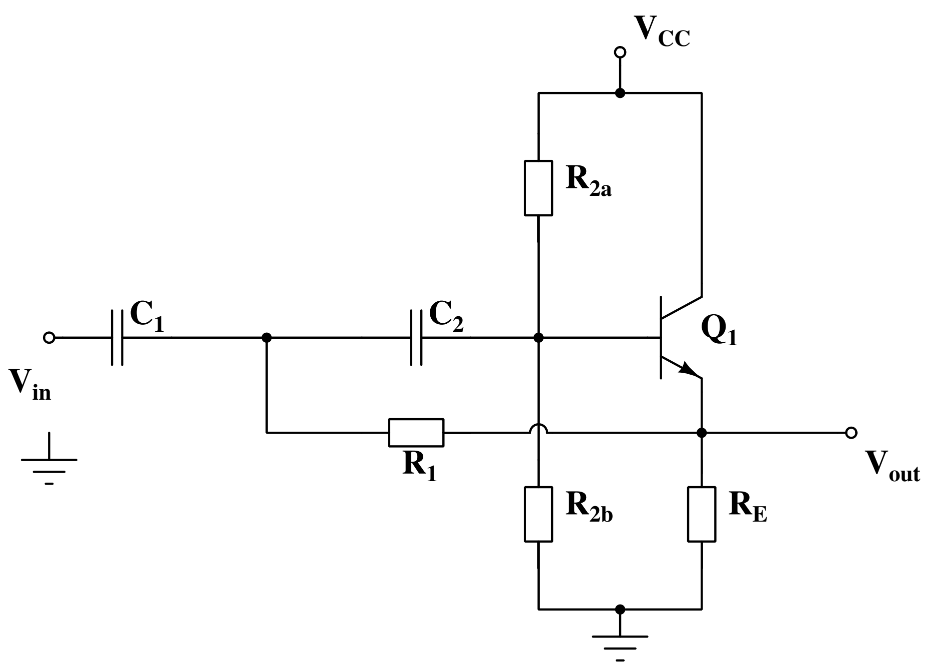

Figure 2: A high-pass Sallen and Key filter using a BJT emitter follower

The small-signal model of this BJT version is drawn in Figure 3. The biasing resistors have been combined as a single resistor R_2, which value equals the parallel resistance of R_{2a} and R_{2b} in Figure 2.

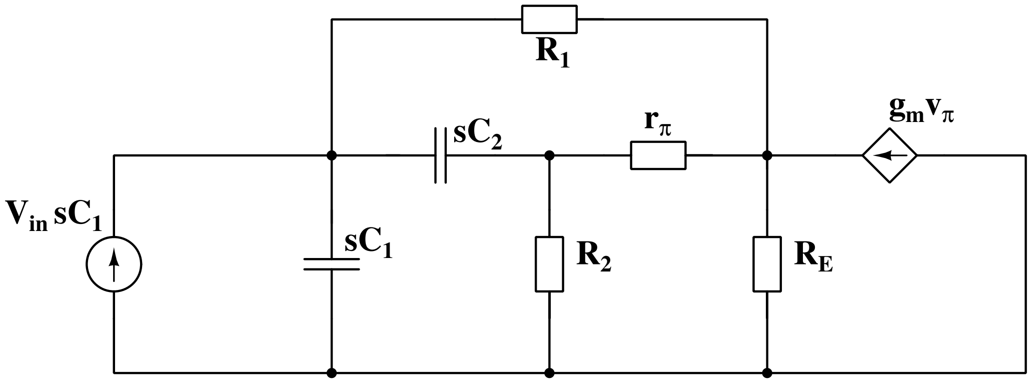

Figure 3: Small-signal model of the BJT high-pass filter

The nodal (admittance) matrix equation for this small-signal model is:

$$\begin{bmatrix} \frac{1}{R_1}+sC_1+sC_2 & -sC_2 & -\frac{1}{R_1} \\ -sC_2 & \frac{1}{R_2}+\frac{1}{r_\pi}+sC_2 & -\frac{1}{r_\pi} \\ -\frac{1}{R_1} & -\frac{\beta_F+1}{r_\pi} & \frac{1}{R_E}+\frac{1}{R_1}+\frac{\beta_F+1}{r_\pi} \end{bmatrix} \times \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{bmatrix} V_{\text{in}} sC_1 \\ 0 \\ 0 \end{bmatrix}.$$

This matrix equation has the dependent source terms already moved into the admittance matrix in row 3.

