Experiment 381: Large-Signal Characteristics of Amplifier Circuits

Aim

The aim of this experiment is to acquaint students with the large-signal characteristics of some simple amplifier circuits.

Introduction

When circuits are used under large signal conditions (i.e. with signals sufficiently large that non-linearity of the semiconductor device characteristics becomes important) their behaviour is considerably different from that observed under small signal conditions.

The circuits selected for study are the basis of many others that are used in the processing of signals from physical experiments. Clearly they are not fully comprehensive, and if students wish to include additional circuits of their own design, they are encouraged to do so.

Comment:

Students may require discussions with the demonstrators during this experiment because some of the concepts and principles of semiconductor circuit operation are not easy to understand.

Equipment

The circuits to be investigated are already assembled on circuit boards. Changes can be made using crocodile-clips on flying leads provided for that purpose. Please **ask a demonstrator** if you feel unsure about how to connect the various flying leads to obtain the desired configuration.

The circuit board housing unit provides a means of holding the range of circuit boards, and it has a built-in 15 V d.c. power supply. Various a.c. signal voltage waveforms are available from a function generator.

The X-Y plotter consists of a PC with an AD/DA card, a Plotter Interface unit and a colour inkjet printer. The Plotter Interface unit has X and Y inputs and a Sweep output. Each input has a range switch which should be set to LOW if the input voltage is within ± 5 V and set to HIGH if the input voltage is outside ± 5 V. Turn on the PC and click on the "softplot" icon to display the plotter's control and display panel. Click the "setup" button and examine the various setup options. For this experiment, setup option 1 is recommended for most plots. Under option 1 a sweep of ± 13 V with X display range of ± 15 V and Y display range of ± 20 V has been pre-set. Option 2 setup with a pre-set sweep of ± 0.25 V, X display range of ± 0.3 V and Y display range of $+4$ V to $+16$ V is recommended for plotting the detailed characteristics of the difference amplifier. There is also a custom option under which other sweep and display ranges may beset.

Check that the X-Y plotter is functioning correctly by getting it to plot SWEEP voltage on both X and Y channels (i.e.Y=X=SWEEP). You should get a line through the origin with a slope of 1 displayed on the screen. Use "help" for descriptions of the control and display parameters. Consult a demonstrator if you need additional assistance.

You should have encountered a dual-trace oscilloscope and a function generator before, but if you are in doubt regarding their operation, either refer to the instruction manual (see technician) or consult a demonstrator. To avoid loading the circuit under study, use oscilloscope probes with $10\times$ attenuation for your observations.

Diagram and circuit convention

Upper case V's refer to d.c. voltages and lower case v's refer to a.c. signal voltages. In the early sections of this pamphlet all the voltages are shown with phasing arrows. In the latter sections, these arrows have been omitted from the circuits and when this occurs, it should be assumed that the voltages are to be measured with respect to "earth".

Modes of operation and equivalent circuits

Fig. 1 shows the circuit symbol an NPN junction transistor. The physical structure of the transistor shows that there are two pn junctions. The base-emitter junction is distinguished from the base-collector junction by the surface area of the emitter and the collector regions. The collector has a much larger surface area to enable it to collect most of the carriers emitted by the emitter.

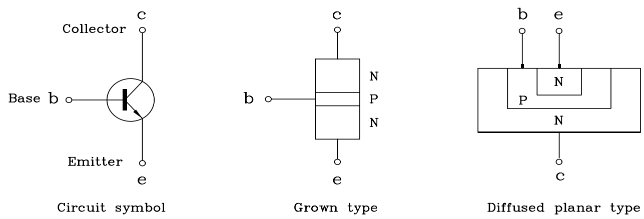

Figure 1: NPN junction transistor

Each of the two pn junctions may be either forward or reverse biased and this gives rise to four modes of operation corresponding to the four biasing possibilities (see Table). Fig. 2 shows models of the transistor for the four modes of operation.

bc junction	be junction	Mode of operation
Reverse biased	Reverse biased	Cut-off
Reverse biased	Forward biased	Active
Forward biased	Reverse biased	Inverse
Forward biased	Forward biased	Saturated

If a two-piece approximation of the diode's I-V curve is assumed, linear equivalent circuits may be derived from the models by replacing reverse-biased diode by an open-circuit and a forward-biased diode by a voltage V_k in series with a resistance r_e. The voltage V_k represents the onset of conduction (typically about 0.7 V for Si) and represents the forward conducting resistance (typically about $5\,\Omega$ at $I_e = 5\,\text{mA}$). The resistance r_e is also called h_{ib} since it is the common-base input resistance of the transistor. You may find these equivalent circuits useful in explaining the behaviour of the amplifiers in this experiment.

