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ABSTRACT

This individualized learning module on special devices is one in a series of modules for a course in basic electricity and electronics. The course is one of a number of military-developed curriculum packages selected for adaptation to vocational instructional and curriculum development in a civilian setting. Four lessons are included in the module: (1) Delay Lines, (2) Dummy Loads, (3) Special Solid State Devices, and (4) Field-Effect Transistors. Each lesson follows a typical format including a lesson overview, a list of study resources, the lesson content, a programmed instruction section, and a lesson summary. (Progress checks and other supplementary material are provided for each lesson in a student's guide, CE 026 590.) (LRA)

Military Curricula for Vocational & Technical Education

CHIEF OF NAVAL EDUCATION AND TRAINING

CNTT-E-055

JULY 1980

BASIC ELECTRICITY AND ELECTRONICS.

MODULE 33. SPECIAL DEVICES.

STUDY BOOKLET.

THE NATIONAL CENTER
FOR RESEARCH IN VOCATIONAL EDUCATION
THE OHIO STATE UNIVERSITY

MILITARY CURRICULUM MATERIALS

The military-developed curriculum materials in this course package were selected by the National Center for Research in Vocational Education Military Curriculum Project for dissemination to the six regional Curriculum Coordination Centers and other instructional materials agencies. The purpose of disseminating these courses was to make curriculum materials developed by the military more accessible to vocational educators in the civilian setting.

The course materials were acquired, evaluated by project staff and practitioners in the field, and prepared for dissemination. Materials which were specific to the military were deleted, copyrighted materials were either omitted or approval for their use was obtained. These course packages contain curriculum resource materials which can be adapted to support vocational instruction and curriculum development.

Military Curriculum Materials Dissemination Is . . .

an activity to increase the accessibility of military-developed curriculum materials to vocational and technical educators.

This project, funded by the U.S. Office of Education, includes the identification and acquisition of curriculum materials in print form from the Coast Guard, Air Force, Army, Marine Corps and Navy.

Access to military curriculum materials is provided through a "Joint Memorandum of Understanding" between the U.S. Office of Education and the Department of Defense.

The acquired materials are reviewed by staff and subject matter specialists, and courses deemed applicable to vocational and technical education are selected for dissemination.

The National Cente or Research in Vocational Educatı is the U.S. Office of Education's designated representative to acquire the materials and conduct the project activities.

Project Staff:

Wesley E. Budke, Ph.D., Director
National Center Clearinghouse

Shirley A. Chase, Ph.D.
Project Director

What Materials Are Available?

One hundred twenty courses on microfiche (thirteen in paper form) and descriptions of each have been provided to the vocational Curriculum Coordination Centers and other instructional materials agencies for dissemination.

Course materials include programmed instruction, curriculum outlines, instructor guides, student workbooks and technical manuals.

The 120 courses represent the following sixteen vocational subject areas:

Agriculture	Food Service
Aviation	Health
Building & Construction Trades	Heating & Air Conditioning
Clerical Occupations	Machine Shop
Communications	Management & Supervision
Drafting	Meteorology & Navigation
Electronics	Photography
Engine Mechanics	Public Service

The number of courses and the subject areas represented will expand as additional materials with application to vocational and technical education are identified and selected for dissemination.

How Can These Materials Be Obtained?

Contact the Curriculum Coordination Center in your region for information on obtaining materials (e.g., availability and cost). They will respond to your request directly or refer you to an instructional materials agency closer to you.

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- Generating knowledge through research
- Developing educational programs and products
- Evaluating individual program needs and outcomes
- Installing educational programs and products
- Operating information systems and services
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Military Curriculum Materials for Vocational and Technical Education

Information and Field Services Division

The National Center for Research in Vocational Education

PREPARED FOR

BASIC ELECTRICITY AND ELECTRONICS

CANTRAC A-100-0010

MODULE THIRTY THREE

SPECIAL DEVICES

PREPARED BY

NAVAL EDUCATION AND TRAINING

PROGRAM DEVELOPMENT CENTER DETACHMENT

GREAT LAKES NAVAL TRAINING CENTER

GREAT LAKES, ILLINOIS 60088

STUDY BOOKLET

JULY 1980

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OVERVIEW
BASIC ELECTRICITY AND ELECTRONICS
MODULE 33

Special Devices

In this module you will learn about special devices used in electronics. The delay lines of lesson 1 and dummy loads of lesson 2 are not semiconductor devices but have been a part of the electronics field for some time.

The specialized devices of lessons 3 and 4 are of two types. The first type of device, covered in lesson 3, is taken from the field of optoelectronics. Optoelectronics deals with devices having an electronic input and using light energy to perform some function. The optoelectronic devices are similar to other less specialized devices. Examples of these devices are light-emitting diodes, photodiodes, phototransistors, etc. All of the special devices you will study in this module were designed to fill some particular need of modern electronics but all are relatively simple and easy to learn.

The second type of specialized device is the special-purpose semiconductor. Three of these will be studied. Each offers an improvement over the transistors and diodes you are familar with and yet is similar in operation. The varactor diode and the triac are covered in lesson 3 and the field-effect transistor in lesson 4.

This module has been divided into four lessons:

Lesson 1 Delay Lines
Lesson 2 Dummy Loads
Lesson 3 Special Solid State Devices
Lesson 4 Field-Effect Transistors

Do not be concerned at this time with names of terms unfamiliar to you. Each will become clear as you proceed. However, if you have any questions, do not hesitate to call upon your Learning Center Instructor.

BASIC ELECTRICITY AND ELECTRONICS

MODULE THIRTY THREE

LESSON I

DELAY LINES

JULY 1980

OVERVIEW
LESSON 1

Delay Lines

In this lesson you will learn about a special device called a delay line. You will become familiar with the operating characteristics of two general types of delay lines, and with the kinds of delay lines available in each type. You will learn the differences between the delay lines, and the situations in which they can be used.

The learning objectives of this lesson are as follows:

TERMINAL OBJECTIVE(S):

33.1.61 When the student completes this lesson (s)he will be able to IDENTIFY the purpose, function and operational characteristics of electromechanical and electromagnetic delay lines by selecting statements from a choice of four. 100% accuracy is required.

ENABLING OBJECTIVES:

When the student completes this lesson (s)he will be able to:

33.1.61.1 IDENTIFY the purpose of delay lines by selecting the correct statement from a choice of four. 100% accuracy is required.

33.1.61.2 IDENTIFY the general principle by which time delay is accomplished in an electromechanical delay line by selecting the correct statement from a choice of four. 100% accuracy is required.

33.1.61.3 IDENTIFY the operating methods and characteristics of specific electromechanical delay line devices by selecting the correct statement from a choice of four. 100% accuracy is required.

33.1.61.4 IDENTIFY the general principle by which time delay is accomplished in an electromagnetic delay line by selecting the correct statement from a choice of four. 100% accuracy is required.

33.1.61.5 IDENTIFY the operating methods and characteristics of specific electromagnetic delay line devices by selecting the correct statement from a choice of four. 100% accuracy is required.

33.1.61.6 IDENTIFY the relationship between impedance matching and the operating characteristics of a delay line by selecting the correct statement from a choice of four. 100% accuracy is required.

BEFORE YOU START THIS LESSON, READ THE LESSON LEARNING OBJECTIVES AND PREVIEW THE LIST OF STUDY RESOURCES ON THE NEXT PAGE.

LIST OF STUDY RESOURCES
LESSON I

Delay Lines

To learn the material in this lesson, you have the option of choosing, according to your experience and preferences, any or all of the following study resources:

Written Lesson presentation in:

Module Booklet:

Summary
Programmed Instruction
Narrative

Student's Guide

Summary
Progress Check

Additional Material(s):

Enrichment Material(s):

Electronics Installation and Maintenance Book (EIMB)(Test Methods and Practices), NAVSHIPS 0967-000-0120

YOU MAY USE ANY, OR ALL, RESOURCES LISTED ABOVE, AND ALSO THE LEARNING CENTER INSTRUCTOR. HOWEVER, ALL MATERIALS LISTED ARE NOT NECESSARILY REQUIRED TO ACHIEVE LESSON OBJECTIVES. THE PROGRESS CHECK MAY BE TAKEN AT ANY TIME.

SUMMARY
LESSON 1

Delay Lines

Many electronic equipments use delay lines to trigger some circuits at later times than others. Most delay lines are divided into two categories: electromechanical and electromagnetic.

Electromechanical delay lines convert electrical input signals into mechanical motion (ultrasonic energy), transfer this energy as motion through some physical medium, and reconvert it to electrical output signals. The time delay depends on the medium used (such as mercury, a steel spring, quartz crystal) and the length of the delay line.

Figure 1 shows the signal characteristics for electromechanical delay lines.

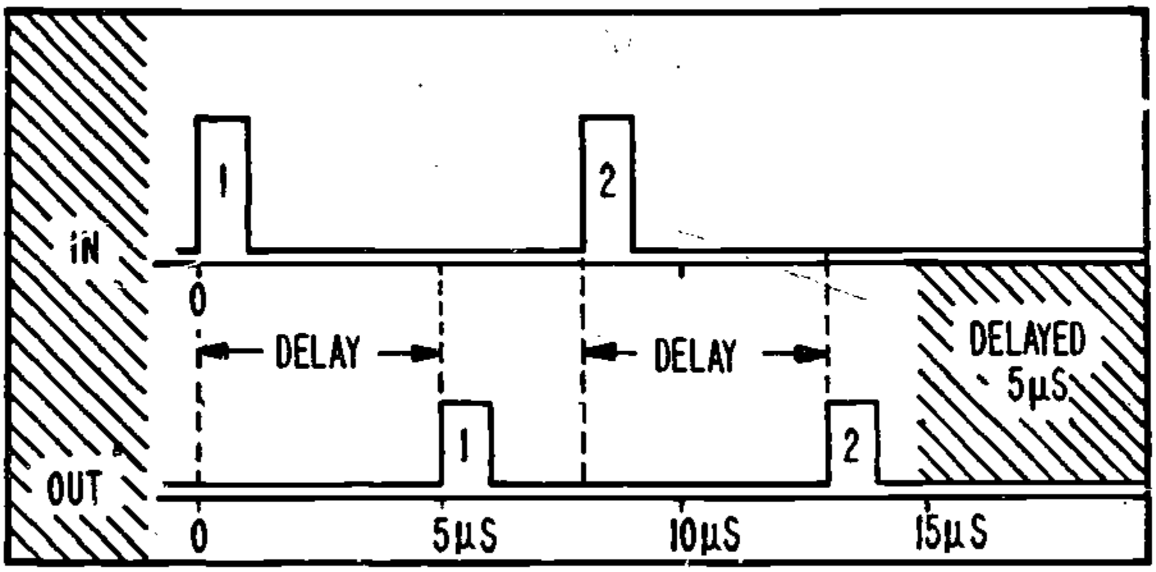


Figure I

ILLUSTRATION OF ELECTROMECHANICAL TIME DELAY

The output signal is a delayed, non-distorted, and attenuated copy of the input signal.

13

One type of electromechanical delay line is made up of a column of mercury with a slab of quartz crystal at each end as shown in Figure 2.

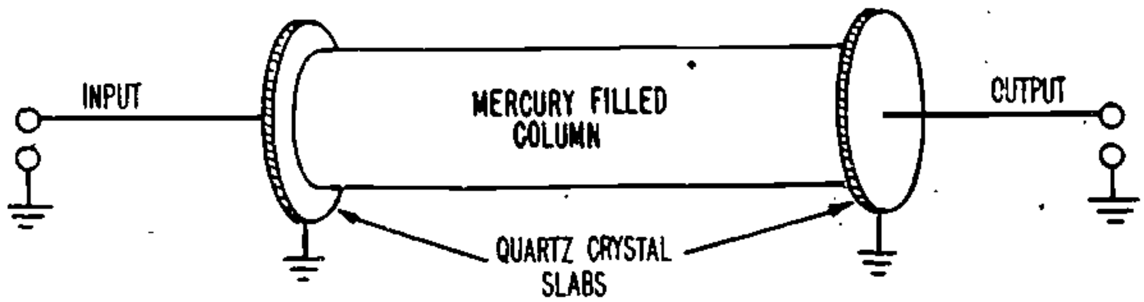


Figure 2

ELECTROMECHANICAL MERCURY DELAY LINE

The mercury delay line uses the piezoelectric effect of the quartz crystals to convert electrical energy into mechanical energy, and reconvert mechanical energy back into electrical energy.

Electromagnetic delay lines are devices which function through the action of charging and discharging capacitance, and expanding and collapsing inductive, or magnetic, fields. Standard coaxial cable (coax), as shown in Figure 3, may be used as a electromagnetic delay line.

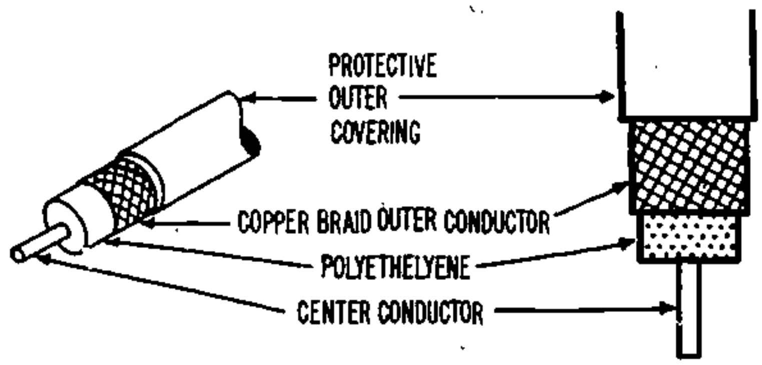


Figure 3

STANDARD COAXIAL CABLE

The time delay in coaxial cable is directly proportional to cable length.

Spiral-wound coaxial cable, as shown in Figure 4, produces a time delay which is about 14 times greater than that of standard coax, because of the coiled center conductor.

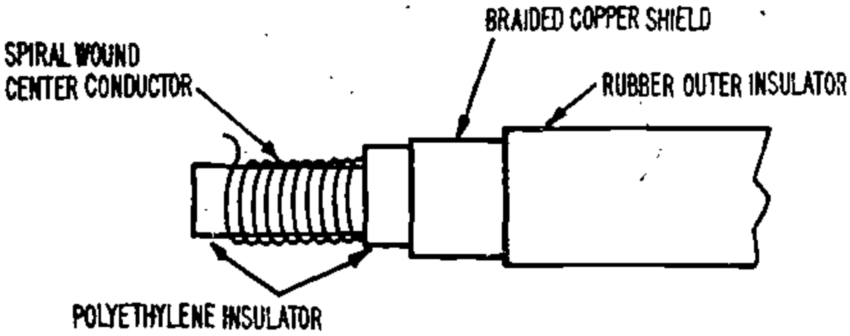


Figure 4

SPIRAL COAX DELAY LINE

Spiral-wound coax is more commonly used because of its space-saving feature.

The lumped constant delay line, as shown in Figure 5, is used to produce very long delays when component size must be minimized. This type of line uses real capacitors and inductors to produce the delay.

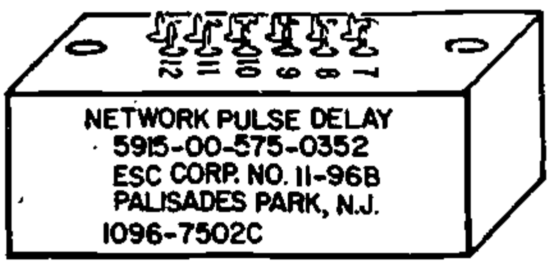


Figure 5

LUMPED CONSTANT DELAY LINE

This type of delay line can be manufactured to provide exact time delays of relatively long duration in a very small package size.

15

Waveguides must be used as a delay line when the frequency of the input signal reaches the microwave frequency range. A waveguide is a cylindrical or rectangular metal pipe, as shown in Figure 6, commonly used as a microwave frequency transmission line.

Figure 6

WAVEGUIDES

In electromagnetic delay lines as in electromechanical delay lines, the output signal has the same shape and pulse width as the input signal. Also, the output signal is attenuated. The amount of time delay and signal attenuation is directly proportional to delay line length.

As a rule of thumb, maximum energy transfer and minimum distortion occur in electromagnetic delay lines if the input source and output load impedances are matched to the delay line. An example of impedance matching is shown in Figure 7. Notice that $Z_g = Z_{in}$ and $Z_{out} = Z_L$

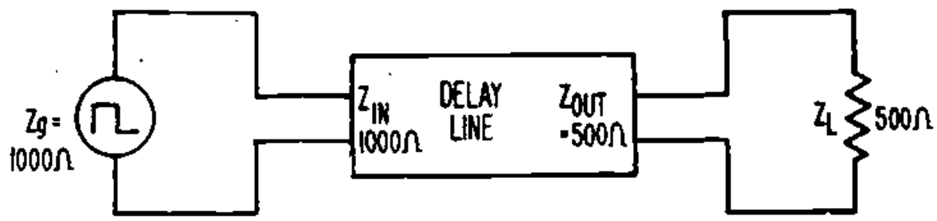


Figure 7

DELAY LINE IMPEDANCE MATCHING

AT THIS POINT YOU MAY TAKE THE LESSON PROGRESS CHECK. IF YOU ANSWER ALL SELF-TEST ITEMS CORRECTLY, PROCEED TO THE NEXT LESSON. IF YOU INCORRECTLY ANSWER ONLY A FEW OF THE PROGRESS CHECK QUESTIONS, THE CORRECT ANSWER PAGE WILL REFER YOU TO THE APPROPRIATE PAGES, PARAGRAPHS, OR FRAMES SO THAT YOU CAN RESTUDY THE PARTS OF THIS LESSON YOU ARE HAVING DIFFICULTY WITH. IF YOU FEEL THAT YOU HAVE FAILED TO UNDERSTAND ALL, OR MOST, OF THE LESSON, SELECT AND USE ANOTHER WRITTEN MEDIUM OF INSTRUCTION, AUDIO/VISUAL MATERIALS (IF APPLICABLE), OR CONSULTATION WITH THE LEARNING CENTER INSTRUCTOR, UNTIL YOU CAN ANSWER ALL SELF-TEST ITEMS ON THE PROGRESS CHECK CORRECTLY.

PROGRAMMED INSTRUCTION

LESSON I

Delay Lines

TEST FRAMES ARE 7, 15, AND 20. PROCEED TO TEST FRAME 7 FIRST AND SEE IF YOU CAN ANSWER THE QUESTIONS. FOLLOW DIRECTIONS GIVEN AFTER THE TEST FRAME.

1. Many electronic equipments use one signal to trigger a number of circuits. When the signal is fed to those circuits, one or more of them may require the signal at a later time than the others. Therefore, the signal must be delayed for a specific time interval without any distortion which would change its shape. A delay line is used to provide the required non-distorted signal time delay.

A signal may be slowed down for a specific time interval by using a special device called a __________________ line.

---

delay

---

2. Most delay lines can be broken down into two major types:

   1. electromechanical delay lines (for longer delays)
   2. electromagnetic delay lines (for shorter delays)

The first type of delay line you will learn about is electromechanical (acoustic). As the name implies, these devices convert electrical input signals into mechanical motion (ultra-sonic energy). This motion then is transferred from input to output through some sort of material such as

mercury, a steel spring, or a large piece of quartz cystal. The signal moves more slowly in the material than in the input wire to the device. Finally, the mechanical motion is reconverted at the output back to electrical signals.

Figure 1 shows a block diagram of the input-conversion-output process in an electromechanical delay line.

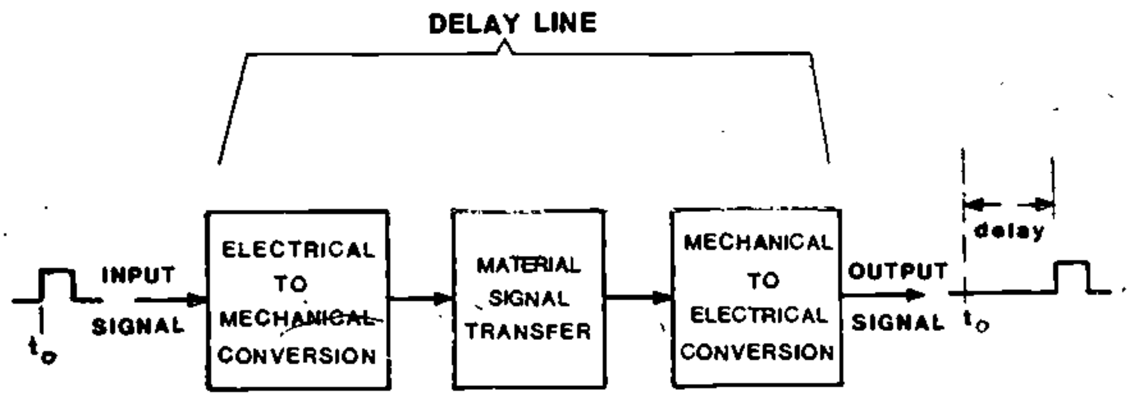


Figure I

ELECTROMECHANICAL DELAY LINE BLOCK DIAGRAM

A practical commercial use of an electromechanical delay line is shown in Figure 2.

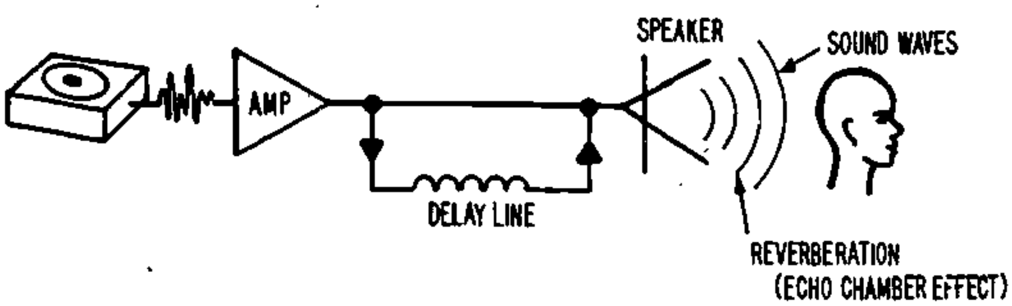


Figure 2

ELECTROMECHANICAL DELAY LINE APPLICATION

In the figure, an audio amplifier uses an electromechanical delay line to introduce a time delay into voice or music signals. The delayed signal is recombined with the non-delayed signal to produce a "reverberated" sound effect similar to an "echo chamber". You may have heard this effect on your favorite music radio station.

The type of delay line which uses some sort of material to cause a time delay from input to output is called ____________________.

---

electromechanical

(3.) How does an electromechanical delay line slow down the input signal? As you would suspect, mechanical motion travels much more slowly than does an electrical pulse. Therefore, the amount of time delay depends on two factors: the <u>type</u> of material used to provide the mechanical transfer, and the <u>distance</u> the mechanical motion travels through the material. The amount of time delay is directly proportional to the distance the mechanical signal travels. For example, if signal A travels twice as far as signal B in the same material, signal A will have twice the delay of signal B.

Electromechanical delay depends on both the type of ________________ used to provide the mechanical transfer, and the ________________ the mechanical signal travels.

---

material, distance

4. In all delay lines, the output signal amplitude is less than the input signal amplitude. The signal loss in electromechanical delay lines occurs because the mechanical motion uses some energy which is not reconverted to the output signal. Therefore, the output signal is attenuated, or reduced. The amount of attenuation, like the amount of delay, depends on both the type of material used and the distance the mechanical signal travels. As you can probably guess, the amount of attenuation also is directly proportional to the distance of travel.

Figure 3 shows an example of the input and output signals for a typical electromechanical delay line.

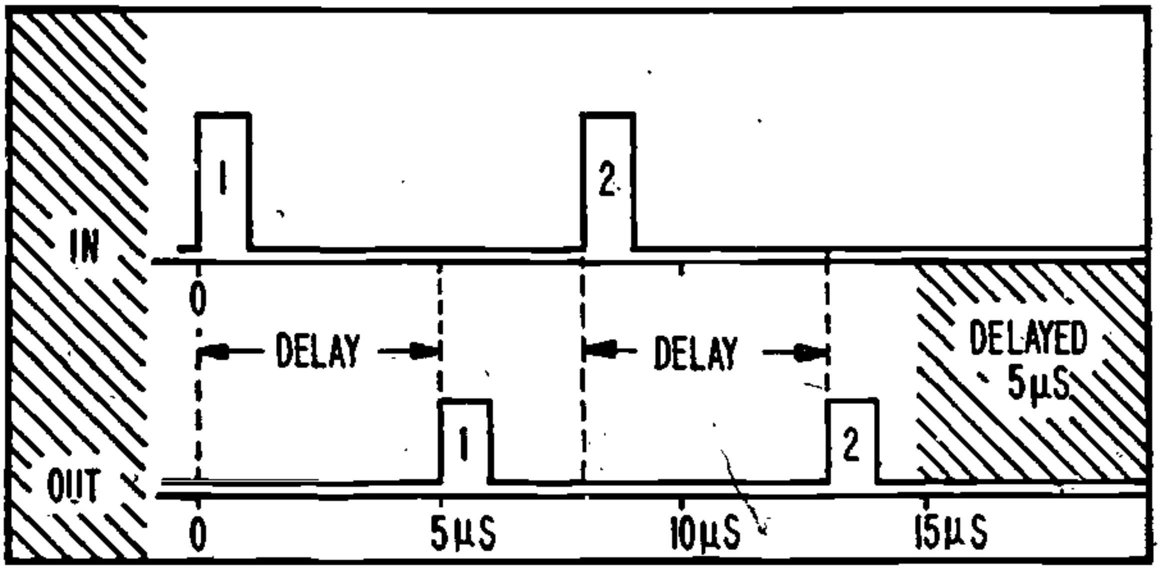


Figure 3

ILLUSTRATION OF ELECTROMECHANICAL TIME DELAY

Notice that the output signal is delayed by 5 microseconds, and is attenuated in amplitude.

In all delay lines, the output signal is reduced in amplitude, or ______.

attenuated

5. One type of electromechanical delay line is made up of a column of mercury with a slab of quartz crystal at each end as shown in Figure 4.

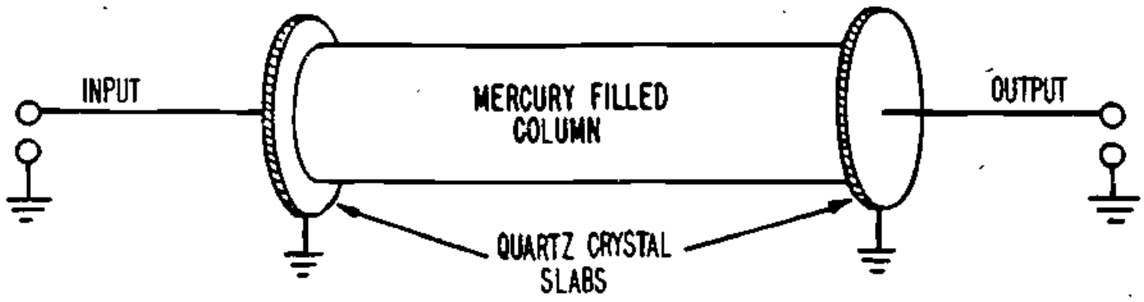


Figure 4

ELECTROMECHANICAL MERCURY DELAY LINE

The quartz crystals have the ability to physically change shape (that is, expand or contract) when either a voltage or mechanical force is applied to them. This quality of crystals, the piezoelectice effect, was discussed in Module 32, Lesson 5.

Figure 5 illustrates how the piezoelectric effect operates in a mercury delay line.

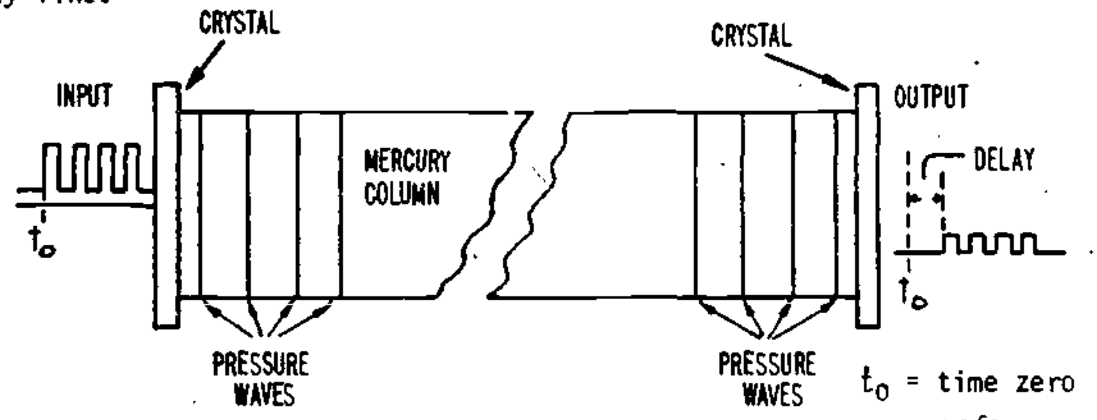


Figure 5

MERCURY DELAY LINE ACTION

In the figure, the crystal at the input end of the column vibrates in reponse to the applied electrical energy. The vibrations generate pressure waves in the mercury. These pressure waves travel through the mercury slowly compared to the speed of an electric signal, and so delay the signal. When the pressure waves strike the output crystal, their mechanical energy is reconverted to electrical energy. The resulting output signal is an undistorted, delayed, and smaller copy of the input signal.

The electromechanical operation of a mercury delay line is caused by the ______________ effect of the quartz crystals.

---

piezoelectric

6. An important limitation in electromechanical delay lines is output signal distortion caused by heat. Distortion can occur if the temperature of the delay line is above its normal operating temperature. Heat can cause the delay line to expand unevenly, and distort the shape of the quartz crystal slabs. As a result, the crystals produce uneven pressure waves, and a distorted output signal. However, if the delay line is not damaged, it will operate normally when the temperature is lowered.

A ________________ output signal can occur if an electromechanical delay line is heated enough above normal operating temperature.

---

distorted

7. THIS IS A TEST FRAME. COMPLETE THE TEST QUESTIONS, AND THEN COMPARE YOUR ANSWERS WITH THE CORRECT ANSWERS GIVEN AT THE TOP OF THE PAGE FOLLOWING THE QUESTIONS.

1. In an electromechanical delay line, the input signal is converted into (electrical/mechanical) energy.

2. The amount of time delay in an electromechanical delay line is (directly/inversely) proportional to the distance the signal travels through the delay line.

3. Delay line output signal amplitudes are attenuated, which means that they are _______________ the input signal amplitudes.

   a. less than

   b. greater than

   c. the same as

4. Mercury delay lines make use of the ____________________ effect of quartz crystals.

5. What is the effect on the output signal of electromechanical delay lines which are operated above normal operating temperatures?

   a. There is no effect.

   b. The output signal can be amplified.

   c. The output signal can be distorted.

25

1. mechanical
2. directly
3. a. less than
4. piezoelectric
5. c. The output signal can be distored.

IF YOUR ANSWERS MATCH THE CORRECT ANSWERS, YOU MAY GO TO TEST FRAME 15. OTHERWISE, GO BACK TO FRAME 1 AND TAKE THE PROGRAMMED SEQUENCE BEFORE TAKING TEST FRAME 7 AGAIN.

8. The second type of delay line you will learn about is electromagnetic. In electromagnetic delay lines, the signal is delayed through the action of charging and discharging capacitance, and expanding and collapsing inductive, or magnetic, fields.

Standard coaxial cable is an excellent example of an electromagnetic delay line. Coaxial cable, or coax, is a type of transmission line used to transfer electrical power or signals between two points. For example, coax is used between antennas and receivers or transmitters.

Coaxial cable is an example of an ______________________________ delay line.

---

electromagnetic

9. How does coaxial cable function as an electromagnetic delay line to high frequency electrical signals? To answer this question, you first must study Figure 6 to see what a piece of standard coax looks like.

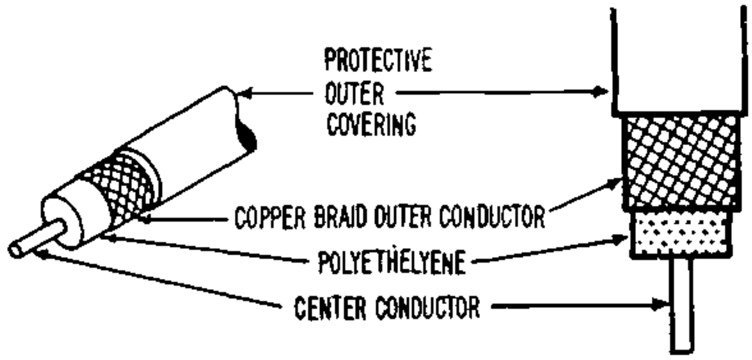


Figure 6

STANDARD COAXIAL CABLE

In the figure, the polyethylene (flexible plastic) insulator between the center conductor and the copper braid outer conductor, or shield, acts like the dielectric in a capacitor. The center conductor acts as an inductor. Therefore, coaxial cable functions electrically like a series of LC circuits as shown in Figure 7.

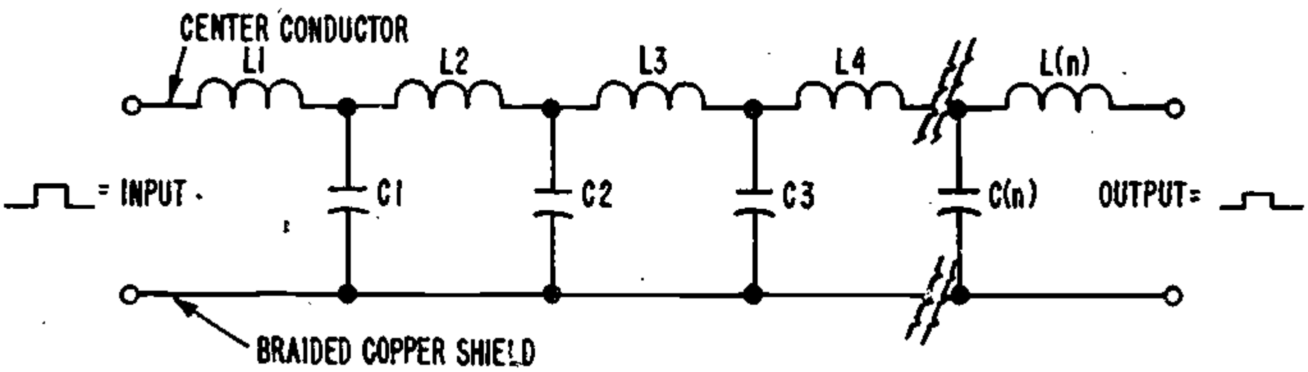


Figure 7

AC EQUIVALENT-COAXIAL CABLE

In the figure, each AC equivalent LC circuit is shown as L1-C1, L2-C2, and so on. The LC circuit shown as L(n)-C(n) means that there are any number of such circuits in a cable. The amount of each inductance is small (a few microhenries), which permits the inductive fields about each inductor to expand and collapse rapidly. Also, the amount of each capacitance is small (about 25 picofarads per foot), which permits a rapid charge and discharge of each capacitance.

In coaxial cable, the time delay results from the rapid expansion and collapse of ____________________ fields, and the rapid charge and discharge of ________________.

---

inductive (or magnetic), capacitances (or capacitors)

(10) The time delay in coaxial cable can be explained by referring to the equivalent inductors and capacitors shown in Figure 8.

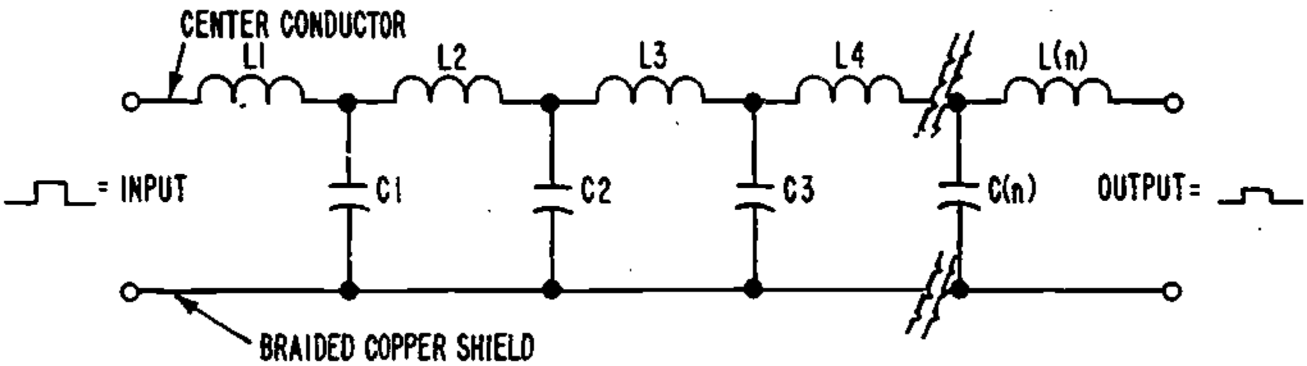


Figure 8

AC EQUIVALENT-COAXIAL CABLE

When the leading edge of a signal pulse is injected into the center conductor in the figure, inductor L1 initially opposes a change in current. This action drops the signal voltage across L1. As the magnetic field around L1 rapidly expands, L1 begins to conduct current which charges capacitor C1. (the time delay to charge C1 equals $\sqrt{LC}$.) As C1 charges, L2 opposes any current flow. This drops the voltage across L2. When L2 begins to conduct current, C2 begins to charge. This inductor-capacitor-inductor transfer is repeated on down the line. Each time an inductor opposes the charge of a capacitor, the signal pulse is delayed.

In Figure 8, L2 will (aid/oppose) the charge of C2, causing a time delay.

---

oppose

(11.) You have learned that the leading edge of a signal pulse which is injected into a coaxial cable receives a time delay. Figure 9 again shows the equivalent LC circuits in coaxial cable.

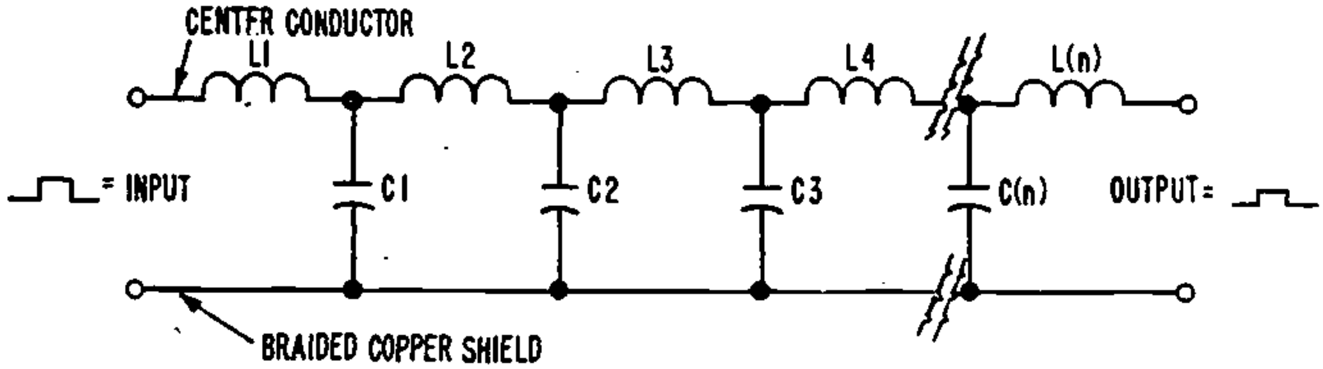


Figure 9

AC EQUIVALENT-COAXIAL CABLE

In the figure, the input signal pulse width is maintained by the charge on the the LC circuit capacitors.

When the <u>trailing edge</u> of the input signal pulse goes back to 0 volts, the capacitors discharge, one at a time, through the inductors. L1 will oppose the discharge current of C1 through L1, and delay C1's voltage drop to 0 volts. L2 then will oppose the discharge current of C2 through L2. The capacitor-inductor interaction at the trailing edge of the signal pulse is repeated on down the line. This interaction keeps the pulse width of the time delayed signals the same as the input signal. Therefore, the waveforms of the output and input signals are the same shape and have the same pulse width.

30

in coaxial cable, the input and output pulse widths are (different/the same), and the input and output waveforms have (different/the same) shapes.

---

the same, the same

12. In electromagnetic delay lines, the output signal is attenuated. This is partially because the capacitor in each equivalent LC circuit never becomes fully charged before it discharges into the next LC circuit. The greater the number of equivalent capacitors that must be charged, the greater are both the time delay and signal attenuation. In addition, all conductors have some resistance which contributes to the signal loss.

Figure 10 illustrates the characteristics of a signal moving through an electromagnetic time delay device such as coaxial cable.

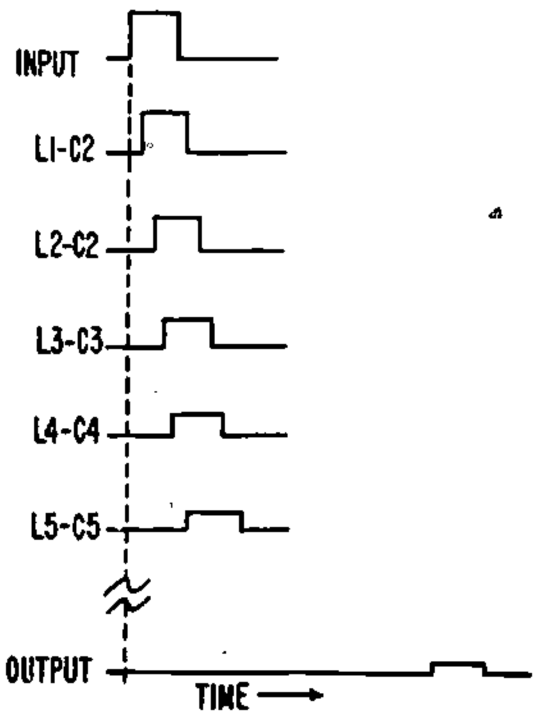


Figure 10

ELECTROMAGNETIC TIME DELAY DEVICE SIGNAL CHARACTERISTICS

In the figure, the output signal from each LC circuit is shown. Notice that the output waveforms for the successive LC circuits have the same shape and pulse width as the input signal, but are attenuated. Also notice that the final output from the coaxial cable has a time delay equal to the sum of the time delays for the individual LC circuits. As you can see, both the time delay and signal attenuation of coaxial cable are directly proportional to cable length.

The longer the coaxial cable, the (less/more) the signal is delayed, and the (less/more) the signal is attentuated.

---

more, more

---

13. A typical time delay for standard coaxial cable is .010 microseconds (.010 μ second) per meter. To produce even a 1 μ second delay would require one hundred meters of coaxial cable. The cable may be coiled to reduce its physical size as shown in Figure 11.

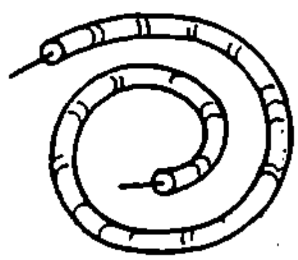


Figure 11

COILED COAX DELAY LINE

32

However, a better method to reduce cable length for a given delay is to use a cable with a special spiral-wound center conductor as shown in Figure 12.

