The Transistor Inverter

BACKGROUND

In this lab, we investigate several forms of the transistor inverter, a basic building block found in digital logic circuits as well as in circuits capable of linear amplification. Our primary focus in this assignment is inverters used for linear amplification.

The voltage transfer function or voltage transfer characteristic of an inverter describes the relationship between its input and output voltages. The transfer function may be expressed in either mathematical form or as a graphical plot in which $v_{IN}$ is plotted on the horizontal axis and $v_{OUT}$ on the vertical axis.

One key property of an inverter operating in the analog regime is that a change in its input voltage causes a proportional, but larger, change in its output voltage. When the input voltage to an inverter goes up, its output voltage goes down, and vice versa; hence the name "inverter". The incremental gain (sometimes called the small-signal, or ac gain) of the inverter is defined as $dV_{OUT}/dV_{IN}$. This derivative is to be evaluated at a fixed (bias) value of $V_{IN}$. When we wish to amplify a signal in analog mode, we intentionally operate the inverter in its high gain region, i.e. where $dV_{OUT}/dV_{IN}$ is large.

LEVEL 1: BJT INVERTER WITH RESISTIVE LOAD

In this level, we examine the voltage transfer function for the simple BJT inverter shown below. The transfer function is derived under the assumption that the transistor operates in the constant-current region, where $i_C = \beta i_B$. Obtaining $i_C$ and $i_B$ from analysis of the circuit, we can derive the following equations:

$$i_C = \frac{V_{CC} - V_{OUT}}{R_C} = \beta F \frac{V_{IN} - V_f}{R_B}$$

or

$$V_{OUT} = V_{CC} - \beta F \frac{R_C}{R_B} (V_{IN} - V_f).$$

Here $V_f$ is the "turn-on" voltage of the transistor’s base-emitter junction ($V_f = 0.5$ to $0.7$ V). For smaller values of $V_{IN}$, the transistor will be in cutoff, and $i_C$ will be zero. Under these conditions, the output voltage $V_{OUT}$ will equal $V_{CC}$, the open-circuit voltage seen via $R_C$. 
If $v_{IN}$ becomes too large, the transistor will reach saturation, where $v_{OUT} = v_{CE}$ drops to just a few tenths of a volt, with the transistor out of the constant-current region, and $i_C$ no longer equal to $\beta F i_B$.

Plotting the above equation plus the cutoff and saturation regions yields the following voltage transfer function:

![BJT Inverter Voltage Transfer Characteristic](image)

The slope in the linear region is given by

$$\frac{dv_{OUT}}{dv_{IN}} = -\beta F \frac{R_C}{R_S}$$

This slope, or gain, can be considerably greater than unity in magnitude if the resistor values are properly chosen.

Construct a simple BJT inverter using the 2N2222 or PN2222 transistor in your lab kit. Aim for a gain of about $-10$. You'll need to add some form of DC offset, or bias, to the input signal, so that the inverter operates in the middle of the linear portion of its transfer characteristic when the signal component of its input signal is zero. Show that your inverter can accept a $\pm 0.1$-V sinusoidal signal and convert it into a $\pm 1$-V signal.

**Level 2:**
Substitute a single NMOS transistor from your parts kit for the BJT in the resistive-load inverter that you built in Level 1. Derive a mathematical expression for the voltage-transfer characteristic, then choose component values so that the amplifier can accept a $\pm 0.1$-V input signal while always operating in the constant-current region.

Show via a simultaneous display of the input and output signals on an oscilloscope that the output signal is not a faithful reproduction of the input signal due to the square-law-device nature of the MOSFET.

**Level 3:**
Find the integrated circuit in your parts kit that contains matched NMOS/PMOS pairs. Connect one such pair as a simple CMOS inverter operating from a 5-V supply voltage. Devise an experiment to measure the small-signal gain of the inverter in the region were both transistors operate in their respective constant-current regions.