

Chapter 4

Bipolar Junction Transistor (BJT) Noise Measurements

Object

The objective of this experiment is to measure the mean-square equivalent input noise, v_{ni}^2 , and base spreading resistance, r_x , of some NPN Bipolar Junction Transistors (BJTs).

Theory

Equivalent Input Noise

It can be shown that v_{ni}^2 , the mean-square equivalent input noise measured over a narrow frequency band Δf centered at frequency f , of a resistively loaded BJT amplifier with zero small-signal impedance from both base to ground and emitter to ground is given by

$$v_{ni}^2 = \left[4kTr_x + \left(2q + \frac{K_f}{f} \right) \frac{I_C}{\beta} r_x^2 + 2qI_C \left(\frac{r_x}{\beta} + \frac{V_T}{I_C} \right)^2 \right] \Delta f \quad (4.1)$$

where, r_x is the base spreading resistance, $\beta = \Delta I_C / \Delta I_B$ is the small-signal current gain, I_C is the dc collector current, I_B is the dc base current, $k = 1.38 \times 10^{-23}$ is Boltzmann's constant, T is the Kelvin temperature, $q = 1.6 \times 10^{-19}$ is the electronic charge, $V_T = kT/q$ is the thermal voltage, K_f is the flicker noise-coefficient, and f is the frequency at which the mean-square noise voltage is measured. If the noise measurement is made at a frequency f where the flicker noise may be ignored, the expression for the mean-square equivalent input noise becomes

$$v_{ni}^2 = \left[4kTr_x + 2q \frac{I_C}{\beta} r_x^2 + 2qI_C \left(\frac{r_x}{\beta} + \frac{V_T}{I_C} \right)^2 \right] \Delta f \quad (4.2)$$

which is not a function of f .

Thus Eq. (4.1) may be used to calculate the equivalent input noise of a BJT if the collector current and transistor parameters are known. The small-signal current gain β may be readily measured from either the output or transfer characteristics of the transistor.

But attempting to measure the base spreading resistance, r_x , from the dc characteristics is essentially impossible. However, it can be determined from noise measurements.

Base Spreading Resistance

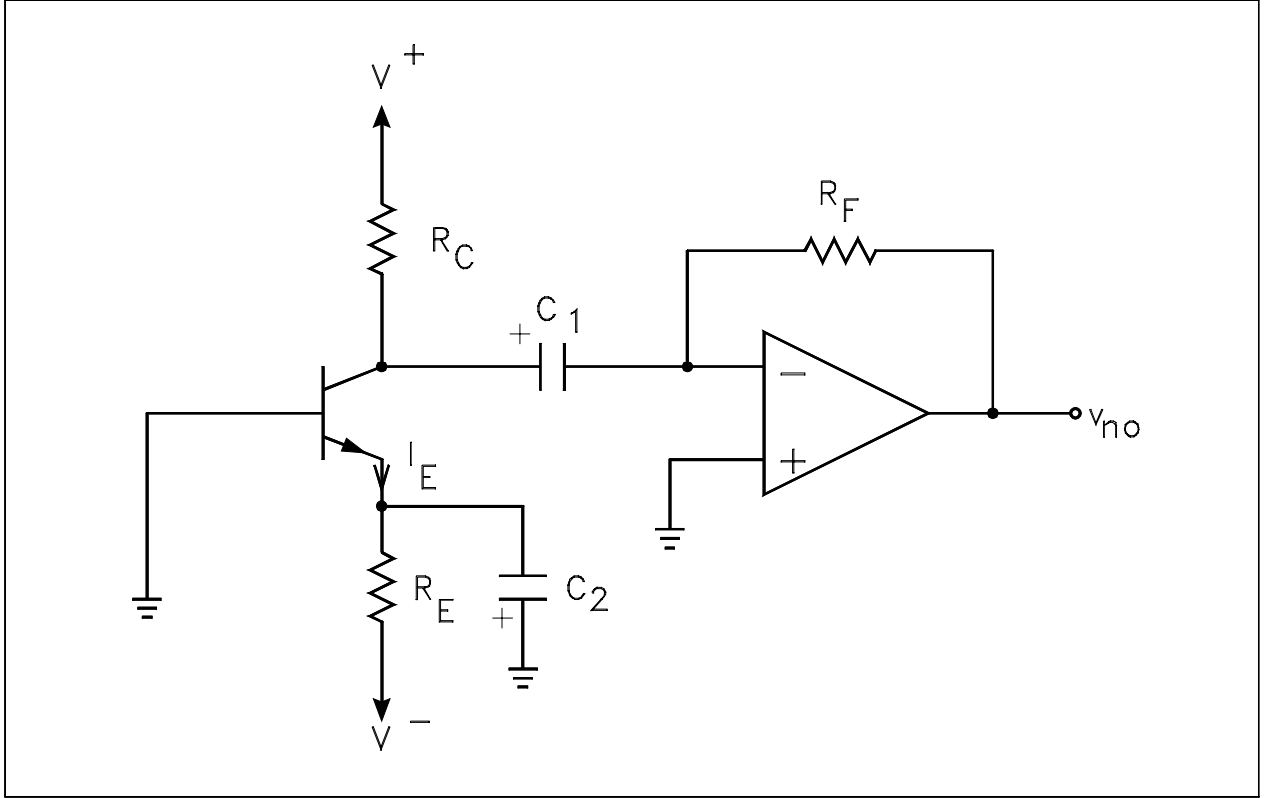


Figure 4.1: Circuit for measuring base spreading resistance.