When the matrix equation is solved for the transfer function, one has:

$$\frac{V_{in}}{V_{out}} = \frac{s^2(\beta_F+1)R_E[R_1C_1R_2C_2] + \text{other terms ...}}{(\beta_F+1)R_E[s^2R_1C_1R_2C_2 + s(R_1C_1+R_1C_2)+1] + \text{other terms ...}}.$$

It is immediately clear that if the factor $(\beta_F + 1)R_E$ is large, the related terms will clearly dominate in the transfer function and the factor $(\beta_F+1)R_E$ cancels itself out from the equation. Then with a few simplifying steps the original Sallen and Key transfer function is obtained. Therefore, this kind of proves that the BJT realisation of the Sallen and Key filter approximates the ideal transfer function is often a good enough replacement for the more common and more ideal op-amp implementation.

A brief simulation testing was carried out to find out the differences between the op-amp and BJT implementations. Using values $R_1 = 3.3$ kΩ, $R_2 = R_{2a}||R_{2b} = 1.5$ MΩ, $C_1 = C_2 = 0.001$ μF and 2N5089 BJT transistor with large β_F and $R_E \approx 10$ kΩ the comparison Figure 4 was obtained. This reveals that at least when aiming for high quality factor in the filter response, the

BJT implementation fails to produce sharp enough peak compared to the op-amp design.

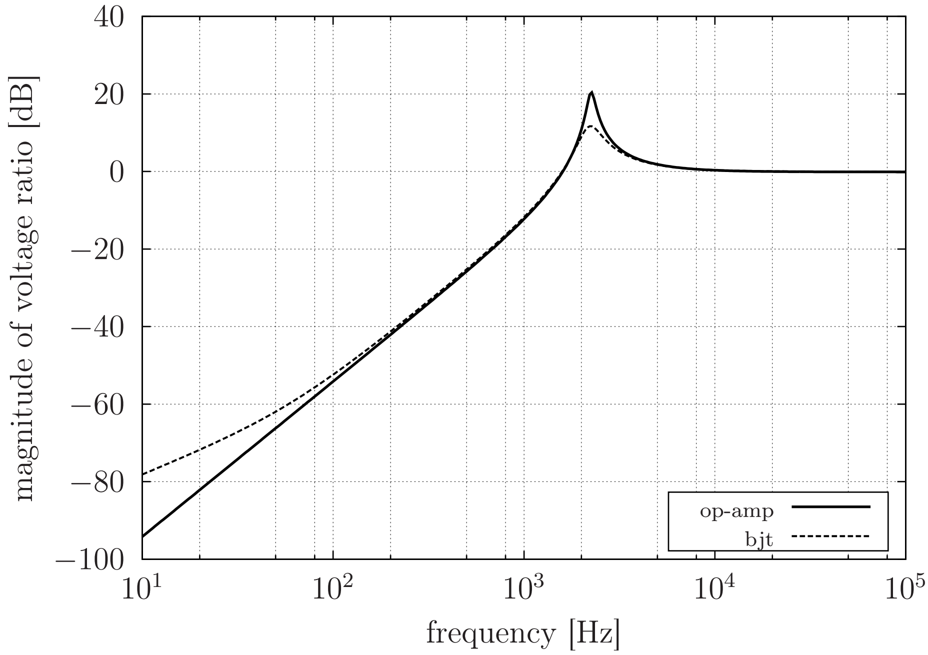

Figure 4: Comparison between op-amp and BJT filters

Also, this simulation limits to the situation where the filter is studied as an independent circuit. Connecting the filter as a part of a larger circuit will most likely bring out the differences even more. But this is not said to make the BJT implementation look bad against the op-amp version, in some cases it is definitely worth while to try out the BJT filter.

3 Simple Gyrators to replace inductors

Gyrators are often used to replace large inductors in audio-related circuits. Gyrator forms an artificial mathematical replica of the inductor using a voltage buffer and a resistor-capacitor network. While the gyrator is only trying to mimic the inductor functionality, it does not offer an identical match for the real inductor, although in some cases it avoids the magnetic distortions arising from the inductor core material.

The op-amp based gyrator drawn in Figure 5 synthesizes an inductor with internal resistance and inductance $R_L + j\omega R_L RC$. The equivalent 'real life' inductor with corresponding internal resistance R_L and inductance L is shown in Figure 6.