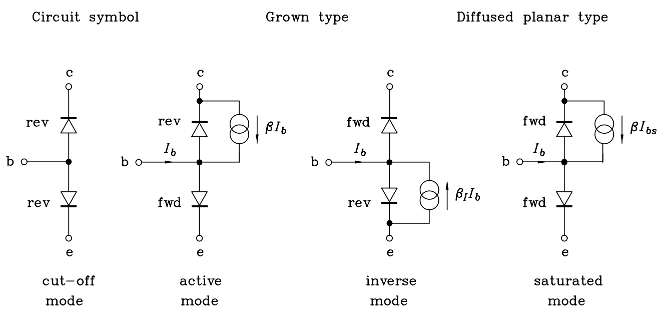

Figure 2: Equivalent circuits of NPN transistor in various modes

In the inverse mode the transistor is operating with the collector functioning as an emitter and the emitter functioning as a collector. Understandably β_I is very poor. For this reason the transistor is rarely operated in this mode but its model is included here for completeness. In the saturated mode most of the base current flows in the base-emitter pn junction and the small voltage between the collector and the emitter (typically 0 to 0.2V) is due to the voltage developed across the r_e of the base-emitter junction by I_b and βI_{bs} where I_{bs} is the value of I_b when the base-collector junction just becomes forward biased.

Caution: Turn off the power supply before you set up your circuit. Check your wiring before turning on the power supply. If in doubt ask a demonstrator to check your wiring.

1 Base-emitter and Base-collector Junction Characteristics

Use the ***left-hand*** *transistor on circuit board 1.* ***Do NOT connect the power supplies*** *to the three terminals marked* −15 V, GND *and* +15 V *on circuit board for this part of the experiment, since you will need to leave the emitter disconnected for some of the procedures.*

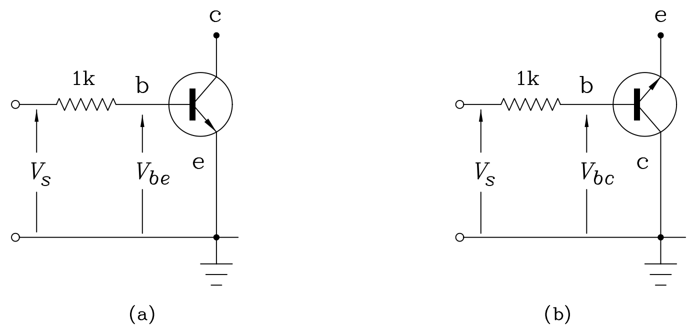

Figure 3: Junction Characteristics

(1) Set up circuits (a) and (b) of Fig. 3 in turn and using the X-Y plotter with option 1 setup and both X-input and Y-input range switches set to HIGH, obtain graphs of V_{be}-versus-V_s and V_{bc}-versus-V_s. Plot both graphs in one diagram using a different colour for each graph. Explain the different regions of your graphs.

(2) Save the data points of the graphs you have plotted as files with names `Vbe.dat` and `Vbc.dat`. Using MATLAB calculate the base currents I_{be} and I_{bc} and plot I_{be}-versus-V_{be} and I_{bc}-versus-V_{bc} in one diagram.

(3) To get a better picture of the forward conducting region obtain V_{be}-versus-V_s and V_{bc}-versus-V_s using the X-Y plotter with the X-input range switch set to HIGH and the Y-input range switch set to LOW and following custom settings:

X display range 0 to 14 V	Y display range 0 to 1 V
X limit 20 V	Y limit 1.25 V
Sweep range 0 to 13 V	

(4) Save the data points as `Vbe.dat` and `Vbc.dat` files. Using MATLAB plot I_{be}-versus-V_{be} and I_{bc}-versus-V_{bc} over a voltage range of 0.4V to 0.8V. From these graphs estimate V_k and r_e.

