Multi-Stage Tuned Amplifier

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Project Start Date: January 22, 2015
Report Submission Date: February 8, 2015

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1 Objective

To compare the operation of common-emitter and common-base tuned amplifier stages, and to design and characterize a multi-stage, high-gain IF amplifier for 10 MHz operation with 50Ω input and output impedances.

2 Principles of Operation

Tuned amplifiers are critical for electronic communications because they increase the power of desired signal but reject other frequencies as noise. At 10 MHz, a tuned amplifier could be used with an antenna to recieve HF amateur radio from the other side of the world [1], or could be used in a computer to recieve 10Base-T ethernet.

There are three possible circuit configurations for bipolar junction transistors (BJT) biased in forward-active mode, based on which terminals are used for input, output, and common reference.

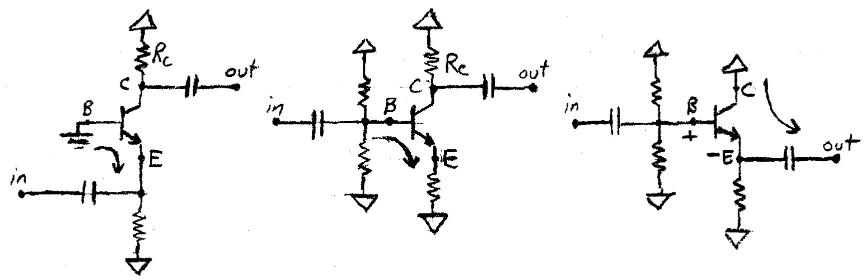

Figure 1: Common-base (left), common-emitter (middle), and common-collector (right) configurations for BJT amplifiers.

Each configuration has its tradeoffs. The common-base (CB) configuration is a good current buffer, with $A_i \approx 1$ and low input impedance. The common-emitter (CE) configuration offers the best overall power gain, but A_v and A_i may vary with loadings. The common-collector configuration is a good voltage buffer ($A_v \approx 1$) with low output impedance.

The three configurations can be cascaded together to gain the benefits of each. If cascaded in the order shown in figure 1, from left-to-right, the resulting 3-stage broadband amplifier would have low input impedance, good power gain, and minimal output impedance.

A slight modification to the CE and CB configurations in figure 1 can apply a filter to the broadband amplifier; tuning the gain to a narrow frequency set by a tank circuit.

Because BJTs are minority carrier devices, they act as current amplifiers without being strongly affected by voltage. For the two configurations where the output is at the collector (CB and CE), the BJT acts like a dependent current source feeding the output load and the biasing resistance R_C. As a result, the voltage gain for these configurations is determined primarily by how difficult it is for the collector current to reach ground; $A_v \propto R_C || R_L$.

One can take advantage of the collector current's obstinance by replacing R_C with an impedance that varies with frequency. Using an inductor and a capacitor in parallel provides a short circuit to ground for both DC and high frequency currents. Additionally, at the LC circuit's resonant frequency, the net impedance $\rightarrow \infty$ due to power oscillating between the two. [2] The result is a narrow bandpass filter at the resonant frequency, where $Z_C \rightarrow \infty$.

[1] 10 MHz waves can traverse the curve of the earth because they get reflected by charged particles in the ionosphere, called ionospheric skip propagation.

[2] For this reason, an $L||C$ circuit is called a tank circuit.

3 Theory

3.1 Common-Base Broadband Amplifier

The basic circuit for an single stage, common-base (CB) amplifier is shown in figure 2. The base terminal is grounded and the input signal passes through the BJT from emitter to collector. In this configuration, the BJT acts like a current buffer, where the input current is repeated at the output regardless of the load.

GET RID OF REX NONSENSE!