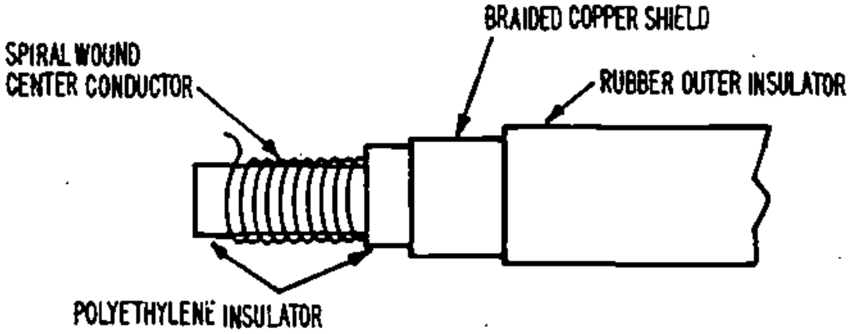


Figure 12

SPIRAL COAX DELAY LINE

The length of the center conductor is greatly increased by spiraling. This type of cable increases the number of apparent inductors and capacitors (LC circuits) per meter, and proportionately increases both the time delay and the signal attenuation. In fact, the delay time for spiral-wound coax is about 14 times greater than that of standard coax. For this reason, spiral-wound coax is the more commonly used cable for time delays.

The type of coax which has the greater time delay per unit length is (standard/spiral-wound).

---

spiral-wound

14. Even spiral-wound coax may require too much cable length for some applications. For very long time delays where the size of components must be kept to a minimum, the lumped constant delay line as shown in Figure 13 may be used.

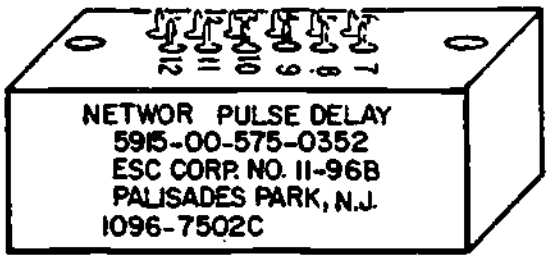


Figure 13

LUMPED CONSTANT DELAY LINE

This type of electromagnetic delay line is made up of real inductors and capacitors. The lumped constant delay line can produce a 30 millisecond delay in a package as small as 2.54 cm (1 inch) square and 1.27 cm (1/2 inch) thick. This same delay time would require about 214 meters of spiral-wound coax. The lumped constant delay line can be manufactured to produce exact time delays and still retain the small package feature.

Which of the following three types of electromagnetic delay lines can produce the longest time delay using the least amount of space?

a. spiral-wound coax

b. standard coax

c. lumped constant

---

c. lumped constant

15. THIS IS A TEST FRAME. COMPLETE THE TEST QUESTIONS, AND THEN COMPARE YOUR ANSWERS WITH THE CORRECT ANSWERS GIVEN AT THE TOP OF THE PAGE FOLLOWING THE QUESTIONS.

1. Coaxial cable is what type of delay line?
   a. electromagnetic
   b. electromechanical
2. Coaxial cable functions electrically as a series of __________ circuits.
   a. RC
   b. LC
   c. piezoelectric
   d. amplifier
3. In coaxial cable, the amount of signal attenuation is (directly/inversely) related to cable length.
4. In coaxial cable, the pulse width of the time delayed signal is (wider than/the same as/narrower than) the pulse width of the input signal.
5. One meter of spiral-wound coax, compared to one meter of standard coax, provides (less/the same/more) time delay and (less/the same/more) signal attenuation.
6. The electromagnetic delay line which is manufactured to provide exact time delays in a small package size is
   a. spiral-wound coax.
   b. mercury delay line.
   c. lumped constant.
   d. standard coax.

1. a. electromagnetic
2. b. LC
3. directly
4. the same as
5. more, more
6. c. lumped constant.

IF YOUR ANSWERS MATCH THE CORRECT ANSWERS, YOU MAY GO TO TEST FRAME 20. OTHERWISE GO BACK TO FRAME 8 AND TAKE THE PROGRAMMED SEQUENCY BEFORE TAKING TEST FRAME 15 AGAIN.

Why don't these delay lines operate properly at microwave frequencies? As you know, electromagnetic delay lines function by using capacitance between the two sides of the line as shown in Figure 15.

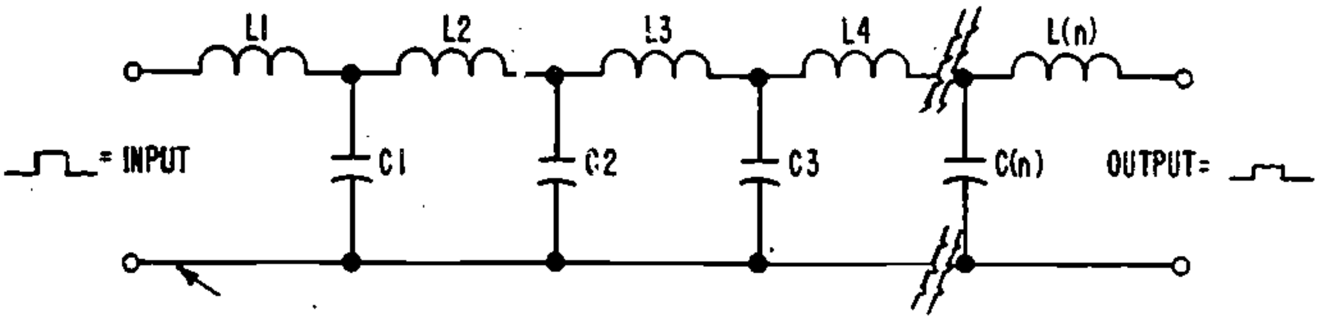


Figure 15

AC EQUIVALENT OF DELAY LINE

As the frequency of the input signal increases, the capacitive reactance (X_c) of these capacitors decreases. This relationship is expressed in the formula $X_c = .159 \div FC$. Now at microwave frequencies, X_c becomes so small that the signal in the coax and lumped constant delay lines will be effectively shorted across the line. This causes intolerable losses and poor operation of these delay lines at microwave frequencies.

The coaxial and lumped constant delay lines (will/will not) operate properly at microwave frequencies.

---

will not

16. The coax and lumped constant delay lines will not operate properly when the frequency of the input signal reaches or exceeds the microwave range used by radar and some communications equipment. Figure 14 shows where the microwave frequency range is in the frequency spectrum.

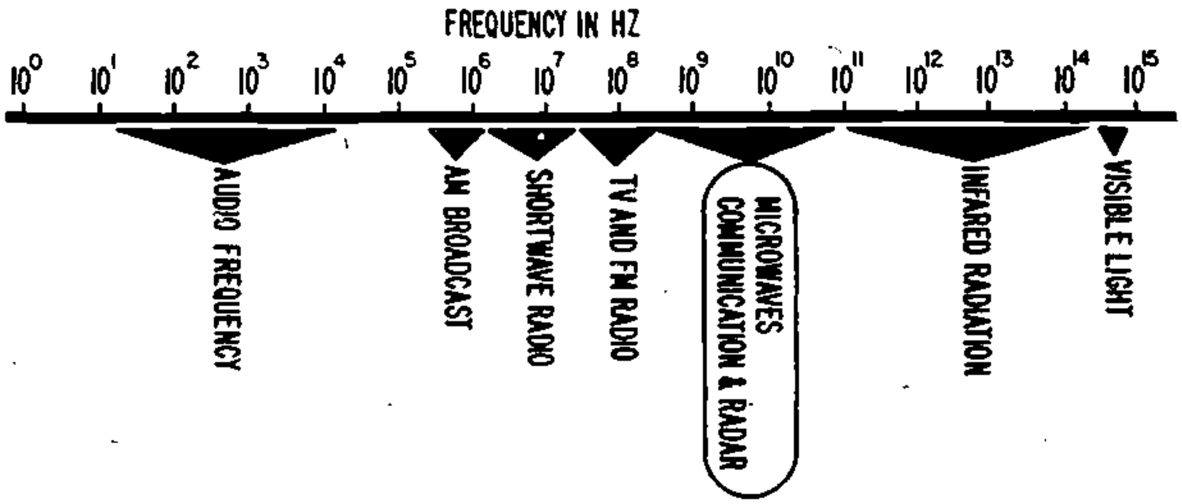


Figure 14

FREQUENCY SPECTRUM CHART

As you can see, microwave frequencies are extremely high and range from about 1000 MHz(10^9Hz) to 100,000 MHZ (10^{11}Hz).

38

18. To make a waveguide act as a delay line, the waveguide is formed into a loop or circle as shown in Figure 17.

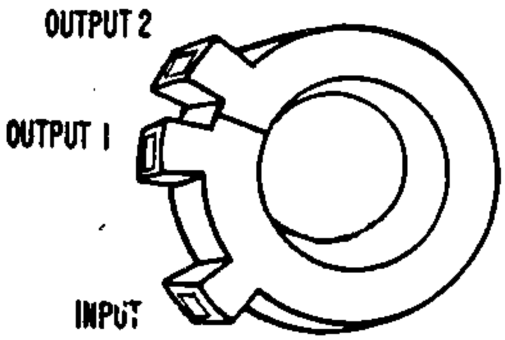


Figure 17

WAVEGUIDE DELAY LINE

A signal at the input will split and travel in both directions around the circle. The signal going to output 2 has farther to travel than the signal going to output 1. This causes output 2 to occur later than output 1. Output 2 is delayed in time with reference to output 1, and both outputs are delayed with reference to the input. The amount of time delay possible with this method is very small. However, when longer time delays are required at microwave frequencies, the signal is converted to a lower frequency to allow one of the other types of delay lines to be used.

17. At microwave frequencies, a transmission line known as a <u>waveguide</u> is used to conduct RF signals. A waveguide is simply a cylindrical or rectangular metal pipe through which microwave signals easily travel. Figure I6 shows an example of two types of waveguides.

Figure I6

WAVEGUIDES

Signal speed through a waveguide is slower than through either free space or a wire conductor. Therefore, the waveguide can be used as a time delay device, although it is primarily used as a transmission line.

An electromagnetic delay line at microwave frequencies is called a

_______________.

---

waveguide

19. As a technician woking with delay lines, you will not be concerned with designing the devices. However, it is necessary for you to know their performance characteristics as previously discussed. One other important characteristic is that a delay line should be impedance matched to both the input source and output load. This is done to provide maximum energy transfer with minimum distortion of the signals. Figure 19 shows an example of impedance matching.

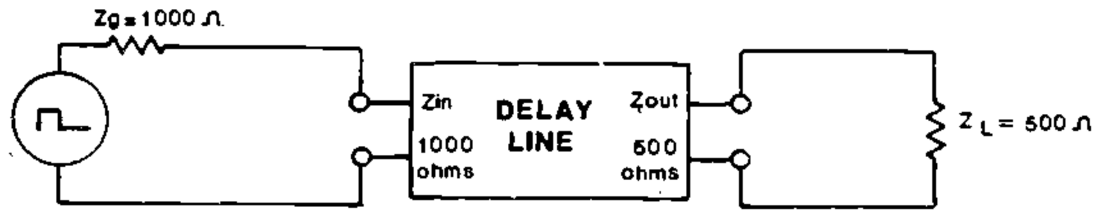


Figure 19

DELAY LINE IMPEDANCE MATCHING

In the figure, the source impedance (Z_g) of an input signal equals 1000 ohms. If you want maximum energy transfer to occur, the "rule of thumb" is to match the source and delay line impedances. Therefore, the delay line input impedance (Z_{in}) also equals 1000 ohms. This rule also applies to the match between the delay line output impedance (Z_{out}) and the load impedance (Z_L). In the example, both equal 500 ohms.

In delay lines maximum energy is transferred with minimal distortion if the input and output ________________ are matched with those of the signal source and load.

---

impedances

Figure 18 shows both output signals in relation to the waveguide input signal.

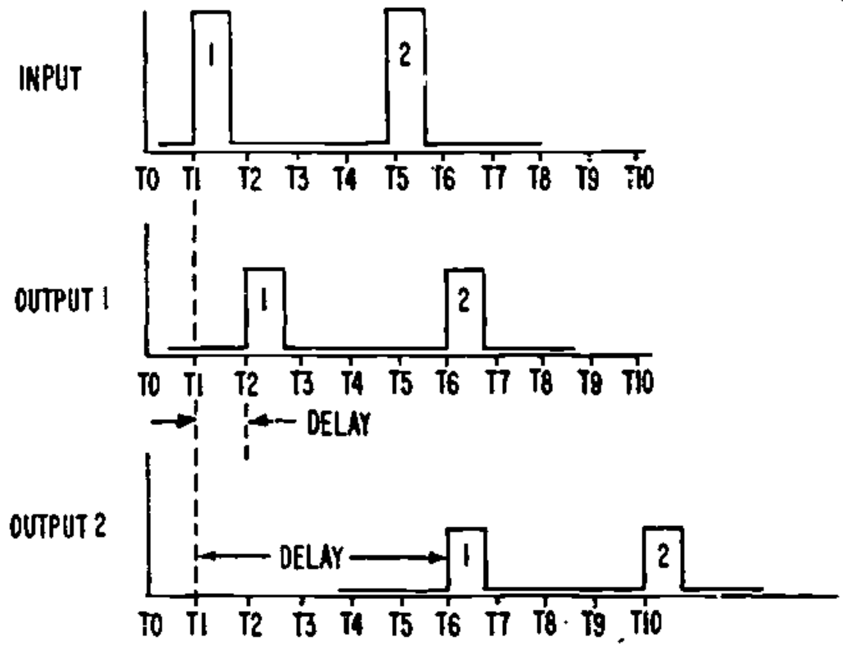


Figure 18

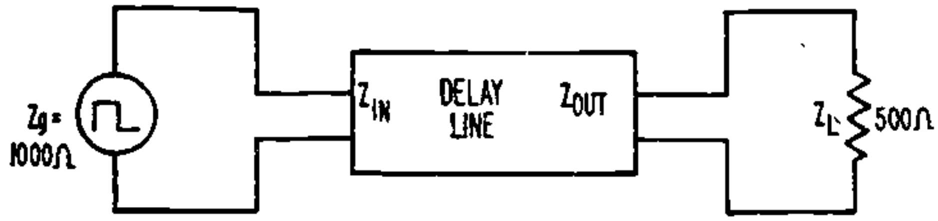
WAVEGUIDE DELAY TIMES

In the figure, you can see that the output 2 signals have a longer time delay than the output 1 signals. You can also see that the shape and pulse width of the output and input waveforms are the same. Notice that the output signals are attenuated.

In Figure 18, an input signal travels the longer distance to reach output (1/2).

2

USE THE FIGURE BELOW TO ANSWER QUESTION #3.



3. What rule is observed with regard to impedance matching in delay lines.

   a. $Z_{out} = Z_{in}$, $Z_g = Z_L$

   b. $Z_g = Z_{out}$, $Z_{in} = Z_L$

   c. $Z_g = Z_L$, $Z_{in} = Z_{out}$

   d. $Z_g = Z_{in}$, $Z_{out} = Z_L$

20. THIS IS A TEST FRAME. COMPLETE THE TEST QUESTIONS, AND THEN COMPARE YOUR ANSWERS WITH THE CORRECT ANSWERS GIVEN AT THE TOP OF THE PAGE FOLLOWING THE QUESTIONS.

1. Coaxial cable and lumped constant delay lines do not operate properly in the ____________________ frequency range.

    a. audio

    b. microwave

    c. shortwave

    d. TV and FM radio

2. What type of delay lines may be used at microwave frequencies for small time delays?

    a. Spiral-wound coax

    b. Electromechanical

    c. Standard coax

    d. Waveguide

1. b. microwave
2. d. Waveguide
3. d. $Z_g = Z_{in}$, $Z_{out} = Z_L$

IF YOUR ANSWERS MATCH THE CORRECT ANSWERS, YOU HAVE COMPLETED THE PROGRAMMED INSTRUCTION FOR LESSON 1, MODULE THIRTY THREE. OTHERWISE GO BACK TO FRAME 16 AND TAKE THE PROGRAMMED SEQUENCE BEFORE TAKING TEST FRAME 20 AGAIN.

AT THIS POINT, YOU MAY TAKE THE LESSON PROGRESS CHECK. IF YOU ANSWER ALL SELF-TEST ITEMS CORRECTLY, PROCEED TO THE LESSON TEST. IF YOU INCORRECTLY ANSWER ONLY A FEW OF THE PROGRESS CHECK QUESTIONS, THE CORRECT ANSWER PAGE WILL REFER YOU TO THE APPROPRIATE PAGES, PARAGRAPHS, OR FRAMES SO THAT YOU CAN RESTUDY THE PARTS OF THIS LESSON YOU ARE HAVING DIFFICULTY WITH. IF YOU FEEL THAT YOU HAVE FAILED TO UNDERSTAND ALL, OR MOST, OF THE LESSON, SELECT AND USE ANOTHER WRITTEN MEDIUM OF INSTRUCTION, AUDIO/VISUAL MATERIALS (IF APPLICABLE), OR CONSULTATION WITH THE LEARNING CENTER INSTRUCTOR, UNTIL YOU CAN ANSWER ALL SELF-TEST ITEMS ON THE PROGRESS CHECK CORRECTLY.

The transfer of the mechanical motion through the material causes the delay. Material motion travels much more slowly than an electrical pulse. Therefore, the amount of time for the transfer will depend on the material used and the distance the mechanical motion travels through the material. Mechanical motion also will be attenuated (reduced in energy) by the material. The amount of attenuation is directly proportional to the distance the mechanical signal travels and to the type of medium. Figure 2 shows the time delay and signal attenuation of a typical electromechancial delay line.

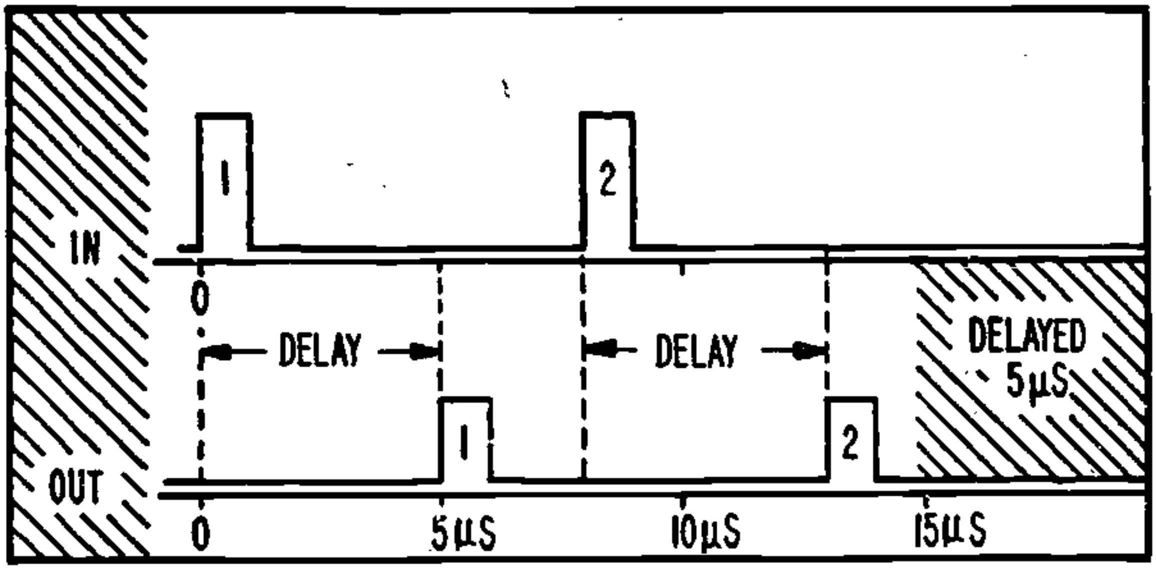


Figure 2

ILLUSTRATION OF ELECTROMECHANICAL TIME DELAY

One type of electromechanical delay line is made up of a column of mercury with a slab of quartz crystal at each end as shown in Figure 3.

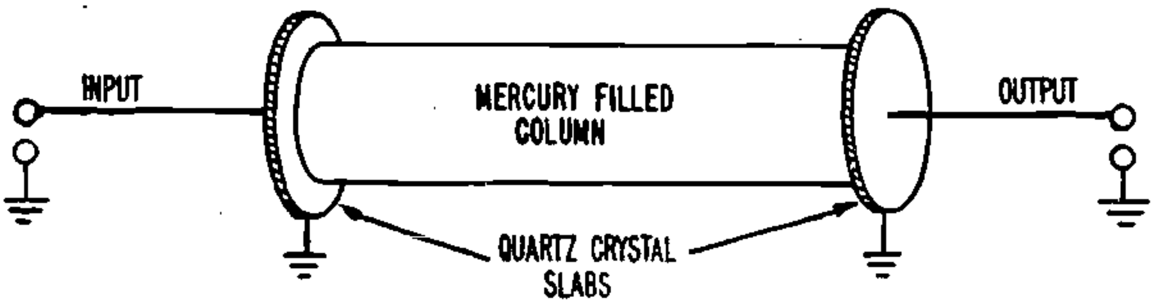


Figure 3

ELECTROMECHANICAL MERCURY DELAY LINE

NARRATIVE
LESSON 1

Delay Lines

Many electronic equipments use one signal to trigger a number of circuits. When the signal is fed to those circuits, one or more of them may require the non-distorted signal at a later time than the others. To do this, a delay line is used. Most delay lines are divided into two categories: electromechanical (for longer delays) and electromagnetic (for shorter delays).

Electromechanical (or acoustic) delay lines are devices which convert electrical input signals into mechanical motion (ultrasonic energy). This motion is transferred from input to output through some sort of material (for example: mercury, a steel spring, or a large piece of quartz crystal), and then reconverted into electrical signals at the output. A practical commercial use of an electromechanical delay line is shown in Figure 1.

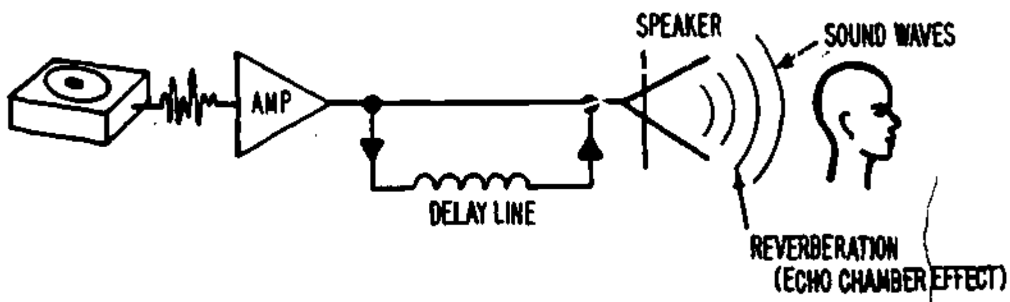


Figure 1

ELECTROMECHANICAL DELAY LINE APPLICATION

Audio amplifiers may use an electromechanical delay line to introduce a time delay into voice or music signals. The delay signal is recombined with the non-delayed signal to produce a reverberated sound effect much like that of an "echo chamber".

Electromagnetic delay lines are devices which function through the action of charging and discharging capacitances, and expanding and collapsing inductive, or magnetic, fields. Coaxial cable, or coax, may be used as an electromagnetic delay time. However, coaxial cable was designed as a type of transmission line for electrical power or signals, as between receivers/transmitters and antennas.

Figure 5 identifies the parts in a section of standard coaxial cable.

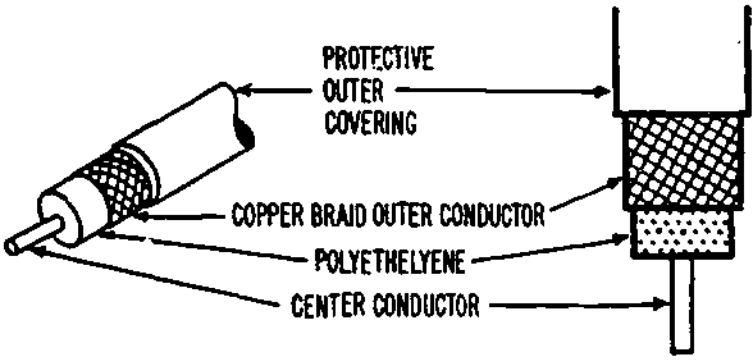


Figure 5

COAXIAL CABLE

Coax cable is constructed in a manner which produces internal capacitances and inductance. In Figure 5, the polyethylene insulator between the center conductor and the copper braid acts like the dielectric in a capacitor. The center conductor itself acts as an inductor. Therefore, the coax functions electrically like a series of LC circuits as shown in Figure 6.

The quartz crystals have the ability to physically expand and contract when either a voltage or mechanical force is applied to them. This quality is the piezoelectric effect, discussed in Lesson 5, Module 32. Figure 4 illustrates how the piezoelectric effect works in a mercury delay line.

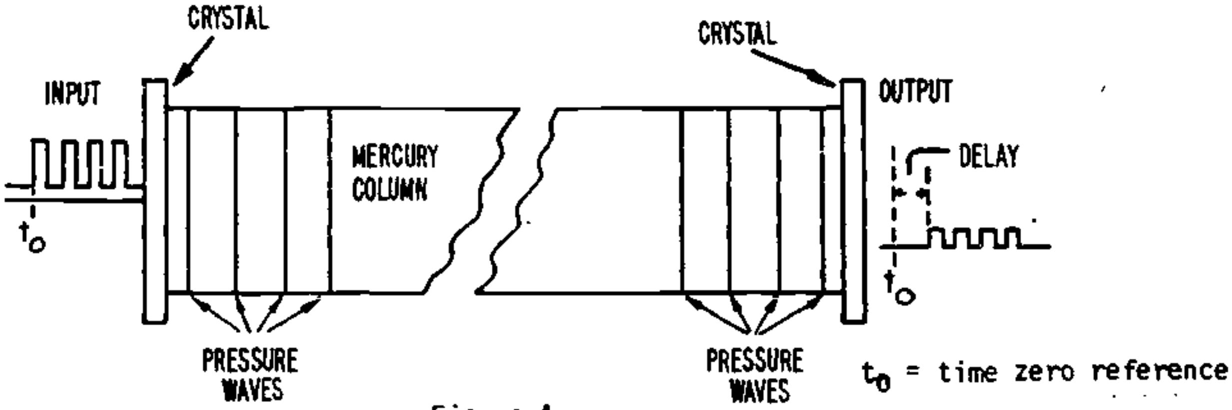


Figure 4

MERCURY DELAY LINE ACTION

In the figure, an electrical signal input is converted to the mechanical energy of motion which moves through the mercury column. This mechanical energy is reconverted to electrical energy at the output, producing a nondistorted, delayed, and attenuated copy of the input signal.

Distortion of the output signal can occur if the temperature of the electromechanical delay line is significantly above its normal operating temperature. Heat can cause the delay line to expand unevenly and distort the signal. However, if the delay line is not damaged, it will resume normal operation when the temperature is lowered.

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The amount of attenuation, like the amount of time delay, is directly proportional to cable length. Figure 7 illustrates the signal characteristics of an electromagnetic time delay device such as coaxial cable.

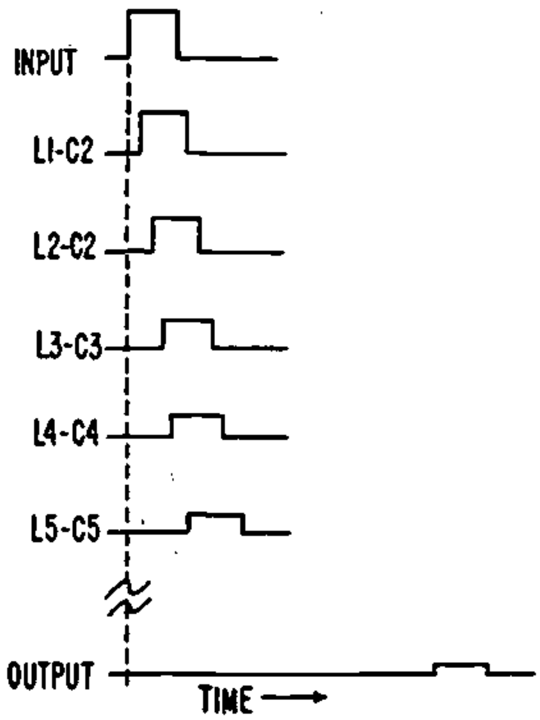

Figure 7

ELECTROMAGNETIC TIME DELAY DEVICE SIGNAL CHARACTERISTICS

Notice that the output waveforms for the successive LC circuits have the same waveform shape and pulse width as the input signal, but are attenuated. You can see that the total amount of both time delay and signal attenuation equals the sum of the time delays and attenuations for each LC circuit.

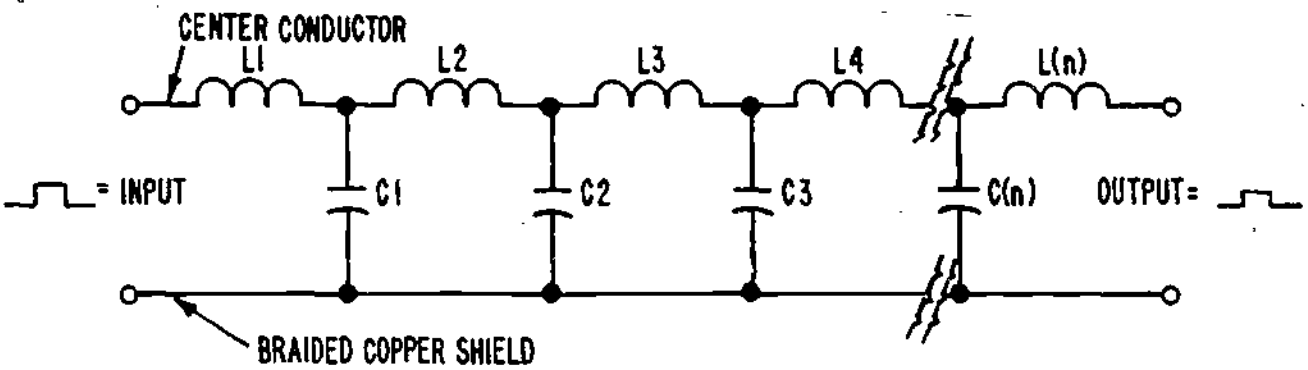

Figure 6

AC EQUIVALENT-COAXIAL CABLE

In Figure 6, there are any number of such LC circuits as indicated by L(n)-C(n). The amount of inductance in each circuit is small (a few microhenries) as is the amount of capacitance (about 25 picoforads per foot). Therefore, there is rapid expansion and collapse of the inductive fields, and rapid charge and discharge of the capacitances.

When the leading edge of a signal is applied at the input in Figure 6, L1 opposes a change in current and drops the voltage of the signal across itself. Then, as the inductor begins to conduct current, capacitor C1 starts to charge. As C1 charges, L2 opposes any current flow and has a voltage drop across itself. When L2 begins to conduct current, C2 begins to charge. This action is repeated down the line of LC circuits with a slight delay in time occuring between each inductor-capacitor-inductor transfer.

The voltage level of the signal pulse is maintained on the line by the charge on the capacitors. Now when the trailing edge of the input signal pulse returns to zero volts, the capacitors discharge through the inductors. L1 will oppose C1's discharge through L1, and delay C1's voltage drop to zero volts. This capacitor-inductor interaction is repeated down the line for each LC circuit, and keeps pace with the time delay at the leading edge of the signal. Therefore, the signal traveling through the cable has the same pulse width and waveform shape as the input signal. The total time delay for the coax is the sum of the time delays for each LC circuit. Therefore, time delay is directly proportional to cable length.

The output signal is attenuated in electromagnetic delay lines because the capacitor in each equivalent LC circuit discharges before it becomes fully charged. Also, there is some normal resistance which causes energy loss.

For relatively long time delays, where the size of components must be kept to a minimum, the lumped constant delay line may be used as shown in Figure 9.

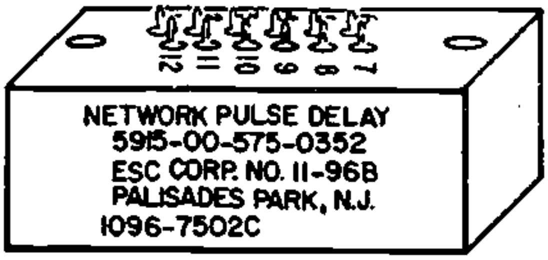

Figure 9

LUMPED CONSTANT DELAY LINE

This type of delay line consists of actual inductors and capacitors, enclosed in a metal shield and can produce a 30 millisecond delay in a package as small as 2.54 cm (1 inch) square and 1.27 cm (1/2 inch) thick. This same time delay replaces about 214 meters of spiral-wound coax. The lumped constant delay line can be manufactured to provide exact time delays.

The coax and lumped constant delay lines do not function properly when the input signal frequency is above about 1000 MHz (10^9 Hz), which is the lower limit of microwave frequencies. Figure 10 shows where the microwave frequency range is in the frequency spectrum.

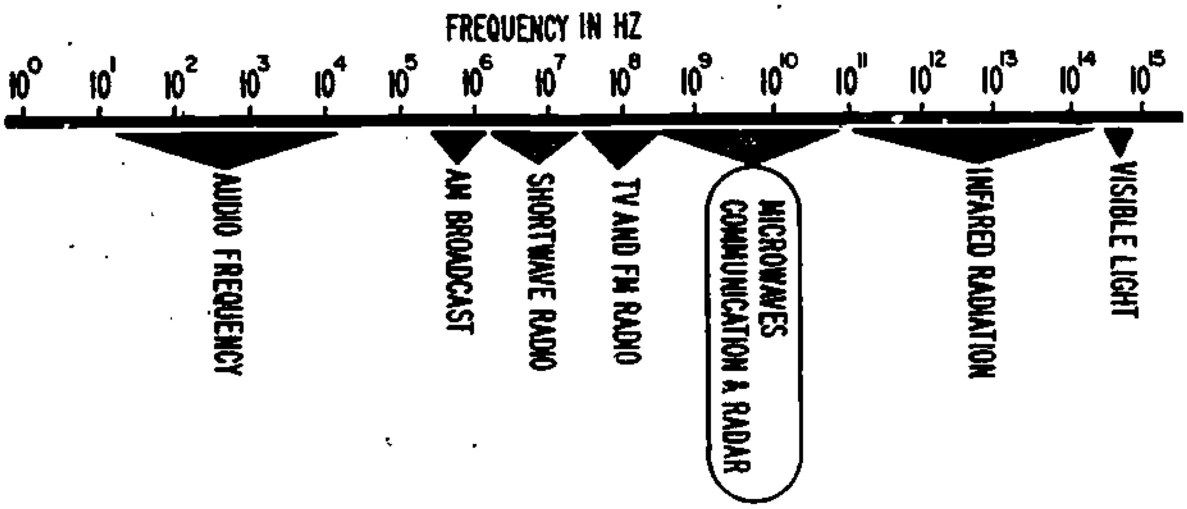

Figure 10

FREQUENCY SPECTRUM CHART

Since standard coaxial cable has a very short delay time of about .010 microseconds per meter, long lengths of cable are required for delay times in the microsecond range. The cable may be coiled to save space. However, a better method to reduce cable length is to use cable with a spiral-wound center conductor as shown in Figure 8.

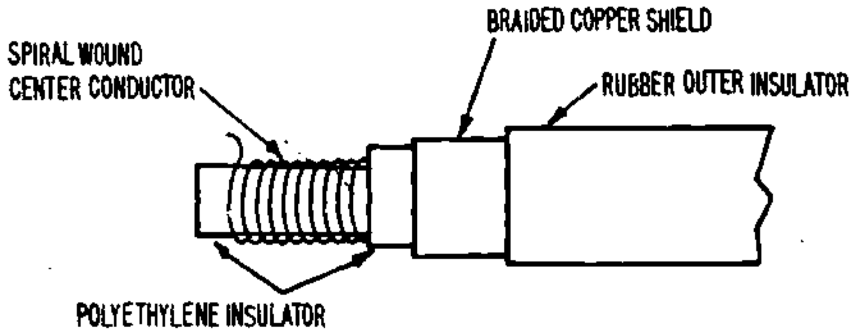

Figure 8

SPIRAL COAX DELAY LINE

The length of the center conductor is greatly increased by spiraling, which increases the number of equivalent inductors and capacitors per unit length. The delay time for spiral-wound coax is about 14 times greater than that of standard coax. The amount of signal attenuation is proportionately increased. Spiral-wound cable is the more commonly used of the two types of coax.

To make a waveguide into a delay line, the waveguide is formed into a loop or circle as shown in Figure 12.

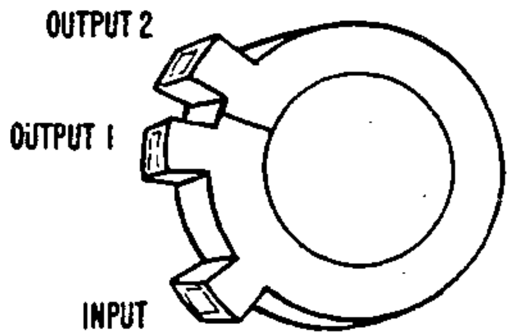

Figure 12

WAVEGUIDE DELAY LINE

A signal at the input will split and travel in both directions around the circle. The signal going to outout 2 has farther to travel than the signal going to output 1, causing output 2 to occur later in time. Both outputs are delayed with reference to the input.

The reason for the problem at microwave frequencies is related to the capacitance in the LC circuits of electromagnetic delay lines. As the input signal frequency increases, the capacitive reactance (Xc) decreases. This relationship is expressed in the formula $Xc = .159 \div FC$. At microwave frequencies, Xc becomes so small that the signal in coax and lumped constant delay lines shorts across the line.

At microwave frequencies, a transmission line called a <u>waveguide</u> is used to conduct and delay signals. Since signals move more slowly through a waveguide than through either free space or a wire, the waveguide can be used as a delay line for small time delays. Examples of waveguides are shown in Figure 11.

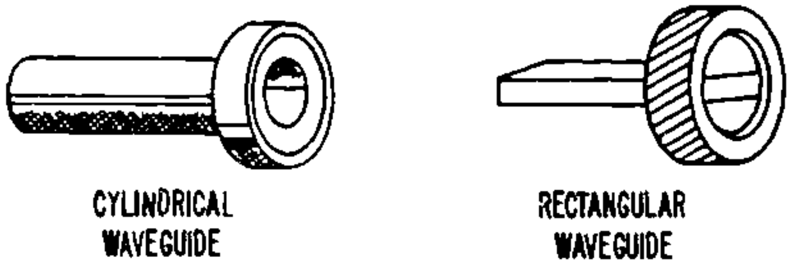

Figure 11

WAVEGUIDES

As a rule of thumb, maximum energy transfer occurs through delay lines if the input source and output load impedances are matched to the delay line. An example of impedance matching is shown in Figure 14.

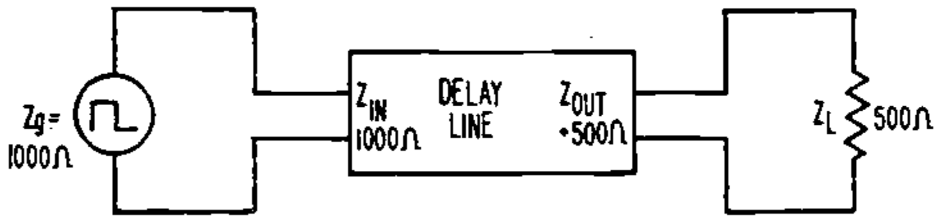

Figure 14

DELAY LINE IMPEDANCE MATCHING

In the figure, the source impedance (Z_g) is impedance matched to the delay line input. The output load (Z_L) is impedance matched to the delay line output (Z_{out}).

AT THIS POINT YOU MAY TAKE THE LESSON PROGRESS CHECK. IF YOU ANSWER ALL SELF-TEST ITEMS CORRECTLY, PROCEED TO THE LESSON TEST. IF YOU INCORRECTLY ANSWER ONLY A FEW OF THE PROGRESS CHECK QUESTIONS, THE CORRECT ANSWER PAGE WILL REFER YOU TO THE APPROPRIATE PAGES, PARAGRAPHS, OR FRAMES SO THAT YOU CAN RESTUDY THE PARTS OF THIS LESSON YOU ARE HAVING DIFFICULTY WITH. IF YOU FEEL THAT YOU HAVE FAILED TO UNDERSTAND ALL, OR MOST, OF THE LESSON, SELECT AND USE ANOTHER WRITTEN MEDIUM OF INSTRUCTION, AUDIO/VISUAL MATERIALS (IF APPLICABLE), OR CONSULTATION WITH THE LEARNING CENTER INSTRUCTOR, UNTIL YOU CAN ANSWER ALL SELF-TEST ITEMS ON THE PROGRESS CHECK CORRECTLY.

Figure 13 shows the signal characteristics for a waveguide delay line.

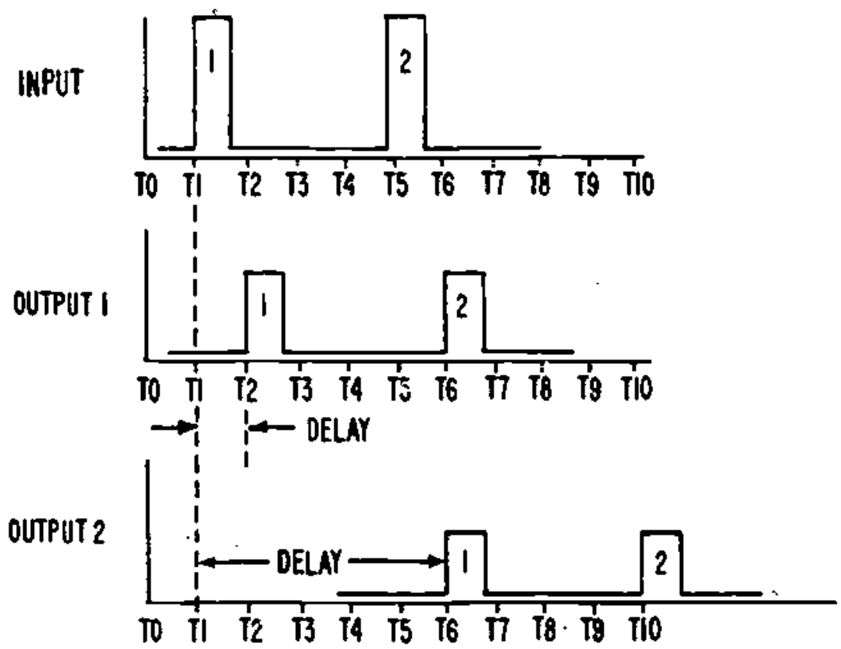

Figure 13

WAVEGUIDE DELAY TIMES

As you can see, waveguides have similar signal characteristics to coax and lumped constant delay lines. The output signals are attenuated, and have the same pulse width and waveform shape as the input signals.

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OVERVIEW
LESSON 2

Dummy Loads

In this lesson you will learn how electrical dummy load devices can be used to simulate real loads on equipments such as power supplies and transmitters. You will become familiar with some basic design features of these dummy loads and some important requirements for, and limitations on, their use. You also will become familiar with some basic uses for mechanical dummy loads.

The learning objectives of this lesson are as follows:

TERMINAL OBJECTIVE(S):

33.2.62 When the student completes this lesson (s)he will be able to IDENTIFY the purpose, function, and operating characteristics of dummy loads by selecting statements from a choice of four. 100% accuracy is required.

ENABLING OBJECTIVES:

When the student completes this lesson (s)he will be able to:

33.2.62.1 IDENTIFY the purpose of electrical dummy loads by selecting the correct statement from a choice of four. 100% accuracy is required.

33.2.62.2 IDENTIFY the operating characteristics and applications of resistive dummy loads by selecting the correct statement from a choice of four. 100% accuracy is required.

33.2.62.3 CALCULATE the resistance and power requirements of dummy loads used on power supplies, given the voltage and current of the actual load, by selecting the correct value from a choice of four. 100% accuracy is required.

33.2.62.4 IDENTIFY the operating characteristics and applications of coaxial and waveguide dummy loads by selecting the correct statement from a choice of four. 100% accuracy is required.