2 Basic Common-Emitter Amplifier

In the basic C-E amplifier circuit (Fig. 4), V_s controls the base current and V_c gives an indication of the collector current. The currents I_b and I_c are given by:

$$I_b = \frac{V_s - V_b}{R_b} \quad \text{and} \quad I_c = \frac{V_{cc} - V_c}{R_c}$$

In the linear region of operation (i.e. where $\delta V_c/\delta V_s$ is constant) both V_{cc} and V_b are constant so that:

$$\delta I_b = \frac{\delta V_s}{R_b} \quad \text{and} \quad \delta I_c = -\frac{\delta V_c}{R_c}$$

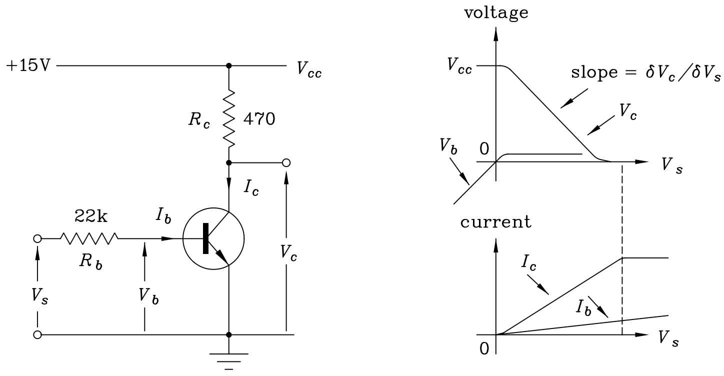

Figure 4: Basic Common-Emitter Amplifier

Then the small-signal current gain β is given by:

$$\beta = \frac{\delta I_c}{\delta I_b} = -\frac{R_b}{R_c}\left(\frac{\delta V_c}{\delta V_s}\right)$$

*Use the **left-hand** transistor on circuit board 1. Connect the power supplies to the three terminals marked* $-15\,\mathrm{V}$, GND *and* $+15\,\mathrm{V}$ *on circuit board. Note that there is a wire on the underside of the board which connects the uppermost rail (red) to* $+15\,\mathrm{V}$.

(5) Set up the circuit of Fig. 4 and using the X-Y plotter with option 1 setup obtain graphs of both V_c-versus-V_s and V_b-versus-V_s.

(6) Save the data points of the graphs you have plotted as `Vc.dat` and `Vb.dat`. Using MATLAB and the relationships given above, determine the small-signal current gain β. Derive I_b and I_c for various values of V_s and plot the graphs for I_c-versus-V_s and I_b-versus-V_s.

Questions

Q1. Identify the ranges of voltage within which the transistor is (a) cutoff, (b) active (c) saturated.

Q2. What is the maximum current that can flow in the collector circuit? Is there a corresponding upper limit to the current that can flow in the base circuit?

Q3. Suppose the value of R_b is reduced to $2.2\,\mathrm{k\Omega}$. How will this affect the overall circuit? Will it change the value of β?

3 Limiting Amplifier

*Use the **left-hand** transistor on circuit board 1. Connect the power supplies to the three terminals marked* $-15\,\mathrm{V}$, GND *and* $+15\,\mathrm{V}$ *on circuit board. Note that there is a wire on the underside of the board which connects the uppermost rail (red) to* $+15\,\mathrm{V}$.

(7) Set up the circuit of Fig. 5(a) and using the X-Y plotter with option 1 setup obtain graphs of V_c-versus-V_s and V_b-versus-V_s with and without the base-clamping diode connected. Plot all four graphs in one diagram using a different colour for each graph.

Questions

Q4. Does the diode affect the V_c-versus-V_s characteristics?

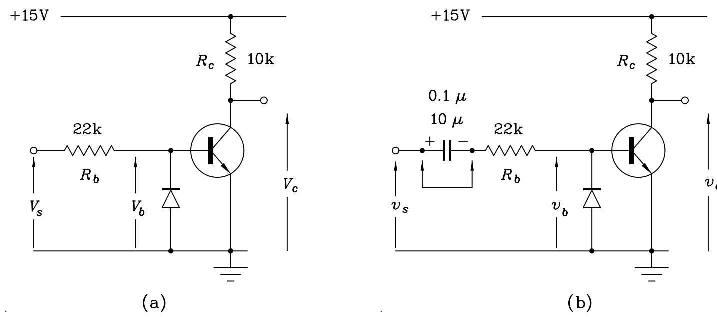

Figure 5: Limiting Amplifier

Q5. What determines the maximum value of the collector current?

