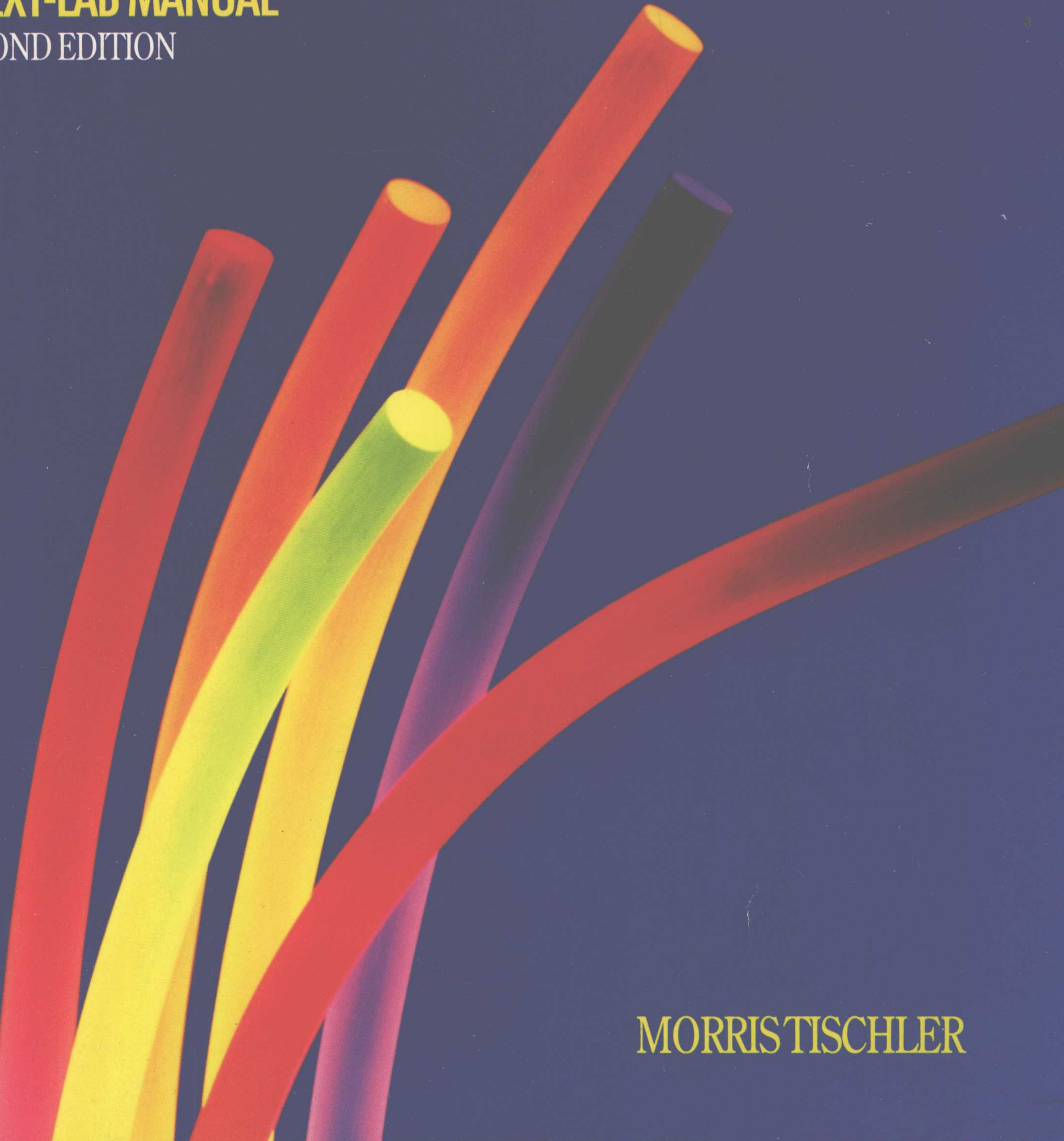
OPTOELECTRONICS: FIBER OPTICS AND LASERS

A TEXT-LAB MANUAL

SECOND EDITION



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PREFACE

I started with the crystal set. It was, and still is, one of the great marvels—music and voice received through the medium of a rock. I learned by teaching and experimenting with tubes, tube receivers, and transmitters. When my students and I were comfortable with these, we were introduced to a new form of voice reception. This time it came from sand-silicon. It was the transistor. I marveled at the crystal set, but the integrated circuit (IC) and large-scale integrated circuit (LSIC) were unbelievable. All my circuits have gone into the IC format, and designing is now a matter of selecting the proper IC.

