8. Common-Emitter Bipolar Junction Transistor Amplifier

Learning Objectives

Construct and characterize a bipolar junction transistor (BJT) amplifier in the common-emitter configuration.

Assignments Before the Laboratory Session

BJTs are basic building blocks of electronic amplifiers. They can provide high gain and some of them can handle high power. BJTs are current-controlled devices. By applying an input current from base to emitter, the current flowing from collector to emitter can be controlled. Since the base-emitter junction is forward biased during normal operation, the input impedance of a BJT is low. The current between collector and emitter is carried by the minority carriers of the base. In an npn BJT, for example, electrons flow from the emitter through base to the collector. Most electrons reach the collector. Only a small fraction, i.e., 0.5%, recombines with holes while passing through the base region. Holes in the base region are provided by the input base current. A 50-μA base current can, therefore, control the flow of a large, e.g., 10 mA, emitter current. This is the basic operational principle of all BJT amplifiers.

Parts needed include: 2N3904 BJT, electrolytic capacitors, 1-μF to 1000μF, resistors from 100 Ω to 1 MΩ.

According to the data sheet, 2N3904 is an npn transistor. Typical V_{BE} is 0.65-0.85 V. Typical h_{FE} is 100-300. Pin assignments are shown in Fig. 1. While you see the label of the device, pins from left to right are emitter, base, and collector.

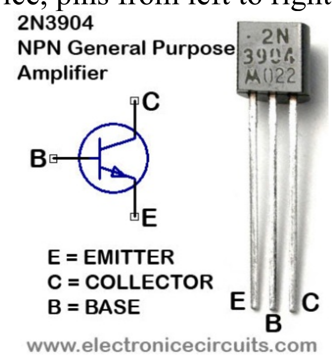


Fig. 1. The pin configuration of a typical BJT.
The label is printed on the flat side.

2N3904 is an npn BJT. Both the collector and emitter are n-type while the base is p-type. When it is biased for linear amplification in the active region, there is a 0.65 to 0.7 V base-emitter forward bias, V_{BE}, and a small base current, I_B. There is also a much larger positive voltage, e.g., 2.5-10 V, applied between the collector and the emitter, V_{CE}. Since the base voltage is only slightly higher than that of the emitter, the base-collector junction is reversely biased.

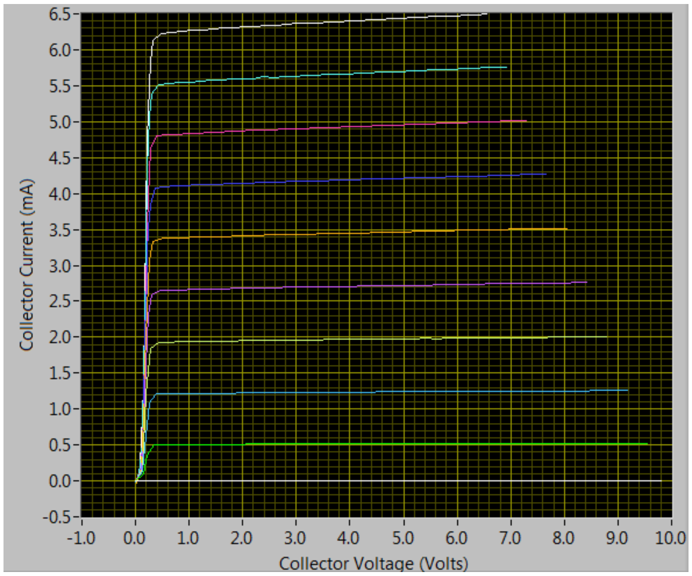


Fig. 2. The collector current versus collector-emitter voltage as a function of base current. The base current of the highest curve colored in white is 43 μA. The base current decreases gradually by 5 μA in each step.

For typical 2N3904, characteristics of the collector current, I_C, versus V_{CE} as a function of I_B are shown in Fig. 2. For each I_B, I_C increases sharply as V_{CE} is increased from zero. As V_{CE} reaches above 0.2 V, I_C becomes nearly independent of V_{CE}. In other words, the transistor behaves like a constant current source. This is the region to operate a linear BJT amplifier.

The relation of I_B versus V_{BE} represents the input characteristics. The input characteristics are closely related to diode characteristics. There are two pn junctions, base-emitter and base-collector. Two diodes, base-collector and base-emitter, are in parallel. When V_{CE} is large, the base-collector junction is reversely biased. When V_{CE} is zero the base-collector junction also conducts. The input characteristics of a typical 2N3904 are shown in Fig 3.