Q6. The limiting amplifier can be used in its non-linear mode as a voltage level discriminator. Over what input voltage range does discrimination take place?

(8) Set up the circuit of Fig. 5(b) with a short-circuited 10 μF input capacitor and the base-clamping diode disconnected. Apply a 4V p-p, 1kHz sinusoidal voltage waveform to the input. Observe the waveforms v_b and v_c simultaneously using the dual-trace oscilloscope with inputs D-C coupled and the vertical sensitivity for v_b set at 1V/div and that for v_c set at 5 V/div. Set the zero voltage level in the middle of the screen.

(9) Connect the base-clamping diode and note any changes, if any, in the waveforms.

(10) Disconnect the base-clamping diode, and whilst observing v_b and v_c, remove the short-circuit from the input capacitor, so that the input signal is a.c. coupled. Replace the short-circuit for a short time, and then remove it again. Explain why the output signal v_c almost "disappears" after about 10 seconds.

(11) Repeat the previous procedure this time observing v_s and v_c. Observe that the output signal now totally "disappears" when the short-circuit across the capacitor is removed. Explain your observations.

(12) With the short-circuit removed, reconnect the base-clamping diode and observed that the output signal is restored.

(13) Repeat the previous two procedures using the 0.1 μF capacitor instead of the 10 μF capacitor. Before proceeding any further, make sure that you understand fully the function of the base-clamping diode when the input signal is a.c. coupled.

4 Emitter Follower

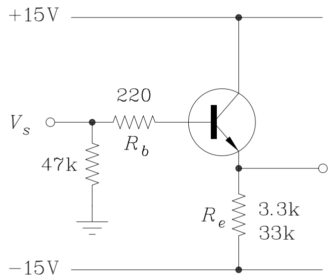

Figure 6: Emitter Follower

R_b is necessary to stop oscillations arising due to the long leads used to connect the circuits to the X-Y plotter. It is so small that its effect on any of the measurements made here is negligible.

*Use the **right-hand** transistor on circuit board 1. Connect the power supplies to the three terminals marked* −15 V, GND *and* +15 V *on circuit board. Note that there is a wire on the underside of the board which connects the uppermost rail (red) to* +15 V *.*

(14) Set up the circuit of Fig. 6 with $R_e = 3.3\,\mathrm{k\Omega}$. Using the oscilloscope, measure the base and emitter voltages with no input signal connected. Determine the β of the transistor from your measurements. Repeat your measurements with $R_e = 33\,\mathrm{k\Omega}$.

(15) Calculate the power dissipated in the transistor and in R_e for each value of R_e.

(16) Using the X-Y plotter with option 1 setup obtain graphs of V_e-versus-V_s for the circuit of Fig. 6 with $R_e = 3.3\,\mathrm{k\Omega}$ and $R_e = 33\,\mathrm{k\Omega}$. Plot both graphs in the same diagram. In both cases determine the average voltage "gain".

Question

Q7. For many applications it is usual to consider the emitter follower as an impedance converter with unity gain, and a constant voltage difference between input and output. What value would you give this voltage difference, and would it have a different value for a Ge transistor?

(17) Set up the circuit of Fig. 7(a) firstly with $R_e = 3.3\,\mathrm{k\Omega}$, and then with $R_e = 33\,\mathrm{k\Omega}$. For each value of R_e use the X-Y plotter with option 1 setup to plot a graph of V_e-versus-V_s. Plot both graphs in the same diagram.

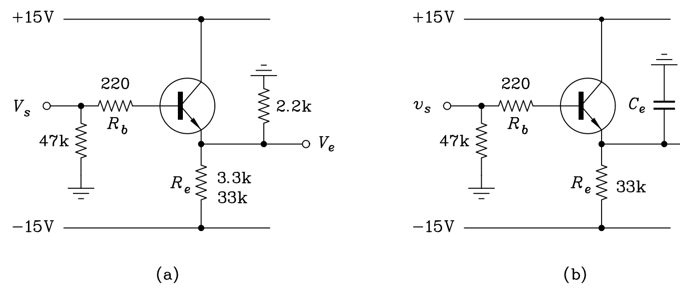

Figure 7: Emitter follower with load

The results should be somewhat different from those obtained with the circuit of Fig.6. The low output impedance of the emitter follower should allow it to "drive" a load impedance of $2.2\,\mathrm{k\Omega}$. However this load is connected between the emitter and ground, and not actually in parallel with. R_e. Explain your results.