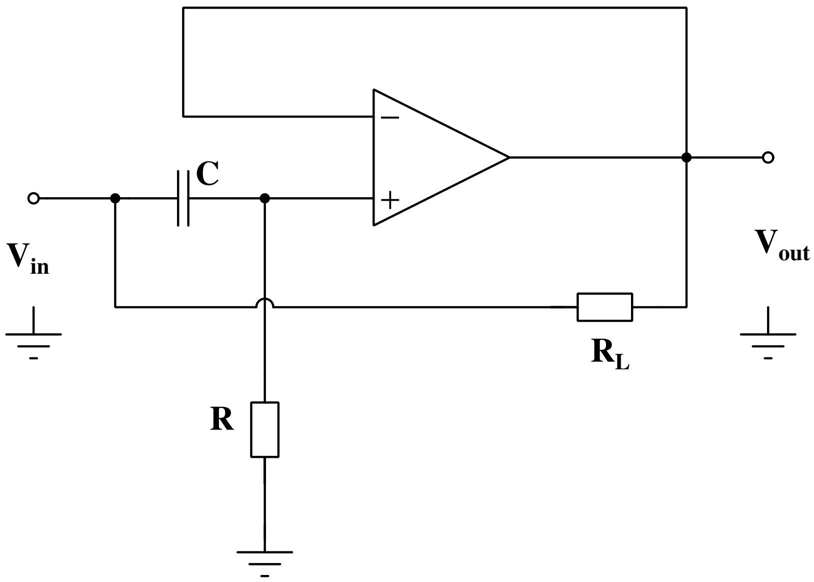

Figure 5: Gyrator using a BJT, inductance $L = R_L RC$.

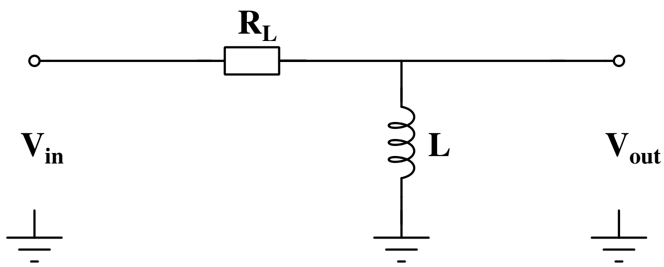

Figure 6: Inductor with internal resistance R_L and inductance L

The BJT implementation of the op-amp inductor is shown in Figure 7. The method to replace the op-amp with the BJT is exactly the same as presented in the Sallen and Key filter example. The unity-gain op-amp buffer is replaced with a high-gain BJT in an emitter-follower configuration with a sufficiently large emitter resistor. Also the biasing resistors should be designed accordingly so that their parallel resistance equals the value of R in Figure 5.

The functionality of the BJT gyrator was tested with a simple simulation scheme, where the results were compared with a 'real life' inductor. This time the gyrator circuit was used in connection with a resonator circuit, which gives a better idea on the usability of the circuit.

The Figure 8 shows the schematic for the inductor-resonator and Figure 9 is the same circuit, but the inductor is replaced by the BJT gyrator. The sim-

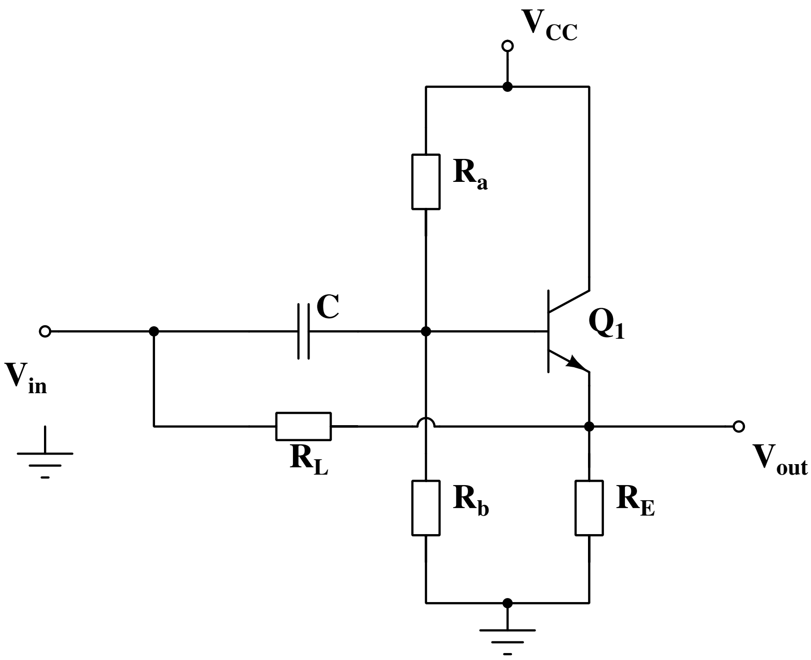

Figure 7: Gyrator using a BJT, inductance $L = R_L(R_a||R_b)C$.

ulation results are shown in Figure 10. According to the results, the BJT gyrator again fails to create a sharp enough resonance peak, but otherwise it produces similar frequency response as the circuit using the ideal inductor. So in some applications this kind of BJT gyrator might be useful, but considerations of use are in order for applications in need of accuracy.