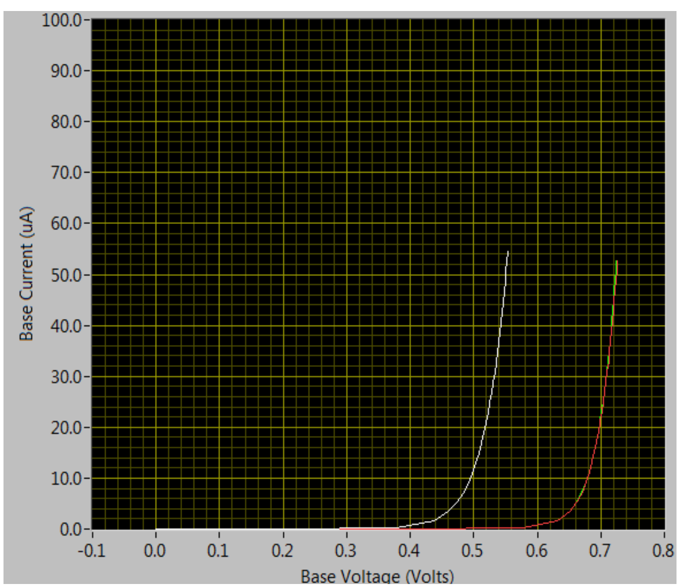


Fig. 3. The digitized input characteristics of BJT with V_{CE} ranging from 0 to 4 V.

The common-emitter BJT amplifier is shown in Fig. 4. There are two bias resistors connected to the base. These resistors are used to derive the required base bias current. The base bias current equals the difference between the current flowing through R_1 and the current flowing through R_2. The bias can control the gain and will affect the maximum output voltage without waveform clipping. It represents the most important operating condition of the circuit. The resistor R_E is used to provide a dc negative feedback to stabilize the circuit against variations of device parameters. Of course, it also affects the base voltage. The output is taken from the collector. There are two coupling capacitors, C_1, C_2 and one bypass capacitor, C_E. The input impedance of the amplifier and C_1 form a high pass filter. So do R_E and C_E. The output impedance of the amplifier, the load resistance and C_2 form yet another high pass filter. They limit the low frequency response of the amplifier.

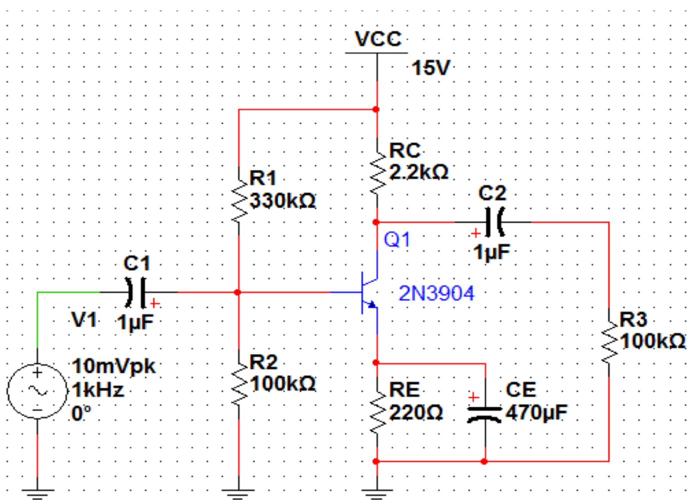


Fig. 4. The schematic diagram of the common-emitter BJT amplifier. C_2 is the output coupling capacitor and R_3 is the load.

To analyze the ac small signal gain and the frequency response of the circuit, the hybrid-π model shown in Fig. 5 is used. The resistance between the base lead and the base-emitter junction is r_x. The resistance of the base-emitter junction is r_π. The ac current gain, β_{ac}, is related to the transconductance, g_m, by

$$\beta_{ac} = g_m r_\pi \tag{1}$$

The internal collector resistance is r_c. There are two junction capacitors C_μ and C_π responsible for reduced gain at high frequencies. They both reduce the voltage gain at high frequencies.

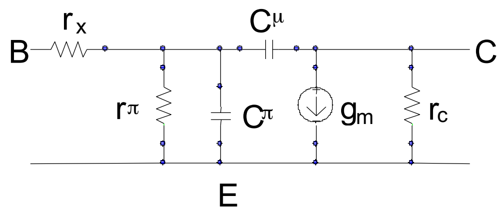


Fig. Fig. 5. The hybrid-π model of the BJT.