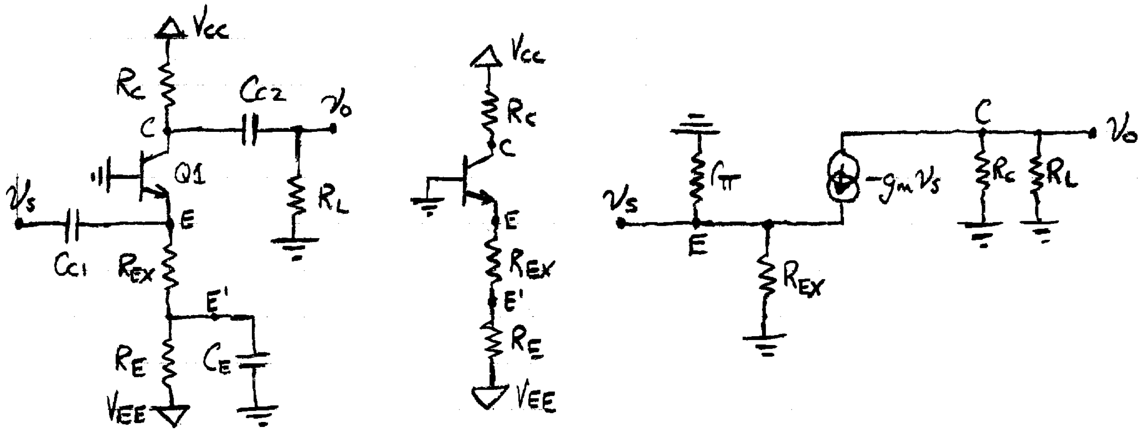

Figure 2: Basic circuit for a common-base broadband amplifier (left), its DC large signal (middle) equivalent, and AC small signal equivalent (right).

Two DC power rails are needed to bias the BJT in forward-active mode. A positive supply holds the collector reverse biased relative to the base which, at ground, is forward biased relative to the negative supplied emitter. Quiescent point analysis of the common-base is easy because the voltage is pinned at every node.

$$I_{EQ} = \frac{-V_{BE(on)} - V_{EE}}{R_E} \tag{1}$$

$$r_\pi = \frac{V_{th}}{I_{BQ}} = \frac{V_{th}(\beta+1)R_E}{-V_{BE(on)} - V_{EE}} \tag{2}$$

$$g_m = \frac{\beta}{r_\pi} = \frac{\alpha(-V_{BE(on)} - V_{EE})}{V_{th}R_E} \tag{3}$$

The hybrid-π model for small signal AC modeling is shown in the right pane of figure 2. Applying Kirchoff's current law at node E can be used to find the input resistance.

$$\text{KCL @ E:} \qquad i_S - \frac{v_s}{r_\pi} - \frac{v_s}{R_E} - g_m v_s = 0$$

$$i_s = v_s \left[\frac{1}{R_\pi} + \frac{1}{R_E} + g_m \right]$$

$$i_s = v_s\left[\frac{R_E + r_\pi + g_m r_\pi R_E}{r_\pi R_E}\right]$$

$$\frac{v_s}{i_s} = \frac{r_\pi R_E}{R_E + r_\pi + g_m r_\pi R_E}$$

$$R_{in} = \frac{r_\pi}{\beta + 1 + \frac{r_\pi}{r_E}} \tag{4}$$

Applying KCL at the collector can be used to calculate the voltage gain of a single common-base stage.

$$-g_m v_s + \frac{v_o}{R_L} + \frac{v_o}{R_C} = 0$$

$$v_o\left[\frac{R_L + R_C}{R_L R_C}\right] = g_m v_s$$

$$A_v = \frac{g_m R_L R_C}{R_L + R_C} \tag{5}$$

3.2 Coupling Capacitors

The coupling capacitors, labeled C_{Cx}, isolate each stage from direct currents but provide a low impedance path for the AC signal. Taken together, they should form a sharp high-pass filter with its corner frequency below 1000 Hz. The 3dB corner occurs when half the signal power is dissipated in the capacitor and half in the stage's input. This occurs when $Z_{Cc} = Z_{in}$.

$$\frac{1}{|j\omega C|} = R_{in}$$

$$C_C \geq \frac{159.15\,\mu F * \Omega}{R_{in}} \tag{6}$$

4 Design and Simulation

4.1 Specifications

4.2 Tank Circuits

4.3 Common-Base Stage

The first stage must be a common-base amplifier in order to achieve low input resistance. The emitter resitance must be chosen to achieve desirable input resistance and voltage gain.

It is clear that R_{in} is strongly related to r_π from equation 4. Substituting equation 2 for r_π into equation 4 yields

$$R_{in} = \frac{-V_{th} R_E}{V_{BE(on)} + V_{EE}} \qquad \text{or} \qquad \left(R_E = \frac{R_{in}(-V_{BE(on)} - V_{EE})}{V_{th}}\right)$$

Using the specified value for V_{EE} and R_{in}, and typical values for V_{th} and $V_{BE(on)}$, the emitter resitance should be

$$R_{in} = \frac{50\Omega(-0.7V + 12V)}{0.0259V} = 21.8k\Omega$$