However, it isn't over yet. Edison gave us the light bulb, and a new technology has evolved, once again from sand and rock. It is called optoelectronics. The mixing of light sources with optics and electronic circuits has created a whole new way of designing. More importantly, it has created a new way of living. Optoelectronics lets us check out of the supermarket more quickly because a machine scans the price code on each individual product. Cameras, dishwashers, and automobiles are now wired with optocouplers, and voice communications across the country are transmitted over glass and plastic fiber links.

Optoelectronics, fiber optics, and lasers are high-tech fields whose development is rapidly advancing. Numerous books have already been written on the subject; however, laboratory experimental books are rather limited in number. In this text-lab manual, I have included experimental studies that provide practical applications for these high-tech materials. The text is structured to provide adequate material for a one-semester course. Emphasis was placed on the use of solid-state lasers and their interface with optical lenses. The laser was also interfaced with the fiber-optic cable, and techniques are demonstrated for transmitting multiple signals using frequency division (also referred to as frequency domain) multiplex on the optical beam. Because of the wide frequency response of the fiber-optic cable, laboratory demonstrations were provided to show how wide bandwidth transmission in the order of 125 MHz can be utilized when using fiber-optic cables and lasers.

Electronics, for me, has offered a lifetime of both challenge and enjoyment. The thrill of the crystal set has not diminished. Music from a rock with a cat's whisker is still a thrill, but now there is a new challenge—the field of optoelectronics, fiber-optics, and lasers. Please join me in the exploration of these new mysteries, and witness the excitement that comes from solving the many mysteries of solid-state communications.

Morris Tischler

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PART 1

Introduction to Optoelectronics

Optoelectronics, broadly defined, is the integration of electronics, optics, and light to more effectively and economically control an electromechanical operation, transfer information, or make measurements. The term *light* means both visible and infrared light. Visible light can be seen by the human eye; infrared light is below the range of human perception. Optoelectronic devices include light emitters, photodetectors or sensors, transmission lines made of optical fibers, and visual displays. A variety of connectors, light-isolated couplers, and transmissive/reflective components are used in bringing the various technologies together. Electric energy can control light, or light can be made to control mechanical movements. All this can be accomplished more effectively than was possible by either technology separately.

Optoelectronic components have proved superior to mechanical sensing and switching, they cost less, and they are smaller and more lightweight. Optoelectronic components are faster, have a longer life, and are more economical. On the negative side, this technology is just emerging, and many innovations will be made. Components will become more compact, and separate components will be integrated into smaller packages. Thus some components will become obsolete. The applications of optodevices range from the space shuttle to the clothes washer. Figure A shows some types of equipment in which optodevices are used.

Optoelectronics makes extensive use of transducers of energy. In transducers, as in our eyes, light is changed to an electric current by photodetectors (photosensors). In the early days of electricity, transducers primarily changed mechanical to electric energy and vice versa. Morse code was sent over lines on land via electricity and was reproduced by mechanical breakers that moved up and down—a far cry from the pictures now transmitted of the planet Mars.

When people started to use wires and the flow of electrons, magnetic fields were also involved. At first, the magnetic fields were low in frequency. Electric power was generated at 25 to 60 cycles per second, or hertz (Hz). This frequency, when transduced to sound, is within the human hearing range. But when people moved into the wireless era, the frequency range of human hearing was left behind. In order for people to interface with this equipment, special transducers had to be designed. Some transducers provided sound and others provided light. Interestingly enough, humans have yet to transduce smell, taste, or the sense of touch.