33.2.62.5 CALCULATE the power requirements of dummy loads used on transmitters, given transmitter outputs, by selecting the correct value from a choice of four. 100% accuracy is required.

33.2.62.6 IDENTIFY the purpose of, and examples of, mechanical dummy loads by selecting the correct statement from a choice of four. 100% accuracy is required.

BEFORE YOU START THIS LESSON, READ THE LESSON LEARNING OBJECTIVES AND PREVIEW THE LIST OF STUDY RESOURCES ON THE NEXT PAGE.

BASIC ELECTRICITY AND ELECTRONICS

MODULE THIRTY THREE

LESSON 2

DUMMY LOADS

JULY 1980 59

SUMMARY
LESSON 2 -

Dummy Loads

Many times you will find it necessary to test electronic equipments, such as power supplies and transmitters, without connecting them to their normal load devices. In these situations, dummy loads are used. A dummy load is a device that appears to any equipment under operation to be the normal load.

Figure I shows two common examples where electrical dummy loads can be used.

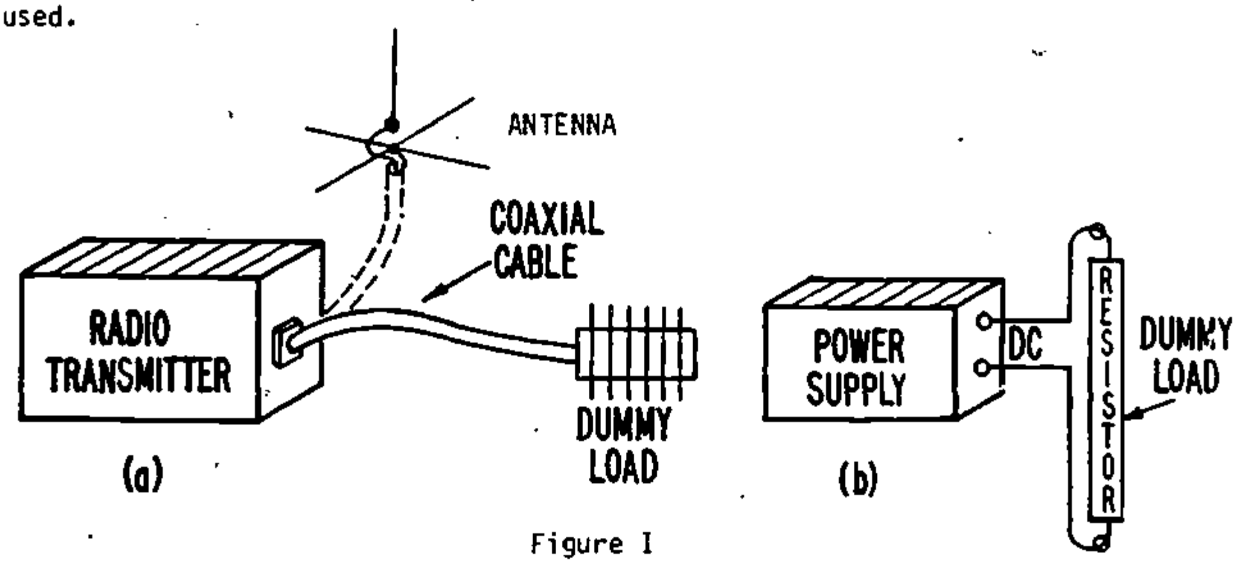


Figure I

DUMMY LOAD APPLICATIONS

When using dummy loads, the normal loads are isolated electrically from the circuits. The dummy loads allow you to operate and troubleshoot the radio transmitter and power supply without the problems related to using the normal loads. Dummy loads can replace the normal loads of circuits as well as of complete equipments.

A resistive dummy load converts the output energy from an operating equipment into heat. Two requirements for using all resistive dummy loads are:

1. The dummy load resistance must be as close as possible to the actual value of load resistance (R_L).

2. The dummy load power rating must be high enough to dissipate the power produced by the equipment or circuit.

LIST OF STUDY RESOURCES
LESSON 2

Dummy Loads

To learn the material in this lesson, you have the option of choosing, according to your experience and preferences, any or all of the following study resources:

Written Lesson presentation in:

Module Booklet:

Summary
Programmed Instruction
Narrative

Student's Guide:

Summary
Progress Check

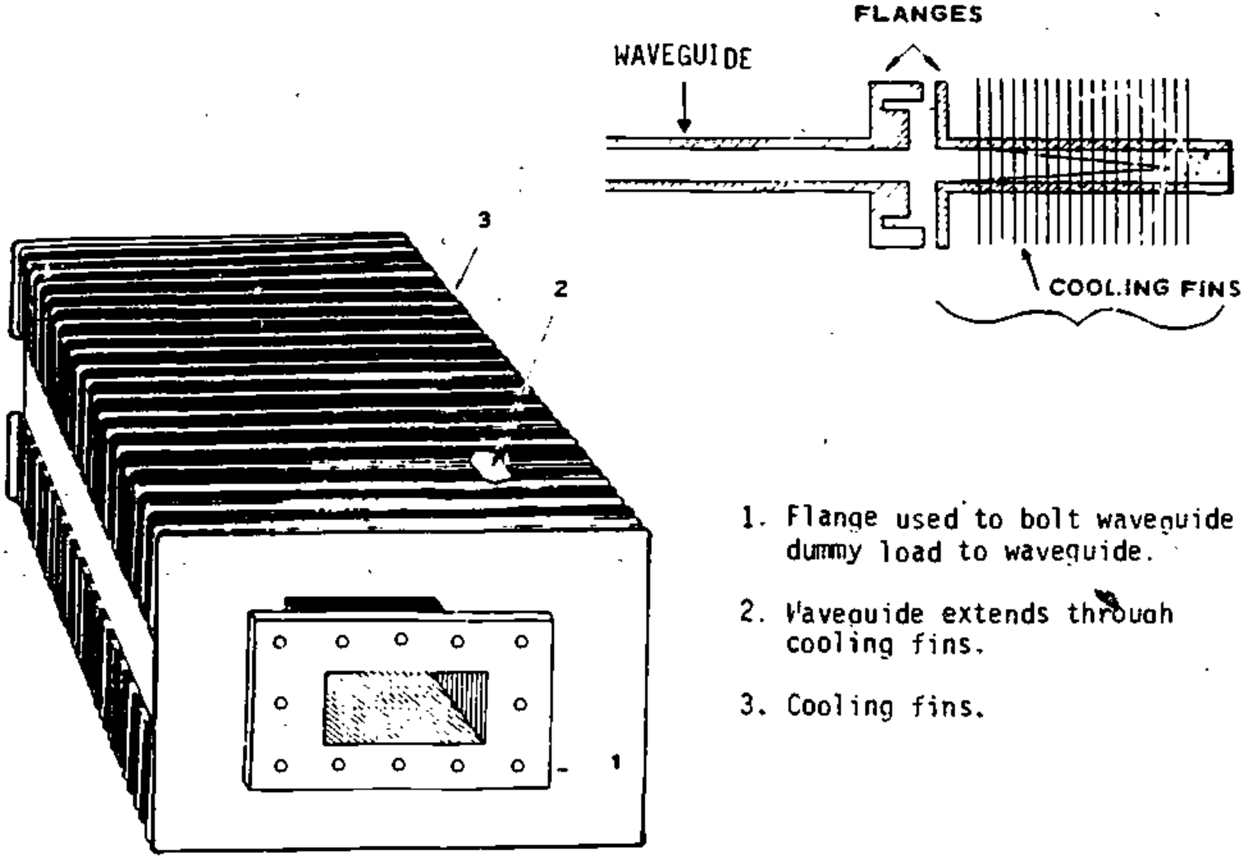
Additional Material(s):

Enrichment Material(s):

Electronics Installation and Maintenance Book (EIMB), (Test Methods and Practices) NAVSHIPS 0967-000-0130
Principles of Radar, 3rd edition, Frances T. Reitzes and Godfred T. Coate, McGraw-Hill Book Co. Inc., New York 1952.

YOU MAY USE ANY, OR ALL, RESOURCES LISTED ABOVE, AND ALSO THE LEARNING CENTER INSTRUCTOR. HOWEVER, ALL MATERIALS LISTED ARE NOT NECESSARILY REQUIRED TO ACHIEVE LESSON OBJECTIVES. THE PROGRESS CHECK MAY BE TAKEN AT ANY TIME.

Figure 3 illustrates a waveguide dummy load.



1. Flange used to bolt waveguide dummy load to waveguide.
2. Waveguide extends through cooling fins.
3. Cooling fins.

Figure 3

WAVEGUIDE DUMMY LOAD

In both coaxial and waveguide dummy loads, some RF energy is not dissipated as heat and leaks into the surrounding space. When radio silence is required, the Commanding Officer must give permission to transmit even into a dummy load.

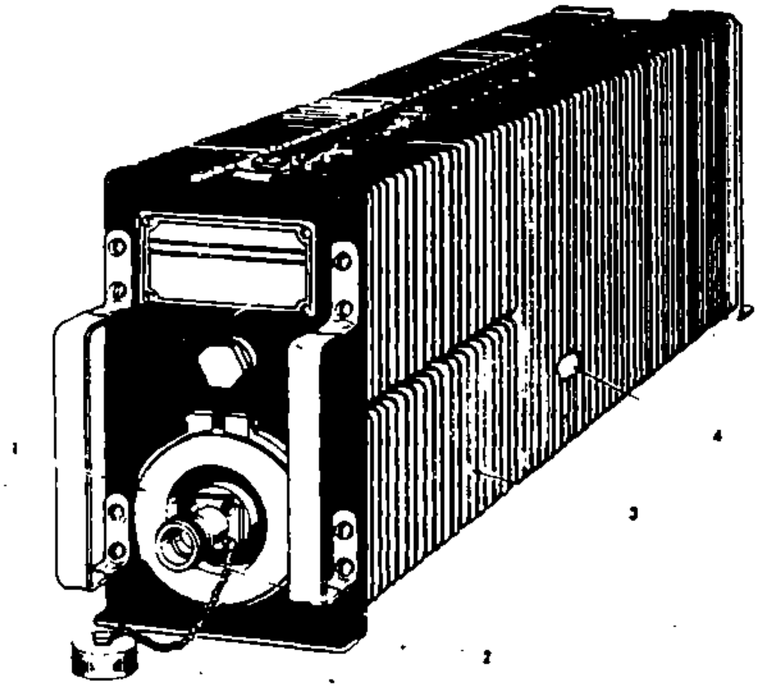
The previous discussion has dealt with electrical dummy loads. One other category of dummy load is the mechanical dummy load which is a device that simulates mechanical loads.

AT THIS POINT, YOU MAY TAKE THE LESSON PROGRESS CHECK. IF YOU ANSWER ALL SELF-TEST ITEMS CORRECTLY, PROCEED TO THE LESSON TEST. IF YOU INCORRECTLY ANSWER ONLY A FEW OF THE PROGRESS CHECK QUESTIONS, THE CORRECT ANSWER PAGE WILL REFER YOU TO THE APPROPRIATE PAGES, PARAGRAPHS, OR FRAMES SO THAT YOU CAN RESTUDY THE PARTS OF THIS LESSON YOU ARE HAVING DIFFICULTY WITH. IF YOU FEEL THAT YOU HAVE FAILED TO UNDERSTAND ALL, OR MOST, OF THE LESSON, SELECT AND USE ANOTHER WRITTEN MEDIUM OF INSTRUCTION, AUDIO/VISUAL MATERIALS (IF APPLICABLE), OR CONSULTATION WITH THE LEARNING CENTER INSTRUCTOR, UNTIL YOU CAN ANSWER ALL SELF-TEST ITEMS ON THE PROGRESS CHECK CORRECTLY.

A resistive dummy load can be a fixed resistor or a rheostat. Fixed resistors of proper values and power ratings are commonly used as dummy loads for AC or DC power supplies over a wide range of power outputs.

A resistive dummy load which replaces the antenna of a radio transmitter must be capable of dissipating a large amount of heat caused by the RF energy. Two types of dummy load used for this purpose are coaxial and waveguide dummy loads. In both types, the resistive element is made of a special mixture containing powdered graphite with an adhesive compound. This mixture is formed into a tapered cone, and placed into a heat sink to dissipate the heat into the air.

Coaxial dummy loads are used at frequencies in the RF communications range. A coaxial cable transmission line connects the radio transmitter to the dummy load. In this case the fixed output impedance of the transmitter (usually 50 ohms resistive) is matched by a 50 ohm coax cable and 50 ohm dummy load. Figure 2 shows an exterior view of a coaxial dummy load.



1. Resistive element
2. RF input connector
3. Metal cooling fins
4. Resistive element extending down through cooling fins

Figure 2

COAXIAL DUMMY LOAD (EXTERIOR VIEW)

Waveguide dummy loads normally are used at microwave (radar) frequencies. A waveguide transmission line connects the radio transmitter to the dummy load. The resistive element is contained within a piece of waveguide.

frequency energy would radiate from the antenna and cause interference to normal communications on the channel. You may have encountered this interference problem on your television or citizen's band radio.

In Figure I(b), a power supply is shown connected to one of its normal loads which is a radio transmitter. In order to test the power supply, you need to operate it. However, the transmitter has fragile semiconductor devices which may be damaged while you are troubleshooting the power supply. You can see from both examples that there is a need both to test equipments under load conditions and to isolate them from their normal loads.

When troubleshooting a piece of electronic equipment, you will sometimes need to isolate it from its normal output ________________________.

---

load

---

2. A <u>dummy load</u> is a device that will appear to any equipment under operation to be the normal load. Dummy loads can replace normal loads so that you may troubleshoot equipment and avoid the problems caused by using the normal load.

PROGRAMMED INSTRUCTION
LESSON 2

Dummy Loads

TEST FRAMES ARE 6 AND 14. PROCEED TO TEST FRAME 6 FIRST AND SEE IF YOU CAN ANSWER THE QUESTIONS. FOLLOW DIRECTIONS GIVEN AFTER THE TEST FRAME.

1. Many times in your electronics career you will have to test a piece of equipment without having it connected to its normal load device. Figure 1 shows two common situations in which this happens.

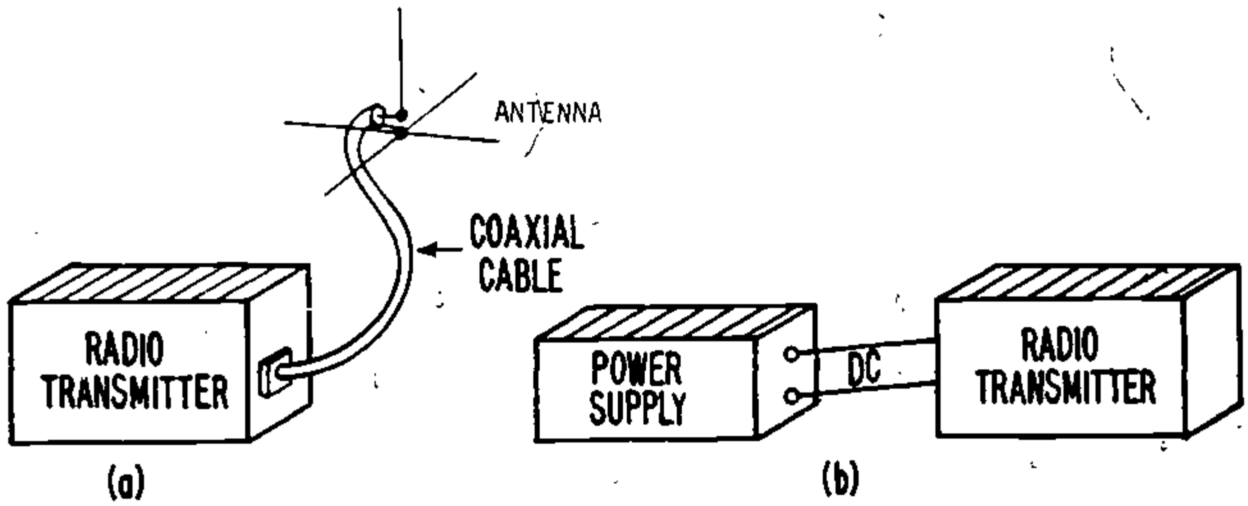


Figure 1
TEST SITUATIONS

In Figure 1(a), a radio transmitter is shown connected to its normal load which is an antenna. In order to test the transmitter, you would need to "key" it (make it transmit). However, when you key the transmitter, radio

In both examples, the dummy loads appeared as units which are external to the equipments. You will find that dummy loads also can substitute for circuits within a piece of electronic equipment.

The type of special device used to replace the normal loads on electronic equipments or circuitry is called a ____________ ____________.

---

dummy load

(3.) You have learned that a dummy load is used whenever it is not desirable or possible to hook up electronic equipments to their normal loads during testing or adjusting. Dummy loads allow you to remove the normal load from the circuit. Now, what is a dummy load? Bascially, a dummy load is a conversion device. It commonly converts the energy produced by the equipment under test into heat. To do this, many dummy loads are made of a piece of resistive material and function as resistors. These are called resistive dummy loads. You are familiar with resistors used as normal loads (R_L) in the circuits of amplifiers and power supplies. Therefore, ordinary resistors often are used as dummy loads.

Resistive dummy loads function electrically as ____________, and convert the energy produced by equipment to which they are connected into ____________.

---

resistors, heat

Figure 2 shows two examples in which dummy loads replace normal loads.

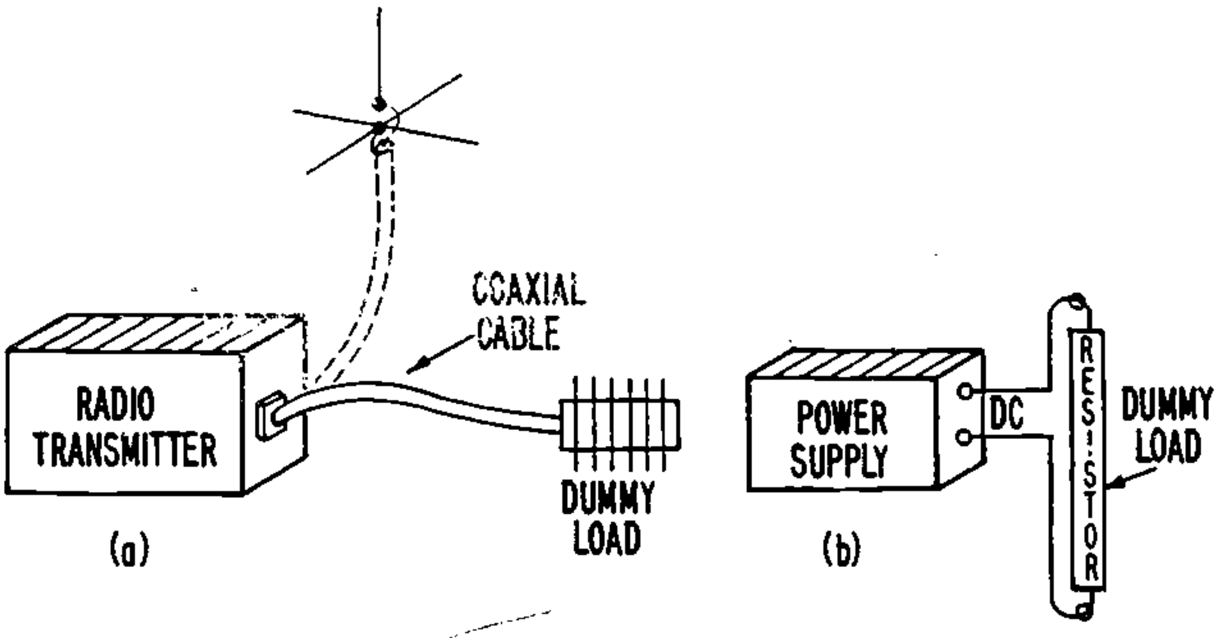


Figure 2

DUMMY LOAD APPLICATIONS

In Figure 2(a), the dummy load replaces the radio transmitting antenna. Thus, the transmitter may be operated and tested without causing interference in other receivers. This is because the RF energy output is confined to the shielded dummy load. Since the dummy load has the same impedance as does the antenna (usually 50 ohms resistive), the transmitter will operate the same as if connected to the antenna.

In Figure 2(b), the dummy load replaces a radio transmitter. The power supply will operate the same as if attached to the radio transmitter. Therefore, a technician can operate and repair the power supply without damaging the transmitter.

Let's replace the normal load with a 0 - 250 ohm rheostat rated at 2 amperes current and 1000 watts maximum power. Figure 3 shows such a rheostat.

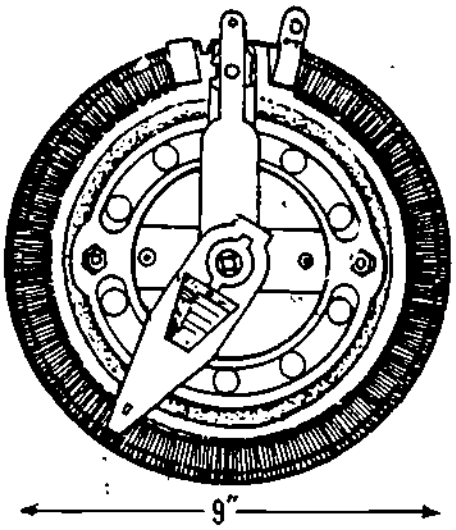


Figure 3

0-250 OHM, 2 AMPERE RHEOSTAT

You have used a similar device in several BE/E job programs. The rheostat should be set to match the normal load resistance of 100 ohms. The power rating of the rheostat at 100 ohms is found by again applying Ohms Law ($P = I^2R$). At 100 ohms, the rheostat has a power rating of 400 watts [(2 amperes)^2 X 100 ohms]. Since the normal load requires only 100 watts, the dummy load can be used to replace the normal load. The dummy load will dissipate the energy produced by the power supply in the form of heat. This type of dummy load can be used on AC or DC power supplies of any power output. Also, a fixed resistor may be used instead of a rheostat.

(4.) There are two requirements for using a resistive dummy load to replace a normal load. They are:

a. The resistance of the dummy load must be as close as possible to the actual value of the load resistance (R_L).

b. The power or wattage rating of the dummy load must be high enough to dissipate the power produced by the equipment or circuit.

Resistors must have the correct resistance values and power ratings before they can be used as dummy loads.

In order to operate properly, resistive dummy loads should have resistance values and ____________ ratings of correct size.

---

power (or wattage)

(5.) Let's look at an example of a resistive dummy load replacing a normal load. Suppose a power supply for a number of circuits (the normal load) produces 100 volts D.C. at 1 ampere. You know that using a dummy load requires knowledge of the resistance and power rating of the normal load. You can apply Ohm's Law to find resistance ($R = E \div I$) and power ($P = IE$). In this example, resistance equals 100 ohms (100 volts/1 ampere), and power equals 100 watts (1 ampere X 100 volts). Therefore, the dummy load should have 100 ohms resistance and a power rating of no less than 100 watts.

The microwave energy travels down the waveguide somewhat like water travels through a pipe. The walls of the waveguide may be lined with silver or other material of high conductivity. This will minimize the energy loss as the signal moves through the waveguide.

A waveguide is a (solid/hollow) cylindrical or rectangular pipe.

---

hollow

10. Since a waveguide has a special shape and no center conductor, a waveguide dummy load is designed a little differently than a coaxial dummy load. Both dummy loads use a resistive element made of powdered graphite in an adhesive compound. Also, both dummy loads use a heat sink with cooling fins. The differences between the two types of dummy loads are obvious when you study the illustrations of a waveguide dummy load shown in Figure 7.

1. isolated from
2. b. heat
3. 250, 1000

IF YOUR ANSWERS MATCH THE CORRECT ANSWERS, YOU MAY GO TO TEST FRAME 14. OTHERWISE, GO BACK TO FRAME 1 AND TAKE THE PROGRAMMED SEQUENCE BEFORE TAKING TEST FRAME 6 AGAIN.

7. You have learned how a rheostat or fixed resistor can be used as a resistive dummy load for a power supply. Now a resistive dummy load which replaces the antenna of a radio transmitter normally is not a common resistor. The dummy load for a radio transmitter must be able to dissipate the large amount of heat produced by the RF energy. For low power levels, a common, non-inductive resistor may do the job. However, at higher power levels many dummy loads use a special resistive element. This element has a center conductor that is a resistive mixture of powdered graphite with an adhesive compound. The resistive mixture is formed into a tapered cone and connected to a piece of coaxial cable tranmission line as shown in Figure 4.

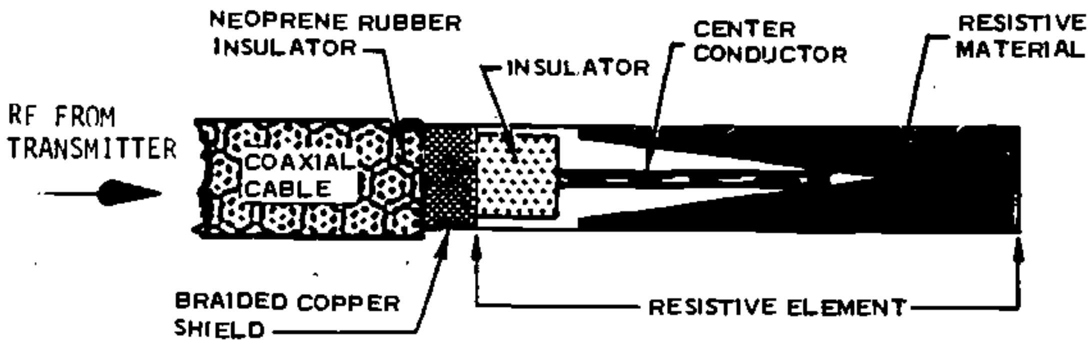
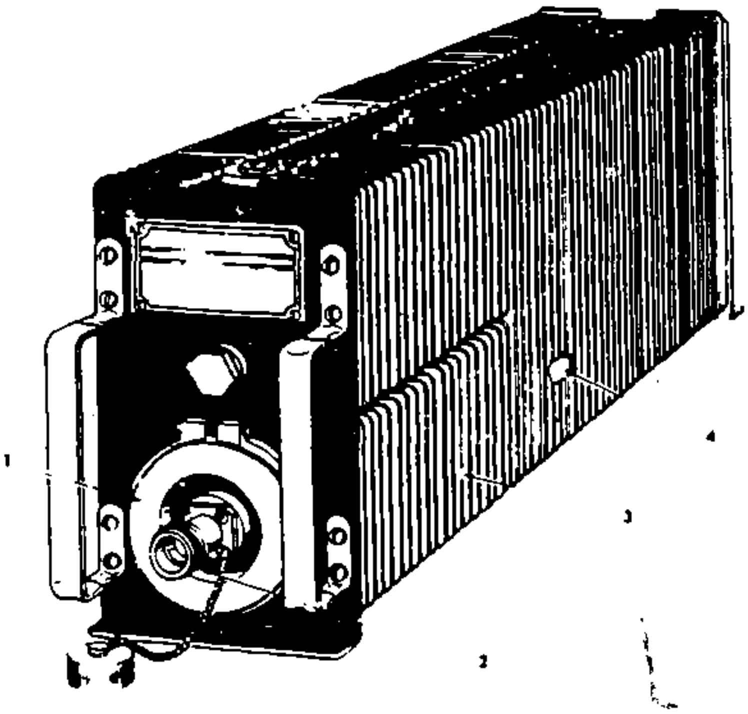


Figure 4

COAXIAL DUMMY LOAD (CUTAWAY VIEW)

In the figure, the coaxial cable couples the RF signal from the transmitter to the dummy load.

The resistive element is placed inside a large heat sink made of metal cooling fins. Figure 5 shows an external view of a complete coaxial dummy load.



1. Resistive element
2. RF input connector
3. Metal cooling fins
4. Resistive element extending down through cooling fins

Figure 5

COAXIAL DUMMY LOAD (EXTERIOR VIEW)

In the figure, the RF energy applied to the input is converted to heat, and then dissipated into the air by the cooling fins of the heat sink.

The coaxial dummy load shown in Figure 5 is commonly used to replace the normal load of a (power supply/radio transmitter)

---

radio transmitter

8. At frequencies in the RF communications range (about 100 kHz to about 500 MHz), coaxial cable is used to couple the RF signal from the transmitter to the dummy load. However, as frequency increases into the microwave frequency range, coaxial cable normally is not used. In the previous lesson on delay lines, you learned about the problems associated with coaxial cable as a transmission line for microwave frequencies, such as are used by radar. Recall that the cable center conductor, insulator, and braided copper shield (which is grounded) function as a capacitor in parallel with the signal (about 25 picofarads per foot.) At microwave frequencies, the capacitor's reactance (Xc) becomes so small that the signal will shunt to ground. The solution to this problem is the same for dummy loads as it was for delay lines: use a waveguide instead of coax.

The transmission line between transmitter and dummy load which is used below microwave frequencies is a length of ______________ ______________, while at microwave frequencies it is a ____________.

---

coaxial cable, waveguide

9. A waveguide is constructed as a hollow metal cylinder (pipe) or rectangular tube as shown in Figure 6.

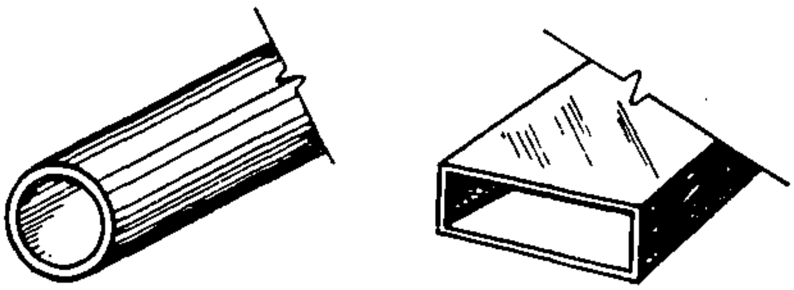


Figure 6

CYLINDRICAL AND RETANGULAR WAVEGUIDES

In the upper right-hand part of the figure, you can see that the resistive element is contained within a piece of waveguide. In the bottom half of the figure, you can see the specially designed flange used to connect the waveguide dummy load to the waveguide transmission line. The waveguide dummy load converts the microwave frequency energy to heat which is dissipated by the cooling fins.

The resistive element in a waveguide dummy load is contained within a

________________.

---

waveguide

(11.) Both the coaxial and waveguide dummy loads used in place of antennas are resistive in nature. You have learned that resistive dummy loads must meet two requirements. These requirements, as applied to antenna dummy loads, are:

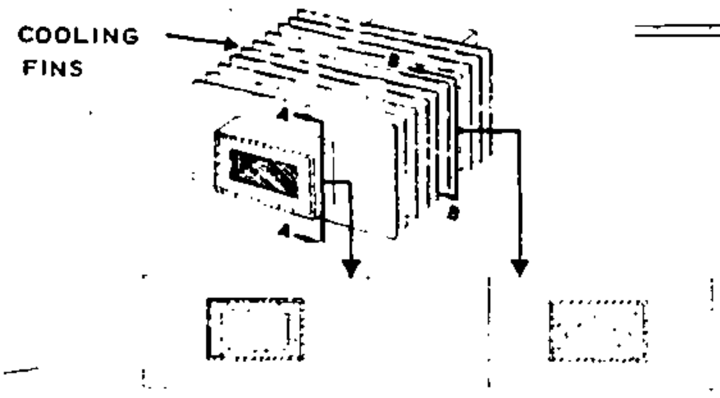
a. The resistance of the dummy load must equal the output load impedance of the transmitter.

b. The power handling ability of the dummy load must be high enough to dissipate the total output power of the transmitter.

In order to be used in place of an antenna, a coaxial or waveguide dummy load must have the same ____________ value and at least the same __________ ______ rating as the transmitter output.

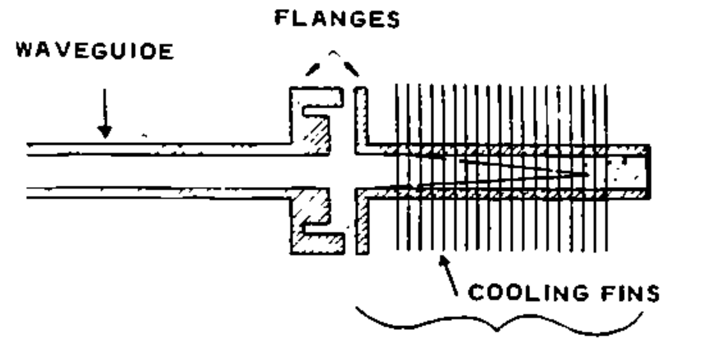
---

resistance, power (or wattage)

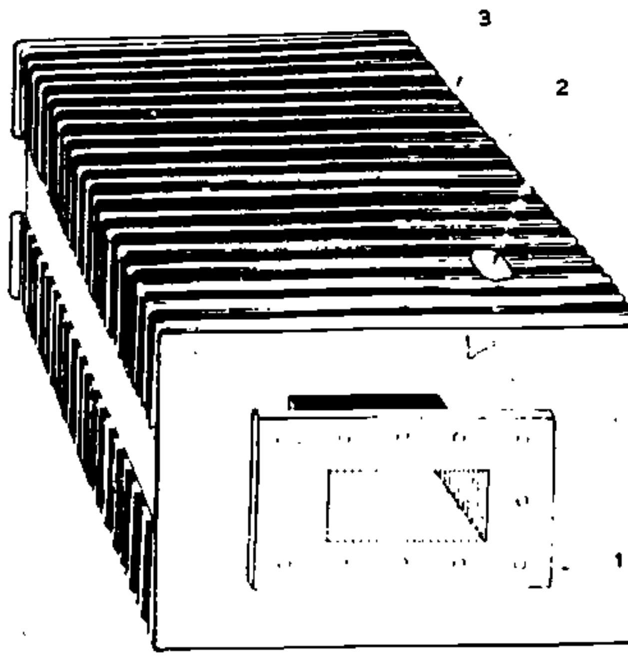


CROSS - SECTIONAL VIEW THROUGH A-A

CROSS - SECTIONAL VIEW THROUGH B-B



WAVEGUIDE DUMMY LOAD



1. Flange used to bolt waveguide dummy load to waveguide.
2. Waveguide extends through cooling fins.
3. Cooling fins

Figure 7

WAVEGUIDE DUMMY LOAD

(14.) THIS IS A TEST FRAME. COMPLETE THE TEST QUESTIONS AND THEN COMPARE YOUR ANSWERS WITH THE CORRECT ANSWERS GIVEN AT THE TOP OF THE PAGE FOLLOWING THE QUESTIONS.

1. A dummy load made of a mixture of powdered graphite with an adhesive compound would be used in place of the normal load on a (power supply/radio transmitter).

2. What type of dummy load would be used in place of an antenna at frequencies in the RF communications range?

   a. Waveguide

   b. Mechanical

   c. Wire wound resistor

   d. Coaxial

3. What type of dummy load normally would be used in place of a radar antenna?

   a. Reactive

   b. Waveguide

   c. Coaxial

   d. Mechanical

4. The resistance of the dummy load used in place of an antenna must be (less than/equal to/greater than) the transmitter's normal output load impedance.

12. Coaxial and waveguide dummy loads used in place of antennas are not perfect energy "sponges". Some of the RF energy generated by the radio transmitter will leak into space. This stray RF energy may be received by sensitive direction-finding equipment which could pinpoint the transmitter's location. Now under certain conditions, radio silence may need to be maintained. At this time, no one is authorized to transmit into a dummy load unless the Commanding Officer gives permission to transmit.

Dummy loads used in place of antennas absorb (all/most) of the RF energy.

---

most

13. So far you have learned about electrical type dummy loads. There is one other category of dummy loads, the mechanical dummy load. Mechanical dummy loads are devices which simulate mechanical loads. As an example, suppose you wish to test if a crane has a 10,000 kilogram lifting capacity. Obviously, you wouldn't pick up a 10,000 kilogram boat valued at $100,000 to make the test. You would use a mechanical dummy load such as a block of lead weighing 10,000 kilograms. Otherwise, you might destroy the boat if the crane didn't work properly! Like electrical dummy loads, mechanical dummy loads must simulate as closely as possible the actual load conditions for the equipment under test.

Two major categories of dummy loads are ____________ and ____________.

---

electrical, mechanical

5. What type of dummy load would be used to test the lifting capability of a crane?

a. Mechanical

b. Resistive

c. Electrical

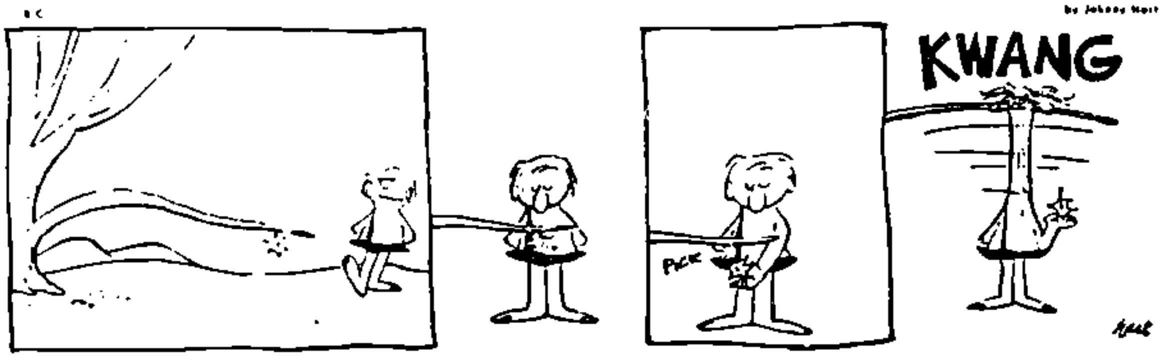
d. Coaxial

---

1. radio transmitter
2. d. coaxial
3. b. waveguide
4. equal to
5. a. mechanical

IF YOUR ANSWERS MATCH THE CORRECT ANSWERS YOU HAVE COMPLETED THE PROGRAMMED INSTRUCTION FOR LESSON 2, MODULE THIRTY THREE. OTHERWISE GO BACK TO FRAME 7 AND TAKE THE PROGRAMMED SEQUENCE BEFORE TAKING TEST FRAME 14 AGAIN.

AT THIS POINT, YOU MAY TAKE THE LESSON PROGRESS CHECK. IF YOU ANSWER ALL SELF-TEST ITEMS CORRECTLY, PROCEED TO THE LESSON TEST. IF YOU INCORRECTLY ANSWER ONLY A FEW OF THE PROGRESS CHECK QUESTIONS, THE CORRECT ANSWER PAGE WILL REFER YOU TO THE APPROPRIATE PAGES, PARAGRAPHS, OR FRAMES SO THAT YOU CAN RESTUDY THE PARTS OF THIS LESSON YOU ARE HAVING DIFFICULTY WITH. IF YOU FEEL THAT YOU HAVE FAILED TO UNDERSTAND ALL, OR MOST, OF THIS LESSON, SELECT AND USE ANOTHER WRITTEN MEDIUM OF INSTRUCTION, AUDIO/VISUAL MATERIALS (IF APPLICABLE), OR CONSULTATION WITH THE LEARNING CENTER INSTRUCTOR, UNTIL YOU CAN ANSWER ALL SELF-TEST ITEMS ON THE PROGRESS CHECK CORRECTLY.



If you don't know what it does don't fool with it!

511

A <u>dummy load</u> is a device that appears to any equipment under operation to be the normal load. For example, dummy loads can be attached to a radio transmitter or power supply in place of the normal loads as shown in Figure 2.

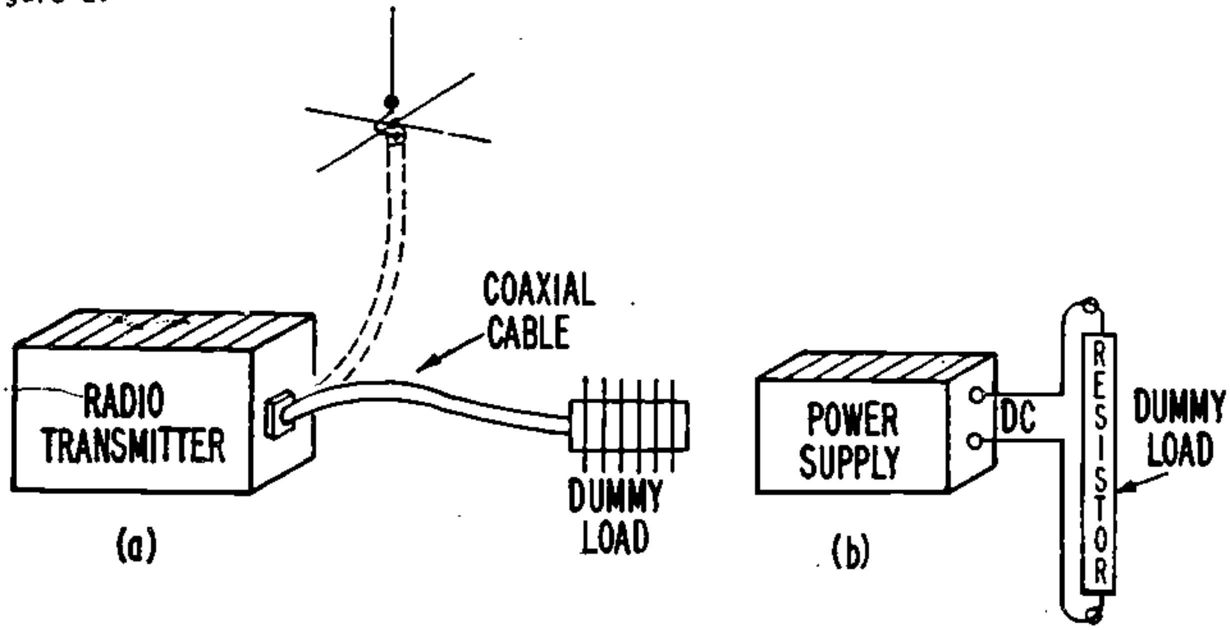


Figure 2

DUMMY LOAD APPLICATIONS

In the figure, the normal loads are electrically isolated from the circuits. The transmitter or power supply can be operated and tested without the problems related to using normal loads. Dummy loads can be used to replace individual circuits within equipments as well as to replace complete equipments.

A resistive dummy load functions by converting the output energy from an operating equipment into heat. Therefore, many electrical dummy loads are made of resistive material. Ordinary resistors often are used as dummy loads.

NARRATIVE
LESSON 2

Dummy Loads

Many times in your electronics career you will find it necessary to test a piece of equipment without having it connected to its normal load device. Two common situations are shown in Figure 1.