(18) Set up the circuit of Fig. 7(b) in which the load is a capacitance of $0.1\,\mu\mathrm{F}$. Apply a 10 V p-p, 1kHz sinusoidal voltage waveform to the input and observe the output and input voltage waveforms simultaneously using the oscilloscope with both channels d.c. coupled at a common sensitivity of 2V/div. Set the zero voltage level in the middle of the screen.

(19) Superimpose the two waveforms by displacing the v_e waveform with the position control knob. Change the signal frequency until some distortion begins to appear. Observe that the distortion commences when the input signal decreases at a rate greater than the maximum discharge rate.

Question

Q8. The phenomenon you are observing is known as "slew rate" distortion. What is the maximum rate that the capacitor can discharge when the transistor is cut-off? Is this rate consistent with the frequency at which you begin to see slew rate distortion for the given input amplitude?

5 Split Load Amplifier

The split load amplifier is used to obtain two output signals that are 180° out of phase with each other. Essentially it is just like an emitter follower with a resistance in the collector circuit across which the second output voltage is developed. Whereas the emitter output voltage gain is still approximately unity, the collector output voltage gain is approximately $-R_c/R_e$.

Use the ***right-hand*** *transistor on circuit board 1. Connect the power supplies to the three terminals marked* −15 V, GND *and* +15 V *on circuit board. Note that there is a wire on the underside of the board which connects the uppermost rail (red) to* +15 V .

(20) Set up the circuit of Fig. 8(a) and using the X-Y plotter with option 1 setup obtain graphs of V_e-versus-V_s and V_c-versus-V_s for $R_c = 1\,\mathrm{k}\Omega$ and $3.3\,\mathrm{k}\Omega$. Plot all four graphs in one diagram.

(21) Explain the non-linearities that occur in the curves, and predict where these would occur for values of $R_c = 2.2\,\mathrm{k}\Omega$ and $R_c = 10\,\mathrm{k}\Omega$. Explain why the slope of the curves changes from approximately unity to $1/\left[1 + (R_b/R_e) + (R_b/R_c)\right]$ after the transistor reaches saturation. From the graphs you have obtained, find the emitter output voltage gain and the collector output voltage gain for each value of R_c.

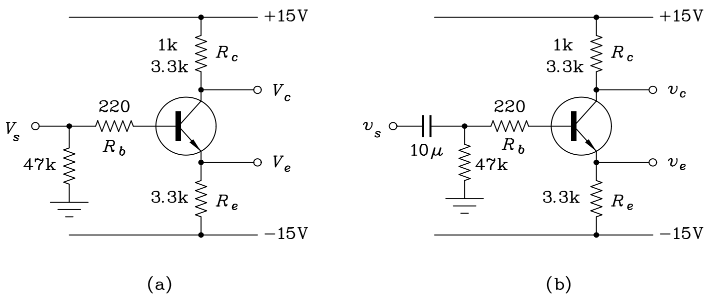

Figure 8: Split Load Amplifier

Question

Q9. For $R_c = 3.3\,\mathrm{k}\Omega$ what is the value of that corresponds to the middle of the linear region of operation for the collector output voltage?

(22) Set up the circuit of Fig. 8(b). Apply a triangle voltage waveform to the input with both channels of the oscilloscope D-C coupled at a common sensitivity of 5V/div. Set the zero voltage level in the middle of the screen.

(23) Check the overall linearity of the amplifier, and show that its maximum signal handling capability is about 15V p-p at each output. (For optimum design both outputs either cut-off or saturate with the same input signal amplitude.)

6 Difference Amplifier

The purpose of this section of the experiment is to observe and compare the characteristics of two alternative difference amplifier circuits. One has a single resistor to define the common emitter current, and the other has a constant current circuit in place of the single resistor. This circuit is set up on circuit board 2.

(24) Set up the circuit of Fig. 9(a) and using the X-Y plotter with option 1 setup obtain graphs of V_e-versus-V_s, V_{c1}-versus-V_s, and V_{c2}-versus-V_s. Plot all three graphs in one diagram. Explain the shapes of the graphs, and account for each value of slope observed. Seek help at this stage if you cannot do this.