All energy converters have an operating wavelength that is located someplace on the electromagnetic spectrum. Figure B shows the distribution of energy on the electromagnetic spectrum. The electromagnetic spectrum is usually scaled in angstroms (Å) or micrometers (μm). Both are units of measure that can be converted to frequency. The velocity of propagation of light is equal to 300×10^6 meters per second (m/s). In this region, magnetic waves are no longer measured in cycles per second, or hertz, but in wavelengths and millionths of a wavelength. The unit of measure used is the angstrom or micrometer.

$$\text{Wavelength (in meters)} = \frac{300{,}000}{f\text{ (in kilohertz)}} = \frac{300}{f\text{ (in megahertz)}}$$

Wavelength, in feet, is $984/f$, in megahertz. Also,

$$1\ \text{Å} = 3.937 \times 10^{-9}\ \text{in.} = 1 \times 10^{-10}\ \text{m} = 1 \times 10^{-4}\ \mu\text{m}$$

In addition,

$$1\ \mu\text{m} = 3.937 \times 10^{-5}\ \text{in.} = 1 \times 10^{-6}\ \text{m}$$

This last value is equal to 1×10^4 Å. As an example,

$$100\ \mu\text{m} = 1{,}000{,}000, \text{ or } 10^6\ \text{Å} \qquad 1\ \mu\text{m} = 10{,}000\ \text{A}$$

As another example, a purple light of 0.40 μm is equal to 4000 Å. Particular attention should be paid to the light frequency range, since optoelectronic devices work in regions of visible and infrared light. Many manufacturers produce only infrared emitters and sensors. Light-emitting diodes (LEDs) that radiate in the infrared region (below visible light) are called *infrared-emitting devices* (IREDs).

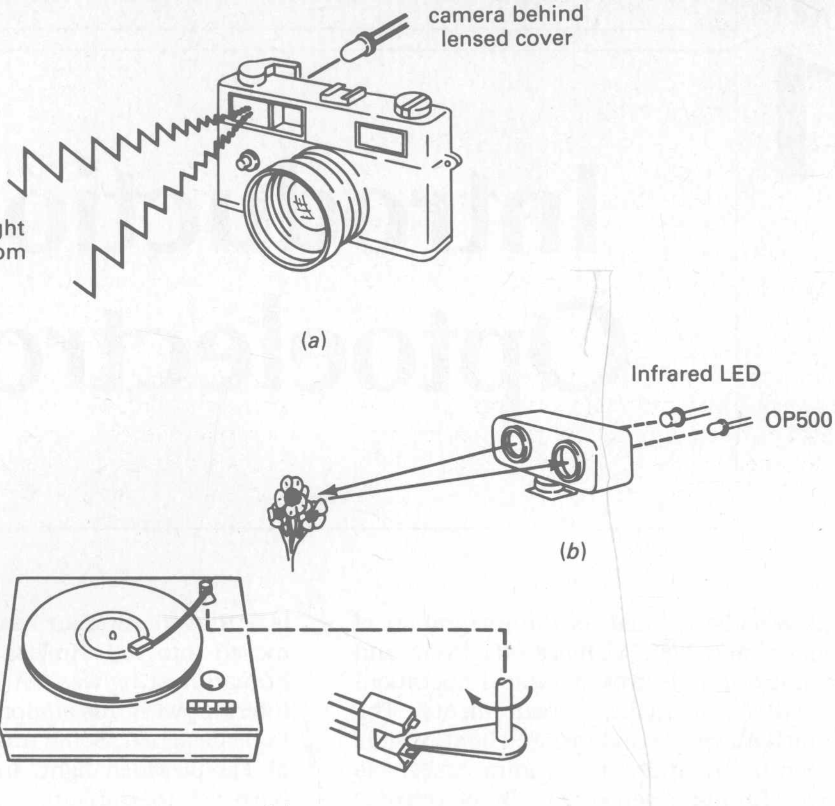

FIG. A Typical uses of optoelectronic devices. (*a*) Automatic light meter. (*b*) Automatic focus control. (*c*) When the tone arm on a phonograph engages the oscillating grooves on the inside of the record, an opaque object connected to the underside of the tone arm interrupts the IR light path in the interrupter, triggering the return-to-rest or record-change cycle.