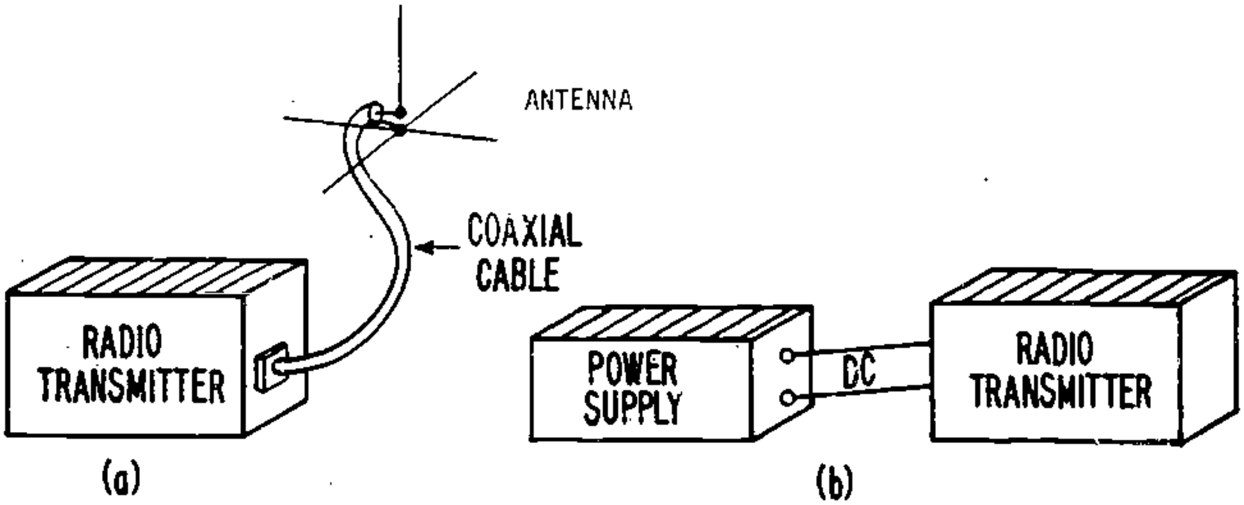


Figure 1

TEST SITUATIONS

In Figure 1(a), a radio transmitter is connected to its normal load, an antenna. If you key the transmitter to test it, RF energy would radiate from the antenna and cause interference to normal communication on the channel.

In Figure I(b), a power supply is connected to one of its normal loads, a radio transmitter. In order to troubleshoot the power supply, you need to operate it. This could cause damage to the transmitter's fragile semiconductors. In these examples, you can see a need both to test equipments under load conditions and to isolate them from their normal loads.

At 100 ohms the power rating is 400 watts. Since the normal load for the power supply requires only 100 watts, the rheostat can be used as a dummy load. In other examples, fixed or variable resistors can be used as dummy loads for AC or DC power supplies of any power output.

Normally, the type of resistive dummy load used to replace the antenna of a high power radio transmitter is not a common resistor. Because of the large amount of heat produced by the RF energy, a special resistive element is used. This element has a center conductor that is a resistive mixture of powdered graphite with an adhesive compound. The resistive mixture is formed into a tapered cone and connected to a piece of coaxial cable transmission line as shown in Figure 4.

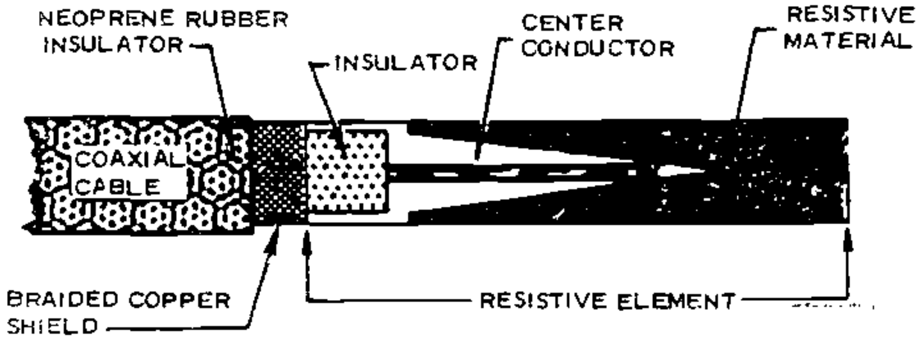


Figure 4

COAXIAL DUMMY LOAD (CUTAWAY VIEW)

To accomplish maximum energy transfer, both the coax cable and the dummy load must be impedance matched to the radio transmitter. The output impedance of radio transmitters is usually fixed at 50 ohms resistive.

The resistive element is placed inside a large heat sink made of metal cooling fins. Figure 5 shows the exterior view of a coaxial dummy load.

There are two requirements for using a resistive dummy load to replace a normal equipment or circuit load. They are:

1. The resistance of the dummy load must be as close as possible to the actual value of load resistance (R_L).

2. The power, or voltage, rating of the dummy load must be high enough to dissipate the power produced by the equipment or circuit.

Let's look at an example of a resistive dummy load replacing a normal load. Suppose a power supply to a number of circuits requires 100 volts and draws 1 ampere. By applying Ohm's Law (R=E÷I and P=IE), the load resistance is 100 ohms and the load power rating is 100 watts. Therefore, the dummy load must have a resistance of 100 ohms, and a power rating of at least 100 watts.

Figure 3 shows a 0-250 ohm rheostat rated at 2 amperes and 1000 watts maximum power which can be used as the dummy load.

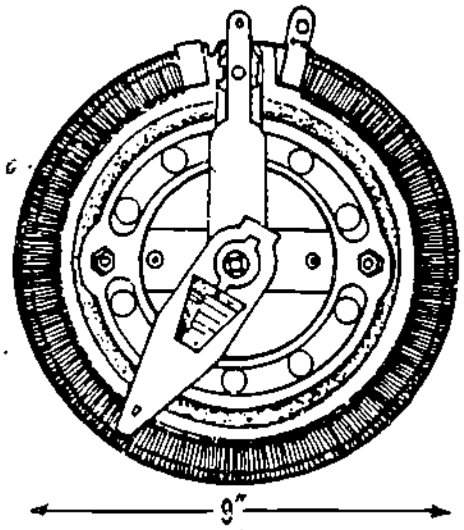
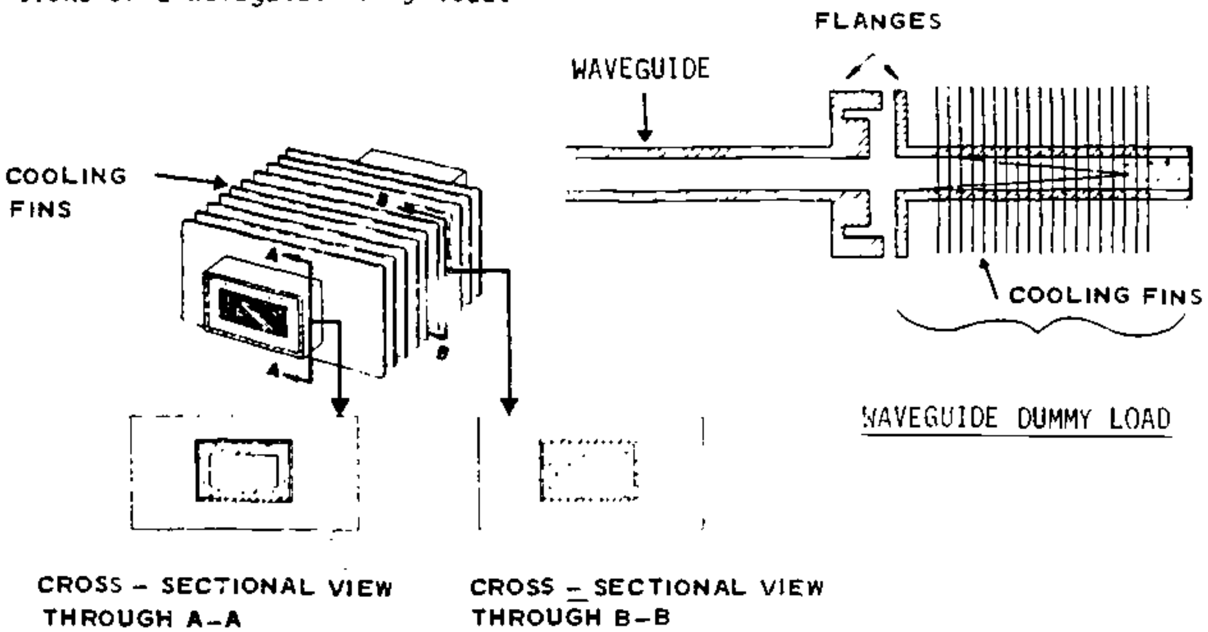


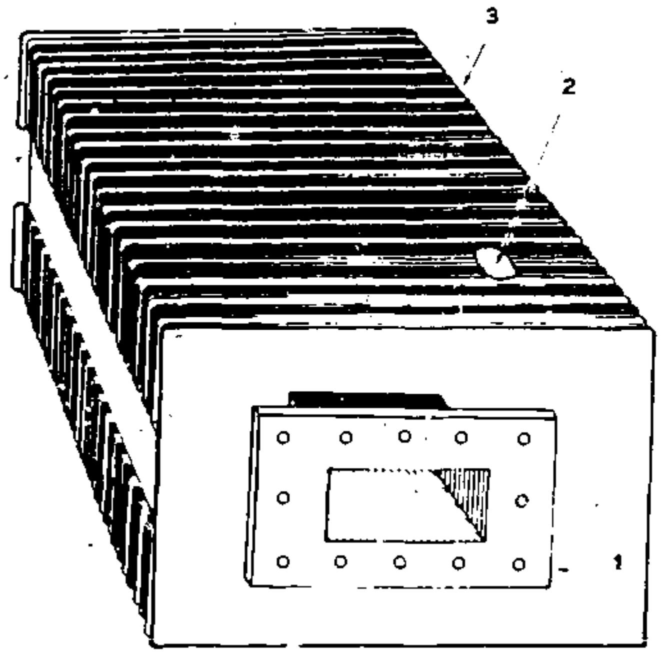
Figure 3

0-250 OHM, 2 AMPERE RHEOSTAT

The power rating of the rheostat, when set at 100 ohms with 2 amperes of current through it, is found by again applying Ohm's Law ($P=I^2R$).

A waveguide dummy load basically functions the same as a coaxial dummy load, although there are some design differences. Figure 7 shows various illustrations of a waveguide dummy load.

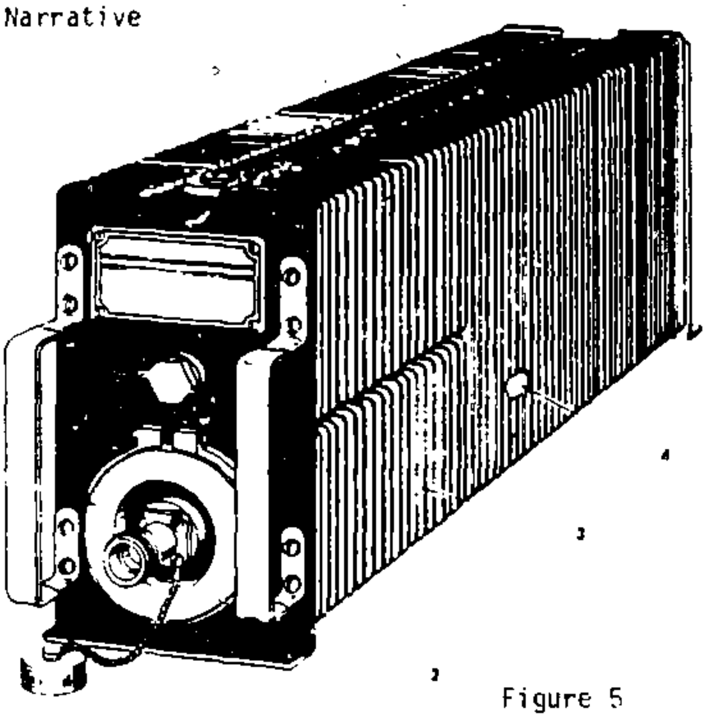




1. Flange used to bolt waveguide dummy load to waveguide.
2. Waveguide extends through cooling fins.
3. Cooling fins.

Figure 7

WAVEGUIDE DUMMY LOAD



1. Resistive element
2. RF input connector
3. Metal cooling fins
4. Resistive element extending down through cooling fins

Figure 5

COAXIAL DUMMY LOAD (EXTERIOR VIEW)

In the figure, the RF energy applied to the input is converted to heat, and then dissipated into the air by the cooling fins.

At frequencies in the RF communications range (about 100 kHz to about 500 MHz), coaxial cable is used to couple the RF signal from the transmitter to the dummy load. However, coaxial cable normally is not used at radar microwave frequencies. This is because the capacitive reactance of the cable at microwave frequencies becomes so small that the signal loss is high. The signal is effectively shunted to ground. Therefore, a waveguide is used at microwave frequencies. A waveguide is a hollow metal cylinder (pipe) or rectangular tube as shown in Figure 6.

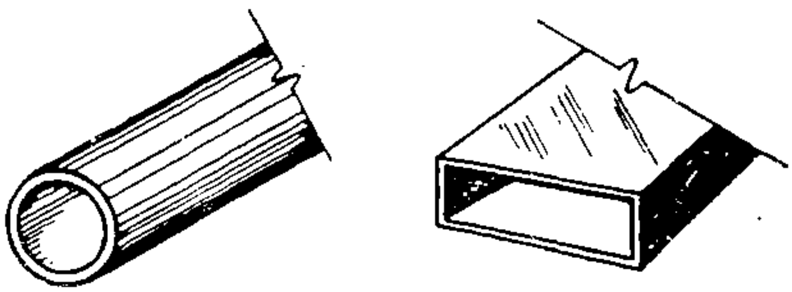


Figure 6

CYLINDRICAL AND RECTANGULAR WAVEGUIDES

BASIC ELECTRICITY AND ELECTRONICS

MODULE THIRTY THREE

LESSON 3

SPECIAL SOLID STATE DEVICES

JULY 1980

As you can conclude from studying the figure, waveguide dummy loads also use a resistive element, and use heat sinks with cooling fins to dissipate the heat. In a waveguide dummy load, the resistive element is contained within a piece of waveguide. Also, there are specially designed flanges which connect the waveguide dummy load to the waveguide transmission line.

Coaxial and waveguide dummy loads used in place of antennas must meet the same requirements as any other resistive dummy load.

These requirements as applied to antenna dummy loads are:

1. The resistance of the dummy load must equal the output load impedance of the transmitter.

2. The power handling ability of the dummy load must be high enough to dissipate the total output power of the transmitter.

Condition one is normally automatically met because of the match between fixed values of RF dummy loads and companion transmission lines.

A small amount of the RF energy generated by a transmitter which is connected to a coaxial or waveguide dummy load will leak into the surrounding space. This stray RF energy may be received by sensitive direction finding equipment and pinpoint the transmitter's location. Now under certain conditions, radio silence may need to be maintained. Therefore, under certain conditions, the Commanding Officer must give permission to transmit even into a dummy load.

You have learned about electrical dummy loads. One other category of dummy load is the mechanical dummy load which is a device that simulates mechanical loads. For example, you would use a mechanical dummy load, such as a block of lead weight, rather than an expensive boat to test the lifting capability of a crane.

Mechanical dummy loads, like electrical dummy loads, must simulate as closely as possible the actual load conditions of the equipment under test.

AT THIS POINT, YOU MAY TAKE THE LESSON PROGRESS CHECK. IF YOU ANSWER ALL SELF-TEST ITEMS CORRECTLY, PROCEED TO THE LESSON TEST. IF YOU CORRECTLY ANSWER ONLY A FEW OF THE PROGRESS CHECK QUESTIONS, THE CORRECT ANSWER PAGE WILL REFER YOU TO THE APPROPRIATE PAGES, PARAGRAPHS, OR FRAMES SO THAT YOU CAN RESTUDY THE PARTS OF THIS LESSON YOU ARE HAVING DIFFICULTY WITH. IF YOU FEEL THAT YOU HAVE FAILED TO UNDERSTAND ALL, OR MOST, OF THE LESSON, SELECT AND USE ANOTHER WRITTEN MEDIUM OF INSTRUCTION, AUDIO/VISUAL MATERIALS (IF APPLICABLE), OR CONSULTATION WITH THE LEARNING CENTER INSTRUCTOR, UNTIL YOU CAN ANSWER ALL SELF-TEST ITEMS ON THE PROGRESS CHECK CORRECTLY.

33.3.63.7 IDENTIFY the schematic symbol, operating characteristics, and applications for the varactor diode by selecting the correct statement or schematic symbol from a choice of four. 100% accuracy is required.

33.3.63.8 IDENTIFY the schematic symbol, operating characteristics, and applications for the triac by selecting the correct statement or schematic symbol from a choice of four. 100% accuracy is required.

BEFORE YOU START THIS LESSON, READ THE LESSON LEARNING OBJECTIVES AND PREVIEW THE LIST OF STUDY RESOURCES ON THE NEXT PAGE.

OVERVIEW
LESSON 3

Special Solid State Devices

In this lesson you will be introduced to a number of special devices which are being used increasingly in electronic circuits today. You will become familiar with their operating characteristics and some of the most recent applications made of them. And you will learn to identify their schematic symbols.

The learning objectives of this lesson are as follows:

TERMINAL OBJECTIVE(S):

33.3.63 When the student completes this lesson (s)he will be able to IDENTIFY schematic symbols, operating characteristics and applications for optoelectronic devices (LED, photodiode, phototransistor, photocell, solar cell, and optical coupler), the varactor diode, and the triac, by selecting statements from a choice of four. 100% accuracy is required.

ENABLING OBJECTIVES:

When the student completes this lesson, (s)he will be able to:

33.3.63.1 IDENTIFY the schematic symbol, operating characteristics, and applications for the light emitting diode (LED) by selecting the correct statement or schematic symbol from a choice of four. 100% accuracy is required.

33.3.63.2 IDENTIFY the schematic symbol, operating characteristics, and applications for the photodiode by selecting the correct statement or schematic symbol from a choice of four. 100% accuracy is required.

33.3.63.3 IDENTIFY the schematic symbol, operating characteristics, and applications for two- and three-terminal phototransistors by selecting the correct statement or schematic symbol from a choice of four. 100% accuracy is required.

33.3.63.4 IDENTIFY the schematic symbol, operating characteristics, and applications for the photocell by selecting the correct statement or schematic from a choice of four. 100% accuracy is required.

33.3.63.5 IDENTIFY the schematic symbol, operating characteristics, and applications for the photovoltaic cell by selecting the correct statement or schematic symbol from a choice of four. 100% accuracy is required.

33.3.63.6 IDENTIFY the schematic symbol, operating characteristics, and applications for an optical coupler by selecting the correct statement or schematic symbol from a choice of four. 100% accuracy is required.

SUMMARY
LESSON 3

Special Solid State Devices

The electronic revolution is producing a continuous series of new special devices. Many of these, although originally created to solve a specific problem, are finding seemingly endless applications. Among the more important new devices are those in the optoelectronic group (LEDs, photodiodes, etc.), the varactor diode, and the triac.

Optoelectronic devices either produce or use light in their operation. Their schematics typically show two arrows pointing either away from the basic symbol (if light is produced) or in toward it (if light is used). The first of these, the Light Emitting Diode (LED) is shown with its schematic in Figure 1.

Figure 1

LED

The LED is a diode which, when forward biased produces visible light. Their extremely small size, low operating voltage and [illegible] life make LEDs ideal replacements for incandescent bulbs used as panel indicators and in displays in pocket calculators and the like. Typically, they are used in seven-segment displays like that shown in Figure 2.

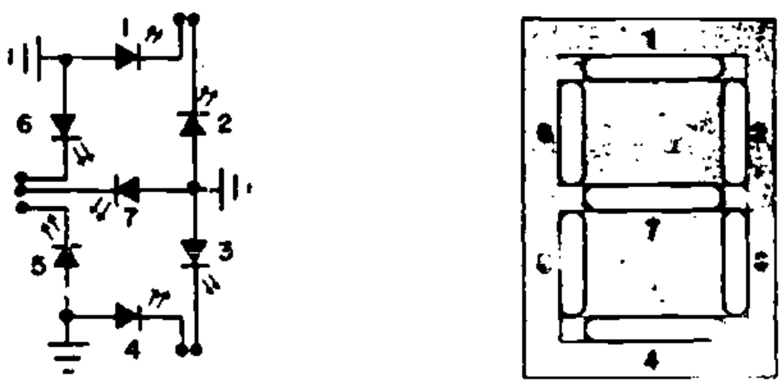


Figure 2

SEVEN SEGMENT LED DISPLAY

LIST OF STUDY RESOURCES
LESSON 3

Special Solid State Devices

To learn the material in this lesson, you have the option of choosing, according to your experience and preferences, any or all of the following study resources:

Written Lesson presentation in:

Module Booklet:

Summary
Programmed Instruction
Narrative

Student's Guide:

Summary
Progress Check

Additional Material(s):

None

Enrichment Material(s):

The Semiconductor Data Book, 4th edition, Motorola Semiconductor Products, Inc., 1969.

Tracton, K.; Display Electronics; Blue Ridge Summit, Pa., Tab Books, 1977.

YOU MAY USE ANY, OR ALL, RESOURCES LISTED ABOVE, AND ALSO THE LEARNING CENTER INSTRUCTOR. HOWEVER, ALL MATERIALS LISTED ARE NOT NECESSARILY REQUIRED TO ACHIEVE LESSON OBJECTIVES. THE PROGRESS CHECK MAY BE TAKEN AT ANY TIME.

The two-terminal NPN type, as an example, consists simply of a photodiode placed in the base-emitter circuit of a transistor. Light intensity determines the base current. In the three-terminal type, an additional lead is used to apply an electrical bias to the base which can alter the effect of light intensity on transistor conductivity (compensate for ambient light levels, etc.).

An older, similar device is the photoconductive cell, or photo cell, shown with its schematic in Figure 5.

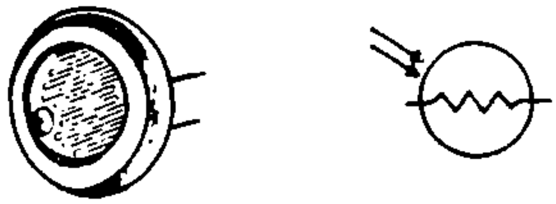


Figure 5

PHOTO CELL

The photo cell is a light-controlled variable resistor with a high light-to-dark ratio--typically 1:1000 or more. Photo cells are used in various timing and control circuits, such as automatic streetlight controllers.

Figure 6 shows the photovoltaic cell, or solar cell, with schematic.

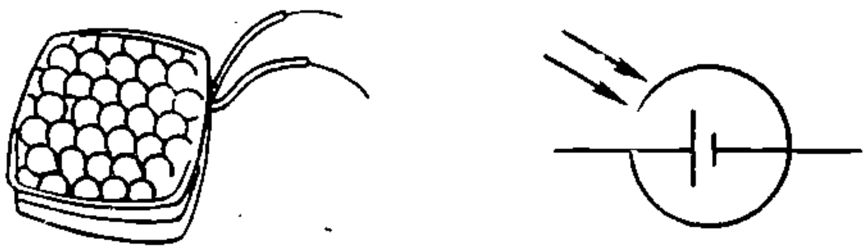


Figure 6

SOLAR CELL

When exposed to light, the solar cell produces about .45 volts and a current in proportion to its size. Connected in series or parallel like batteries, solar cells can produce higher voltages and currents. They are used widely in communications satellites and solar-powered homes.

This display uses seven LED segments (or bars) which can be lit in different combinations to form any number from "0" through "9". Each segment draws about 10 mA of current when lit. Displays are of the common-anode type, as shown, or the common-cathode type. Often several displays are packaged together in a stack, as for 7- or 9-digit calculators.

A second optoelectronic device, one that <u>uses</u> rather than produces light, is the <u>photodiode</u>, shown with schematic in Figure 3.

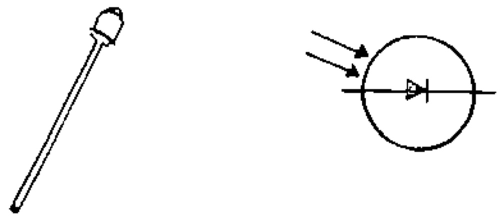


Figure 3

PHOTODIODE

The photodiode is a light-controlled variable resistor. A transparent "window" placed over the semi-conductor chip allows light to reach the diode. When reverse biased, the diode conducts current in direct proportion to the intensity of the light source. Photodiodes are used in computer card readers, photographic light meters, and some types of optical scanning equipment.

Another light-using optoelectronic device, the <u>phototransistor</u>, is even more sensitive to light and capable of higher output current than the photodiode. Four types of phototransistors are shown, with schematics, in Figure 4.

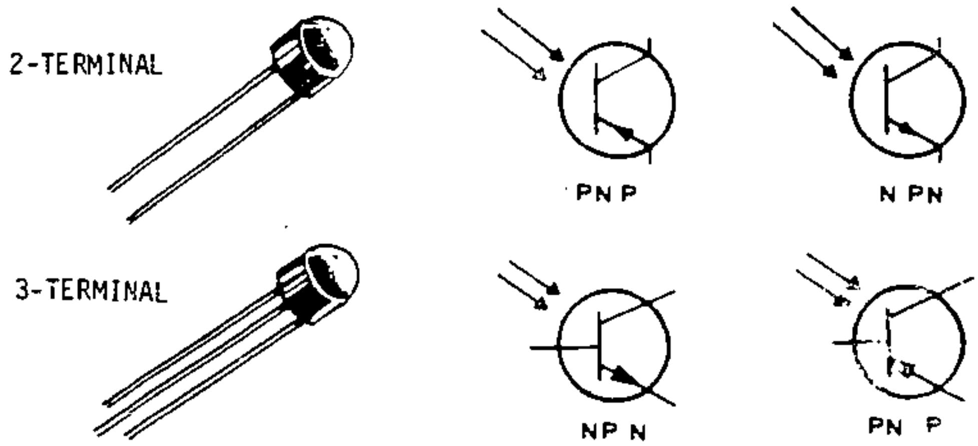


Figure 4

2-TERMINAL AND 3-TERMINAL PHOTOTRANSISTOR

The varactor, or varicap, is a diode made to function like a variable capacitor. This is possible due to the effect of reverse biasing on the size of the depletion region surrounding a diode's PN junction, which is illustrated in Figure 9.

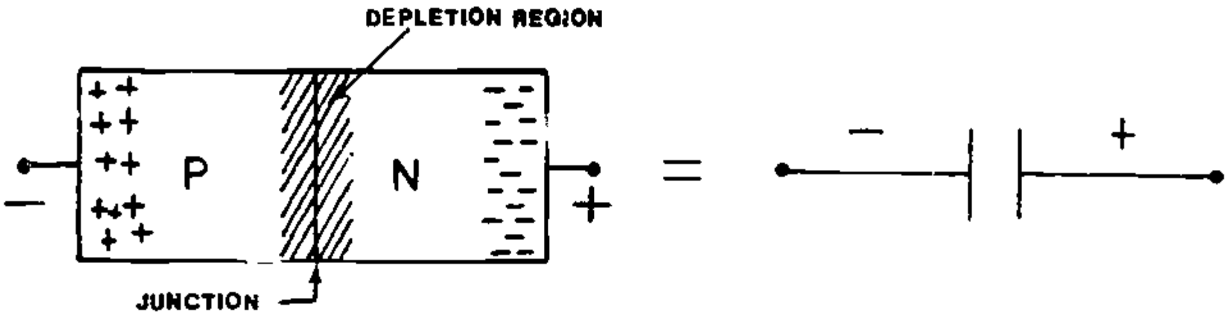


Figure 9

PN JUNCTION VS. CAPACITANCE

Increasing the reverse bias voltage causes the depletion region to widen into an insulating gap comparable to the dielectric in a capacitor. Applying the formula $C = \frac{A\,K}{d}$ (where A = plate area, K = a constant value, and d = distance between plates), it is found that the varactor's capacitance (C) is inversely proportional to applied reverse bias.

Varactors have replaced variable capacitors in many circuit applications, especially sophisticated tuning circuits. One advantage of the varactor is that it allows a DC voltage to be used to tune a circuit automatically as shown in Figure 10.

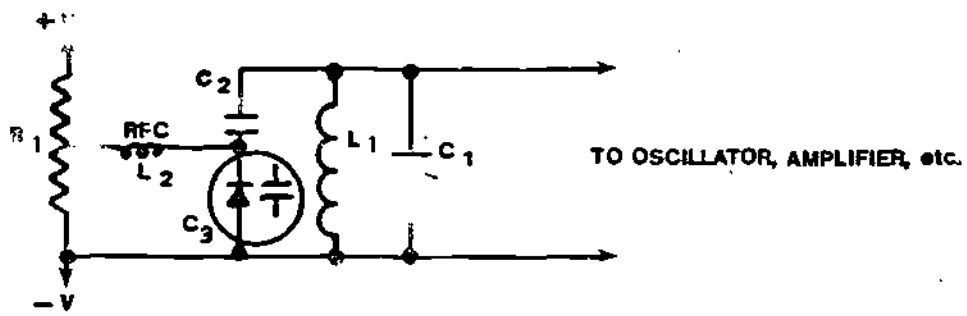


Figure 10

VARACTOR TUNED TANK

The optical coupler, shown in Figure 7, combines two optoelectronic devices to achieve total electrical isolation of circuits.

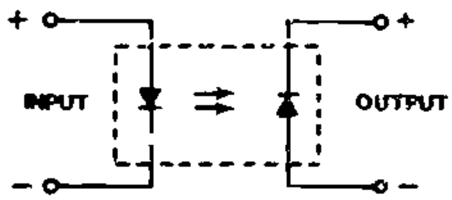


Figure 7

OPTICAL COUPLER

The coupler consists of a forward-biased LED and a reverse-biased photodiode encapsulated so that changes in the input signals are transmitted by light to the output. Couplers like this are suitable for frequencies in the low megahertz range. Where more output is required, couplers combining a phototransistor with an SCR can be used. Optical scanners are replacing transformers in low voltage and current applications, such as digital control circuits.

The varactor diode, the first of two non-optical devices to be covered, is shown with its schematic in Figure 8.

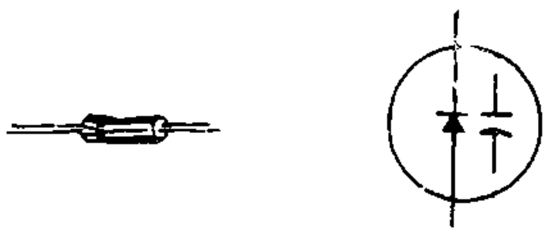


Figure 8

VARACTOR DIODE - PICTORIAL AND SCHEMATIC

AT THIS POINT, YOU MAY TAKE THE LESSON PROGRESS CHECK. IF YOU ANSWER ALL SELF-TEST ITEMS CORRECTLY, YOU MAY TAKE THE LESSON TEST. IF YOU INCORRECTLY ANSWER ONLY A FEW OF THE PROGRESS CHECK QUESTIONS, THE CORRECT ANSWER PAGE WILL REFER YOU TO THE APPROPRIATE PAGES, PARAGRAPHS, OR FRAMES SO THAT YOU CAN RESTUDY THE PARTS OF THIS LESSON YOU ARE HAVING DIFFICULTY WITH. IF YOU FEEL THAT YOU HAVE FAILED TO UNDERSTAND ALL, OR MOST, OF THE LESSON, SELECT AND USE ANOTHER WRITTEN MEDIUM OF INSTRUCTION, AUDIO/VISUAL MATERIALS (IF APPLICABLE), OR CONSULATION WITH THE LEARNING CENTER INSTRUCTOR, UNTIL YOU CAN ANSWER ALL SELF-TEST ITEMS ON THE PROGRESS CHECK CORRECTLY.

The variable DC voltage felt at R1 acts to reverse bias varactor diode C3. Because C3 is in series with C2 and the equivalent capacitance of C2 and C3 is in parallel with tank circuit L1-C1, any variation in the DC voltage at R1 will vary both the capacitance of C3 and the resonant frequency of the tank circuit.

The triac, the last special device to be covered, is a three-terminal device similar to an SCR, as Figure 11 shows.

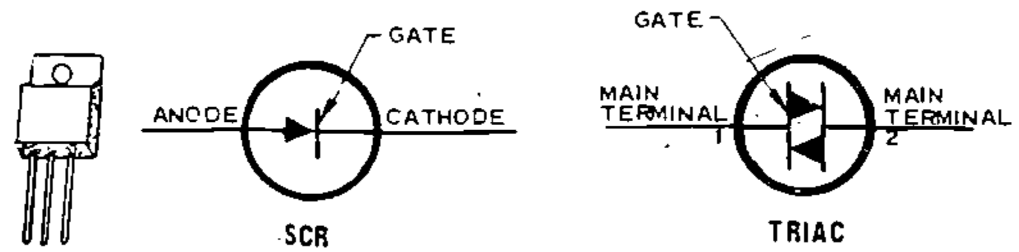


Figure 11

TRIAC VS SCR SCHEMATIC SYMBOLS

The triac is essentially two SCRs back to back, sharing a common gate. It controls current flow during both alternations of an AC cycle, instead of only one as the SCR does, and conducts in both directions. The triac is widely used in circuits which control light intensity and motor speed. A comparison of the waveforms seen at the input, gate, and output of the SCR and the triac is shown in Figure 12.

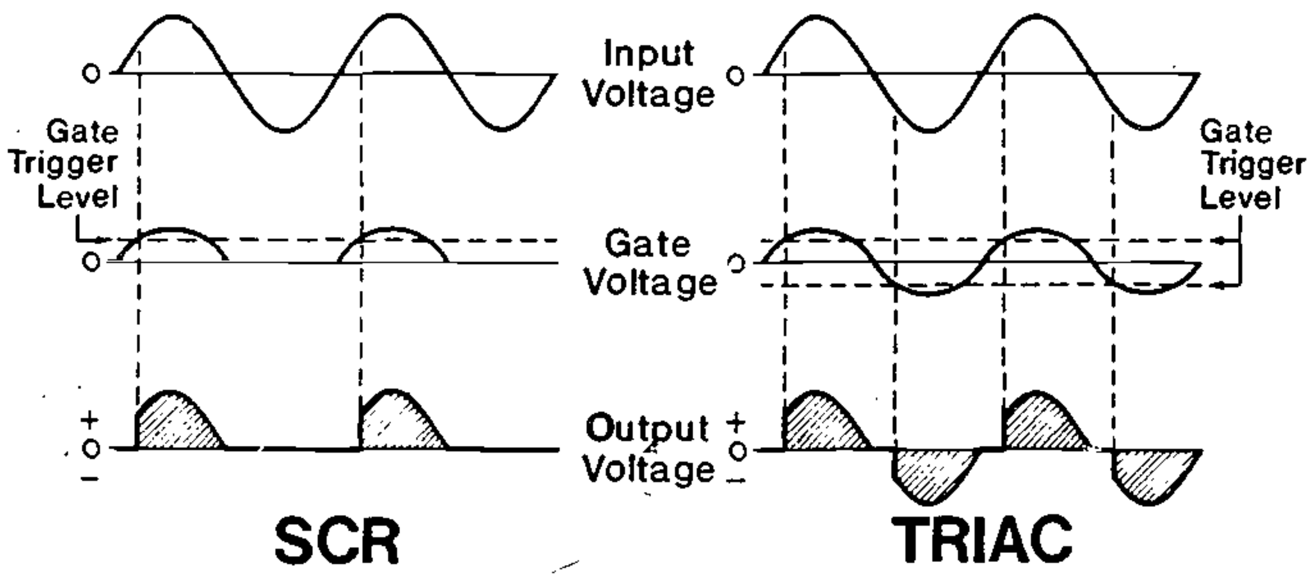


Figure 12

SCR VS TRIAC WAVEFORMS

amber depending upon the material used to make the diode. LEDs are very small devices. The actual diameter of the semi-conductor "chip" may be only about one-half a millimeter. The chip is contained in a larger plastic package 3 mm to 6 mm in diameter.

An illustration of a LED along with its schematic symbol is shown in Figure 1.

Figure 1

LED

As you can see, the LED is designated by a standard diode symbol with two arrows pointing away from the cathode. The arrows indicate light leaving the diode. You will find that the schematic symbols for optoelectronic devices all have arrows pointing towards them (if they use light) or away from them (if they produce light).

A diode which produces red, green, or amber light when forward biased is called a(n)____________________.

LED (or Light Emitting Diode)

PROGRAMMED INSTRUCTION
LESSON 3

Special Solid State Devices

TEST FRAMES ARE 6, 12, 17, 26, AND 29. PROCEED TO TEST FRAME 6 FIRST AND SEE IF YOU CAN ANSWER THE QUESTIONS. FOLLOW DIRECTIONS GIVEN AFTER THE TEST FRAME.

1. The electronic revolution is continuing at a rapid pace. Electronic circuits are required to do more specialized functions with fewer and smaller parts. For example, the needs of the space exploration program have led to the development of new devices, or the re-designing of old devices. In this lesson, you will learn about some special solid state devices that are becoming increasingly important as a result of our modern electronics technology.

The first six of the special solid state devices you will learn about fall into the optoelectronic category. Optoelectronic devices either produce light or use light in their operation.

Special solid state devices which either produce light or use light fall into the general group called ______________________________.

---

optoelectronic

2. The first type of optoelectronic device you will learn about was developed to replace the fragile power-consuming, short-life incandescent light bulbs used as status indicators on control panels, among other uses. This device is a Light Emitting Diode (LED). A LED is a PN junction diode which, when forward biased, produces a visible light. The light may be red, green or

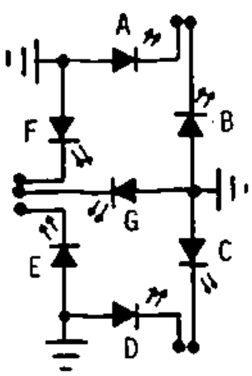
(3.) LEDs are low power devices. The normal operating voltage is small, about 1.6V forward bias, and the current drain is generally about 10 mA. The power requirement for LEDs is much lower than for incandescent (filament) lamps. Also, the life expectancy of a LED is very long (over 100,000 hours of operation). Because of their low power consumption and long life, LEDs commonly are used as "power on" indicators and as alpha-numeric displays for pocket calculators, digital voltmeters, and frequency counters.

When compared to incandescent lamps, LEDs have a much (higher/lower) power consumption and a much (shorter/longer) life expectancy.

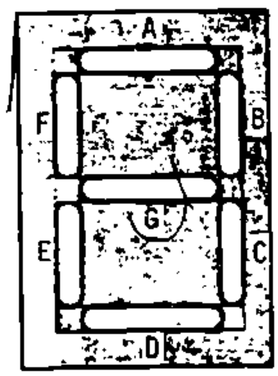
---

lower, longer

(4.) A LED may be used alone. However, a very common application for the device is the segmented LED display such as is found on pocket calculators. A typical LED numerical display uses seven LED segments (or bars) which can be lit in different combinations to form any number from "0" through "9". Figure 2 shows a schematic diagram and illustration of a typical seven-segment LED display.



(a)



(b)

Figure 2

SEVEN SEGMENT LED DISPLAY

Figure 2(a) is the diagram for a common-anode seven-segment display. This means that all the anodes are connected internally to each other and externally to the same potential. When a negative voltage is applied to the proper cathodes, a number is formed. In Figure 2(b), LEDs A, B, C, D, F, and G will light and produce the number "9" when a negative voltage is applied to their cathodes. Likewise a negative voltage applied to the cathodes of LED's A, C, D, E, F, and G produces the number "6". The display of numbers "9" and "6" are shown in Figure 3.

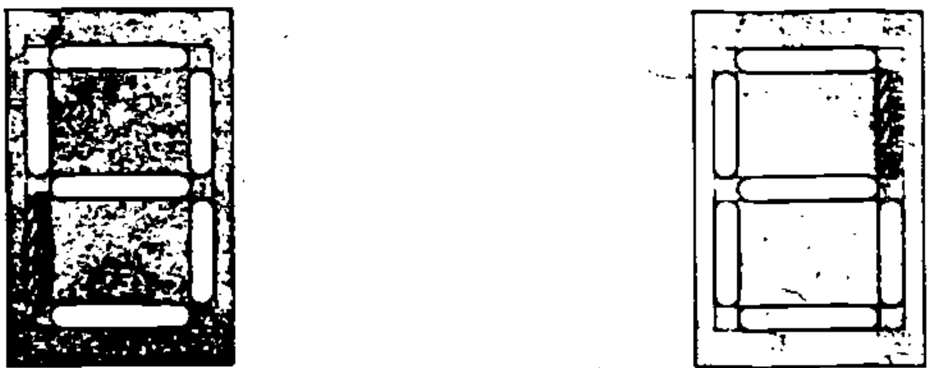


Figure 3

DISPLAY EXAMPLES

Of course, common-cathode seven-segment displays are also available. In these displays, all the cathodes are connected to the same potential. When you are replacing LED displays, you must make sure that the replacement is of the same type as the faulty display. Since both LED types may look alike, you should check the manufacturer's type number carefully.

In a common-anode seven-segment LED display, an individual LED will light if a negative voltage is applied to its (anode/cathode).

---

cathode

5. Each LED in a seven-segment display is very small. In fact, the actual size of a display number may be no larger than a standard typewritten number. Several seven-segment displays may be put together into a compact package containing any number of displays per package. Figure 4 shows a package containing seven of these seven-segment displays.

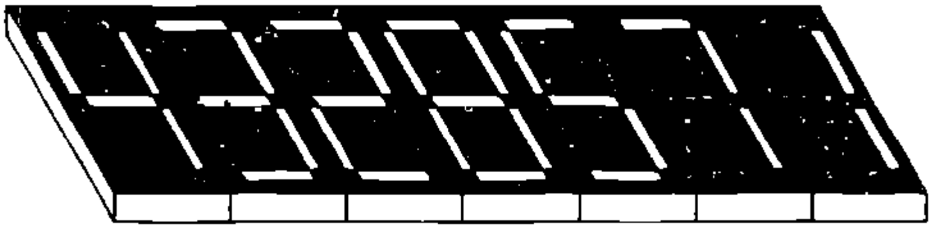


Figure 4

STACKED SEVEN-SEGMENT DISPLAY OF "4328571"

The package in the figure could be used for the numbers on a pocket calculator.

The current drain for each number display in Figure 4 varies with the digit displayed. For example, the number "1" requires two LED's to be lit, and draws about 20 mA of current (10 mA per segment). The number "8" requires about 70 mA of current.

In Figure 4, the number "5" draws about ________ mA of current.

50

6. THIS IS A TEST FRAME. COMPLETE THE TEST QUESTIONS AND THEN COMPARE YOUR ANSWERS WITH THE CORRECT ANSWERS GIVEN AT THE TOP OF THE PAGE FOLLOWING THE QUESTIONS.

1. A solid state device is called "optoelectronic" if it

   a. produces light but does not use light.

   b. uses light but does not produce light.

   c. either produces or uses light.

USE THE DIAGRAM BELOW TO ANSWER QUESTIONS 2 AND 3.

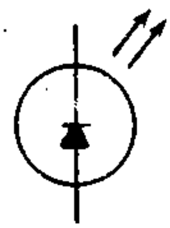


Figure 5

2. The diagram is the schematic symbol for what device?

3. The arrows indicate that the device is designed to

   a. conduct current when light is applied.

   b. produce visible light.

   c. conduct current when heat is applied.

   d. produce heat energy.

4. In a common-anode seven-segment display, all (cathodes/anodes) are at the same voltage potential.

5. A pocket calculator contains several common-anode seven-segment digital displays. The display of the digit "1" draws (less current than/the same current as) the display of the digit "8".

Figure 6 shows a photodiode and its schematic symbol.

Figure 6

PHOTODIODE

Notice that the symbol for a photodiode has arrows pointing toward the standard diode symbol. This indicates that light is required for operation of the device.

The arrows in Figure 6 indicate that a photodiode (produces/uses) light while operating as a variable (light source/resistor).

---

uses, resistor

8. Photodiodes are packaged so that a transparent "window" is placed over the semiconductor chip. The light source is then aimed through the window. By switching the light source on and off, you can switch the conduction level of the photodiode. By varying the light intensity, you can control the amount of conduction. Photodiodes have a fast response to light changes, which is a distinct advantage in digital applications. Photodiodes are used in computer card readers, paper tape readers, and photographic light meters. They also are used in some types of optical scanning equipment.

If you vary the amount of light reaching a photodiode, the amount of conduction in the device (remains constant/varies).