Based on the ideal diode model for the base-emitter junction and assume $I_C \cong I_E$, which is linearly proportional to the base current, it can be shown:

$$g_m = I_C \cdot \frac{e}{kT} \tag{2}$$

where *e* is the fundamental electron charge and k is the Boltzmann constant. At room temperature with the current in unit of mA,

$$g_m = 38.9 \cdot I_C \quad \text{mS} \tag{3}$$

By neglecting r_c at the output and r_x at the input of the hybrid-π model, the voltage gain becomes:

$$A_v = g_m R_C \tag{4}$$

Since g_m increases as I_C is increased, the gain of the amplifier depends on the bias condition. For the same R_C, the higher the power supply voltage, hence, the larger the current, the higher is the voltage gain. The full gain can only be fully realized for small input signals. As the input signal is increased, the output will eventually reach the saturation point like the operational amplifier. The output voltage is bound by the power supply voltage and ground. If the input signal is too large, the output waveform will become clipped.

The h parameters that you calculated in Exp. 7 are related to those of the hybrid-π model. In comparison with the hybrid-π model, the following relations and approximation apply:

$$h_{FE} = \beta_{ac} = g_m r_\pi \tag{5}$$

$$h_{IE} = r_\pi + r_x \tag{6}$$

$$h_{OE} = \frac{1}{r_c} \quad (7)$$

$$h_{RE} \approx 0 \quad (8)$$

Typical value of h_{FE} is in the 80-250 range. Typical value of h_{IE} is in the range of few hundred Ω to few kΩ. Both h_{RE} and h_{OE} can be neglected. Curves obtained from computer-assisted data acquisition can be used to determine h_{IE}, h_{FE}, and h_{OE}. Subsequently, by neglecting r_x, three parameters, r_π, g_m and r_c, can be obtained from Eqs. 5-7.

The internal junction capacitances and the gain of the amplifier determine the high frequency cut off. Again there is a tradeoff. The higher the gain, the lower is the bandwidth.

Activities During the Laboratory Session

Verify the integrity of the oscilloscope probe by connecting it to the internal square wave source. Verify the integrity of the multimeter test lead by measuring its resistance. By going through the following procedures, you will build, adjust the bias condition, and characterize the frequency response of a BJT amplifier in the common emitter configuration.

1. Use the multimeter in the resistance mode to measure the resistance between the base and the emitter. First, measure it with the red lead connected to the base and the black lead connected to the emitter. Record the resistance value. Then measure it again with leads interchanged. It is important not to touch the part with fingers while measuring a high resistance. The human body is a conductor of finite resistance. Do the same for the base-collector junction and between the collector and emitter. Please note that the resistance of a pn junction can be too large to measure, i.e., open or infinity. It should never be zero. Based on resistance measurements, what are the criteria to identify a good transistor?
2. Build the BJT amplifier shown in the circuit diagram. Do not attach any load resistor. Verify the polarity of the bypass capacitor connected to the emitter. Adjust the dc bias condition by varying resistors connected to the base so that V_{CE} is approximately half of the power supply voltage. Don't randomly make adjustments. Think before you act. If V_{CE} is too large, you need to increase I_C. If V_{CE} is too small, you need to decrease I_C. I_C is controlled by I_B. If you want I_C to go down, you need to reduce I_B. Do you increase R_1 or decrease R_1 to achieve this? Of course, you may use a potentiometer and adjust R_2 instead. Rarely but sometimes self-oscillation appears at high frequency, as evidenced by a smeared trace with large amplitude on the oscilloscope. If this happens, you need to rebuild the circuit with short leads. You may add a small capacitor, from 10 pF to 100 pF between the collector and base.

This will suppress the high frequency gain. It will eliminate the self-oscillation. It will also reduce the high frequency -3dB frequency.