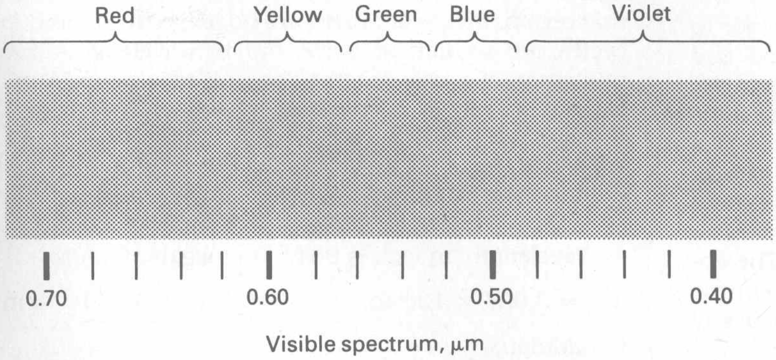

FIG. B Electromagnetic spectrum.

Although optoelectronics is a new technology, optical transducers have been used as controllers for some years. Vacuum-type photocells were used to control solenoids and motors for moving doors and regulating the flow of people. The motion picture projector incorporated a light transducer along with mechanical devices to create sound from photographically produced sound tracks. Today a similar technique is used to read codes on products at the supermarket checkout. The newer devices are more versatile, and a greater variety is available for circuit design.

Advances in semiconductors have contributed enormously to the growth of optoelectronics. The invention and development of semiconductor devices, such as the PN junction and transistors, gave real impetus to the emergence of the optical electronics (optoelectronics) industry. In place of a tungsten lamp, heated to 2000 or 3000 kelvins (K) to produce light, black sand is refined into silicon disks to which are added "doped" materials such as arsenide. Under proper conditions, the junction of P- and N-type semiconductors is able to radiate light. Although this light is not as bright as that from light bulbs, we can still use the LED and add highly sensitive detectors to compensate for the difference. The LED, depending on its structure and doping, will give off light from near ultraviolet to near infrared. Units are made in plastic or metal cases, with and without plastic lenses for focusing. The LED is the most popularly used emitter, although tungsten, neon, lasers, and other light sources have been and are used.

Light detectors or sensors, also made from semiconductors, are used to convert light energy (photons) back to electricity. The PN junction diode, when provided with a forward current (bias), will radiate light; but when back-biased (or reverse-biased), the diode produces electron flow from light. The three-terminal transistor (NPN) can also be used as an amplifier. The base connection is left open, and radiant energy on the base-collector junction produces an electron flow which is increased by the forward gain (h_{fe}) of the transistor.

The LED and sensor can be used for counting. The beam of light between them is interrupted (transmissive control), and each break is recorded. The light can also be reflected off a turning wheel or object to determine its speed. The key elements are the emitter and detector, coupled to perform a specific function. These devices are called *couplers*. Some couplers contain the emitter and sensor, each electrically separated from the other. High-voltage isolation and low capacitance enable the device to control high-power circuits with low-voltage control. In the hospital, for example, where some patients have been electrocuted while undergoing diagnostic tests, optical couplers now separate the patient from the electric instrument.

The emitter and sensor need not be in close proximity. In fact, the sensor could be thousands of miles away. The emitted light is coupled into a clear, flexible, glass or plastic fiber, located inside a protective covering. This fiber link enables light to transverse it by bouncing back and forth off its walls. In this way, lightweight cables, carrying thousands of voices and computer data, replace heavy, costly, copper cables.

At the ends of the fiber lines might be telephone users, TV stations, and computers. In some cases, the transferred data is displayed on LEDs, seven-segment alphanumeric displays. Light displays are an additional use of semiconductor illuminators.

The optoelectronic system is composed of an emitter, a sensor, coupler (isolator) fiber links, and a variety of fittings. Some systems may require only a coupler, whereas others may use an emitter and sensor in a reflective mode.