---

varies

(9.) Another optoelectronic device which uses light is the phototransistor. A phototransistor, like a photodiode, conducts current when exposed to light. The difference between them is that a phototransistor is much more sensitive to light, and produces more output current for a given intensity of light than does a photodiode.

A phototransistor is made by combining a photodiode with a transistor as shown in Figure 7.

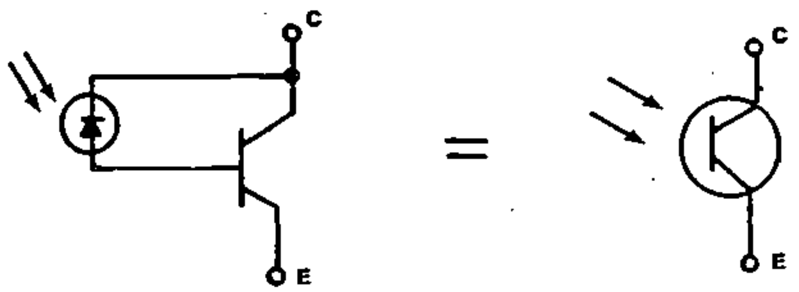


Figure 7

PHOTOTRANSISTOR

You can see in the figure that a phototransistor is simply a transistor with a photodiode placed in the base-emitter circuit. Light falling on the photodiode will change the base current of the transistor. This causes the transistor to produce an amplified output collector current.

A phototransistor is made by combining a photodiode with a ____________

and has (more/less) output current capability than a photodiode.

---

transistor, more

(10) Phototransistors have a transparent window over the photodiode's light sensitive material. The intensity of the light source on this window determines how much current the transistor will conduct.

A phototransistor may be either of the PNP or NPN type. An illustration of a two-terminal (no base lead) phototransistor, and the schematic symbols for PNP and NPN types, are shown in Figure 8.

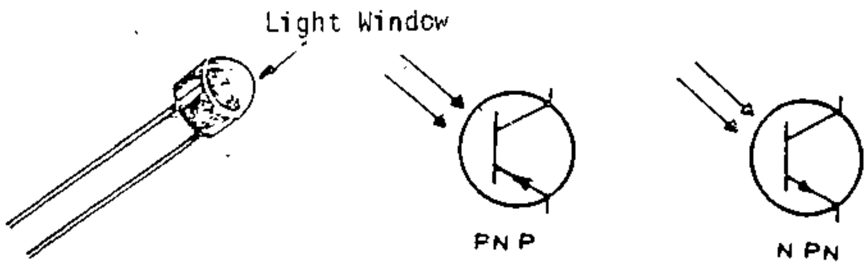


Figure 8

2-TERMINAL PHOTOTRANSISTOR

You can see that the symbol for a phototransistor is similar to the standard transistor symbol with the addition of two arrows pointing toward it.

A phototransistor's conduction varies with the intensity of ____________ on the transparent window.

---

light

(11) Some phototransistors have an external base lead. One function of the base lead is to allow an electrical bias to be applied to the base which may compensate for ambient (normal room) light. This bias allows the transistor to operate at the optimum point with normal room light intensity. The two-and three-terminal phototransistors operate the same when a separate light source is switched on.

An illustration of a three-terminal (with base lead) phototransistor, and the schematic symbols for PNP and NPN types, are shown in Figure 9.

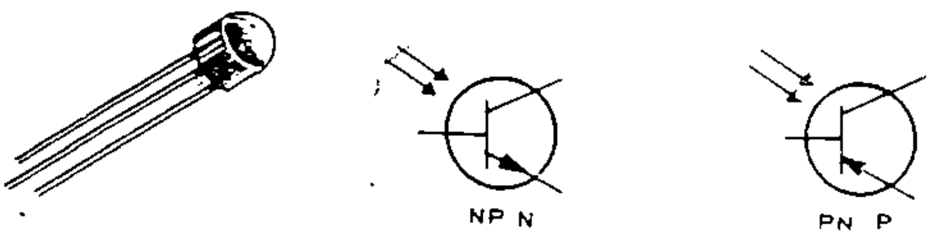


Figure 9

3-TERMINAL PHOTOTRANSISTOR

In the figure, notice that the schematic symbols for three-terminal phototransistors are very similar to the schematic symbols for two-terminal phototransistors.

A function of the ____ lead on a three-terminal phototransistor is to provide a way to control phototransistor conduction under ambient light.

---

base

(12) THIS IS A TEST FRAME. COMPLETE THE TEST QUESTIONS AND THEN COMPARE YOUR ANSWERS WITH THE CORRECT ANSWERS GIVEN AT THE TOP OF THE PAGE FOLLOWING THE QUESTIONS.

1. In order to conduct current, photodiodes must be (forward/reverse) biased.
2. As the intensity of an external light source increases, the conduction level of a photodiode (decreases/remains the same/increases).
3. A(n) ____________________________ replaces a photodiode in order to provide increased conduction for a given light intensity.
4. An electrical bias can be placed on a (two/three)-terminal phototransistor in order to compensate for ambient light.

USE THE SCHEMATIC SYMBOLS BELOW TO ANSWER QUESTIONS 5 THROUGH 7.

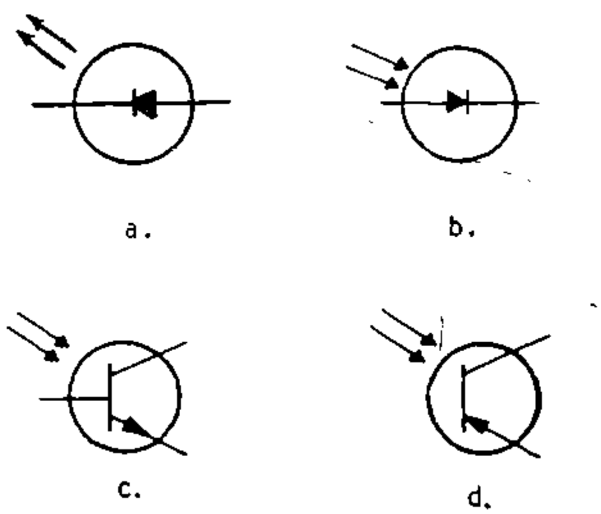


Figure 10

5. The schematic symbol for a photodiode is

   a. a

   b. b

   c. c

   d. d

6. The schematic symbol for a two-terminal phototransistor is

   a. a

   b. b

   c. c

   d. d

7. The schematic symbol for a three-terminal phototransistor is

   a. a

   b. b

   c. c

   d. d

110

1. reverse
2. increased
3. phototransistor
4. three
5. b
6. d
7. c

IF YOUR ANSWERS MATCH THE CORRECT ANSWERS YOU MAY GO TO TEST FRAME 17. OTHERWISE, GO BACK TO FRAME 7 AND TAKE THE PROGRAMMED SEQUENCE BEFORE TAKING TEST FRAME 12 AGAIN.

13. A device which uses light and is similar in operation to the photodiode is the photoconductive cell, or <u>photocell</u>. Photocells have been around for a much longer time than have photodiodes. Like the photodiode, the photocell is a light-controlled variable resistor. A typical light-to-dark resistance ratio for a photocell is 1:1000. This means that the resistance of the device could range from 1000 ohms in bright light to 1000 kilohms in the dark, or from 2000 ohms in the light to 2000 kilohms in the dark, and so on. Of course, other ratios also are available.

Figure 11 shows an illustration and schematic symbol for a photocell.

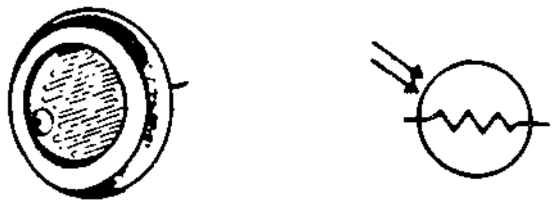


Figure 11

PHOTOCELL

Photocells are used in various types of control and timing circuits as, for example, the automatic street light controllers in many cities.

A photocell is a device that is most similar in operation to a(n)

a. LED

b. photodiode

c. phototransistor

---

photodiode

(14) A device which converts light energy into electrical energy is called a <u>photovolaic cell</u>. More popular names you have heard are "solar cell" and "solar battery". A solar cell is a device that acts like a battery with light providing the energy source. An example of a solar cell and the schematic symbol are shown in Figure 12.

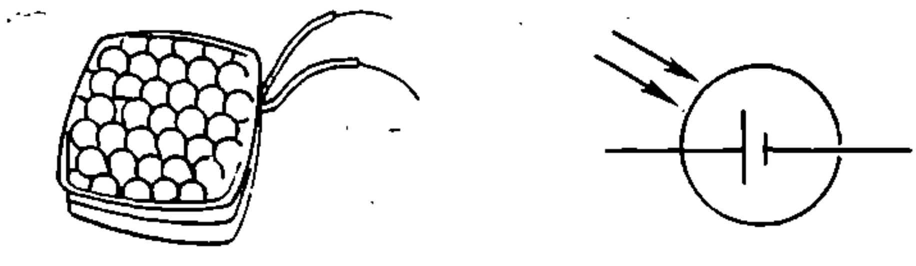


Figure 12

SOLAR CELL

In the figure, notice that the schematic symbol is similar to that of a battery. This device will produce a voltage of about .45 volts across its terminals, with a current capacity determined by its size. Higher voltages and currents are produced by series and/or parallel connections of the solar cells, just as in batteries. The device is finding widespread use in communications satellite and solar-powered home applications.

The operation of a solar cell most closely resembles the operation of a

a. LED.

b. photodiode.

c. photocell.

d. battery.

---

d. battery

(15) Often in electronics it is desirable to separate the voltage in one electrical circuit from another, yet couple the signal between the circuits. Although the coupling capacitor in an RC coupled amplifier does block DC between amplifier stages, the voltage isolation is not complete. Figure 13 shows a circuit diagram of a typical coupling capacitor between two amplifiers, and the charging current through the capacitor which prevents total isolation.

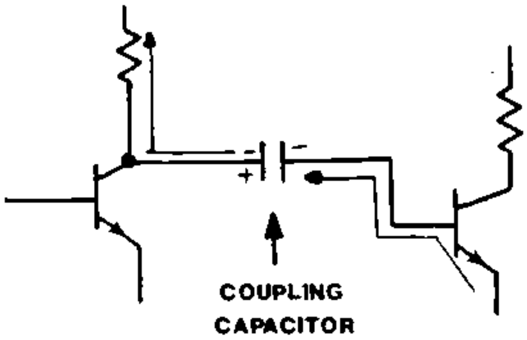


Figure 13

DC BLOCKING WITH COUPLING CAPACITOR

The coming of both the LED and the photodiode have made it possible to get complete electrical isolation, and yet transfer signals between two circuits. In this set-up, light becomes the coupling agent. The device which uses this principle of transfer is called an optical coupler. The diagram for an optical coupler is shown in Figure 14.

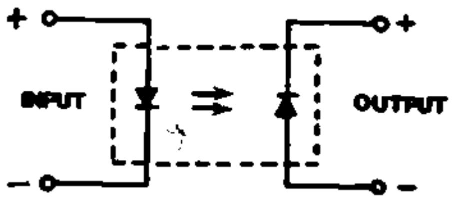


Figure 14

OPTICAL COUPLER

In the figure, the arrows indicate the transfer of light from a LED to a photodiode.

In an optical coupler, the coupling agent is (electricity/light).

light

(16.) The basic optical coupler is composed of a LED and photodiode in an encapsulated housing. The LED operates with forward bias, while the photodiode uses reverse bias as shown by the polarity signs on the input/output leads in Figure 15.

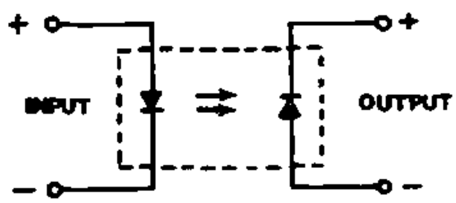


Figure 15

OPTICAL COUPLER

When the input signal causes current through the LED to increase, the light produced by the LED also increases. This more intense light passes through a light-conducting medium and falls on the photodiode PN junction. Thus, more current flows through the photodiode external circuit. The level of current through the photodiode varies in relation to the level of LED current. However, both are electrically isolated.

The optical coupler is suitable for frequencies in the low megahertz range. Also, the photodiode can handle only small currents. However, phototransistor and SCR devices can be used in optical couplers where more output current is required.

Optical couplers are replacing transformers in low voltage and current applications. Sensitive digital circuits can use this device to control large currents and voltages with low voltage logic levels. In fact, your CMI tests are graded by an optical coupler scanning device.

A basic optical coupler is composed of a (LED/solar battery) and a (photocell/photodiode).

LED, photodiode

17. THIS IS TEST A FRAME. COMPLETE THE TEST QUESTIONS AND THEN COMPARE YOUR ANSWERS WITH THE CORRECT ANSWERS GIVEN AT THE TOP OF THE PAGE FOLLOWING THE QUESTIONS.

1. Two devices which act as variable resistors when exposed to light are
   a. photocells and solar cells.
   b. LEDs and photocells.
   c. photodiodes and photocells.
   d. solar batteries and optical couplers.

2. A device which produces a voltage when exposed to a light source is a
   a. photodiode.
   b. photovoltaic cell.
   c. photoconductive cell.
   d. phototransistor.

3. A device which uses light to transfer a signal between a LED and a photodiode located in two separate circuits is called a(n)

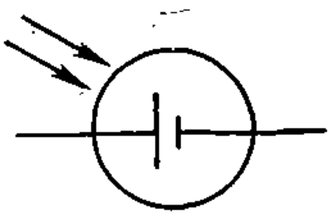
a. solar cell.

b. optical coupler.

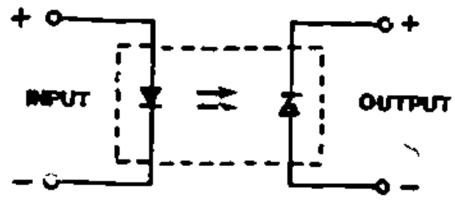
c. solar battery.

d. phototransistor.

USE THE SCHEMATIC SYMBOLS BELOW TO ANSWER QUESTIONS 4 THROUGH 6.

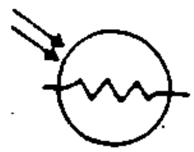


a.



b.

c.



d.

Figure 16

4. The schematic symbol for an optical coupler is

a. a

b. b

c. c

d. d

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5. The schematic symbol for a solar battery is

   a. a

   b. b

   c. c

   d. d

6. The schematic symbol for a photoconductive cell is

   a. a

   b. b

   c. c

   o. d

---

1. c. photodiodes and photocells.
2. b. photovoltaic cell.
3. b. optical coupler.
4. b.
5. a.
6. d.

IF YOUR ANSWERS MATCH THE CORRECT ANSWERS YOU MAY GO TO TEST FRAME 26. OTHERWISE, GO BACK TO FRAME 13 AND TAKE THE PROGRAMMED SEQUENCE BEFORE TAKING TEST FRAME 17 AGAIN.

(18) This lesson has covered optoelectronic devices. You now will learn about some other types of special devices that are becoming more important as a result of modern solid-state technology. The first one to be covered is the varactor diode. A varactor, also called a varicap, is a diode that behaves electrically like a variable capacitor. A varactor uses the property of the PN junction of a diode to replace the dielectric of a common capacitor.

A varactor is a diode that behaves electrically like a variable ____________.

capacitor

(19) This discussion now will cover some basic principles on how varactors operate. You need to become familiar with these principles so that you can understand the operation of varactors and also field-effect transistors (FETs) covered in the next lesson.

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As you know, a diode consists of two types of material: one is P-type and the other is N-type. P-type material has an excess of positively-charged particles. N-type material has an excess of negatively-charged particles, called electrons, which carry current. (In some textbooks, these P and N current carriers are referred to as "majority carriers").

Now when a semiconductor device is built with P and N materials, a PN junction is formed as shown in Figure 17.

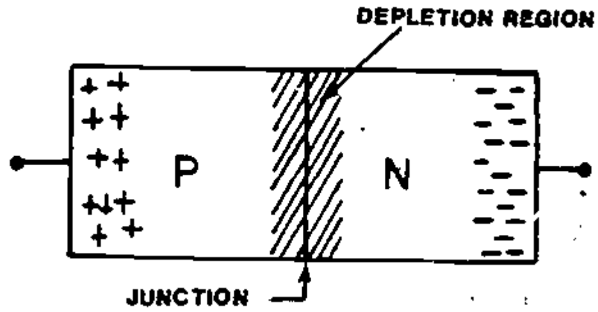

Figure 17

PN JUNCTION

In the figure, you can see a narrow internal region near the junction in which the P and N materials are void of current carriers. This area is called the <u>depletion region</u>.

In a PN junction, the depletion region

a. carries an excess of positively-charged particles.

b. carries an excess of electrons.

c. is void of current carriers.

---

c. is void of current carriers.

(20) The size of the depletion region in a PN junction is related to the bias and strength of an applied voltage. Recall the rule "like charges repel, unlike charges attract". Therefore, a positive voltage applied to the P-type material will repel the positive particles in the material toward the PN junction. In a similar manner, a negative voltage applied to the N-type material will repel the negative particles in the material toward the PN junction. This <u>forward bias</u> voltage makes the depletion region smaller in size. If the applied voltage is large enough (about .5 volts for silicon material), the negative particles will cross the PN junction and join with the positive particles. Figure 18 shows this condition.

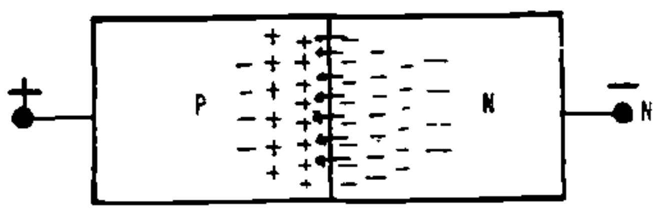

Figure 18

FORWARD BIASED PN JUNCTION

In the figure, the forward bias on the PN junction has caused the depletion region to disappear. This produces a low resistance at the PN junction, and a large current flow across it. This condition is all right for rectification, but not for the varactor diode. The conditions that cause current flow through a PN junction are the same as those that occur in any forward biased diode.

When a silicon PN junction has abnut a .5 volt forward bias voltage applied, the depletion region (increases/decreases), causing current to (flow/stop flowing) across the PN junction.

---

decreases, flow

(21) A varactor diode must be operated with reverse bias. In a varactor, a negative voltage applied to the terminal of the P-type material will attract the positive particles. This causes them to move away from the PN junction. In a similar manner, a positive voltage applied to the terminal of the N-type material will attract the negative particles, causing them to move away from the PN junction. This reverse bias voltage increases the size of the depletion region. Figure 19 shows this condition.

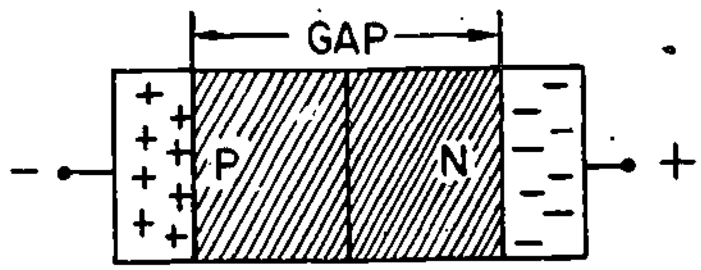

Figure 19

REVERSE BIASED PN JUNCTION

In the figure, the reverse bias on the varactor has caused the depletion region to form a relatively large gap. This produces a high resistance between the terminals, and little current flow (only in the uA range).

A reverse bias voltage applied to the terminals of a varactor causes the depletion region to become (smaller/larger).

---

larger

22 A reverse bias voltage applied to a varactor causes an insulation gap to form between the charged particles in the P and N materials. The gap has a reduced number of current carrying particles. Therefore, the gap can be compared to the dielectric of a capacitor as shown in Figure 20.

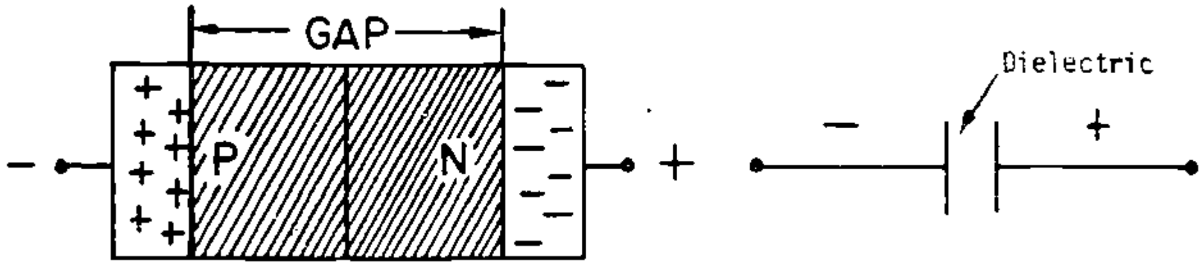

Figure 20

PN JUNCTION VS. CAPACITANCE

The same factors influence capacitance in a common capacitor and in a varactor. These factors include plate area and distance between plates. Recall the formula for capacitance: C equals AK divided by d; where A equals plate area, d equals distance between plates, and K equals constant for measurement system.

As you can see, increasing the gap between a capacitor's plates will decrease its capacitance. (Increasing "d" in the formula makes "C" smaller.) Since a varactor is a diode that behaves electrically like a capacitor, the same formula applies. By varying the reverse bias on the diode, you can vary the width of the "gap". An increase in reverse bias increases the width of the gap which reduces the capacitance of the PN junction. Therefore, the diode's capacitance is inversely proportional to the applied reverse bias. Since the gap only occurs under the reverse bias condition, varactors are always reversed biased for proper operation.

As reverse bias increases in a varactor, the size of the insulation gap (increases/decreases) and the capacitance (increases/decreases).

---

increases, decreases

(23.) In a varactor diode, the ratio of capacitance change to reverse bias voltage change may be as high as 10 to 1. An example of capacitance change to voltage change ratios is shown in Figure 21.

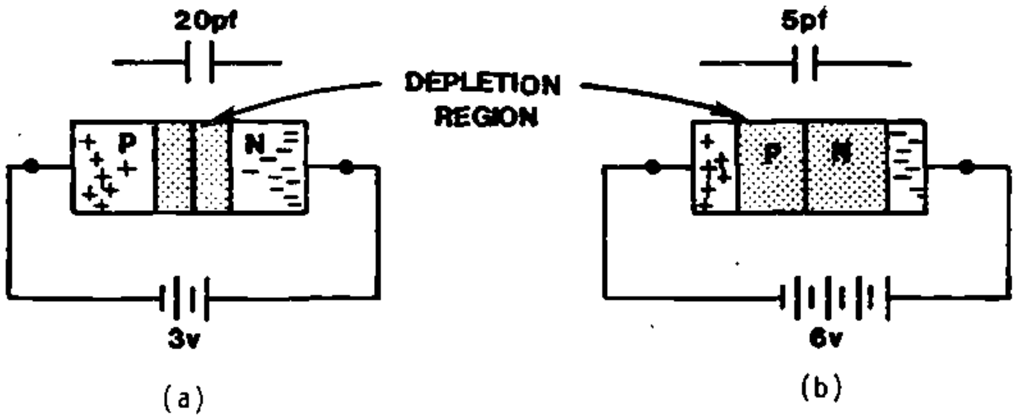

Figure 21

VARACTOR-CAPACITANCE VS BIAS VOLTAGE

In Figure 21(a), the reverse bias is 3 volts which produces a capacitance of 20 pF. If the reverse bias is increased to 6 volts, the change in reverse bias is 3 volts. In Figure 21(b), you can see that at 6 volts the capacitance has dropped to 5 pF, which is a change of I5 pF. Therefore, this example shows a I5 pF capacitance change to a 3 volt reverse bias change. Simple division shows that the change ratio is 15 divided by 3, or 5 to I. You should notice that the increase in reverse bias voltage causes a decrease in varactor capacitance. If the reverse bias voltage were decreased, the capacitance would increase. Also notice that the value of varactor capacitance is very small (picofarad, 10^{-12} range).

A varactor diode has a 10 volt reverse bias voltage applied to it. If this reverse bias voltage were dropped to 5 volts, the capacitance of the varactor would (decrease/remain the same/increase).

---

increase

(24) An illustration and schematic symbol of a varactor are shown in Figure 22.

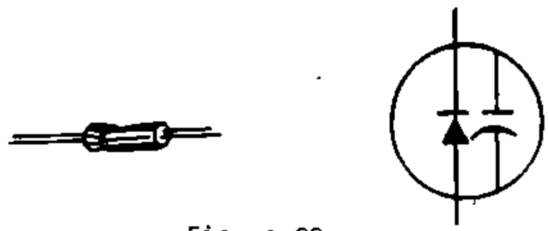

Figure 22

VARACTOR DIODE - PICTORIAL AND SCHEMATIC

Note that the symbol for a varactor diode contains the symbols for both a diode and a capacitor.

Varactors are generally used in the tuning circuits of more sophisticated communications equipment. They replace the old style variable capacitor tuning. They also may be used in other circuits where a small variable capacitance is required. One advantage of this device is that a DC voltage can be used to tune a circuit for simple remote control and automatic tuning functions.

The schematic symbol for a varactor contains the symbols for a ____________ and a ____________.

---

diode, capacitor

(25.) Let's place a varactor diode into a circuit to see how it functions. A common application for the varactor is to function as a variable tuning capacitor in the tank circuits of receivers and transmitters. An example is shown in Figure 23.

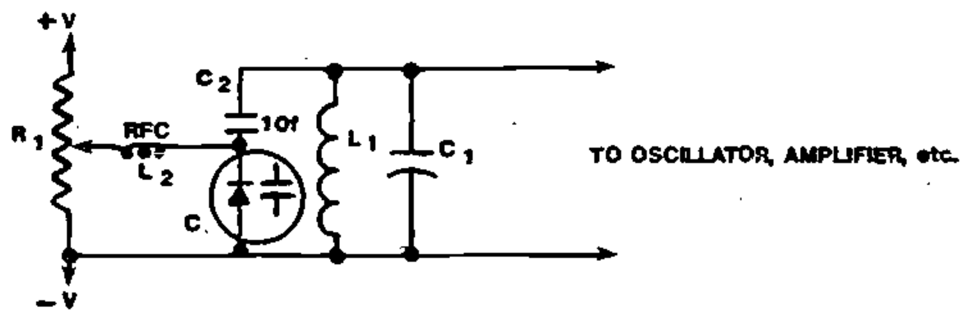

Figure 23

VARACTOR TUNED TANK

In the figure, a DC voltage is felt at the wiper of potentiometer R1, and may be adjusted between +V and -V. This DC voltage is passed through the low resistance of L2, a radio frequency choke, to varactor diode C3. This DC voltage acts to <u>reverse bias</u> the diode. Now the capacitance of C3 is in series with C2. Also, the equivalent capacitance of C2 and C3 is in parallel with tank circuit L1-C1. Thus any variation in the DC voltage at the wiper of R1 varies both the capacitance of C3 and the tank circuit resonant frequency. The radio frequency choke provides a high inductive reactance at the tank frequency to prevent tank loading by ~~R1~~. C2 acts to block DC from the tank, and fixes the tuning range of C3. You may use an ohmmeter to check the resistance of a varactor diode in a circuit just as you would to check any other diode. You would expect to find a high reverse bias resistance, and a low forward bias resistance. A 10 to 1 ratio of reverse bias resistance to forward bias resistance would be considered normal.

A varactor diode is in parallel to the input of a tuned tank in a radio receiver. If the reverse bias voltage on the varactor is changed, the frequency of the tank circuit (remains the same/changes).

---

changes

(26) THIS IS A TEST FRAME. COMPLETE THE TEST QUESTIONS AND THEN COMPARE YOUR ANSWERS WITH THE CORRECT ANSWERS GIVEN AT THE TOP OF THE PAGE FOLLOWING THE QUESTIONS.

1. A varactor diode behaves electrically like a variable ____________.

2. The size of the depletion region gap in the varactor diode illustration below indicates which bias condition applied to the varactor?

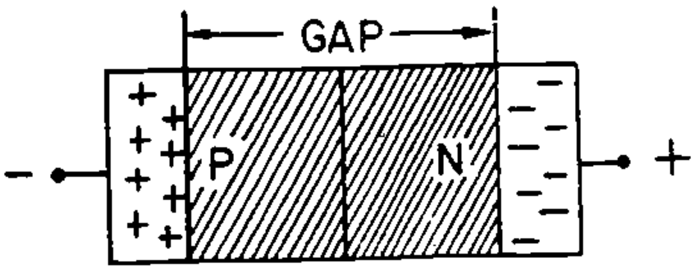

Figure 24

a. forward bias

b. reverse bias

c. zero (0) bias

A varactor diode is in parallel to the input of a tuned tank in a radio receiver. If the reverse bias voltage on the varactor is changed, the frequency of the tank circuit (remains the same/changes).

---

changes

(26) THIS IS A TEST FRAME. COMPLETE THE TEST QUESTIONS AND THEN COMPARE YOUR ANSWERS WITH THE CORRECT ANSWERS GIVEN AT THE TOP OF THE PAGE FOLLOWING THE QUESTIONS.

1. A varactor diode behaves electrically like a variable ______________.

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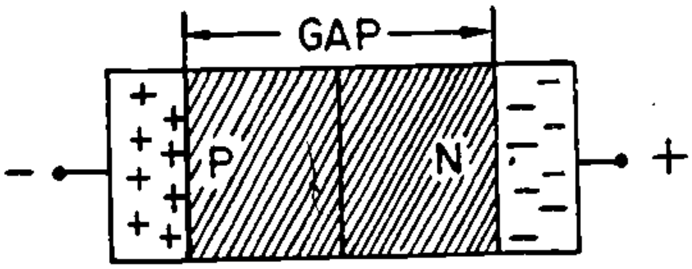


Figure 24

a. forward bias

b. reverse bias

c. zero (0) bias

3. As the size of the depletion region around the PN junction in a varactor increases, the ____________________ across the PN junction decreases.

   a. capacitance

   b. frequency

   c. resistance

   d. inductance

4. Which of the following figures is the schematic symbol for a varactor?

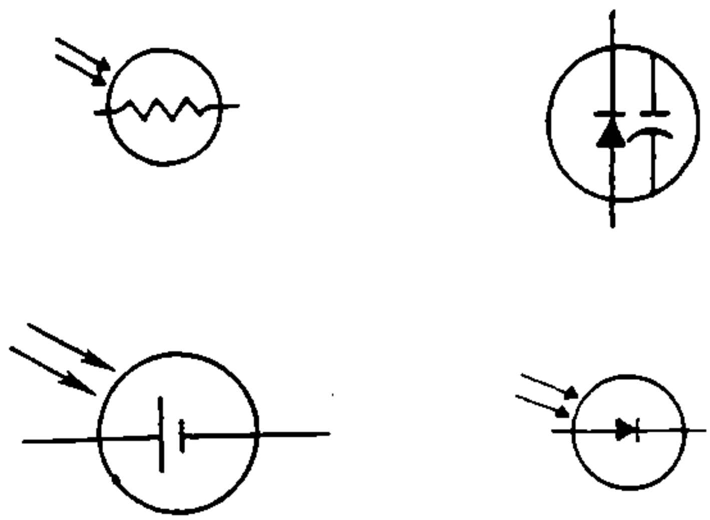


Figure 25

   a. a

   b. b

   c c

   d. d

5. If you were using an ohmmeter to measure the resistance of a properly functioning varactor in a circuit, you would expect to find a (low/high) forward bias resistance and a (low/high) reverse bias resistance.

1. capacitor
2. b. reverse bias
3. a. capacitance
4. b.
5. low, high

IF ALL YOUR ANSWERS MATCH, GO ON TO TEST FRAME 29. OTHERWISE, GO BACK TO FRAME 18 AND TAKE THE PROGRAMMED SEQUENCE BEFORE TAKING TEST FRAME 26 AGAIN.

27. The last special device covered in this lesson is the <u>triac</u>. A triac is similar to an SCR (silicon-controlled rectifier). The difference between them is that a triac controls current flow during <u>both</u> alternations of an AC cycle instead of only one alternation, as in the SCR. In other words, the triac is an AC device that conducts in both directions.

In operation, the triac is essentially two SCRs with a common gate. Figure 26 shows the labeled schematic symbols for both an SCR and a triac.

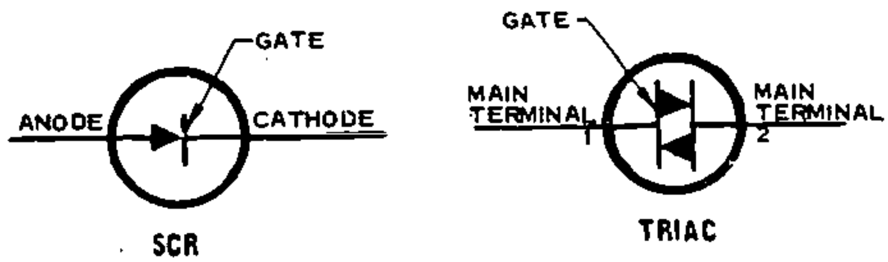


Figure 26

TRIAC VS SCR SCHEMATIC SYMBOLS

In the figure, the triac is shown to operate like two back-to-back SCRs. Notice the differences between them in labeled leads. In the triac, the lead on the same side as the gate is called "main terminal 1". The lead opposite the gate is called "main terminal 2". Since the triac is an AC device, either terminal may be the input.

A triac is an AC device that operates like two back-to-back ____________.

SCRs (or silicon-controlled rectifiers)

2B. A triac may be formed by connecting two SCRs as shown in Figure 27.

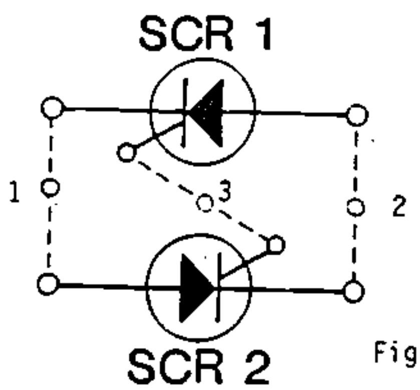
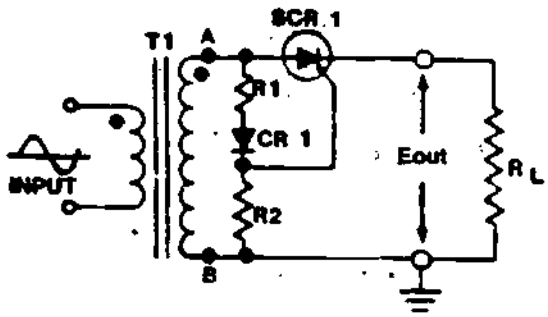


Figure 27

BACK-TO-BACK SCRs

Of course, this connection forms a three terminal device. The anode-cathode connections form two terminals, and the common gates form the third.

Now let's connect the triac into a circuit to show how it can control current through a load. Look at Figure 28.



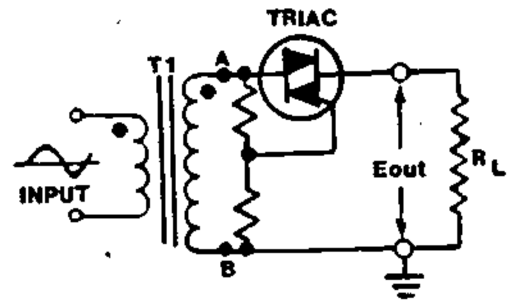


Figure 28

SCR VS TRIAC CIRCUITS

In circuit (a), the SCR is connected in the familiar half-wave arrangment. Current will flow through the load resistor (R_L) for one alternation of each input cycle. Diode CR1 is necessary to ensure a positive trigger voltage.

In circuit (b), the triac is inserted in place of the SCR. Current will flow through the load resistor during each alternation of the input cycle. This current will be in reverse directions for each half of the input cycle.

This can best be seen by comparing the waveforms for each circuit shown in Figure 29.

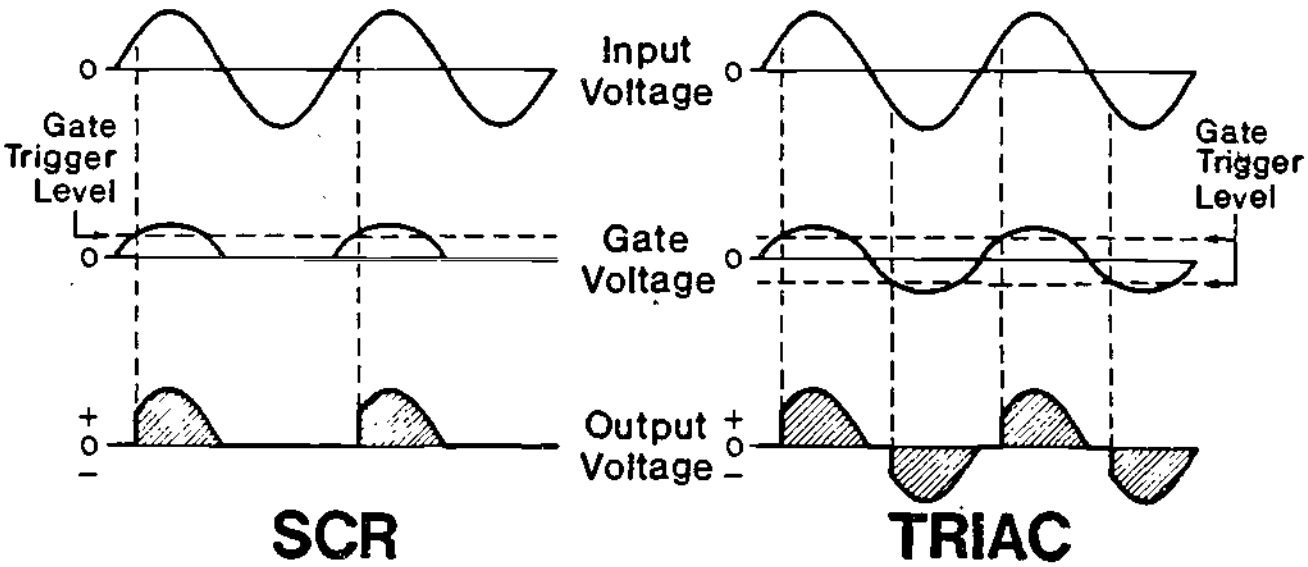


Figure 29

SCR TRIAC CURRENT WAVEFORMS

As you can see, the SCR produces an output waveform over a portion of one alternation of the input cycle. The triac produces an output waveform over a portion of both input cycle alternations. The triac is finding widespread use in motor, light, temperature, and other control devices.

A device which conducts during a portion of both half-cycles of an input AC voltage is the (diode/SCR/triac).

---

triac

(29) THIS IS A TEST FRAME. COMPLETE THE TEST QUESTIONS AND THEN COMPARE YOUR ANSWERS WITH THE CORRECT ANSWERS GIVEN AT THE TOP OF THE PAGE FOLLOWING THE QUESTIONS.

1. A triac operates like two back-to-back SCRs with a common ____________.

2. A triac conducts over a portion of the

   a. positive alternation of the input cycle only.

   b. negative alternation of the input cycle only.

   c. positive and negative alternations of the input cycle.

3. Which of the following figures is the schematic symbol for a triac?

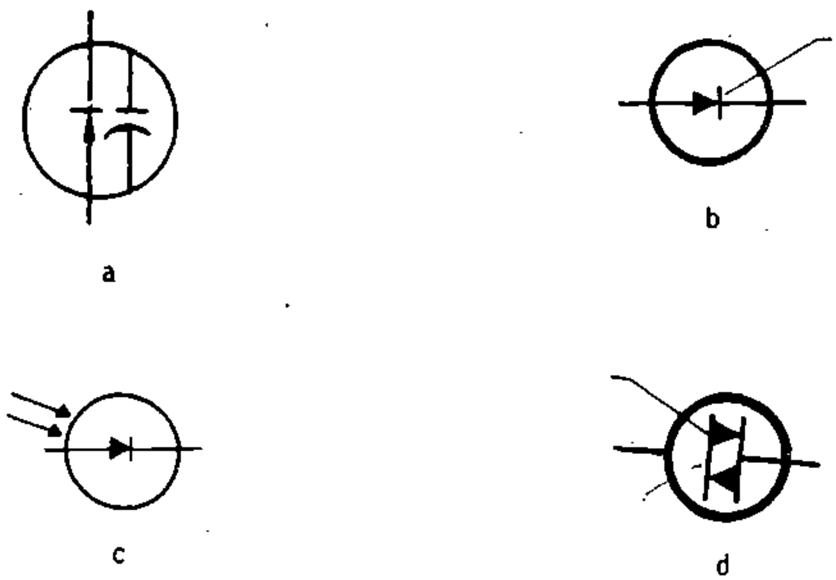


Figure 30

   a.

   b.

   c.

   d.

1. gate
2. c. positive and negative alternations of the input cycle.
3. d.

IF YOUR ANSWERS MATCH THE CORRECT ANSWERS, YOU HAVE COMPLETED LESSON 3, MODULE 33 -- CONGRATULATIONS! IF YOUR ANSWERS DO NOT MATCH, GO BACK TO FRAME 27 AND TAKE THE PROGRAMMED SEQUENCE BEFORE TAKING TEST FRAME 29 AGAIN.

AT THIS POINT, YOU MAY TAKE THE LESSON PROGRESS CHECK. IF YOU ANSWER ALL SELF-TEST ITEMS CORRECTLY, PROCEED TO THE LESSON TEST. IF YOU INCORRECTLY ANSWER ONLY A FEW OF THE PROGRESS CHECK QUESTIONS, THE CORRECT ANSWER PAGE WILL REFER YOU TO THE APPROPRIATE PAGES, PARAGRAPHS, OR FRAMES SO THAT YOU CAN RESTUDY THE PARTS OF THIS LESSON YOU ARE HAVING DIFFICULTY WITH. IF YOU FEEL THAT YOU HAVE FAILED TO UNDERSTAND ALL, OR MOST, OF THE LESSON, SELECT AND USE ANOTHER WRITTEN MEDIUM OF INSTRUCTION, AUDIO/VISUAL MATERIALS (IF APPLICABLE), OR CONSULTATION WITH THE LEARNING CENTER INSTRUCTOR, UNTIL YOU CAN ANSWER ALL SELF-TEST ITEMS ON THE PROGRESS CHECK CORRECTLY.

NARRATIVE
LESSON 3

Special Solid State Devices

The electronic revolution is continuing at a rapid pace. As new needs arise, electronic circuits are required to perform more and more specialized functions with fewer and smaller parts. For example, the needs of the space exploration program have led to the development of many new devices and the re-designing of old ones. Among the specialized devices resulting from recent technological advances are those in the optoelectronic group--the Light Emitting Diode (LED), photodiode, etc.--the varactor diode, and the triac.

Optoelectronic devices either produce light or use light in their operation. The first of these, the Light Emitting Diode (LED), was developed to replace the fragile, short life incandescent light bulbs used to indicate on/off conditions on panels. A light emitting diode is a diode which, when forward biased, produces visible light. The light may be red, green or amber depending upon the material use to make the diode. LEDs are very small, consisting of a semi-conductor "chip" only a few tenths of a millimeter in diameter contained in a larger plastic package 3 mm to 6 mm in diameter.

Figure 1 shows a LED and its schematic symbol.

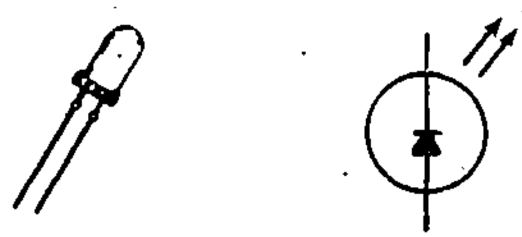


Figure 1

LED

The LED is designated by a standard diode symbol with two arrows pointing away from the cathode. The arrows indicate light leaving the diode. The circuit symbols for all optoelectronic devices have arrows pointing either towards them (if they use light) or away from them (if they produce light).