3. The next step is to characterize the ac gain. Since the expected voltage gain is large, you need a voltage divider to reduce the output of the function generator to a level of 10 mV peak-to-peak. Don't rely on the automatic read out of the oscilloscope for V_{pp} measurement of the small input signal. It will read the peak of the noise instead of the sinusoidal waveform. Measure V_{pp} manually. The voltage divider is discussed in Exp. 1. As a signal source, the second resistor in the voltage divider should be small, i.e., 47 Ω. Connect the divided, small input signal through a coupling capacitor, e.g., 1-10 μF to the base of the transistor. The polarity of the coupling capacitor should be arranged such that the positive lead is connected to the base of the transistor. Why? Measure the ac gain at 1 kHz.
4. Increase the amplitude of the function generator until the output waveform of the amplifier becomes distorted, i.e., clipped or grossly rounded. Use the dc coupling mode at the input of the oscilloscope. If the clipping starts at bottom, i.e., near the ground voltage, the voltage at the collector should be increased by reducing the base current. If the waveform is grossly rounded at the top, i.e., near V_{CC}, then the base current should be increased. The base current can be changed by changing either R_1 or R_2. If distortion occurs evenly at both the top and the bottom, there is no further adjustment needed. V_{CE} should be approximately half the power supply voltage. For the large signal operation, there is always some waveform distortion. The waveform may be rounded at the top, for example. It reflects the intrinsic nonlinearity of the transistor. After obtaining the maximum voltage swing without distortion, measure the gain again. Record the circuit diagram showing values of all components, power supply voltage, and dc voltages at the base, collector, and emitter. Record input and output waveforms with large voltage swing but without clipping. The recorded waveform data should contain at least 10 sinusoidal cycles.

   When an amplifier is linear and the input is at one frequency, i.e., 1 kHz, there should be no harmonics, i.e., at 2 kHz, 3 kHz, etc., present in the output. In reality, all amplifiers become nonlinear when the signal becomes large. By performing the fast Fourier transform, you will find that the output contains harmonics of the input frequency. The amount of harmonic content is one of the characteristics of amplifiers. A high fidelity amplifier should have low harmonic distortion, e.g., 0.2%. Analyze the harmonic content of your recorded waveform. You can do it by either using the oscilloscope or by using Excel. Instructions on how to use the oscilloscope to perform spectral analysis can be found in the oscilloscope manual. If you want to learn how to use Excel for spectral analysis, search the web for "waveform distortion analysis excel" or "harmonic content excel." Browse and read the online information, e.g., http://www.stem2.org/je/Excel_FFT_Instructions.pdf.

5. Measure and record the gain as a function of frequency from 1 Hz to as high as the function generator can go. Determine the low frequency -3 dB point and the high frequency -3 dB point. -3 dB means 70.7% of the maximum voltage gain which occurs at the mid-frequency, i.e., at 1 kHz. Which component(s) do you change in order to extend to lower frequency?

Activities After the Laboratory Session

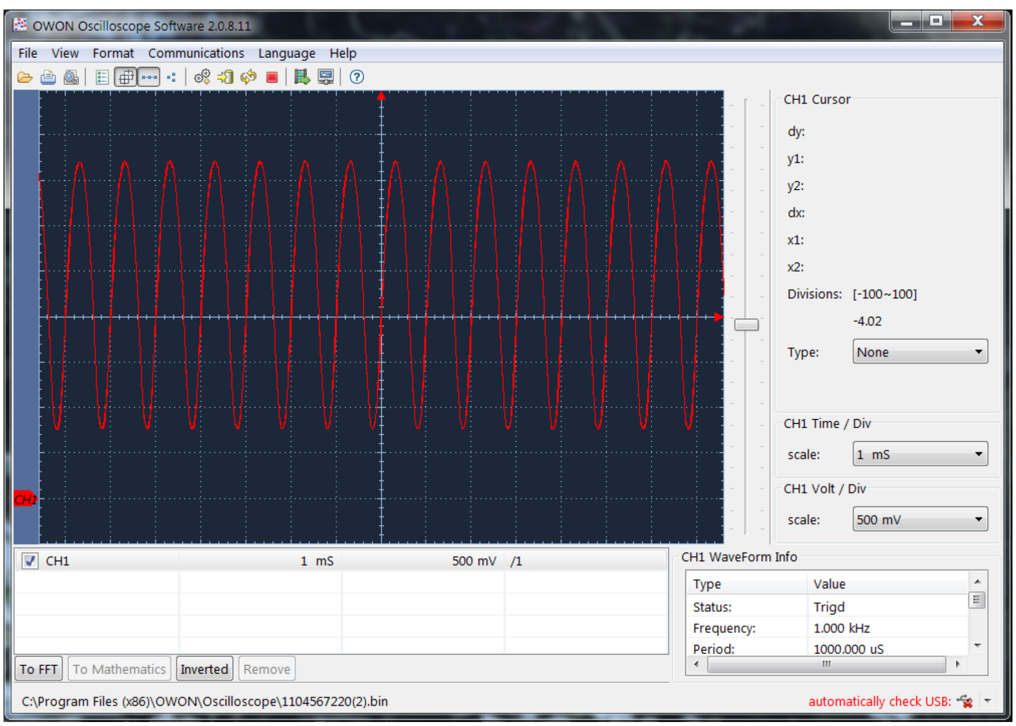
Prepare a short summary with data and conclusion.