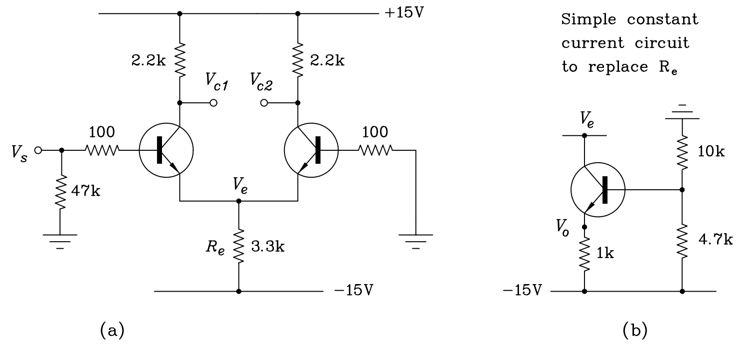

Figure 9: Difference Amplifier

(25) Replace the common emitter resistor with the constant-current circuit of Fig. 9(b). Repeat all the graphs of the previous procedure and in addition plot V_0-versus-V_s in the same diagram. This latter graph will check the effectiveness of the constant current circuit.

(26) Plot graphs of V_{c1}-versus-V_s and V_{c2}-versus-V_s using option 2 setup with the X-input range switch set to LOW and the Y-input range switch set to HIGH. Plot both graphs in one diagram. Measure the difference gain of the amplifier for small signals, and find the change in V_s corresponding to a 10 to 90 % change in I_{c1} or I_{c2}.

(27) Disconnect the base lead of the right transistor from "earth", and connect it to the input of the left transistor, i.e. to V_s. Using the X-Y plotter with option 1 setup obtain graphs of V_e-versus-V_s, V_{c2}-versus-V_s and V_0-versus-V_s. You will need to toggle the X-input range switch on the Plotter Interface Unit from LO to HI. Plot all three graphs in one diagram.

(28) Replace the constant-current circuit with the common emitter resistor R_e and plot graphs of V_e-versus-V_s and V_{c2}-versus-V_s. Explain the shapes of the graphs of the last two procedures.

Common-mode Gain

If a circuit for comparing two voltages is any good, then its output voltage should depend only on the difference between the input voltages, i.e. with both inputs connected together the output voltage should be independent of the input voltage. The ratio of any output voltage change to the input voltage change under these conditions is known as the common-mode voltage gain. Ideally the common-mode gain should be zero. In practice it is never quite zero, although with careful design it can be made very small.

Question

Q10. The slope of V_{c2}-versus-V_s over its linear region for the difference amplifier with the both inputs tied together is the common-mode gain. Show that it should be $-\frac{1}{3}$ for the amplifier with R_e connected. What is it for the constant-current case?

Common-mode Rejection Ratio (CMRR)

An indication of the "quality" of a difference amplifier is provided by the ratio of the difference mode gain to the common-mode gain. This ratio is known as the common-mode rejection ratio (CMRR). A substantial increase in the CMRR is obtained by using a constant current circuit in place of the emitter resistor.

Question

Q11. What is the common-mode rejection ratio for each form of the difference amplifier in Fig.9?

Signal Comparison

The difference amplifier is often used to compare two signals, but the configuration employed in this experiment utilises only one input signal. With reference to circuit of Fig. 9(a), assuming identical transistors, when the input voltage is zero, i.e. the two bases are at the same voltage, the current through the emitter resistor will divide equally between each transistor, and both outputs will be at the same voltage. If one base is at a voltage that is more than a hundred or so millivolts different from the voltage at the other base, then the transistor with the higher base voltage will conduct all the emitter current defined by R_e, and the other transistor will be cut-off.

Questions

Q12. The current through R_e is determined by the higher base voltage. Why?

Q13. Why is one output voltage more or less symmetrical about the zero input voltage level, while the other is not?

Q14. How reasonable is it to consider the difference amplifier as a common base amplifier with its input signal applied at the emitter, and this input signal supplied via an emitter follower.

List of Equipment

1. IBM PC with AD/DA card and "softplot" program installed
2. Wavetek 130 or Noy-Tronics 300 MSTPC/02 Function Generator
3. Hitachi V212 Dual-trace Oscilloscope with Probes
4. Circuit board housing unit with integral 15V Power supply
5. Circuit board holder
6. 2 Circuit boards with pre-wired circuits

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February 2000