The base spreading resistance of a BJT is one of the more prickly parameters to accurately measure. It can be measured using the circuit shown in Fig. 4.1. If it is assumed that the op amp is ideal and that the thermal noise in the feedback resistor R_F can be ignored, the mean-square output voltage of the op amp is given by

$$v_{no}^2 = R_F^2 G_m^2 \left[4kT r_x + \left(2qI_b + \frac{K_f I_B}{f} \right) r_x^2 + \frac{2qI_C}{G_m^2} \right] \Delta f \quad (4.3)$$

where

$$G_m = \frac{1}{\frac{r_x}{\beta} + \frac{V_T}{I_C}} \quad (4.4)$$

If the measurement is made at a high enough frequency so that the flicker noise component can be neglected, the base spreading resistance satisfies the quadratic equation

$$\left[\frac{A}{\beta^2} - \frac{2qI_C}{\beta} \Delta f \right] r_x^2 + \left[\frac{2AV_T}{\beta I_C} - 4kT \Delta f \right] r_x + \frac{AV_T^2}{I_C^2} = 0 \quad (4.5)$$

where

$$A = \frac{v_{no}^2}{R_F^2} - 2qI_C\Delta f \quad (4.6)$$

Thus Eq (4.5) may be solved to determine r_x using the measured value of v_{no}^2 . Only the positive solution for r_x should be used since the negative value has no physical meaning.

The capacitor C_1 is a coupling capacitor which prevents dc current from the transistor from flowing into the resistor R_F while forcing the entire signal component of the collector current to flow through this feedback resistor. The op amp inverting terminal is at a virtual ground which means that the signal component of the collector voltage is zero which eliminates the Early effect. The capacitor C_2 is a bypass capacitor which places the emitter at signal ground. Both of these capacitors are chosen to be large so that the low frequency noise spectrum is not altered. This means that these capacitors are electrolytic and the polarity is shown.

Laboratory Procedure

Base Spreading Resistance

Assemble the circuit shown in Fig. 4.1 on a solderless breadboard using a 2N4401 NPN BJT. Use an OP27 as the op amp. Use $V^+ = +15\text{ V}$ and $V^- = -15\text{ V}$ (these may be reduced to 9 V if the experimenters choose to assemble the circuits in the shielded boxes). Pick $C_1 = 10\ \mu\text{F}$ and $C_2 = 100\ \mu\text{F}$. The power supply decoupling network consisting of $100\ \Omega$ resistors and $100\ \mu\text{F}$ capacitors should be used. Insert a $100\ \Omega$ resistor between the output node of the circuit and the lead to the oscilloscope or signal analyzer. Insert a $100\ \text{pF}$ capacitor between the base and emitter terminals to eliminate possible rf electromagnetic interference.

Bias the circuit so that the collector current is $1\ \text{mA}$. The collector current is given by

$$I_C = \frac{-V^- - V_{BE}}{R_E} \quad (4.7)$$

where V_{BE} may be assumed to be 0.65 V . Eq (4.7) may be used to determine R_E . (It should be borne in mind that V^- is a negative voltage so $-V^-$ is a positive voltage.)

Select $R_C = R_E/2$. This places the collector-emitter bias voltage at approximately one half the positive power supply voltage. The choice of this bias is somewhat arbitrary.

The selection of the feedback resistor R_F is somewhat arbitrary. The larger R_F is the larger the output noise will be. But the larger R_F , the larger the thermal noise produced by this resistor will be. A value of $R_F = 100\ \text{k}\Omega$ should suffice.

Measure the collector current by using the DMM (Digital Multimeter) to measure the dc voltage across R_C and then use Ohm's law to determine the current. Measure the dc voltage at each terminal of the transistor.

Use the Dynamic Signal Analyzer to measure the mean-square output noise voltage v_{no}^2 at a frequency that is large enough so that the flicker noise may be neglected and at a low enough frequency so that the op amp and transistor combination have not begun rolling off the frequency response, i.e. make the measurement at a frequency where the output voltage is white or flat as a function of frequency.

Repeat the measurement for bias currents of 3 mA and 5 mA for the 2N4401 NPN BJT. Repeat the measurement for the 2N3904 NPN BJT.

NPN Equivalent Input Noise

The mean-square input noise v_{ni}^2 is related to the mean-square output noise by

$$v_{ni}^2 = \frac{v_{no}^2}{G_m^2 R_F^2} \quad (4.8)$$

This expression is to be compared with Eq. (4.1) once the base spreading resistance and small-signal current gain are determined.

Transistor Parameters

Use a transistor curve tracer to measure the small-signal current gain, β , of the 2N4401 and 2N3904 NPN BJTs for collector currents of 1 mA, 3 mA, and 5 mA that were used above.

Resistance Measurement

Use the DMM (Digital Multimeter) or the LCR meter to measure the value of each resistor that was used.

Measurement Bandwidth

Record the measurement bandwidth that was used by the **HP35665A** Dynamic Signal Analyzer. Press Disp Format and then Measurement State.

Laboratory Report

Bias

Tabulate the quiescent bias voltages and currents for each transistor for each of the three values of collector current for which data was taken.

Base Spreading Resistance

From the data obtained calculate the r_x of each transistor at the three collector bias currents that were used. What is the average value of r_x for each transistor type at the three collector bias currents? Also tabulate the values of r_x for each of the transistors.

Equivalent Input Noise

Use the values of that r_x were obtained to calculate v_{ni}^2 using Eq. (4.1). Compare these results to those obtained from Eq. (4.8) and the measured values of v_{no}^2 . Explain any significant differences between these results.