Because their operating voltage is small (about 1.6 V forward bias, and current generally about 10 mA) and their life expectancy is very long (over 100,000 hours of operation), LEDs are used widely as "power on" indicators and displays for pocket calculators, digital voltmeters, and frequency counters.

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LESSON 3

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LED

The LED is designated by a standard diode symbol with two arrows pointing away from the cathode. The arrows indicate light leaving the diode. The circuit symbols for all optoelectronic devices have arrows pointing either towards them (if they use light) or away from them (if they produce light).

Because their operating voltage is small (about 1.6 V forward bias, and current generally about 10 mA) and their life expectancy is very long (over 100,000 hours of operation), LEDs are used widely as "power on" indicators and displays for pocket calculators, digital voltmeters, and frequency counters.

For use in calculators and the like, LEDs are typically placed together in seven-segment displays, as shown in Figure 2.

(a) (b)

Figure 2

SEVEN SEGMENT LED DISPLAY

This display uses seven LED segments (or bars) which can be lit in different combinations to form any number from "0" through "9". The schematic, Figure 2(a), shows a <u>common-anode</u> display. All anodes in a display are internally connected. When a negative voltage is applied to the proper cathodes, a number is formed. For example, if negative voltage is applied to all cathodes except that of LED "E", the number "9" is produced. Applying a negative voltage to LED "E" and removing it from LED "B" changes the "9" to a "6", as Figure 3 shows.

Figure 3

DISPLAY EXAMPLES

Seven segment displays are also available in common-cathode form, in which all cathodes are at the same potential. When replacing LED displays, care must be taken to insure the replacement display is of the same type as the faulty display. Since both types look alike, it is a good idea always to check the manufacturer's number.

LED seven segment displays range from the very small, often not much larger than standard typewritten numbers, to about an inch. Several displays may be combined in a package such as that shown in Figure 4.

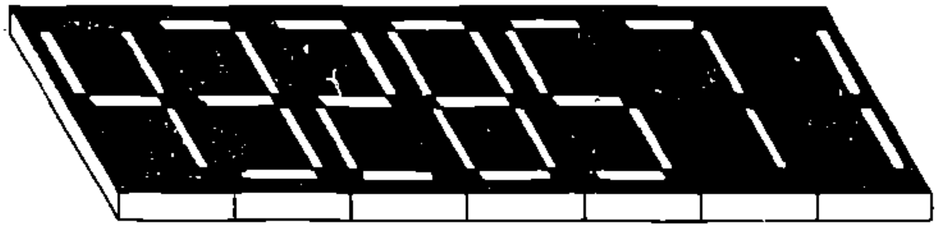

Figure 4

STACKED SEVEN SEGMENT DISPLAY OF "4328571"

Current drain for any single display varies depending on which number is being shown. For example, the number "1" in Figure 4 requires two LEDs to be lit and draws about 20 mA of current (approximately 10mA per segment). The number 8, which uses all seven segments, requires about 70 mA.

Another special optoelectronic device in common use today is the photodiode. Unlike the LED, which produces light, the photodiode uses light to accomplish special circuit functions. Basically, the photodiode is a light-controlled variable resistor. In total darkness, it has a relatively high resistance and therefore conducts little current. However, when the PN junction is exposed to an external light source, internal resistance decreases and current flows. The photodiode is operated with reverse-bias, and conducts current in direct proportion to the intensity of the light source.

Figure 5

PHOTO DIODE

Figure 5 shows a photodiode with its schematic. The arrows pointing toward the symbol indicate that light is required for operation of the device. A transparent "window" placed over the semi-conductor chip allows a light source to be aimed at it. By switching the light source on or off the conduction level of the photodiode is changed. By varying the light intensity, the amount of conduction can be controlled. Because photodiodes respond quickly to changes in light intensity, they are extremely useful in digital applications such as computer card readers, paper tape readers, and photographic light meters. They are also used in some types of optical scanning equipment.

A second optoelectronic device which conducts current when exposed to light is the phototransistor. A phototransistor, however, is much more sensitive to light and produces more output current for a given light intensity than does a photodiode.

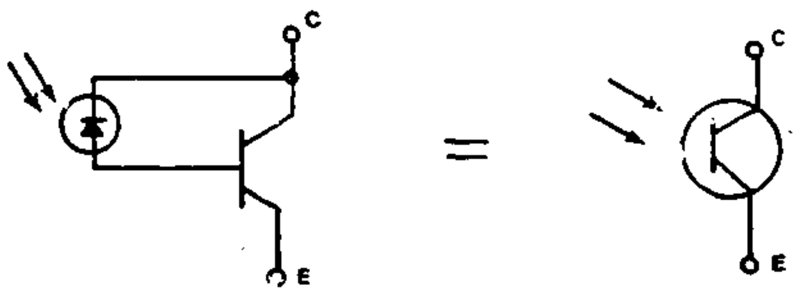

Figure 6

PHOTOTRANSISTOR

Figure 6 shows one type of phototransistor, made by placing a photo-diode in the base-emitter circuit of an NPN transistor. Light falling on the photodiode changes the base current of the transistor, causing the collector current to be amplified. Phototransistors may also be of the PNP type, with the photodiode placed in the base-collector circuit.

Phototransistors may be of the two-terminal type as shown above, where the light intensity on the photodiode alone determines how much current will be conducted. There are also, however, three-terminal types. These have an added base lead which allows an electrical bias to be applied to the base. The bias allows an optimum transistor conduction level, and thus compensates for ambient (normal room) light intensity.

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Figure 7 shows illustrations and schematic symbols for the various types of phototransistors.

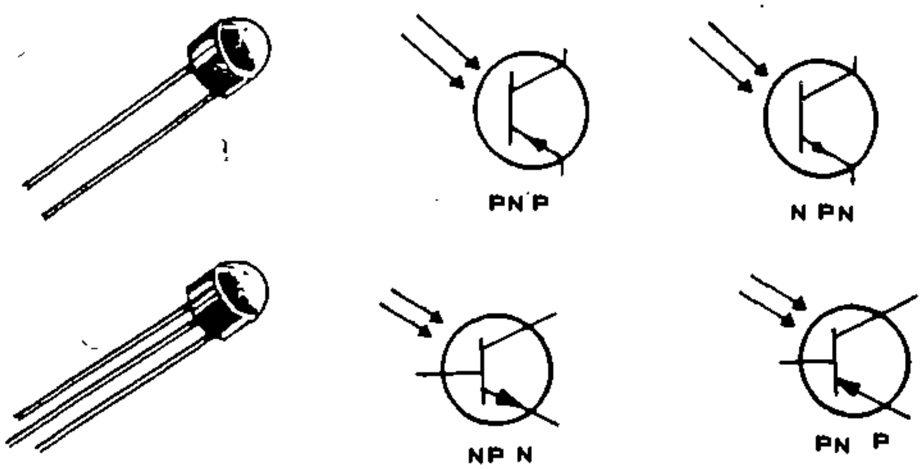

Figure 7

2-TERMINAL AND 3-TERMINAL PHOTOTRANSISTORS

An older device which uses light in a way similiar to the photodiode is the photoconductive cell, or photocell, shown with its schematic symbol in Figure 8.

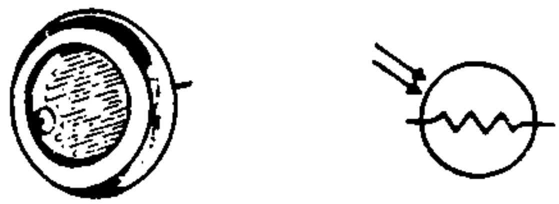

Figure 8

PHOTOCELL

Like the photodiode, the photocell is a light-controlled variable resistor. However, a typical light to dark resistance ratio for a photocell is 1:1000. This means that its resistance could range from 1000 ohms in the light to 1000K ohms in the dark, or from 2000 ohms in the light to 2000K ohms in the dark, and so forth. Of course, other ratios are also available. Photocells are used in various types of control and timing circuits as, for example, the automatic street light controllers in most cities.

The photovoltaic cell, or solar cell, is a device which converts light energy into electrical energy. An example of a solar cell and the schematic symbol are shown in Figure 9.

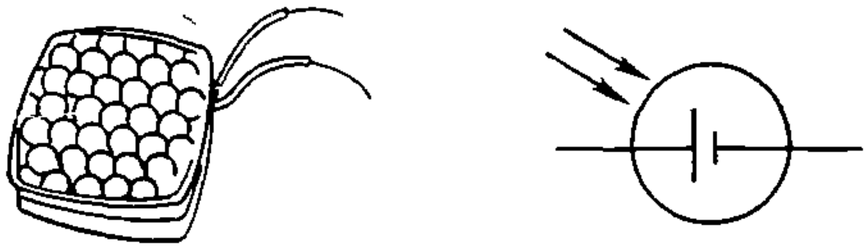

Figure 9

SOLAR CELL

The symbol is similar to that of a battery, and the device itself acts much like a battery when exposed to light, producing about .45 volts across its terminals, with a current capacity determined by its size. As with batteries, solar cells may be connected in series or parallel to produce higher voltages and currents. The device is finding widespread application in communications satellites and solar-powered homes.

When it is necessary to block the voltage between one electronic circuit and another, while at the same time transfering the signal, an amplifier coupling capacitor is often used as shown in Figure 10.

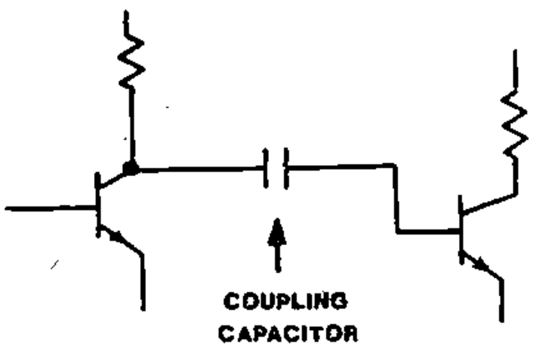

Figure 10

DC BLOCKING WITH COUPLING CAPACITOR

Although this method of coupling does block DC between the circuits, voltage isolation is not complete. A newer method, making use of optoelectronic devices to achieve electrical isolation, is the optical coupler, shown in Figure 11.

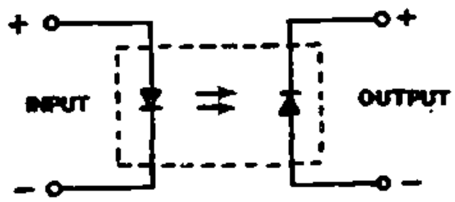

Figure 11

OPTICAL COUPLER

The coupler is composed of a LED and a photodiode encapsulated in a light conducting medium. As the polarity signs in Figure 11 show, the LED is forward-biased, while the photodiode is reverse-biased. When the input signal causes current through the LED to increase, the light produced by the LED increases. This increased light intensity causes current flow through the photodiode to increase. In this way, changes in input current produce proportional changes in the output, even though the two circuits are electrically isolated.

The optional coupler is suitable for frequencies in the low megahertz range. The photodiode type shown above can handle only small currents; however, other types of couplers, combining phototransistors with SCRs (silicon controlled rectifiers), can be used where more output is required. Optical couplers are replacing transformers in low voltage and current applications. Sensitive digital circuits can utilize the coupler to control large current and voltages with low-voltage logic levels. The scanning device used to grade CMI tests in this course is, in fact, one example of a device which uses an optical coupler.

This discussion of special solid state devices will conclude with the varactor diode and the triac. Neither of these is an optoelectronic device, but both represent important breakthroughs in recent solid-state technology.

Figure 12 shows a varactor diode with its schematic.

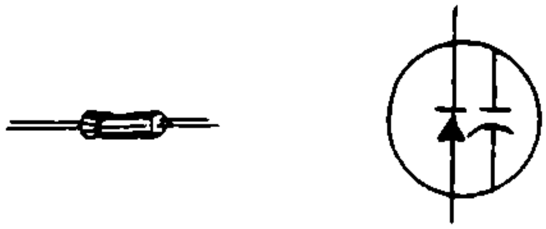

Figure 12

VARACTOR DIODE - PICTORIAL AND SCHEMATIC

The varactor, or varicap, as the schematic suggests, is a diode that behaves like a variable capacitor, with the PN junction functioning like the dielectric and plates of a common capacitor. Understanding how the varactor operates is an important prerequisite to understanding field-effect transistors, covered in the next lesson.

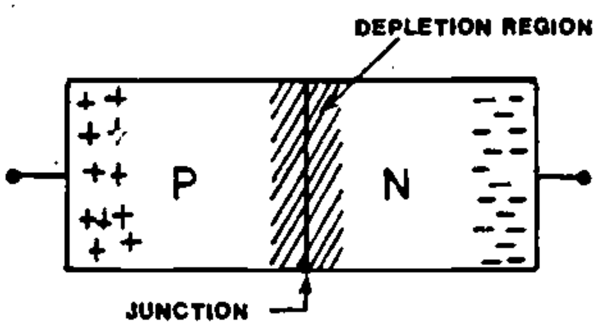

Figure 13

PN JUNCTION

Figure 13 shows a PN junction. Surrounding the junction of the P and N materials is a narrow region void of both positively and negatively charged current carriers. This area is called the depletion region.

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The size of the depletion region in a varactor diode is directly related to the bias and strength of applied voltage. Forward biasing makes the region smaller by repelling the current carriers toward the PN junction. If the applied voltage is large enough (about .5 volts for silicon material) the negative particles will cross the junction and join with the positive particles, as shown in Figure 14.

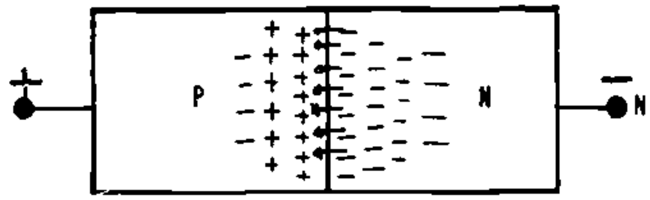


Figure 14

FORWARD BIASED PN JUNCTION

This forward biasing caused the depletion region to decrease, producing a low resistance at the PN junction and a large current flow across it. This is the condition for a forward biased diode, but not the varactor.

On the other hand, if reverse bias voltage is applied to the PN junction the size of its depletion region increases as the charged particles on both sides move away from the junction. This condition, shown in Figure 15, produces a high resistance between the terminals and allows little current flow (only in the ua range). This is the operating condition for the varactor diode, which is nothing more than a special PN junction.

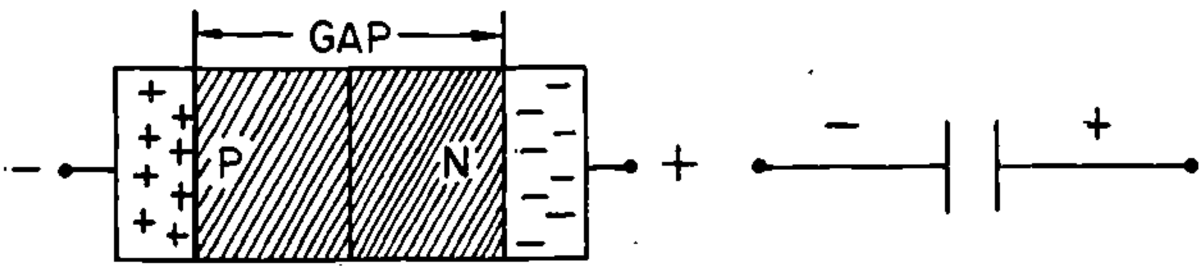


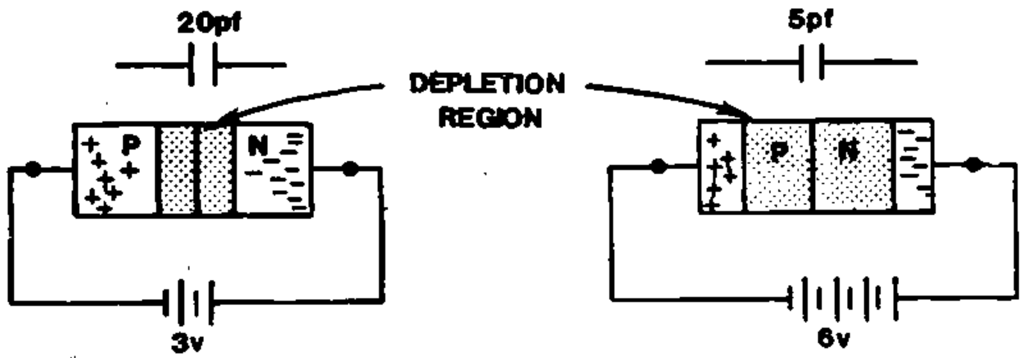
Figure 15

REVERSE BIASED PN JUNCTION VS. CAPACITANCE

As the figure shows, the insulation gap formed by reverse biasing of the varactor is comparable to the layer of dielectric material between the plates of a common capacitor.

Furthermore, the formula used to calculate capacitance: $C = \frac{A\,K}{d}$ (where A= plate area, K = a constant value, and d = distance between plates) can be applied to the varactor in the same way that it can to a capacitor. In this case, the size of the varactor's insulation gap, or depletion region, is substituted for the distance between the capacitor's plates. By varying the reverse bias voltage applied to the varactor, the width of the "gap" may be varied. An increase in reverse bias increases the width of the gap (d) which reduces the capacitance (C) of the PN junction. Therefore, the varactor's capacitance is inversely proportional to the applied reverse bias.

The ratio of varactor capacitance to reverse bias voltage change may be as high as 10 to 1. Figure 16 shows one example.



(a) Figure 16 (b)

VARACTOR - CAPACITANCE VS BIAS VOLTAGE

Figure 16(a) shows that a reverse bias of 3 volts produces a capacitance of 20 pf in the varactor. If the reverse bias is increased to 6 volts, as shown in Figure 16(b), the depletion region widens and capacitance drops to 5 pf. Each 1 volt increase in bias voltage causes a 5 pf decrease in the varactor's capacitance; the ratio of change is therefore 5 to 1. Of course any decrease in applied bias voltage would cause a proportionate increase in capacitance, as the depletion region narrows. Notice the value of the capacitance is small, in the picofarad range.

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Varactors are in general use in tuning circuits of more sophisticated communications equipment, replacing the old style variable capacitor tuning, and in other circuits where variable capacitance is required. One advantage of the varactor is that it allows a DC voltage to be used to tune a circuit for simple remote control or automatic tuning functions. One such application of the varactor is as a variable tuning capacitor in a receiver or transmitter tank circuit like that shown in Figure 17.

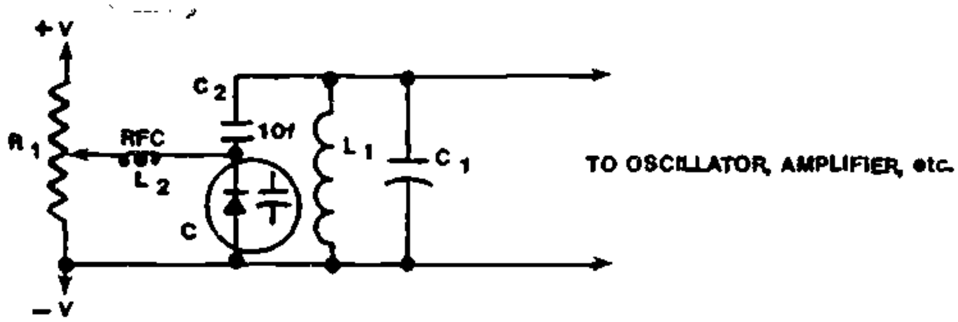

Figure 17

VARACTOR TUNED TANK

Figure 17 shows a DC voltage felt at the wiper of potentiometer R1 which can be adjusted betweeen +V and -V. This DC voltage, passed through the low resistance of radio frequency choke L2, acts to reverse bias varactor diode C3. The capacitance of C3 is in series with C2, and the equivalent capacitance of C2 and C3 is in parallel with tank circuit L1-C1. Therefore, any variation in the DC voltage at R1 will vary both the capacitance of C3 and the resonant frequency of the tank circuit. The radio frequency choke provides high inductive reactance at the tank frequency to prevent tank loading by R1. C2 acts to block DC from the tank as well as to fix the tuning range of C3.

A varactor diode in a circuit can be checked in the same way as would any diode, using an ohmmeter. A high reverse bias resistance and a low forward bias resistance would be expected, and a 10 to 1 ratio in reverse to forward bias resistance would be considered normal.

The triac, the last special device to be covered, is a three-terminal device similar in construction and operation to an SCR (silicon controlled rectifier). The difference between them is that the triac controls current flow during both alternations of an AC cycle, instead of only one as the SCR does, and conducts current in both directions.

The schematic symbols for the SCR and the triac are compared in Figure 18.

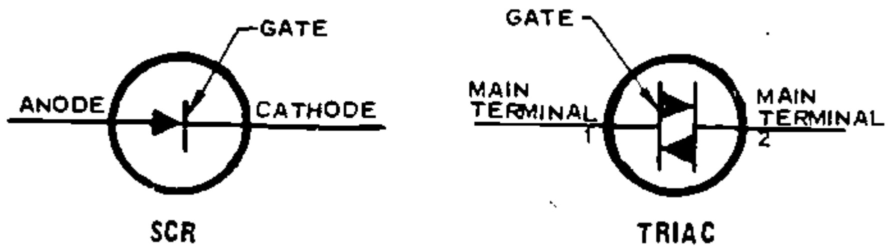

Figure 18

SCR VS TRIAC SCHEMATIC SYMBOLS

Although both the SCR and the triac have a gate lead, in the triac the lead on the same side as the gate is called "main terminal 1" and the lead opposite the gate is called "main terminal 2". This change in lead labeling is necessary because the triac is essentially <u>two</u> SCRs back to back, with a common gate and common terminals. Each terminal is, in effect, the anode of one SCR and the cathode of another, and either terminal can receive an input.

In fact, the functions of a triac can be duplicated by connecting two actual SCRs as shown in Figure 19.

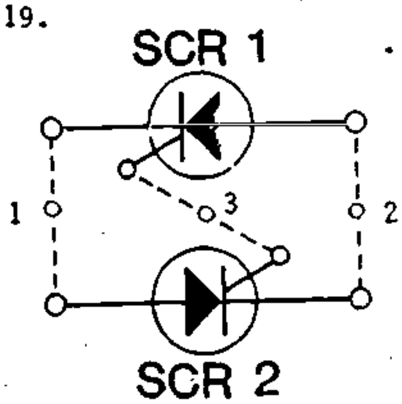

Figure 19

BACK-TO-BACK SCRs

The result is a three-terminal device identical to the triac. The common anode-cathode connections form main terminals 1 and 2, and the common gate (3) forms the third.

The difference in current control between the SCR and the triac can be seen by comparing their operation in the basic circuit from Module 30, Lesson 3 shown in Figure 20.

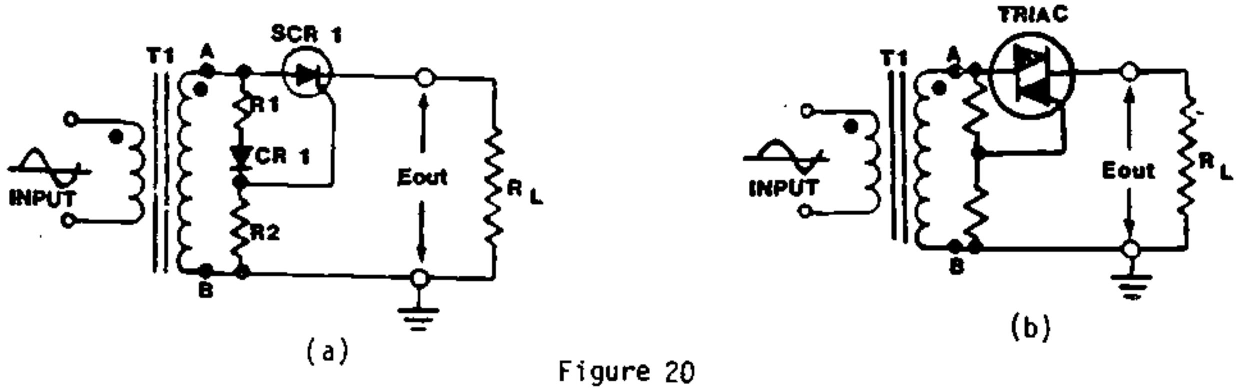

Figure 20

SCR VS TRIAC CIRCUITS

In circuit (a), the SCR is connected in the familiar half-wave arrangement. Current will flow through the load resistor (R_L) for one alternation of each input cycle. Diode CR1 is necessary to ensure a positive trigger voltage.

In circuit (b), with the triac inserted in place of the SCR, current flows through the load resistor during both alternations of the input cycle. Because either alternation will trigger the gate of the triac, CR1 is not required in the circuit. Current flowing through the load will reverse direction for half of each input cycle.

To clarify this difference, a comparison of the waveforms seen at the input, gate, and output points of the two devices is shown in Figure 21.

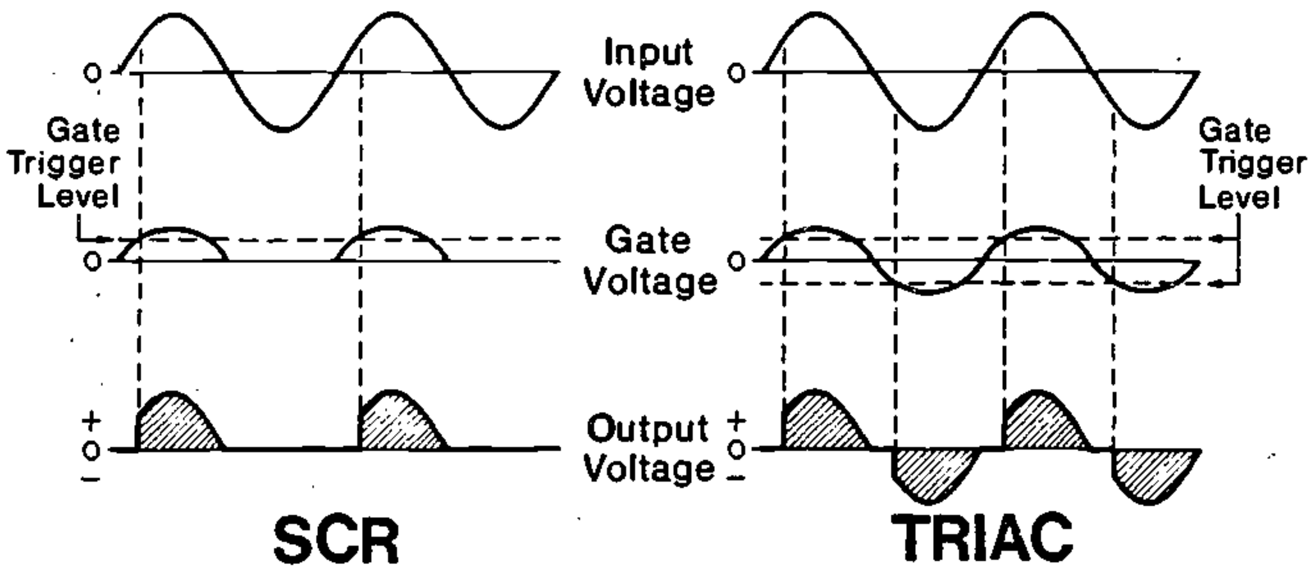

Figure 21

SCR VS TRIAC WAVEFORMS

AT THIS POINT, YOU MAY TAKE THE LESSON PROGRESS CHECK. IF YOU ANSWER ALL SELF-TEST ITEMS CORRECTLY, PROCEED TO THE LESSON TEST. IF YOU INCORRECTLY ANSWER ONLY A FEW OF THE PROGRESS CHECK QUESTIONS, THE CORRECT ANSWER PAGE WILL REFER YOU TO THE APPROPRIATE PAGES, PARAGRAPHS, OF FRAMES SO THAT YOU CAN RESTUDY THE PARTS OF THIS LESSON YOU ARE HAVING DIFFICULTY WITH. IF YOU FEEL THAT YOU HAVE FAILED TO UNDERSTAND ALL, OR MOST, OF THE LESSON, SELECT AND USE ANOTHER WRITTEN MEDIUM OF INSTRUCTION, AUDIO/VISUAL MATERIALS (IF APPLICABLE), OR CONSULTATION WITH THE LEARNING CENTER INSTRUCTOR, UNTIL YOU CAN ANSWER ALL SELF-TEST ITEMS ON THE PROGRESS CHECK CORRECTLY.

BASIC ELECTRICITY AND ELECTRONICS

MODULE THIRTY THREE

LESSON 4

FIELD-EFFECT TRANSISTORS

JULY 1980

OVERVIEW
LESSON 4

Field Effect Transistors

In this lesson you will learn the operating characteristics of two types of field effect transistors, JFETS and MOSFETS. You will understand how these devices are constructed, how they use voltage to control conduction, and how they achieve higher input impedance than the bipolar transistor. You will learn the special handling precautions necessary for MOSFETS and the proper methods and equipment for troubleshooting both FET devices.

The learning objectives of this lesson are as follows:

TERMINAL OBJECTIVE(S):

33.4.64 When the student completes this lesson, (s)he will be able to IDENTIFY the schematic symbols, construction, operating characteristics and methods for handling and testing field-effect transistor devices, by selecting statements from a choice of four. 100% accuracy is required.

ENABLING OBJECTIVE(S):

When the student completes this lesson, (s)he will be able to:

33.4.64.1 IDENTIFY the schematic symbol, construction, and operating characteristics of N-channel and P-channel JFET devices by selecting the correct statement or schematic symbol from a choice of four. 100% accuracy is required.

33.4.64.2 DEFINE "pinch-off" voltage as it applies to JFET operation by selecting the correct statement from a choice of four. 100% accuracy is required.

33.4.64.3 IDENTIFY the schematic symbol, construction, and operating characteristics of single-gate and dual-gate MOSFET devices by by selecting the correct statement or schematic symbol from a choice of four. 100% accuracy is required.

33.4.64.4 IDENTIFY the proper methods and equipment to use when handling and troubleshooting FET devices by selecting the correct statement from a choice of four. 100% accuracy is required.

BEFORE YOU START THIS LESSON, READ THE LESSON LEARNING OBJECTIVES AND PREVIEW THE LIST OF STUDY RESOURCES ON THE NEXT PAGE.

LIST OF STUDY RESOURCES
LESSON 4

Field Effect Transistors

To learn the material in this lesson, you have the option of choosing, according to your experience and preferences, any or all of the following study resources:

Written Lesson presentation in:

Module Booklet:

Summary
Programmed Instruction
Narrative

Student's Guide:

Summary
Progress Check

Additional Material(s):

Audio/Visual Program: "Field Effect Transistors" (Video Tape)

Enrichment Material(s):

The Semiconductor Data Book, 4th Edition, Motorola Semiconductor Products, Ind., 1969.

RCA Transistor, Thyristor, and Diode Manual, RCA Corporation, 1971.

YOU MAY USE ANY, OR ALL, RESOURCES LISTED ABOVE, AND ALSO THE LEARNING CENTER INSTRUCTOR. HOWEVER, ALL MATERIALS LISTED ARE NOT NECESSARILY REQUIRED TO ACHIEVE LESSON OBJECTIVES. THE PROGRESS CHECK MAY BE TAKEN AT ANY TIME.

SUMMARY
LESSON 4

Field Effect Transistors

Impedance matching problems, resulting from the bipolar transistor's low input impedance, have for years lead scientists to search for a solid state device that retains the high input impedance of the vacuum tube. The result is the field-effect transistor, or FET. Whereas the bipolar transistor uses bias current to control conductivity, the FET is voltage-controlled, much like a vacuum tube.

Figure 1 shows how one type of FET, the junction type, or JFET, is constructed.

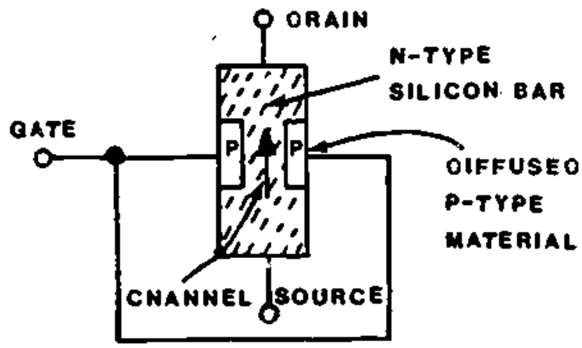

Figure 1

JFET

The three elements of the JFET operate like the familiar transistor and vacuum tube elements, "gate" like base and grid, and "source" and "drain" like emitter/collector and cathode/plate, respectively. The main body of this type of JFET is a bar of N-type material, connecting source and drain elements. Deposits of P-type material on either side are connected to form the gate element and create a narrow "channel" in the bar.

The key to FET operation is the effective cross-sectional area of the channel, which can be controlled by variations in the voltage applied to the gate. This is demonstrated in the figures that follow.

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Figure 2 shows how the JFET operates in a zero gate bias condition.

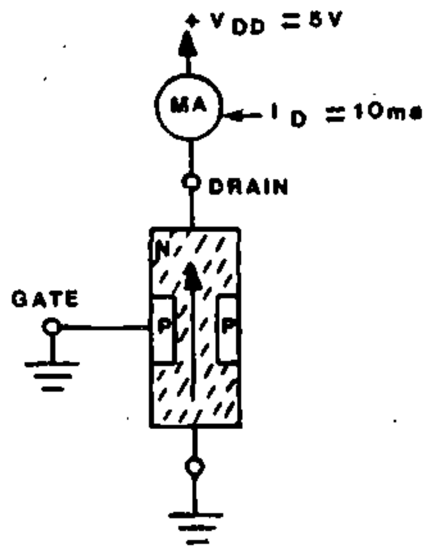

Figure 2

JFET OPERATION-ZERO GATE BIAS

With the gate terminal tied to ground (0 volts), a drain supply (V_{DD}) of 5 volts gives a drain current (I_D) reading of 10 mA. In this condition, the bar represents a resistance of about 500 ohms.

In Figure 3, a small reverse bias is applied to the JFET's gate.

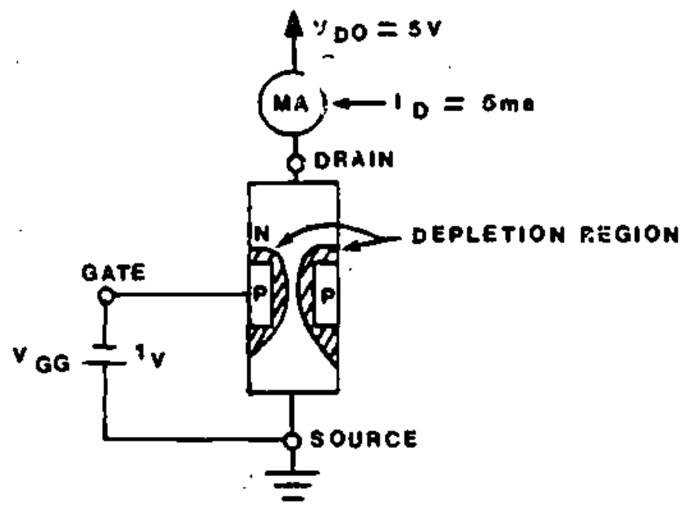

Figure 3

JFET OPERATION - REVERSE BIAS

One negative volt (V_{GG}) applied to the gate causes a reverse bias condition at the PN junction of the JFET. The resulting "depletion region" reduces the effective cross-sectional area of the channel, thus increasing source-to-drain resistance (to about 1 K Ohms) and decreasing current flow as shown.

The high gate input impedance of the JFET under reverse gate bias conditions can be seen by connecting a microammeter in series with V_{GG} as shown in Figure 4.

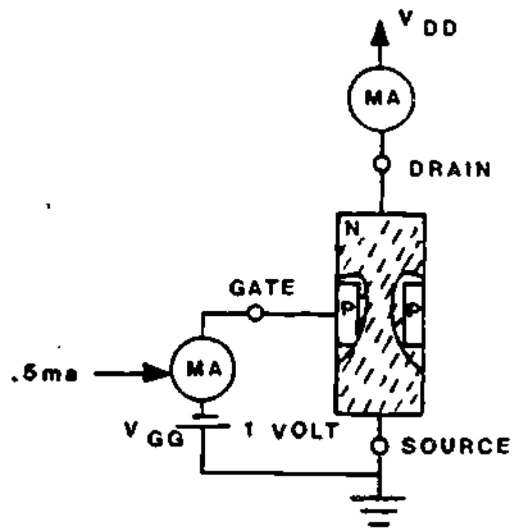

Figure 4

JFET INPUT IMPEDANCE

The very small amount of current flow (.5 microamps) results in a gate input impedance of about 2 megohms. By contrast, a bipolar transistor with a forward biased base-emitter junction, would provide in the vicinity of 1000 ohms or less.

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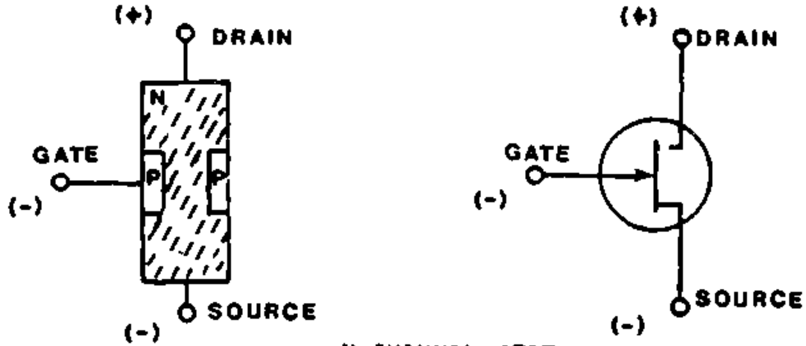
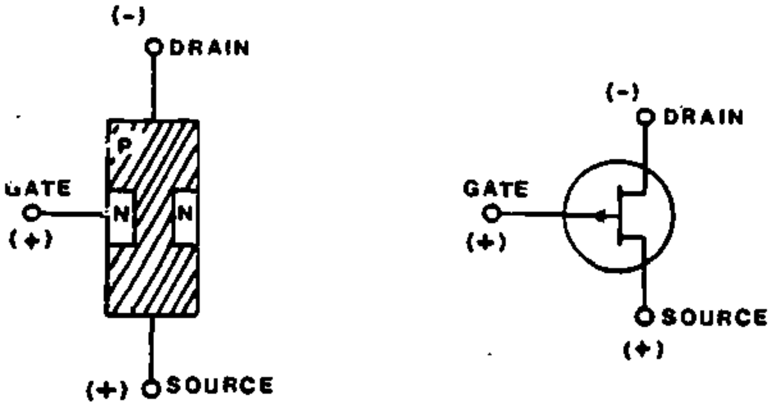
JFETS can be either N-channel type, as shown in the above example, or P-channel type. Operation, bias voltages, and schematic symbols for the two types are compared in Figure 5. Note the bias voltage potentials are reversed for the two JFET types, just as for bipolar transistors.



N-CHANNEL JFET



P-CHANNEL JFET

Figure 5

SYMBOLS AND PICTORAL WITH BIAS VOLTAGE-JFETS

Figure 6 demonstrates the operation of an N-channel JFET in a basic common-source amplifier circuit.

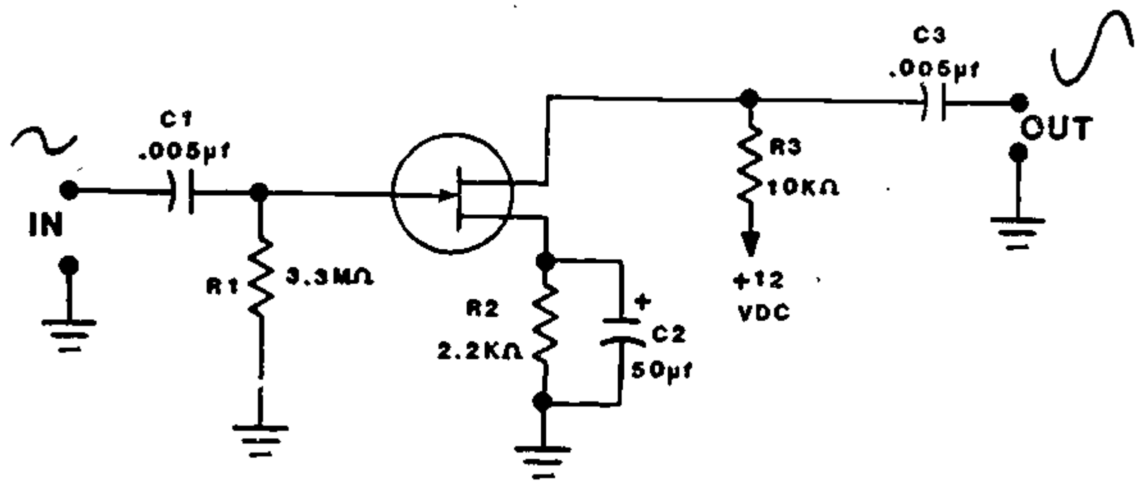


Figure 6

FET COMMON SOURCE AMPLIFIER

Circuit characteristics include high input impedance and a voltage gain of abou 10 (20 db.). The function of components and the 180° phase shift are simi to those in common-cathode VT and common-emitter transistor circuits. The son for the phase shift here is the effect of the input signal on the JFET gate bias. On the positive alternation, reverse bias is decreased. This creases the channel's effective cross-section, decreases source-to-drain resistance, and increases current. The result is an increase in the voltage drop across R3 and a decrease in drain voltage. On the negative alternation, reverse gate bias is increased, and circuit action is reversed.

An FET with even higher input impedance than the JFET is the "metal oxide semiconductor field-effect transistor" or MOSFET. Its extremely high input impedance, 10 to 100 million megohms (10^{13}-10^{14} ohms), will not load down preceeding circuits and makes the MOSFET an extremely efficient input device.

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Figure 7 shows how one type of MOSFET, the N-channel type, is made.

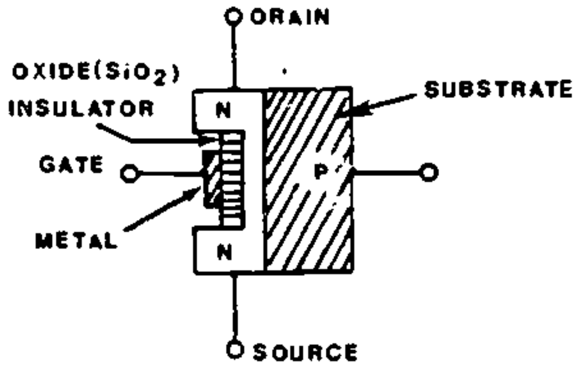

Figure 7

N-CHANNEL MOSFET CONSTRUCTION

The MOSFET is a four-element device. Source and drain elements are connected by a "channel" of N-type material just as in an N-channel JFET. The channel material forms a PN junction with the "substrate" material. Although biasing the substrate element permits control of the MOSFET's gain characteristics, often the substrate terminal is connected directly to the source terminal, and the biasing capability is not used.

The gate element is made of metal and is electrically insulated from the source-drain channel by a layer of silicon oxide (SiO_2). This total insulation results in the MOSFET's extremely high input impedance and gives rise to another common name for the device: "insulated gate field effect transistor," or IGFET.

MOSFETs can be N-channel or P-channel, and single-gate or dual-gate. Schematic symbols for dual-gate MOSFETs (only) are show in Figure 8.