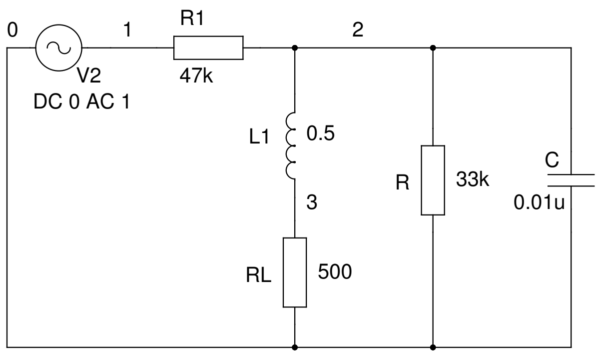

Figure 8: Schematic of a voltage divider using a RLC resonance circuit

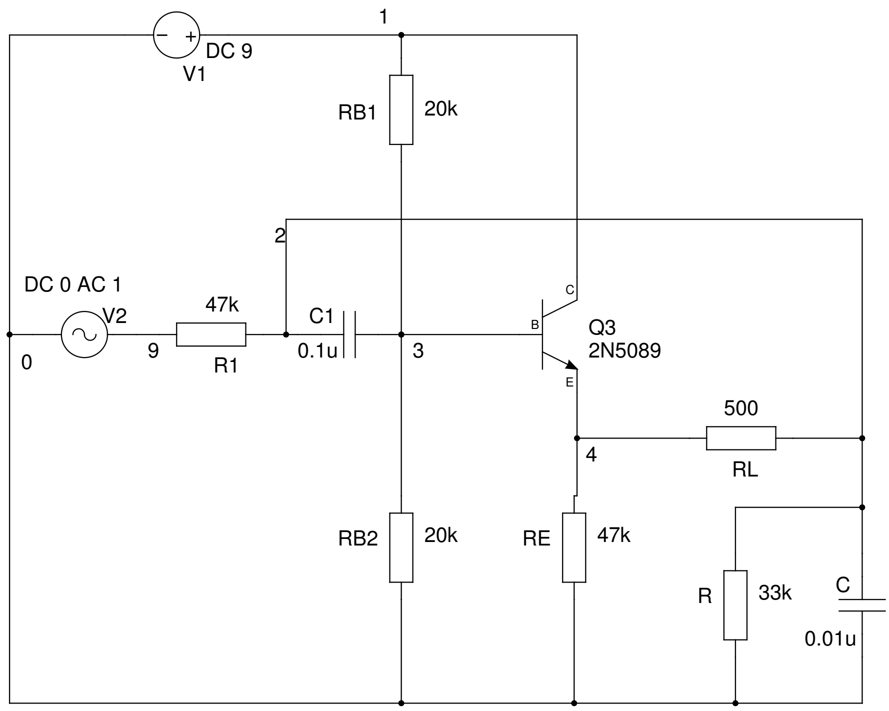

Figure 9: Same voltage divider implemented using the BJT gyrator

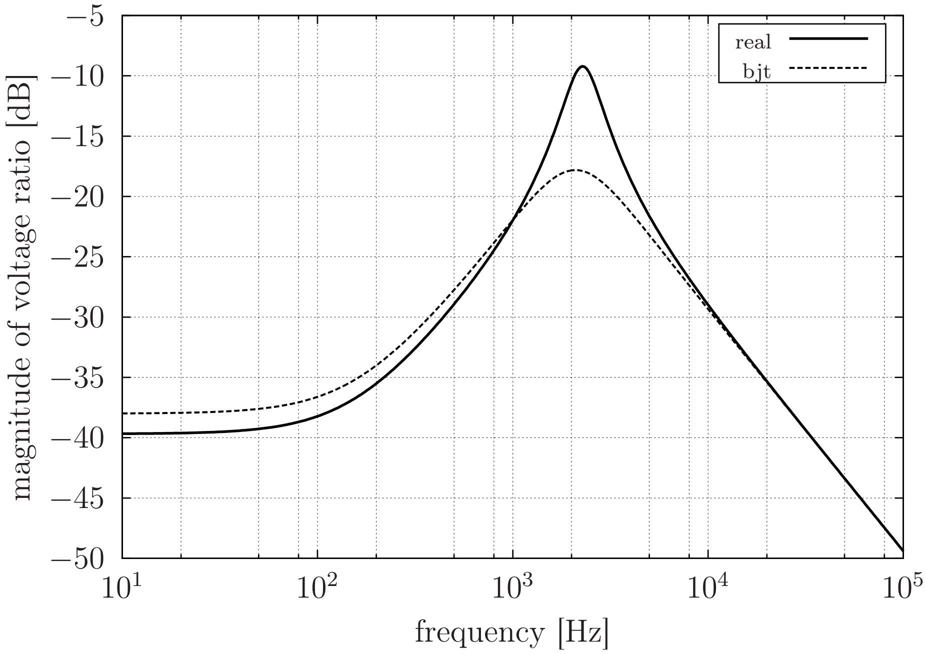

Figure 10: Comparison between op-amp and BJT filters