As time passes, systems engineers and circuit designers will find greater applications for this new technology. The layperson, however, accepts the change with apathy. Calculators, computers, digital watches that play songs, highway cruise controls, pushbutton telephones, and TV sets with 1-inch (in.) screens are now considered routine. But what brought it all about was science fiction that came true. Optoelectronics is not just another step; it is a leap into newer and better ways of controlling machines and communicating around the world.

SUMMARY

The generation of electricity evolved into the field of electronics, and vacuum-tube technology gave way to semiconductor technology. People found ways of making more efficient electronics components out of treated silicon, wafers, or chips. The new technology of optoelectronics includes transducers (emitters and detectors), fiber links, displays, and a variety of fittings to link computers, telephones, and televisions.

EXPERIMENT

1 An Optical Communications System

SCOPE OF STUDY

This laboratory experiment is intended for a student having little or no knowledge of fiber-optic communications systems. An overall concept is developed.

OBJECTIVES

Upon completion of this experiment, construction of circuitry, testing, and evaluation of data, you will be able to:

1. Describe, in general, how communications take place by means of a fiber-optic link.
2. Name and describe the key components used in a fiber-optic link.
3. Adjust the optical transmitter and receiver to achieve good communications.

BACKGROUND

Telecommunications can take place between distant transmitters and receivers by four means:

1. Wire as the communications medium.
2. Radio waves sent through space; this is a wireless process.
3. Microwaves, used for high-frequency communications.
4. Light, in the form of the ultrahigh-frequency communications.

At the transmitter site the intelligence to be transmitted modulates a carrier wave, and at the receiver the intelligence is separated from the carrier.

In a wireless system, antennas are used for the transmitting and receiving of the signal. In optoelectronics, the linkage is made with a glass or plastic fiber-optic cable. The carrier is a light wave; instead of transmitting through a radio-frequency (RF) amplifier, an LED, IRED, or laser is used to transmit the signal. The light is received by a photodetector, which may be a light-sensitive diode, transistor, or Darlington transistor circuit.

Plastic and glass fiber-optic cables have long since passed the experimental stage in applications to telecommunications. Telephone companies nationally and internationally are installing thousands of miles of fiber-optic cable for the conduction of voice signals. Frequency division and pulse-code-modulated signals are being transmitted over glass fibers, whose diameter is less than 10 μm.

Basically, a fiber-optic system has three major components: a light-emitting source (such as a laser or high-powered LED), a fiber-optic cable having a low level of attenuation, and a photosensor. The photosensor is followed by a variety of amplifiers and decoders.

Much of the light in communications over fiber-optic cables operates in the infrared region of 820 to 1600 nanometers (nm). Silica material, used in the making of light emitters and sensors, operates more effectively in the infrared region. Thus it is easy to fabricate infrared devices by using standard technology. Where a high level of energy is required, solid-state lasers are incorporated. The optical fibers come in three basic types:

1. The step-index fiber
2. The graded-index fiber
3. The single-mode, step-index fiber

The single-mode fiber can also be made in the graded-index format. Within the step-index fiber, the light bounces off the walls of the fiber, thus making a zigzag path through the fiber cable. Some light enters the plastic coating, referred to as cladding. The light entering the cladding may continue for a short time, but it is rapidly attenuated. The step-index fiber is often used in the manufacture of plastic fibers, where short runs are encountered. For long runs, such as in telephone communications, high-quality glass fibers, which use single-mode conduction techniques, are in general use.

In the graded-index fiber, a sensing effect causes the beam to be refocused as it travels down the fiber's length. The losses in this type of fiber are not nearly as great as in the step-index, multimode fiber. Once again, in the step-index fiber, the light zigzags through the cable, and a high level of loss occurs.

As the cable is made smaller in diameter, it becomes more effective in conducting a single-mode light wave. Although there are losses in the single-mode fiber, they are minor compared with those in the larger cables made of the step-index form. Attenuation levels of 1 to 5 decibels per kilometer (dB/km) have been experienced in glass fibers as compared to 500 to 9000 dB/km in plastic cables. Once again, plastic cables are best used for short runs, where amplifiers can make up for the signal losses.