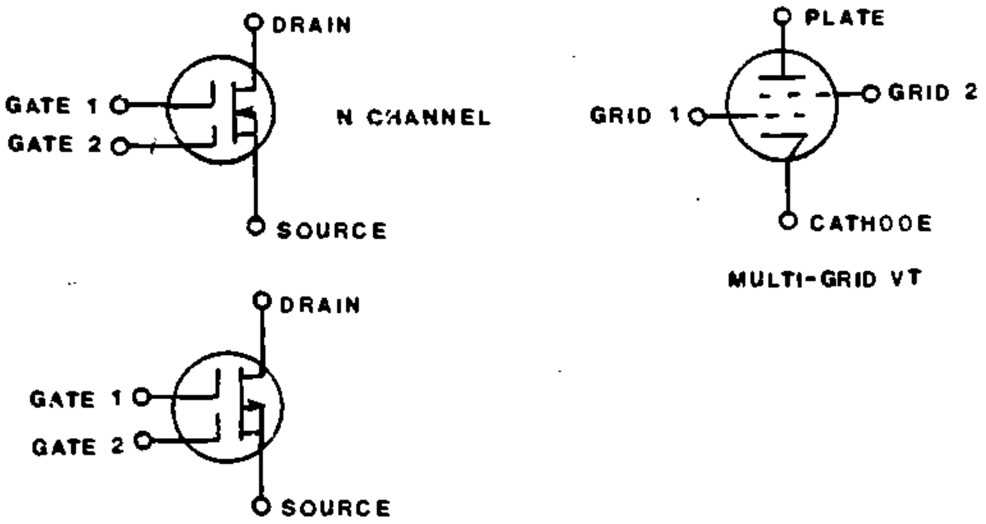

Figure 8

DUAL-GATE MOSFETS

As the figure shows, the gates are comparable to the grids in a multigrid VT. Either gate can control conduction independently, making the dual-gate MOSFET ideal for applications involving two separate signals (for example, AFC-controlled amplifiers).

To avoid accidental damage from static electricity, replacement MOSFETs come packaged with their leads shorted together with a shorting spring. <u>This spring must not be removed until after the MOSFET is installed.</u> A complete list of handling precautions for MOSFET devices is shown in Figure 9.

NOTICE

SPECIAL HANDLING OF MOS DEVICES

The MOS metal oxide semiconductor devices have a fairly high input resistance making them subject to damage from charges of static electricity through improper handling. The thin layer of oxide can be damaged from discharges of static electricity or improper handling in or out of circuit. The damage may be apparent immediately or may show up only after a short operating time. To avoid possible damage, the following procedures should be followed when handling or testing these devices.

1. The use of synthetic clothing such as nylon should be avoided as this will generate static charges. Dry weather (relative humidity less than 30%) also tends to increase static buildup.

2. Keep the leads of the device in contact with a conducting material or shorted, except when testing, inserting or removing from the circuit.

3. A wrist strip with a 1 megohm resistor in series to common ground should be worn by the technician when inserting, removing or testing MOS devices.

4. Do not remove or insert an MOS device with the power to the circuit or test instrument "ON".

5. Do not apply or inject test signals into the circuit when an MOS device is used with the circuit power "OFF".

6. Do not turn the circuit power "ON" with an MOS device removed from the circuit. Charges can build up causing possible damage when the device is replaced in the circuit.

7. Soldering iron tips, metal bench tops, test equipment and tools should be grounded to a common ground along with the chassis of the set being serviced.

8. Soldering guns should not be used in MOS circuits. AC line leakage from the gun tip could cause damage to an MOS device.

9. Do not apply heat for longer than 10 seconds or closer than 1/16 of an inch to any MOS device when soldering. Use of a heat sink is recommended to prevent damage to the device.

Figure 9

MOSFET PRECAUTIONS

Some MOSFETs have protection diodes built in, back to back, designed to limit transient voltage without causing distortion. Even so, it is best to observe all the above precautions when working with any type of MOSFET equipment.

Some common FET base diagrams are shown in Figure 10.

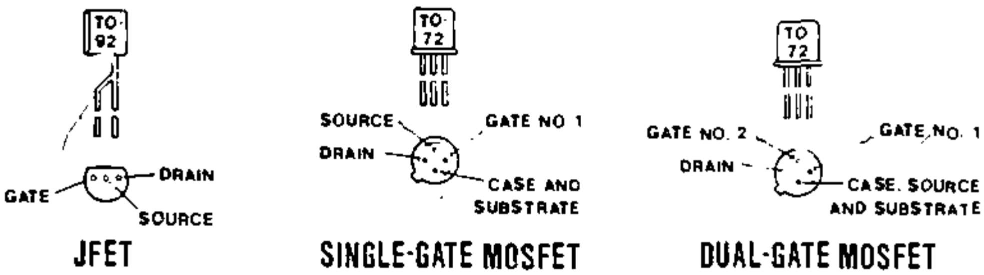

Figure 10

FET BASE DIAGRAMS

Pin arrangements for FETs are not standardized. For accurate identification of leads, a data book should be used. Signal tracing or signal injection methods can be used to locate faulty FET stages. Voltage measurements using a high impedance voltmeter are recommended. An ohmmeter should not be used, since ohmmeter battery voltages vary widely and may easily exceed maximums permitted between FET elements.

AT THIS POINT, YOU MAY TAKE THE LESSON PROGRESS CHECK. IF YOU ANSWER ALL SELF-TEST ITEMS CORRECTLY, YOU MAY TAKE THE LESSON TEST. IF YOU INCORRECTLY ANSWER ONLY A FEW OF THE PROGRESS CHECK QUESTIONS, THE CORRECT ANSWER PAGE WILL REFER YOU TO THE APPROPRIATE PAGES, PARAGRAPHS, OR FRAMES SO THAT YOU CAN RESTUDY THE PARTS OF THIS LESSON YOU ARE HAVING DIFFICULTY WITH. IF YOU FEEL THAT YOU HAVE FAILED TO UNDERSTAND ALL, OR MOST, OF THE LESSON, SELECT AND USE ANOTHER WRITTEN MEDIUM OF INSTRUCTION, AUDIO/VISUAL MATERIALS (IF APPLICABLE), OR CONSULTATION WITH THE LEARNING CENTER INSTRUCTOR, UNTIL YOU CAN ANSWER ALL SELF-TEST ITEMS ON THE PROGRESS CHECK CORRECTLY.

PROGRAMMED INSTRUCTION
LESSON 4

Field Effect Transistors

TEST FRAMES ARE 5, 14, AND 24. PROCEED TO TEST FRAME 5 FIRST AND SEE IF YOU CAN ANSWER THE QUESTIONS FOLLOW DIRECTIONS GIVEN AFTER THE TEST FRAME.

1. The two-junction, or bipolar, transistor has brought about a revolution in electronic equipment design. However, as you would expect, there are some characteristics of the transistor which are not desirable. One important drawback is the low input impedance of the base-emitter junction. This low input impedance can cause impedance matching design problems between interstage amplifiers.

During the vacuum tube era, high input impedances were available. As the transistor became more prominent in electronics, scientists searched for a way to develop a solid state transistor-type device which also would have high input impedance. The result of this research is the Field Effect Transistor, or FET. The FET in all of its variations produces a high input impedance.

The most important feature of the FET is its __________ input impedance.

---

high

2. Field effect transistors are available in two major types:

1. JFET (junction FET)
2. MOSFET (metal-oxide semiconductor FET)

Both types are similar to bipolar transistors, with one difference. Bipolar transistors use a bias current between the base and emitter in order to operate. FETs operate by using a voltage to control an electrostatic field within the transistor. Since FETs are solid state devices which are voltage controlled, they are sometimes called "solid state vacuum tubes".

Two major types of FETs are the ________ FET and the ________ FET.

J (or junction), MOS (or metal-oxide semiconductor)

3. You are familiar with the three major elements in a bipolar transistor, namely "base", "emitter", and "collector". As you know, the three similar elements in a vacuum tube are called "grid", "cathode", and "plate". FETs also have their three major elements called by different names which are "gate", "source", and "drain". The names of related elements in vacuum tubes, bipolar transistors, and FETs are shown in Figure 1.

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VACUUM TUBE		BIPOLAR TRANSISTOR		FET
Grid	=	Base	=	Gate
Cathode	=	Emitter	=	Source
Plate	=	Collector	=	Drain

Figure 1

COMPARISON OF ELEMENTS IN AMPLIFIER DEVICES

The three major elements in a JFET or MOSFET are called __________, __________, and __________.

---

gate, source, drain (in any order)

4. First you will learn about JFETs. The schematic symbol for a type of junction FET, or JFET, is compared to the symbols for a two-junction (bipolar) transistor and a vacuum tube in Figure 2.

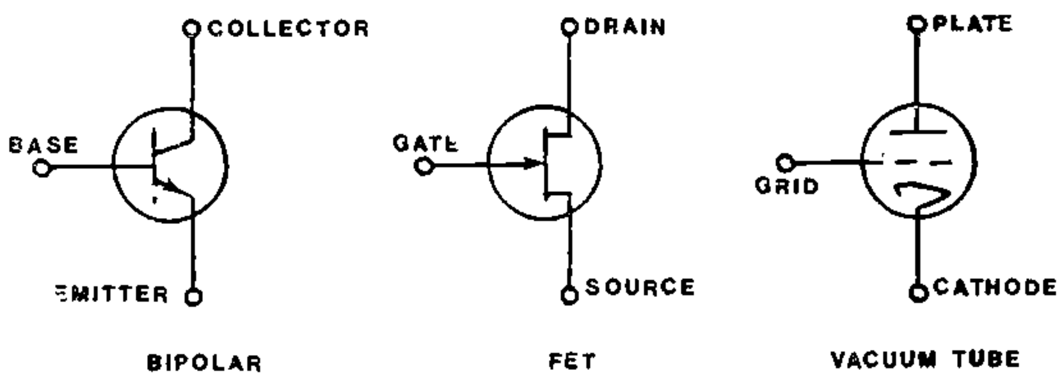

Figure 2

SYMBOLS - JUNCTION FET VS TRANSISTOR/VACUUM TUBE

In the figure, you can compare the elements between the three devices. For example, the gate of the JFET compares very closely in operation with the grid of the vacuum tube and the base of the transistor. The other elements of the JFET, source and drain, compare with the emitter/collector and cathode/plate. As you would expect, there are important operational differences between similar elements of the three devices.

The base of a transistor serves a function similar to the __________ of a JFET.

---

gate

(5.) THIS IS A TEST FRAME. COMPLETE THE TEST QUESTIONS AND THEN COMPARE YOUR ANSWERS WITH THE CORRECT ANSWERS GIVEN AT THE TOP OF THE PAGE FOLLOWING THE QUESTIONS.

1. FETs operate by using a
   a. bias current between the base and emitter.
   b. voltage to control an electrostatic field.
   c. static charge to control a magnetic field.

2. Two types of amplifier devices which have a high input impedance are the
   a. FET and the bipolar transistor.
   b. vacuum tube and the bipolar transistor.
   c. vacuum tube and the FET.

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3. The three major elements of an FET are the

   a. gate, source, and drain.

   b. base, emitter, and drain.

   c. grid, anode, and cathode.

   d. grid, source, and plate.

4. Which of the following diagrams is the schematic symbol for a JFET?

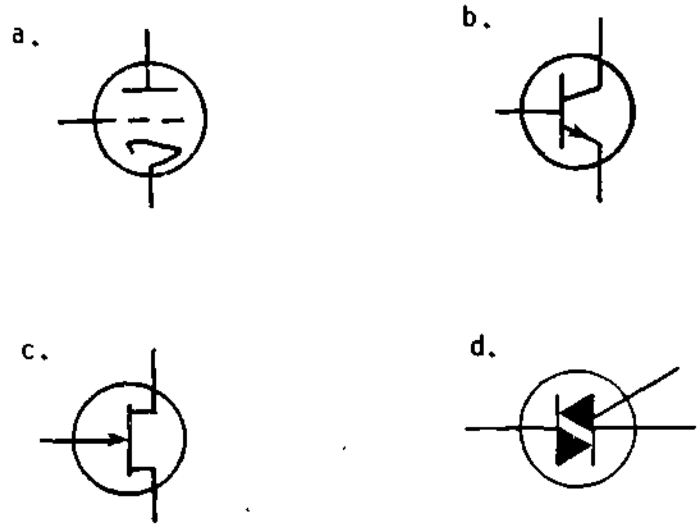

Figure 3

   a. a

   b. b

   c. c

   d. d

1. b. voltage control an electrostatic field.
2. c. vacuum tube and the FET.
3. d. gate, source, and drain.
4. c.

IF YOUR ANSWERS MATCH THE CORRECT ANSWERS, YOU MAY GO ON TO TEST FRAME 14. OTHERWISE GO BACK TO FRAME 1 AND TAKE THE PROGRAMMED SEQUENCE BEFORE TAKING TEST FRAME 5 AGAIN.

(6.) Just as there are two types of bipolar transistors (NPN and PNP), there are two types of JFETs (N-channel and P-channel). The labeled schematic diagrams for both types of transistors and FETs are shown in Figure 4.

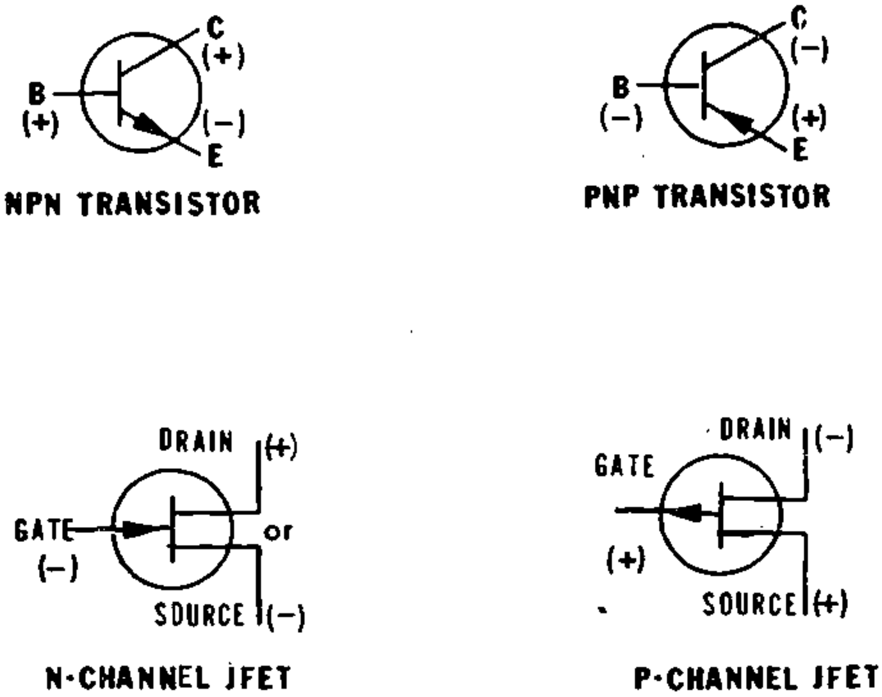

Figure 4

COMPARISON OF TRANSISTOR AND JFET
SCHEMATIC SYMBOLS AND BIAS VOLTAGES

The pictorial diagram in Figure 5 will help you understand how the types of JFETs get their names. A clue to the identity of the type is the fact that the arrow always points <u>toward</u> the "N" type material. If the arrow points away from the material, the material is "P" type.

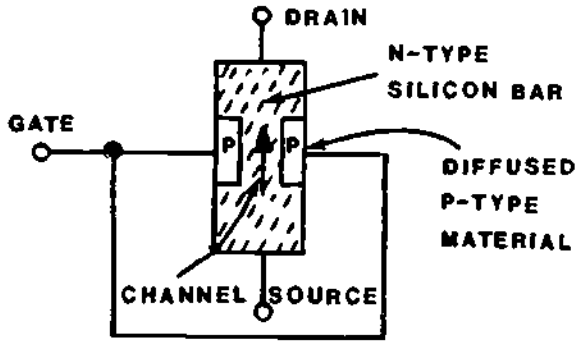

Figure 5

PICTORIAL DIAGRAM OF N-CHANNEL JFET

In a FET, a solid bar of either N-type or P-type material forms the main body of the device. Diffused into the sides of the bar are two materials of the opposite type which form the "gate" element. Figure 5 shows a bar made of N-type material, and a gate made of P-type material. The N-type material b the gate is of smaller cross-section than the rest of the bar, and forms a "channel" between the source and drain. Hence the name N-channel JFET. A P-channel JFET would have the bar and gate materials of the opposite type from an N-channel JFET.

In an N-channel JFET, the source and drain are made of a solid bar of

_______-type material and the gate is made of ______-type material.

N, P

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7. The effective cross-sectional area of the channel is the key to FET operation. Now let's apply a voltage across the bar of an N-channel JFET, as shown in Figure 6, to see what happens.

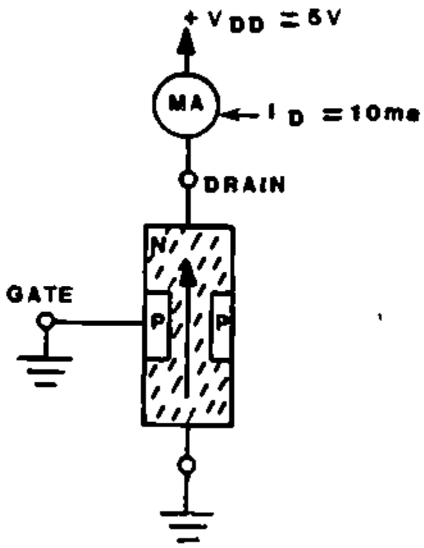

Figure 6

N-CHANNEL JFET OPERATION - ZERO GATE BIAS

In the figure, 5 volts are applied across the JFET. Note that the gate terminal has been tied to ground, or zero (0) volts. This is a zero gate bias condition. Current will flow through the bar from source to drain as indicated by the arrow. A milliammeter is connected in series with the drain lead and DC power to indicate the amount of current flow. Now, a typical bar of material has about 500 ohms resistance with zero gate bias. Therefore for a drain supply of 5 volts (V_{DD}), the milliammeter should read a drain current (I_D) of 10 mA. Notice that the voltage and current subscript letters for FETs (for example V_{DD} and I_D) correspond to the elements of the device, just as in transistors.

Current flow through an "N" channel JFET is from ________ to __________

---

source, drain

(8.) You have learned that there is a small current flow through a JFET with zero gate bias. Let's apply a small negative voltage to the gate of the JFET shown in Figure 7, and see what happens.

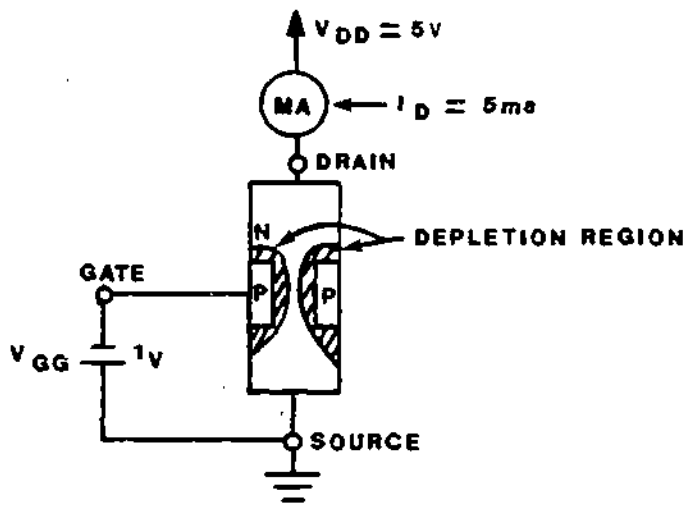

Figure 7

N-CHANNEL JFET OPERATION - REVERSE GATE BIAS

In the figure, 1 volt (V_{GG}) is applied between the gate and source. The negative voltage on the P-type gate material causes the junction region between the P-and N-type materials to become reverse biased.

Recall from your study of varactor diodes that a reverse bias condition causes a depletion region around the PN junction. The same thing happens in JFETs. In Figure 7, you can see a depletion region in the channel which is void of current carriers. The depletion region has the same effect as reducing the cross-sectional area of the bar material. This reduced area increases the JFET source-to-drain resistance.

Applying a reverse bias voltage to the gate of a JFET causes the source-to-drain resistance of the JFET to (increase/decrease).

---

increase

9. Figure 8 again shows what happens to the current flow in a JFET under reverse bias conditions.

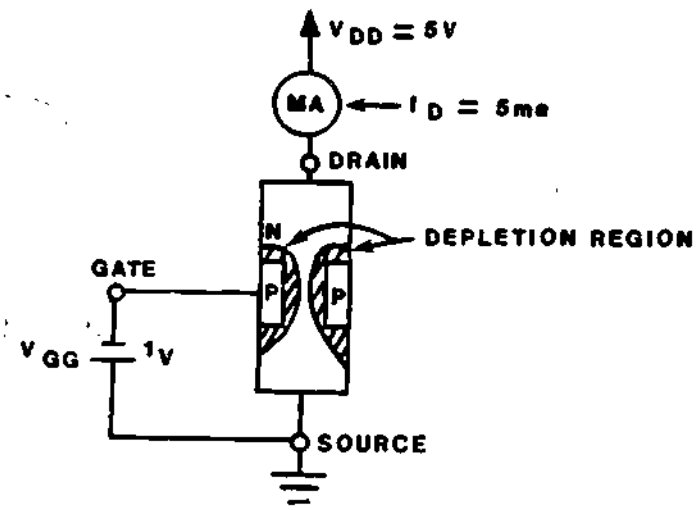

Figure 8

N-CHANNEL JFET OPERATION - REVERSE GATE BIAS

In the figure, the milliameter shows a 5 mA drain current flow through the JFET with a 1 volt reverse bias voltage applied to the gate. Recall that at zero gate bias, the current flow was 10 mA and the resistance was 500 ohms. Therefore, a 1 volt gate bias has caused the drain current to drop to 5 mA. If you calculated the resistance of the bar for this condition you would find that the resistance has doubled to 1000 ohms.

It is possible to make the depletion region large enough to stop conduction through the bar material. The gate voltage required to reduce the drain current to zero is called the "pinch-off" voltage. This is comparable to the cut-off voltage in a vacuum tube.

The current flow through an FET at zero gate bias will drop if a (forward/reverse) bias voltage is applied to the gate.

---

reverse

10. You have learned that the operation of a JFET is similar to that of a bipolar transistor, even though it is constructed differently. So why use JFETs instead of bipolar transistors? The answer is that JFETs have high input impedances, whereas bipolar transistors have relatively low input impedances.

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Figure 9 illustrates the measurement of input impedance in a JFET.

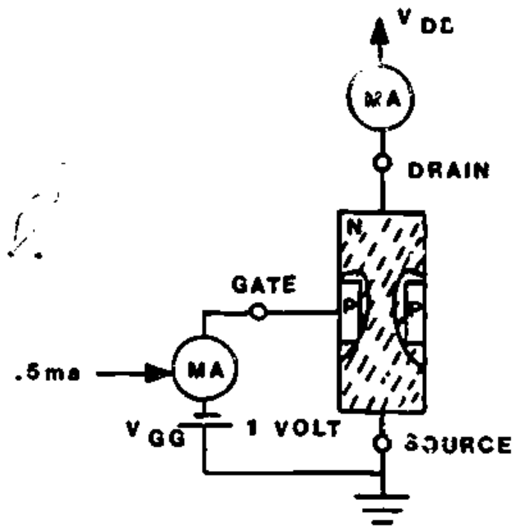

Figure 9

N-CHANNEL JFET INPUT IMPEDANCE

In the figure, a microammeter has been connected in series with the gate-source voltage, V_{GG}. The microammeter reads .5 microamps with I volt V_{GG}. Applying Ohm's Law, the input impedance is 2 megohms (I volt ÷.5uA). In contrast, the input impedance of a bipolar transistor would be only about I000 ohms or less. The high input impedance of the JFET is due to the reverse biased gate-channel junction.

JFETs have (lower/the same/higher) input impedances that bipolar transistors.

---

higher

(11.) You have learned about JETs by studying the operation of the N-Channel type. P-channel JFETs are identical in principles of operation to N-channel JFETs. The difference between them is that the P and N materials in the solid bar and gate are reversed. Thus source voltage potentials must also be reversed. Figure 10 shows source voltages and symbols for both N- and P-channel JFETs.

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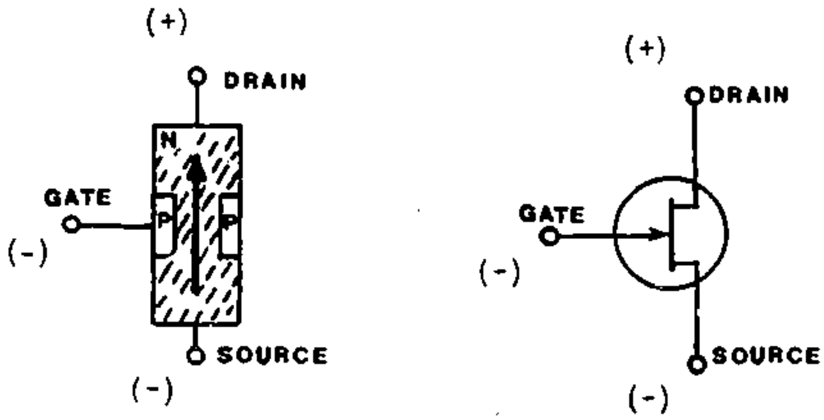
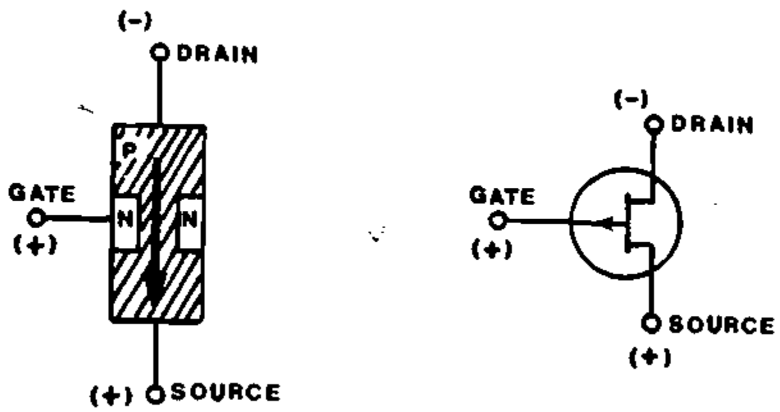


N-CHANNEL JFET



P-CHANNEL JFET

Figure 10

COMPARISON OF N AND P-CHANNEL JFETS
SYMBOLS AND BIAS VOLTAGES

In the figure, notice that the P-channel JFET has a solid bar of P-type material, and a gate of N-type material. The arrows in the bar indicate the direction of current flow through the material. The arrows on the schematic symbols point toward the N-type materials just as in bipolar transistors.

In a P-channel JFET, the solid bar is made of (P/N)-type material, and the gate is made of (P/N)-type material.

P, N

(12) Figure 11 shows an amplifier circuit, using an N-channel JFET.

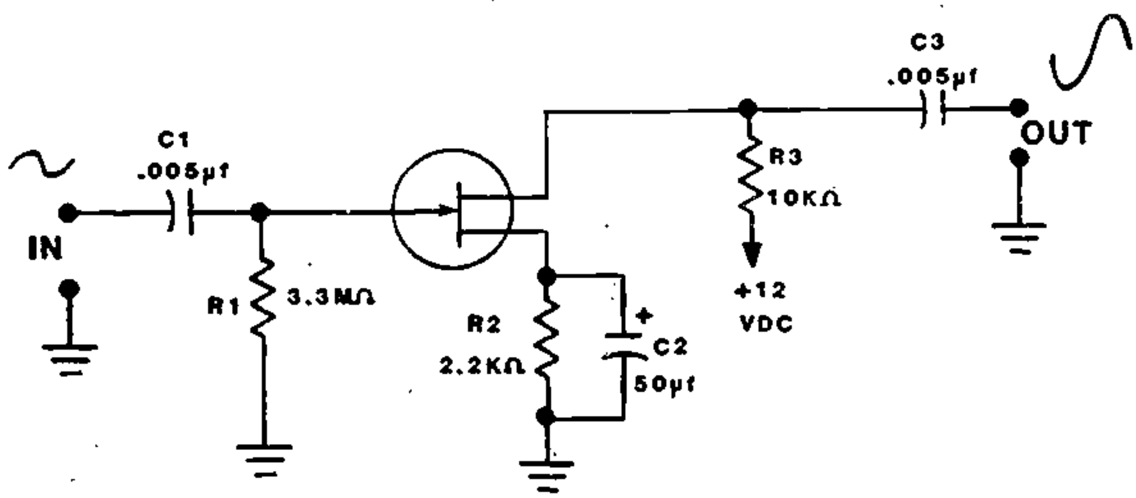


Figure 11

JFET COMMON-SOURCE AMPLIFIER

The circuit is a basic common-source amplifier. Operating characteristics include a high input impedance, and a voltage gain of about 10. This voltage gain converts to about 20 dB.

The function of components is very similar to the components in a triode vacuum tube amplifier circuit. In the figure, C1 and C3 are the input and output coupling capacitors. R1 is the gate return resistor, and serves a function similar to that of the grid return resistor in a vacuum tube circuit. This resistor prevents an unwanted charge build-up on the gate by providing a discharge path for C1.

R2-C2 provide source self-bias for the JFET, which is similar to the cathode self-bias in a vacuum tube circuit. R3 is the drain load resistor. In a vacuum tube circuit, R3 would be the collector or plate load resistor.

In Figure 11, source self-bias for the JFET is provided by components

__________ and __________.

R2, C2

(13.) Take a look at the input and output signals in the JFET amplifier circuit shown again in Figure 12.

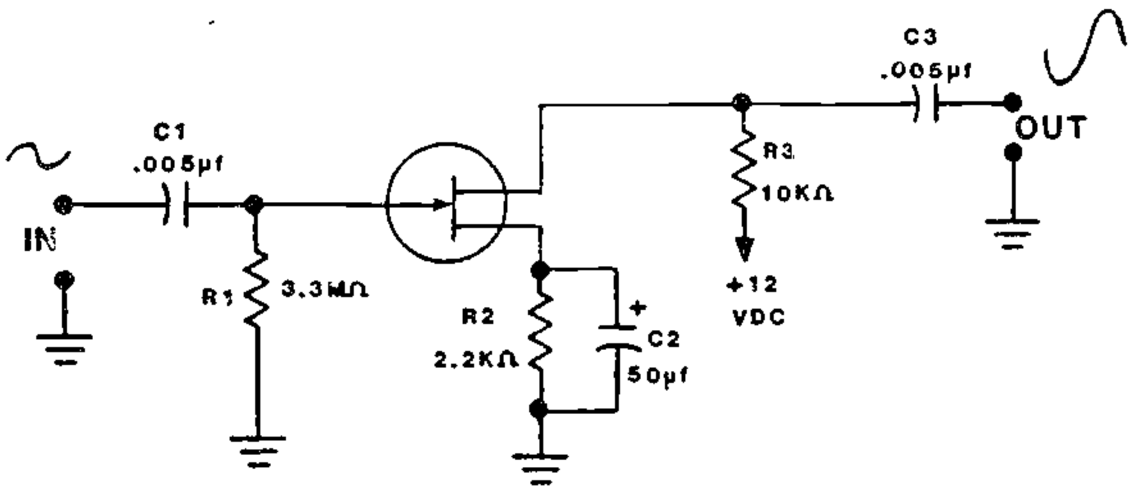


Figure 12

JFET COMMON-SOURCE AMPLIFIER

Notice the 180° phase shift between the input and output signals. This same effect happens in common-emitter transistor circuitry and in common-cathode vacuum tube circuits.

The reason for the phase shift should be easy to understand now that you know about JFET operation. In the figure, the circuit uses an N-channel JFET. Now, on the positive alternation of the input signal, the P-type gate material will decrease the depletion region in the JFET. This decreases the source-drain resistance of the JFET. When this resistance decreases, the current through the JFET increases, causing the voltage drop across R3 to increase thus causing the drain voltage to decrease.

The negative alternation of the input cycle will reverse the action described above. Therefore, the output signal is an amplified 180° out-of-phase version of the input signal.

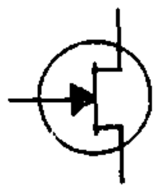
In a JFET amplifier circuit, the input and output signals are (in-phase/180° out-of-phase)

180° out-of-phase

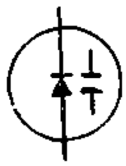
(14) THIS IS A TEST FRAME. COMPLETE THE TEST QUESTIONS AND THEN COMPARE YOUR ANSWERS WITH THE CORRECT ANSWERS GIVEN AT THE TOP OF THE PAGE FOLLOWING THE QUESTIONS.

1. Which of the following symbols is the schematic symbol for an N-channel JFET?

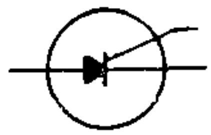
a.



b.



c.



d.

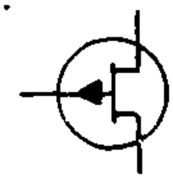


Figure 13

2. In an N-channel JFET, the solid bar of material between the source and drain is made of ___________-type material, and the gate is made of ___________-type material.

3. In an N-channel JFET, the depletion region is largest under conditions of

a. forward gate bias.

b. reverse gate bias.

c. zero gate bias.

4. A small negative voltage applied to the gate of an N-channel JFET causes the resistance of the device to (increase/decrease), and current flow through the device to (increase/decrease).

5. The "pinch off" voltage in a JFET is the gate voltage ...ed to

a. decease the depletion region to its smallest size.

b. overdrive the output from the JFET.

c. forward bias the JFET.

d. reduce the drain current to zero.

6. The input impedance of a bipolar transistor is (larger/smaller) than that of a JFET.

15...

7. The figure below is a common-source amplifier circuit using a JFET. Which statement describes the purpose of c... ...onent R1?

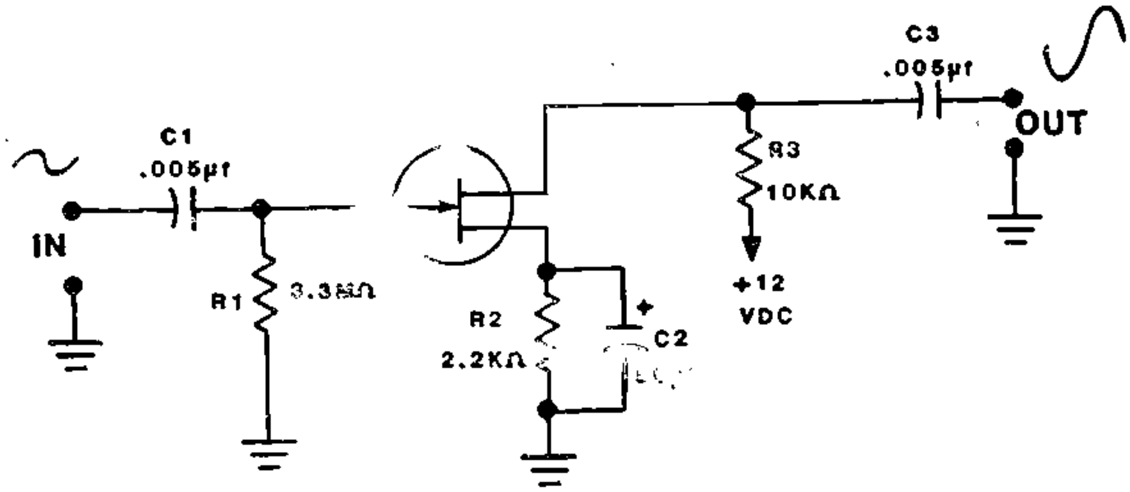


Figure 14

a. Source s...f-bias resistor

b. Gate return resistor

c. Drain load resistor

8. The input and output signals in a basic common-source JFET amplifier are

a. in-phase.

b. 90° out-of-phase.

c. 120° out-of-phase.

d. 180° out-of-phase.

1. a.
2. N, P
3. b. reverse gate bias.
4. increase, decrease
5. d. reduce the drain current to zero.
6. smaller
7. b. Gate return resistor
8. d. 180° out-of-phase.

IF YOUR ANSWERS MATCH THE CORRECT ANSWERS, YOU MAY GO TO TEST FRAME 24. OTHERWISE, GO BACK TO FRAME 6 AND TAKE THE PROGRAMMED SEQUENCE BEFORE TAKING THE TEST FRAME 14 AGAIN.

15. Earlier in this lesson, you learned that there are two types of FETs--the JFET and the MOSFET. The MOSFET devices now will be discussed in the rest of this lesson.

MOSFET stands for "metal oxide semiconductor field-effect transistor". MOSFETs have an extremely high input impedance which is on the order of 10 to 100 million megohms (10^{13} - 10^{14} ohms). Therefore, MOSFETs will not load down preceding circuits. This device also has a high gain factor. The input impedance of MOSFETs is much higher than that of JFETs. MOSFETS commonly are used in RF/IF amplifiers and mixers, and in many types of test equipment where high input impedance is desired.

MOSFETs have a (higher/lower) input impedance than do JFETs.

---

higher

(16) There are two types of MOSFETs: N-channel and P-channel. The labeled schematic symbol for each type is shown in Figure 15.

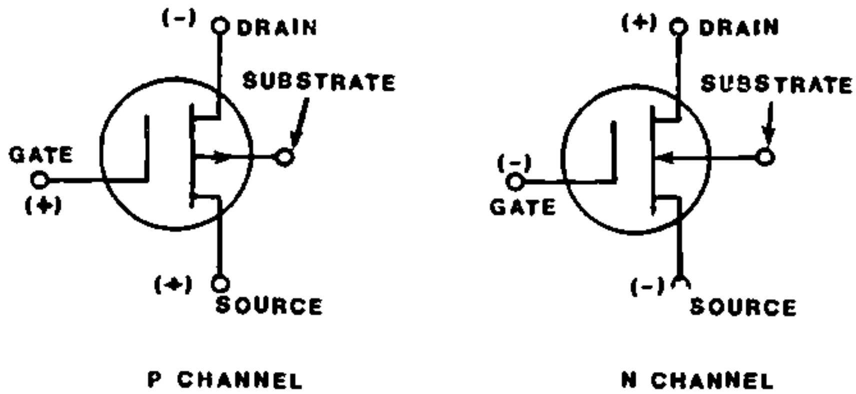


Figure 15

METAL OXIDE SEMICONDUCTOR FETs (MOSFET)
SCHEMATIC SYMBOLS AND BIAS VOLTAGES

In the figure, you can see that the standard MOSFET has four elements, each tied to a separate lead. Three of these elements are the same as in JFETs. They are the "gate, "source", and "drain". The fourth element is the substrate", and will be discussed in a later frame. The biasing polarities are placed near the elements of each device to show the type of voltage (positive or negative) needed for operation. As you can see, the polarities are the same as they are for JFETs.

The four elements of a MOSFET are the ____________, ____________, ____________, and ____________.

---

gate, source, drain, substrate (in any order)

(17.) Some of the important design features of MOSFETs now will be discussed. Figure 16 shows an illustration of the components in a typical N-channel MOSFET.

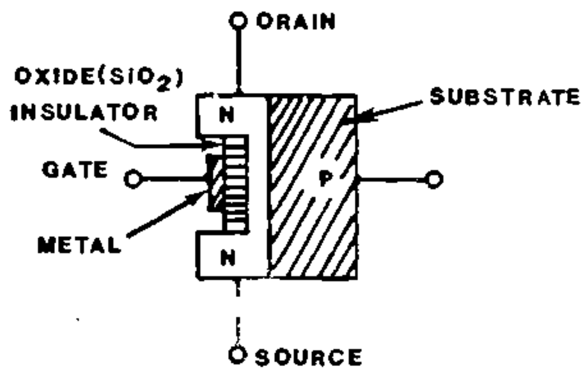


Figure 16

N-CHANNEL MOSFET CONSTRUCTION

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As you can see, MOSFETs are made a little differently than JFETS. Notice that in an N-channel MOSFET, there is a solid bar of N-type material between the source and drain. This is called the channel material. This channel material is mounted on the substrate material, which is of the P-type in this example.

In an N-channel MOSFET, the channel material is of the (P/N)-type, and the substrate material is of the (P/N)-type.

N,P

(18) F re 17 repeats the illustration of an N-channel MOSFET.

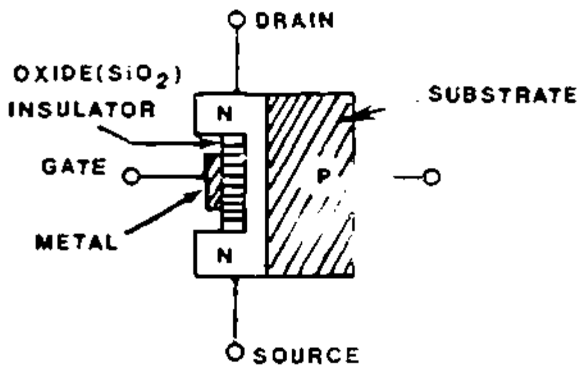

Figure 17

N-CHANNEL MOSFET CONSTRUCTION

If you look carefully, you can see there is) PN junction in the gate circuit. A layer of silicon oxide (chemically SiO_2) separates the metal gate terminal from the N-chann aterial. Therefore, the gate is iv electrically insulated from the channel and substrate materials. This design feature

causes the high input impedance found in MOSFETs. It also has brought about another common name for the device, which is "insulated gate field-effect transistor", or IGFET.

In a MOSFET, the gate terminal is electrically (connected to/insulated from) the channel material.

---

insulated from

19. Recall that there are four elements in a MOSFET, and therefore four device leads. Figure 18 points out the substrate elements on the schematic symbols for N-and P-channel MOSFETs.

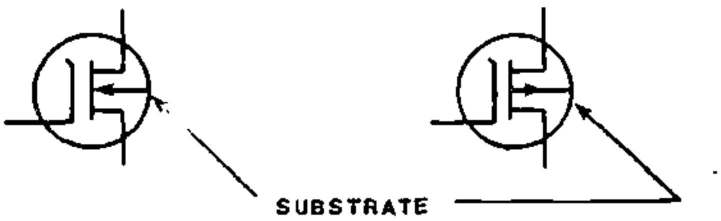

Figure 18

MOSFET (OR IGFET) SUBSTRATE TERMINAL

The substrate element can be used to control the gain characteristics of MOSFETs. Current conduction between the substrate and source or drain occurs if the substrate is biased into conduction. However, the substrate lead often is simply connected to the source terminal, either internal or external to the device

If the substrate of a MOSFET is biased into conduction, it can be used to control the (frequency/gain) of the device.

---

gain

(20) The MOSFETs you have learned about have only one gate, and are called single-gate MOSFETs. Some MOSFETs have an additional gate, and are called dual-gate MOSFETs. The dual-gate MOSFET operates very much like a multi-grid vacuum tube. The labeled schematic symbols for N-and P-channel dual-gate MOSFET's, and a multi-grid vacuum tube, are shown in Figure 19.