Self Study

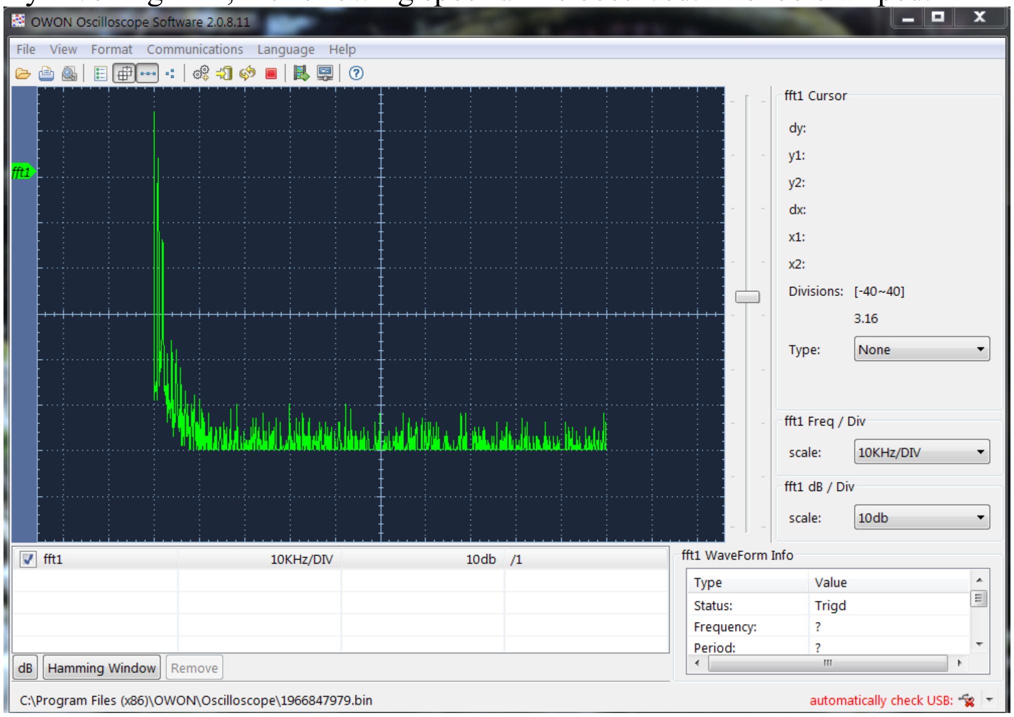
1. How do you know that a BJT is in good operating condition?
2. What are the typical characteristics of a common-emitter amplifier in terms of gain, input impedance, and output impedance?
3. How do you improve the low frequency response?

FFT and Harmonic Distortion Using Owon Oscilloscope

The following oscillogram shows the time-domain waveform of the output of BJT amplifier. As indicated, the time scale is 1 mS per horizontal division and 500 mV per vertical unit. The waveform is slightly rounded.



By invoking FFT, the following spectrum is observed. It is too cramped.



After adjusting the time scale and the vertical sensitivity of the oscilloscope, the following spectrum is observed.

As indicated, the horizontal scale is at 500 Hz/Division. The vertical scale is at 10 dB/unit. The leftmost peak is the zero frequency marker. The first peak, two horizontal units away, is the fundamental peak at 1 kHz. The next peak is the second harmonic peak at 2 kHz, approximately

-18 dB below the fundamental peak. The dB unit can be translated into linear scale by $10^{-18/10}$ or 0.0158. The second harmonic distortion is 1.58%. The subsequent harmonics, i.e., 3rd, 4th, and 5th, are much lower.

It is very important that you adjust the time base and sensitivity scale properly until the spectrum is clearly observable. Furthermore, you need to confirm which peak corresponds to the fundamental frequency. As you adjust the frequency of the function generator, the fundamental peak will shift while the zero frequency marker won't.

Cover and Score Sheet

Experiment 8 – Common-Emitter Bipolar Junction Transistor Amplifier

Author:______________________________ Partner:_________________________

Score

Item	Credit	Score
Data	4	
Transistor Condition Based on Measured Resistances		
Circuit Diagram of Amplifier Built		
DC Operating Conditions		
Bode Plot With -3dB Frequencies		
Input and Output Waveforms Showing Voltage Swing Without Clipping		
Fourier Transform and Harmonic Content		
Conclusion	1	
Total	**5**	

TA Signature:________________________ Date:______________________________