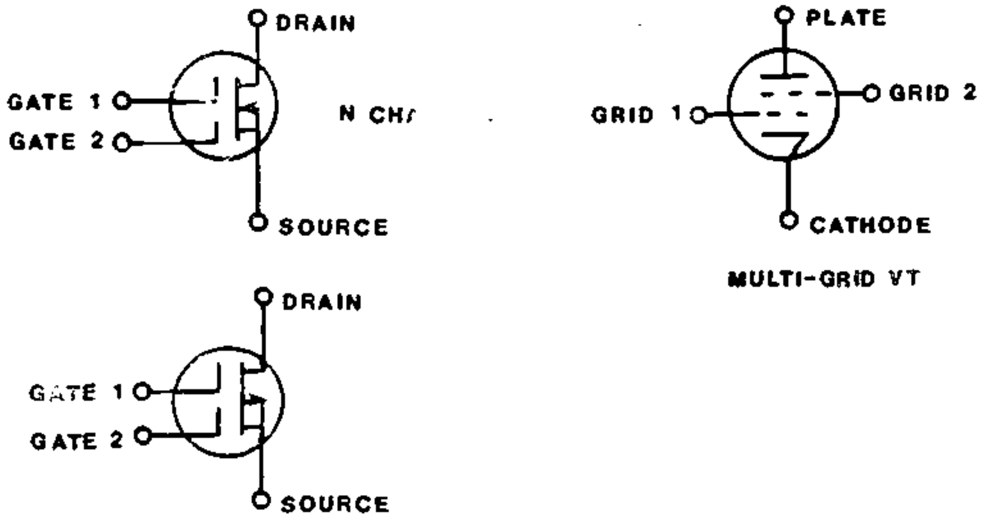

Figure 19

DUAL-GATE MOSFET MULTI-GRID VACUUM TUBE

In the figure, notice that the substrate leads in the MOSFETs are connected to the source leads. Therefore, dual-gate MOSFETs have four leads --two for the gates, and one each for the source and drain.

The dual-gate MOSFET is a truly versatile device. Both gates independently control conduction of the device. This dual control capability lends itself to applications where two separate signals must control device operation. Some applications include AGC-controlled amplifiers and mixer-oscillator circuits.

Two separate signals can independently control the operation of (single/dual) gate MOSFETs.

---

dual

21. One problem with the design of both single-gate and dual-gate MOSFETs is that they can be destroyed very easily by a discharge of static electricity. As you know, static electricity is the charge that causes you to get a shock when you touch grounded objects on a low humidity (dry) day. To combat this problem, MOSFETs are packaged with their leads all shorted together with a shorting spring (wire). This spring must not be removed until the MOSFET is soldered or plugged into a circuit. One such spring is shown in Figure 20.

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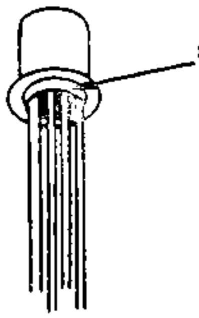

Figure 20

PROTECTING MOSFETS

Remember: Do not forget to remove the spring or wire once the MOSFET is installed, or you may short out the supply voltages. There are other special precautions that must be observed when working on equipment using MOSFETs. Study the special handling information shown in Figure 21.

NOTICE

SPECIAL HANDLING OF MOS DEVICES

The MOS metal oxide semiconductor devices have a fairly high input resistance making them subject to damage from charges of static electricity through improper handling. The thin layer of oxide can be damaged from discharges of static electricity or improper handling in or out of circuit. The damage may be apparent immediately or may show up only after a short operating time. To avoid possible damage, the following procedures should be followed when handling or testing these devices.

1. The use of synthetic clothing such as nylon should be avoided as this will generate static charges. Dry weather (relative humidity less than 30%) also tends to increase static buildup.

2. Keep the leads of the device in contact with a conducting material or shorted, except when testing, inserting or removing from the circuit.

3. A wrist strap with a I megohm resistor in series to common ground should be worn by the technician when inserting, removing or testing MOS devices.

4. Do not remove or insert an MOS device with the power to the circuit or test instrument "ON".

5. Do not apply or inject test signals into the circuit when an MOS device is used with the circuit power "OFF".

6. Do not turn the circuit power "ON" with an MOS device removed from the circuit. Charges can build up causing possible damage when the device is replaced in the circuit.

7. Soldering iron tips, metal bench tops, test equipment and tools should be grounded to a common ground along with the chassis of the set being serviced.

8. Soldering guns should not be used in MOS circuits, AC line leakage from the gun tip could cause damage to an MOS device.

9. Do not apply heat for longer than 10 seconds or closer than 1/16 of an inch to any MOS device when soldering. Use of a heat sink is recommended to prevent damage to the device.

Figure 21

MOSFET PRECAUTIONS

You should read this notice carefully to be aware of the necessary measures to observe when repairing MOSFET equipment.

The safety precautions you must observe when handling MOSFETs help you to avoid damage caused by the build-up and discharge of ________________

________________.

---

static electricity

(22.) Some MOSFETs have built-in gate protection circuits to avoid damage due to excessive voltages. Figure 22 shows an example of internal diode protection circuits placed in the circuit schematics of dual and single-gate MOSFETs.

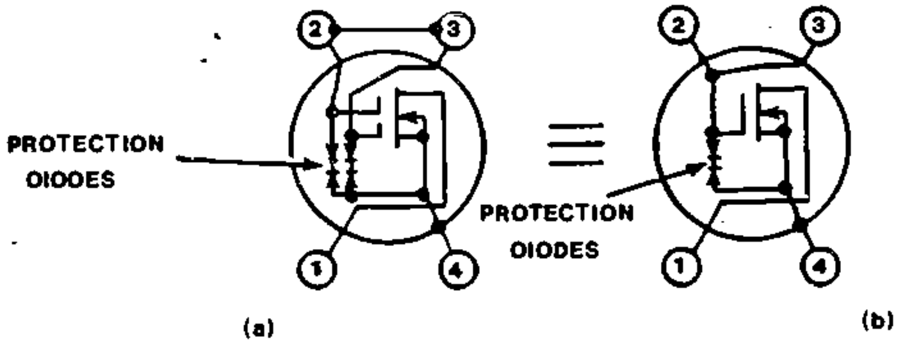

Figure 22

INTERNAL GATE PROTECTION

The back-to-back diodes across the gate-to-source elements are designed to limit transient voltages to a safe operating level and yet allow signals to be amplified without distortion.

In Figure 22, the internal protection circuits are made of back-to-back

____________________.

---

diodes

(23) Now for some pointers about testing and repairing FET circuits. You already know about the safety precautions, so let's look at pin arrangements and troubleshooting tehniques.

The pin arrangements for FETs (both JFETs and MOSFETs) have not been standardized. To determine which leads are gate, source, drain or substrate, you must look up the device by part number in a data book. Examples of typical common-base arrangements for JFETs, and both single and dual-gate MOSFETs, are shown in Figure 23.

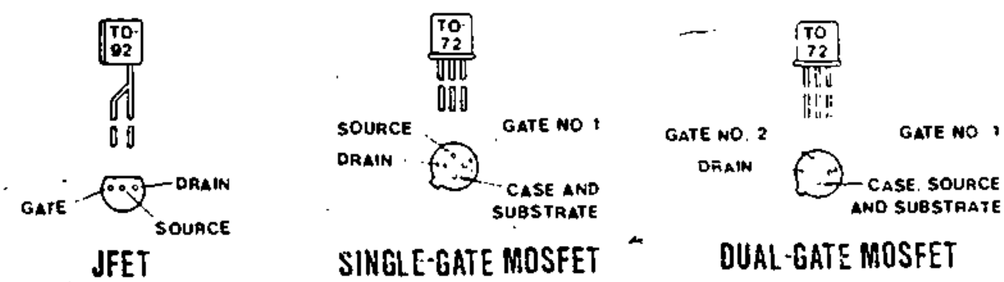

Figure 23

FET BASE DIAGRAMS

The location of a faulty FET stage would be found by the signal tracing or signal injection methods used in previous lessons. Once a stage is isolated, voltage measurements with a high impedance voltmeter will help determine if the stage is defective. Measurement of resistance between elements with an ohmmeter is not recommended. Ohmmeter battery voltages have a wide variation, and could result in damage to the FET.

Voltage measurements in FET circuits should be done with a (low/high) impedance voltmeter.

---

high

(24.) THIS IS A TEST FRAME. COMPLETE THE TEST QUESTIONS AND THEN COMPARE YOUR ANSWERS WITH THE CORRECT ANSWERS GIVEN AT THE PAGE FOLLOWING THE QUESTIONS.

1. Which of the following devices has the highest input impedance?

   a. JFET

   b. MOSFET

   c. Bipolar transistor

2. Which MOSFET element is identified by the arrow in the schematic symbol below?

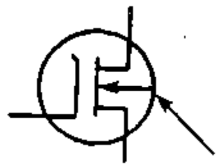

Figure 24

a. Substrate

b. Source

c. Gate

d. Drain

3. In an N-Channel MOSFET, the gate is attached to the

a. PN junction.

b. P-type material.

c. N-type material.

d. silicon oxide layer.

4. Which of the symbols below is the schematic symbol for an N-channel dual-gate MOSFET?

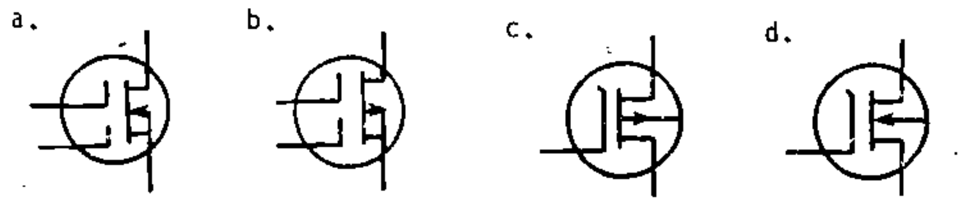

Figure 25

a. a

b. b

c. c

d. d

5. The purpose of the shorting ring in MOSFETs is to

a. shunt the substrate to either the source or gate during operation.

b. protect the device from static electricity discharge during replacement.

c. shunt the gates of a dual-gate MOSFET to make it operate like a single-gate MOSFET.

d. change the gain characteristics of the MOSFET.

6. The pin arrangements of FETs are (standardized/unstandarized).

7. When troubleshooting a FET, use of a standard ohmmeter is (recommended/not recommended).

---

1. b. MOSFET

2. a. Substrate

3. d. silicon oxide layer.

4. a.

5. b. protect the device from static electricity discharge during replacement.

6. undstandardized

7. not recommended

IF YOUR ANSWERS MATCH THE CORRECT ANSWERS YOU HAVE COMPLETED THE PROGRAMMED INSTRUCTION FOR LESSON 4, MODULE THIRTY THREE. OTHERWISE GO BACK TO FRAME 15 AND TAKE THE PROGRAMMED SEQUENCE BEFORE TAKING TEST FRAME 24 AGAIN.

AT THIS POINT, YOU MAY TAKE THE LESSON PROGRESS CHECK. IF YOU ANSWER ALL SELF-TEST ITEMS CORRECTLY, YOU MAY TAKE THE LESSON TEST. IF YOU INCORRECTLY ANSWER ONLY A FEW OF THE PROGRESS CHECK QUESTIONS, THE CORRECT ANSWER PAGE WILL REFER YOU TO THE APPROPRIATE PAGES, PARAGRAPHS, OR FRAMES SO THAT YOU CAN RESTUDY THE PARTS OF THIS LESSON YOU ARE HAVING DIFFICULTY WITH. IF YOU FEEL THAT YOU HAVE FAILED TO UNDERSTAND ALL, OR MOST, OF THE LESSON, SELECT AND USE ANOTHER WRITTEN MEDIUM OF INSTRUCTION, AUDIO/VISUAL MATERIALS (IF APPLICABLE), OR CONSULTATION WITH THE LEARNING CENTER INSTRUCTOR, UNTIL YOU CAN ANSWER ALL SELF-TEST ITEMS ON THE PROGRESS CHECK CORRECTLY.

NARRATIVE
LESSON 4

Field Effect Transistors

Although it has brought about a revolution in the design of electronic equipment, the bipolar (PNP/NPN) transistor still has one very undesireable characteristic. This is the low input impedance associated with its base-emitter junction. Low input impedance causes problems in matching impedances between interstage amplifiers.

For years, scientists searched for a solution which would combine the high input impedance of the vacuum tube with the many other advantages of the transistor. The result of this research is the field-effect transistor, or FET. In contrast to the bipolar transistor, which uses bias current between base and emitter to control conductivity, the FET uses voltage to control an electrostatic field within the transistor. Because the FET is voltage-controlled much like a vacuum tube, it is sometimes called the "solid state vacuum tube".

The elements of one type of FET, the junction type, or JFET, are compared with the bipolar transistor and the vacuum tube in Figure 1.

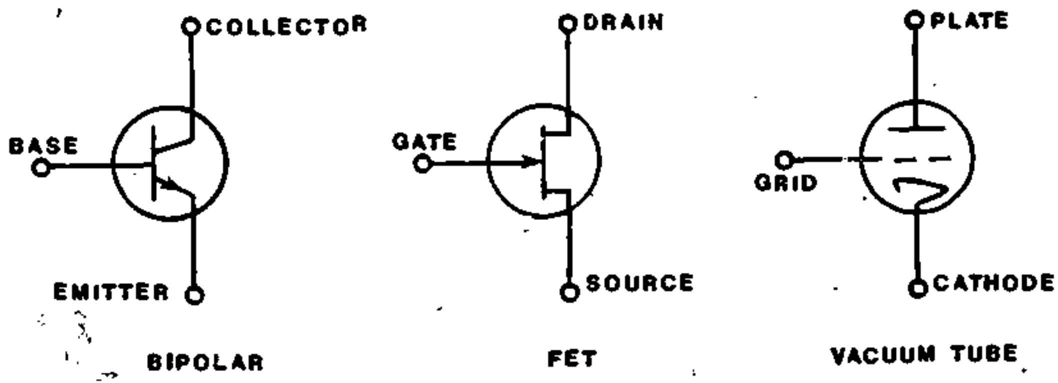

Figure 1

SYMBOLS - JUNCTION FET VS TRANSISTOR/VACUUM TUBE

As the figure shows, the JFET is a three-element device comparable to the other two. The JFET's "gate" element corresponds very closely in operation to the base of the transistor and the grid of the vacuum tube. The other elements of the JFET, "source" and "drain", correspond to the emitter/collector and cathode/plate.

The construction of a JFET is shown in Figure 2.

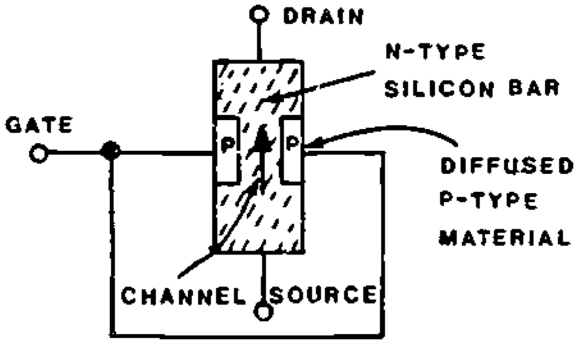

Figure 2

PICTORIAL DIAGRAM - JFET

A solid bar, made either of N-type or P-type material, forms the main body of the device. Diffused into each side of this bar are two deposits of material of the opposite type, which form the "gate". The portion of the bar between the deposits of gate material is of smaller cross section than the rest of the bar and forms a "channel" connecting the source and the drain. Figure 2 shows a bar of N-type material and a gate of P-type material. Because the material in the channel is N-type, the device is called an N-channel JFET.

In a P-channel JFET, the channel is made of P-type material and the gate of N-type material. Schematic symbols for the two types of JFET, compared with those of the NPN and PNP bipolar transistor, are shown in Figure 3.

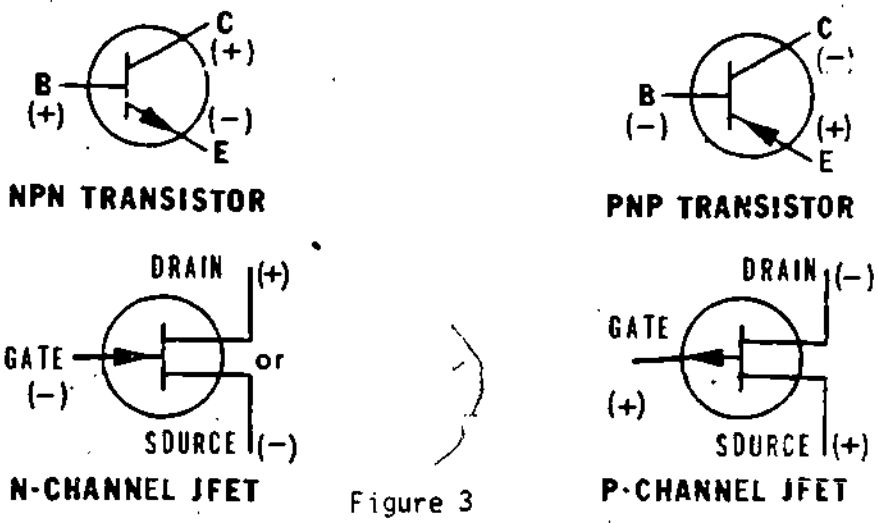

Figure 3

SYMBOLS AND BIAS VOLTAGES-TRANSISTORS AND JFETS

Like the bipolar transistor types, the two types of JFET differ only in the configuration of bias voltages required and in the direction of the arrow within the symbol. Just as it does in transistor symbols, the arrow in a JFET symbol always points towards the N-type material. Thus the symbol of the N-channel JFET shows the arrow pointing towards the drain/source channel, whereas the P-channel symbol shows the arrow pointing away, towards the gate.

The key to FET operation is the effective cross sectional area of the channel, which can be controlled by variations in the voltage applied to the gate. This is demonstrated in the figures which follow.

Figure 4 shows how the JFET operates in a zero gate bias condition.

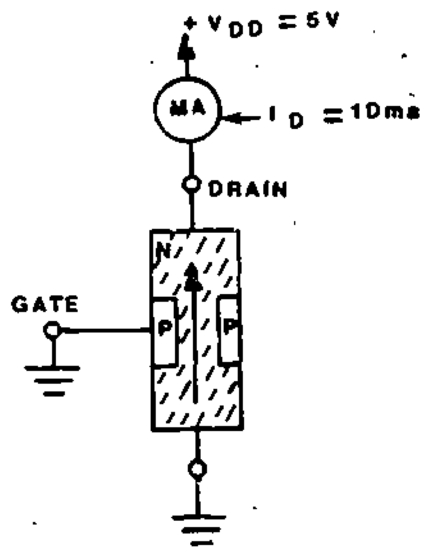

Figure 4

JFET OPERATION - ZERO GATE BIAS

Five volts are applied across the JFET so that current flows through the bar from source to drain, as indicated by the arrow. The gate terminal is tied to ground, or zero (0) volts. This is a zero gate bias condition. In this condition, a typical bar represents a resistance of about 500 ohms. A milliammeter, connected in series with the drain lead and DC power, indicates the amount of current flow, which with a drain supply (V_{DD}) of 5 volts gives a drain current (I_D) reading of 10 mA. The voltage and current subscript letters (V_{DD}, I_D) used for FETs correspond to the elements of the device just as they do for transistors.

In Figure 5, a small reverse bias voltage is applied to the gate of the JFET.

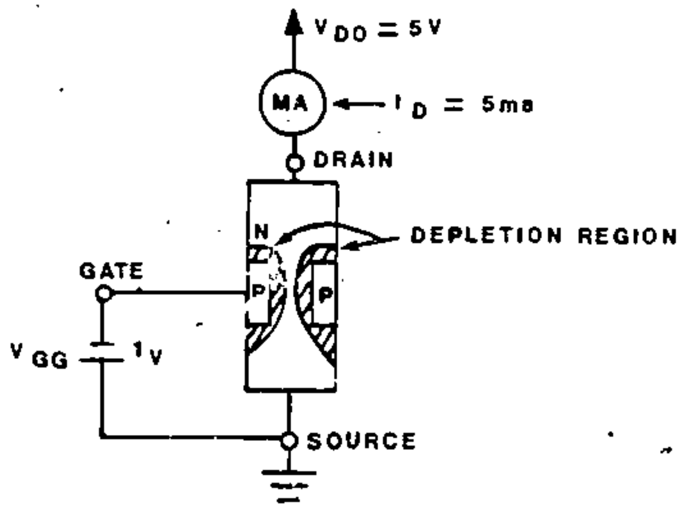

Figure 5

JFET OPERATION - REVERSE GATE BIAS

A gate-source voltage (V_{GG}) of 1 negative volt applied to the P-type gate material causes the junction between the P- and N-type material to become reverse biased. Just as it did in the varactor diode, studied in the previous lesson, a reverse bias condition causes a "depletion region" to form around the PN junction of the FJET. Because this region has a reduced number of current carriers, the effect of reverse biasing is to reduce the effective cross sectional area of the "channel". This reduction in area increases the source-to-drain resistance of the device and decreases current flow.

By applying a large enough negative voltage to the gate, it is possible to make the depletion region so large that conduction of current through the bar stops altogether. The voltage required to reduce drain current (I_D) to zero is called "pinch-off" voltage and is comparable to "cut-off" voltage in a vacuum tube. In Figure 5, the 1 negative volt applied, although not large enough to completely stop conduction, has caused the drain current to decrease markedly (from 10 mA under zero gate bias conditions, to 5 mA). Calculation shows that the I volt gate bias has also increased the resistance of the JFET (from 500 ohms to 1 kilohms). In other words, a one volt change in gate voltage has doubled the resistance of the device and cut current flow in half.

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These measurements, however, show only that a JFET operates in a manner similar to a bipolar transistor, even though the two are constructed differently. As stated at the beginning of this lesson, the main advantage of a FET is that its input impedance is significantly higher than that of a bipolar transistor. The higher input impedance of the JFET under reverse gate bias conditions can be seen by connecting a microammeter in series with the gate-source voltage (V_{GG}), as shown in Figure 6.

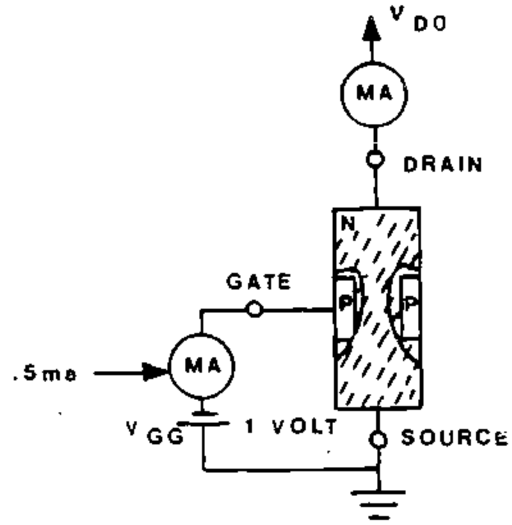
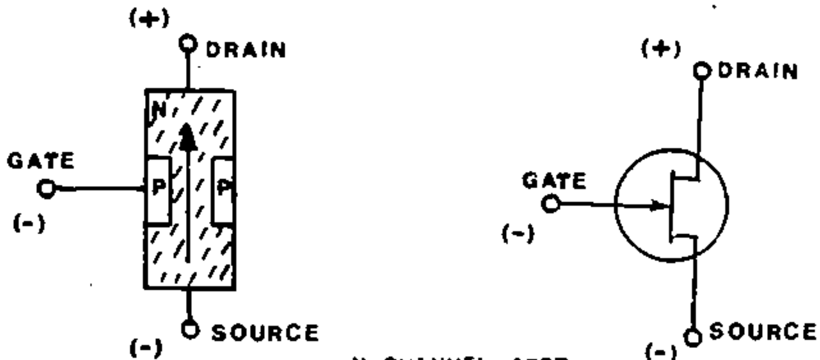


Figure 6

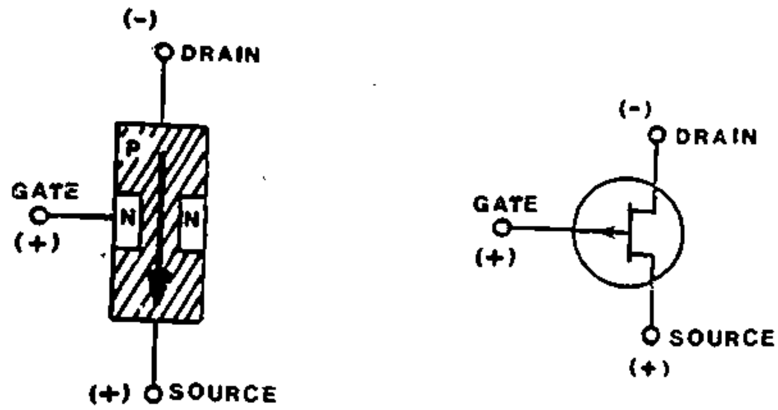
JFET INPUT IMPEDANCE

With a V_{GG} of 1 volt, the microammeter reads .5 microamps. By applying Ohm's Law (1 V ÷ .5 μa), it can be seen that this very small amount of current flow results in a very high input impedance, about 2 megohms. By contrast, a bipolar transistor in similar circumstances would require higher current flow (e.g., .1-1 mA), resulting in a much lower input impedance, only about 1000 ohms or less. The higher input impedance of the JFET is possible because of the way reverse bias gate voltage effects the cross-sectional area of the channel.

The preceeding example of JFET operation uses an N-channel JFET. However, P-channel JFETs operate on identical principles. The differences between the two types are shown in Figure 7.



N-CHANNEL JFET



P-CHANNEL JFET

Figure 7

SYMBOLS & PICTORIAL WITH BIAS VOLTAGES - JFETS

Because the materials used to make the bar and the gate are reversed, source voltage potentials must also be reversed. The P-channel JFET therefore requires a positive gate voltage in order to be reverse biased, and current flows through it from drain to source.

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Figure 8 shows a basic common-source amplifier circuit containing an N-channel JFET.

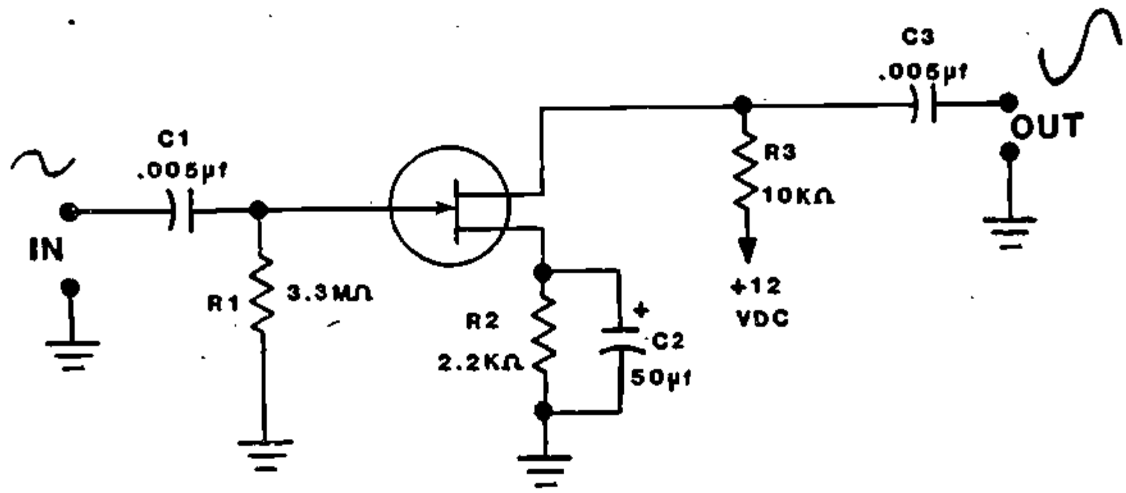

Figure 8

FET COMMON SOURCE AMPLIFIER

The characteristics of this circuit include high input impedance and a voltage gain of about 10 (20 dB). The function of circuit components here is very similar to those in a triode vacuum tube common-cathode amplifier circuit. C1 and C3 are the input and output coupling capacitors. R1 is the gate return resistor and functions much like the grid return resistor in a vacuum tube circuit. It prevents unwanted charge build-up on the gate by providing a discharge path for C1. R2 and C2 provide source self-bias for the JFET, which operates like cathode self-bias. R3 is the drain load resistor, which acts like the plate or collector load resistor.

The phase shift of 180° between input and output signals is the same as that of common-cathode vacuum tube circuits (and common-emitter transistor circuits). The reason for the phase shift can be seen easily by observing the N-channel JFET's operation. On the positive alternation of the input signal, the amount of reverse bias on the P-type gate material is reduced, thus increasing the effective cross-sectional area of the channel and decreasing source-to-drain resistance. When resistance decreases, current flow through the JFET increases, causing the voltage drop across R3 to increase, which in turn causes the drain voltage to decrease. On the negative alternation of the cycle, the amount of reverse bias on the gate of the JFET is increased and the action of the circuit is reversed. The result is an output signal which is an amplified and 180° out-of-phase version of the input signal.

A second type of field-effect transistor has been introduced in recent years which has some advantages over even the JFET. This newest device is the "metal oxide semiconductor field-effect transistor," or MOSFET. MOSFETs have even higher input impedances than JFETs, on the order of 10 to 100 million megohms (10^{13}-10^{14} ohms). Therefore, they are even less of a load on preceding circuits. Their extremely high input impedance, combined with a high gain factor, makes them highly efficient input devices in RF/IF amplifiers and mixers and in many types of test equipment.

Figure 9 shows schematic symbols for the two types of MOSFETS.

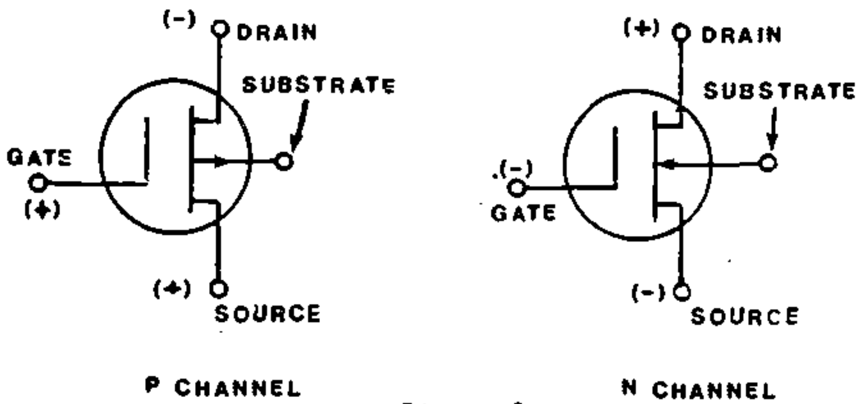

Figure 9

METAL OXIDE SEMICONDUCTOR FET's (MOSFET)

MOSFETs, like JFETs, are of either the P-channel or the N-channel type. Each type has four elements, "gate," "source" and "drain" like the JFET, and one addtional element, "substrate," which will be discussed later. The biasing polarities shown for the elements are the same as those of corresponding P-channel and N-channel JFETs.

The construction of an N-channel MOSFET is shown in Figure 10.

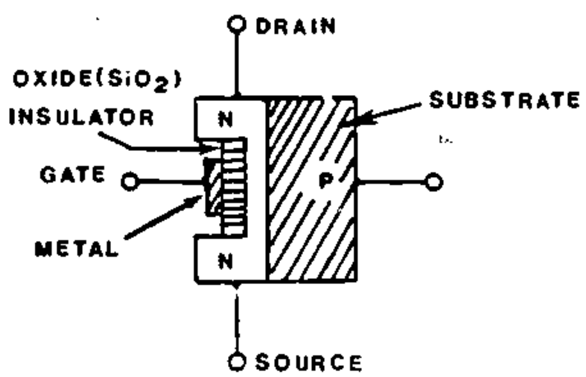

Figure 10

N-CHANNEL MOSFET CONSTRUCTION

MOSFETs consist of a solid bar of either N-type or P-type material, called the channel material, which connects the source and drain terminals. This channel material is joined to the substrate, a layer of material of the opposite type. In the N-channel MOSFET shown in Figure 10, the channel material is N-type and the substrate material is P-type. Just as in transistor and JFET symbols, in schematic symbols for MOSFETs the arrow points towards the N-type material.

A PN junction exists between the channel material and the opposite-type substrate material, and current conduction between the two can occur provided the substrate is biased into conduction. Biasing the substate element in this way permits control of the MOSFET's gain characteristics. Often, however, the substrate terminal is simply connected to the source terminal, either internally or externally, and the biasing capability is not used.

On the gate side of the MOSFET, no PN junction if formed. Instead, a layer of silicon oxide (SiO_2) separates the N-channel material from the metal gate terminal. This layer totally insulates the gate electrically from the N-channel and results in the extremely high input impedance of the MOSFET. It also gives rise to another common name for the device: "insulated gate field-effect transistor," or IGFET.

The MOSFETs discussed up to this point have been single-gate MOSFETs. Another type of MOSFET, the dual-gate type, is shown in Figure 11.

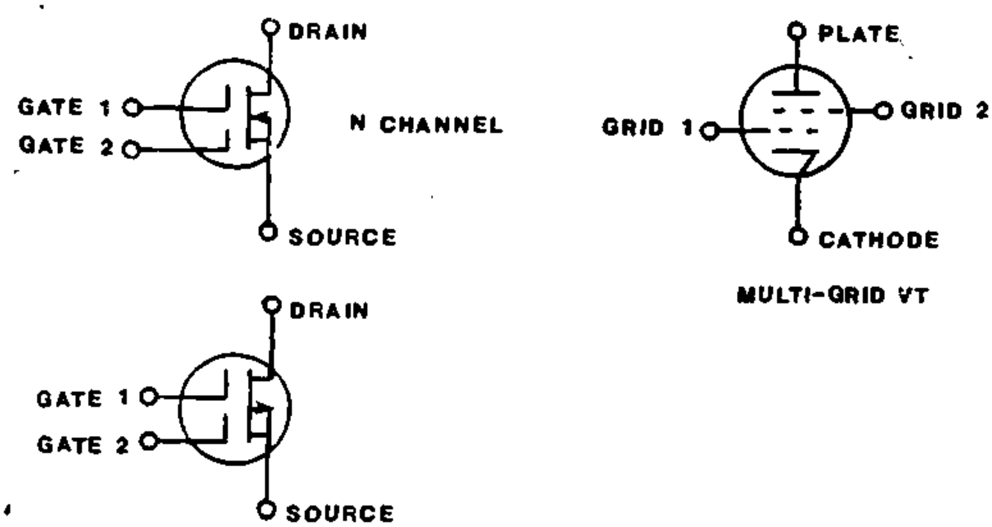

Figure 11

DUAL-GATE MOSFETS

As the figure shows, the gates in a dual-gate MOSFET can be compared to the grids in a multi-grid vacuum tube. Because the substrate has been connected directly to the source terminal, the dual-gate MOSFET still has only four leads: one each for source and drain, and two for the gates. Either gate can control conduction independently, making this type of MOSFET a truly versatile device. Its dual control capability lends itself to applications where two separate signals must control device operation, such as AGC-controlled amplifiers and mixer-oscillator circuits.

One problem with both single- and dual-gate MOSFETs is that the oxide layer between gate and channel can be destroyed very easily by ordinary static electricity, like that which causes a shock when grounded objects are touched on a dry day. To avoid accidental damage, replacement MOSFETs come packaged with their leads shorted together by a special wire loop or spring. The rule to remember with these shorting springs is that they must not be removed until after the MOSFET has been soldered or plugged into a circuit. One such spring is shown in Figure 12.

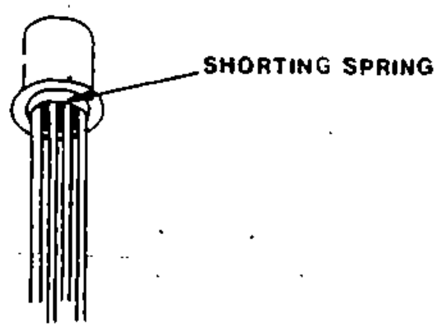

Figure 12

PROTECTING MOSFETS

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Once the MOSFET has been installed, it is important to remember to remove the shorting ring in order to avoid shorting out supply voltages. A complete list of the special precautions that must be taken when handling MOSFETs is shown in Figure 13.

NOTICE

SPECIAL HANDLING OF MOS DEVICES

The MOS metal oxide semiconductor devices have a fairly high input resistance making them subject to damage from charges of static electricity through improper handling. The thin layer of oxide can be damaged from discharges of static electricity or improper handling in or out of circuit. The damage may be apparent immediately or may show up only after a short operating time. To avoid possible damage, the following procedures should be followed when handling or testing these devices.

1. The use of synthetic clothing such as nylon should be avoided as this will generate static charges. Dry weather (relative humidity less than 30%) also tends to increase static buildup.

2. Keep the leads of the device in contact with a conducting material or shorted, except when testing, inserting or removing from the circuit.

3. A wrist strap with a megohm resistor in series to common ground should be worn by the technician when inserting, removing or testing MOS devices.

4. Do not remove or insert an MOS device with the power to the circuit or test instrument "ON"

5. Do not apply or inject test signals into the circuit when an MOS device is used with the circuit power "OFF".

6. Do not turn the circuit power "ON" with an MOS device removed from the circuit. Charges can build up causing possible damage when the device is replaced in the circuit.

7. Soldering iron tips, metal bench tops, test equipment and tools should be grounded to a common ground along with the chassis of the set being serviced.

8. Soldering guns should not be used in MOS circuits, AC line leakage from the gun tip could cause damage to an MOS device.

9. Do not apply heat for longer than 10 seconds or closer than 1/16 of an inch to any MOS device when soldering. Use of a heat sink is recommended to prevent damage to the advice.

Figure 13.

MOSFET PRECAUTIONS

Read this notice carefully and be aware of the necessary measures to observe when repairing MOSFET equipment.

Some MOSFETs have built-in devices to protect against excessive voltage. Figure 14 shows how protective diodes can be placed in dual-and single-gate MOSFETs.

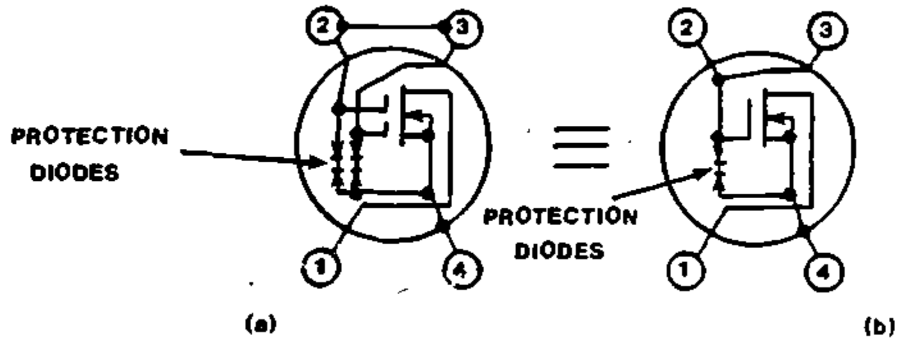

Figure 14

INTERNAL GATE PROTECTION

The back-to-back diodes shown in the figure are designed to limit transient voltages to a safe operating level, while still allowing signals to be amplified without distortion. Although protection diodes work well, it is best to observe the same precautions when working with any type of MOSFET equipment.

Although handling precautions are very important, there are a couple of other important points to remember when testing and repairing FET circuits. These are in the areas of pin arrangements and fault location techniques.

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Once the MOSFET has been installed, it is important to remember to remove the shorting ring in order to avoid shorting out supply voltages. A complete list of the special precautions that must be taken when handling MOSFETs is shown in Figure 13.

NOTICE

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9. Do not apply heat for longer than 10 seconds or closer than 1/16 of an inch to any MOS device when soldering. Use of a heat sink is recommended to prevent damage to the advice.

Figure 13

MOSFET PRECAUTIONS

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Read this notice carefully and be aware of the necessary measures to observe when repairing MOSFET equipment.

Some MOSFETs have built-in devices to protect against excessive voltage. Figure 14 shows how protective diodes can be placed in dual-and single-gate MOSFETs.

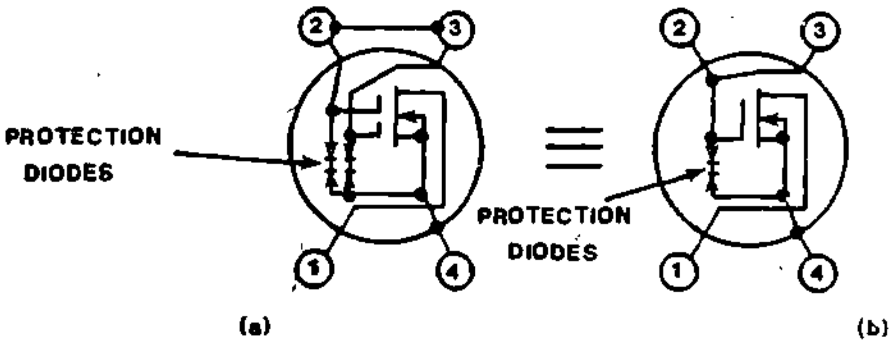

Figure 14

INTERNAL GATE PROTECTION

The back-to-back diodes shown in the figure are designed to limit transient voltages to a safe operating level, while still allowing signals to be amplified without distortion. Although protection diodes work well, it is best to observe the same precautions when working with any type of MOSFET equipment.

Although handling precautions are very important, there are a couple of other important points to remember when testing and repairing FET circuits. These are in the areas of pin arrangements and fault location techniques.

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Pin arrangements for FETs (JFETs and MOSFETs) have not been standardized. Therefore, to determine which lead is the gate, source, drain, or substrate, a data book must be referred to. Devices are indexed in the data book according to part number. Figure 15 shows what the bases of some common FETs look like.

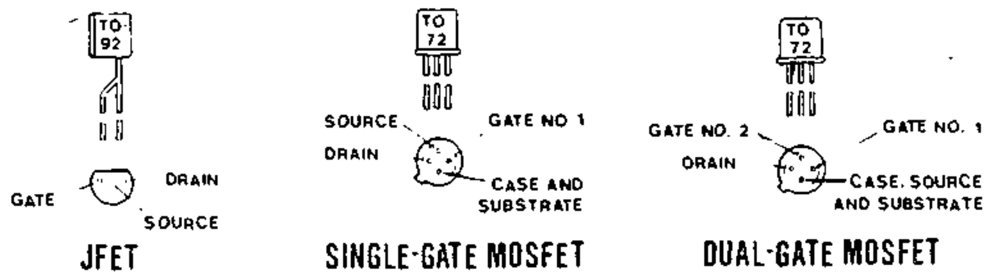

Figure 15

FET BASE DIAGRAMS

Faulty FET stages can be located using the signal tracing or signal injection methods introduced in earlier lessons. Once a stage is isolated, voltage measurements will help to determine if the stage is defective. A high impedance voltmeter should be used. Measurement of resistance between FET elements with an ohmmeter is not recommended. This is because ohmmeter battery voltages vary widely and may easily exceed the maximum voltage permitted between elements of the FET.

AT THIS POINT, YOU MAY TAKE THE LESSON PROGRESS CHECK. IF YOU ANSWER ALL SELF-TEST ITEMS CORRECTLY, YOU MAY TAKE THE LESSON TEST. IF YOU INCORRECTLY ANSWER ONLY A FEW OF THE PROGRESS CHECK QUESTIONS, THE CORRECT ANSWER PAGE WILL REFER YOU TO THE APPROPRIATE PAGES, PARAGRAPHS, OR FRAMES SO THAT YOU CAN RESTUDY THE PARTS OF THIS LESSON YOU ARE HAVING DIFFICULTY WITH. IF YOU FEEL THAT YOU HAVE FAILED TO UNDERSTAND ALL, OR MOST, OF THE LESSON, SELECT AND USE ANOTHER WRITTEN MEDIUM OF INSTRUCTION, AUDIO/VISUAL MATERIALS (IF APPLICABLE), OR CONSULTATION WITH THE LEARNING CENTER INSTRUCTOR, UNTIL YOU CAN ANSWER ALL SELF-TEST ITEMS ON THE PROGRESS CHECK CORRECTLY.