Glass and fiber cables offer many advantages not available in metallic conductors. Some of these advantages are as follows:

1. The spacing of repeaters ranges from 20 to 70 miles (mi), compared with 1 mi for copper cables.

2. Fiber cable is immune to water and moisture conditions.
3. The light weight and lower cost of the cable make it advantageous to install.
4. A single-fiber cable can conduct as many voice channels as can be handled by a metallic cable containing 900 wire pairs.
5. The light weight of the cable suggests applications in aircraft and other mobile vehicles.
6. Fibers made of glass use silica as the base material, compared with copper and lead used in making metallic cables.

In the transmission of voice or data communications, it is extremely important that the light-emitting source and the photosensing source have high-speed characteristics. Slow rise and fall times could result in the overlapping of pulses.

Since the fiber-optic cables are conducting light, they offer a very wide frequency response as compared with RF carrier signals used on metallic cables. In view of the wide band-pass, a much larger number of voice channels can be accommodated.

One of the problems currently encountered in using fiber cables is the variety of couplings, plugs, and jacks available for interfacing fiber cables to hardware. Standardization has yet to be achieved, although the telephone industry is more likely to standardize sooner than other telecommunication organizations.

Fiber cables, although small and fragile, are often bundled into tubes that contain a polyvinyl chloride (PVC) outer jacket. The center of the cable consists of steel fibers, which give strength to the overall cable. Single-mode fibers used in such cables can handle TV channels as well as thousands of individual voice channels.

Although reference has been made to the losses that exist in fiber-optic cable, still other losses must be taken into consideration. Losses exist at the connectors where a LED or laser couples into the fiber cable. The spacing between the laser and the cable is an area of potential loss. The same problem exists where the fiber cable couples into the photodetector. The frequency responses of the cable, emitter, and sensor determine the overall frequency response of the system. Besides losses in the cable, there are losses at the photodiode sensor.

In general, the photodiode is back-biased with a very small amount of current flowing through the diode. The radiant flux causes the photodiode to change its current flow. This current flow passes through a resistor across which a signal voltage is developed.

Plastic cables range in diameter from 50 μm to over 1 millimeter (mm). In the laboratory experiment, Crofon cable is used. This cable is similar to the ESKA cable, which is a trademark of the Mitsubishi Rayon Company, Inc., of Japan. The Crofon cable, formerly made by the Dupont Company, is now being produced by the Japanese firm. This cable, made of plastic, is designed for use in the visible light range. In this range, the cable has an attenuation of approximately 500 dB/km. When the cable is used in the infrared region (above 820 nm), however, the cable appears as a cement wall, and light will not pass through it. Once again, for short runs plastic cable can be used. However, it must be used in the visible light or near-infrared range. The cable exhibits a loss of approximately 1 dB/m (type EH4001) or 0.9 dB/m (type OE-1040).

In summary, a voice-, video-, or data-encoded signal can be transmitted through a fiber-optic cable. The carrier is a light wave whose frequency can be in the visible light, near-infrared, or deep-infrared range. The fiber cables, using solid-state light emitters and sensors, offer many advantages over standard metallic cable. Fiber-optic communications, now in its infancy, will become widespread in the coming years.

In this experiment, light-sensitive components are used to demonstrate the principles of a basic fiber-optic link.

TESTS AND MEASUREMENTS

Materials Required for Experiment

ACTIVE DEVICES
- SE4352 IRED emitter/connector
- SD3443-2 IRED detector/connector
- M8706 Operational amplifier (op amp)

RESISTORS
- 330 ohm (Ω)
- 1 kΩ (2)
- 10 kΩ (2)
- 8.2 kΩ
- 100 kΩ

SWITCHES
- 4PST dip switch (2)

CAPACITOR
- 47 microfarad (μF)

MISCELLANEOUS
- Fiber cable, OE-1040, 50 cm, with connector plugs

The purpose of these laboratory experiments is to familiarize you with the basic concepts and some applications of light emitters, sensors, and fiber-optic cables and connectors. You will modulate an IRED, transmit a signal over a fiber-optic link, and then view the received signal coming from the photodetector.

Refer to Appendices A and B for technical data.

Note: If using Science Instruments equipment, Panel SIP375-1, Sections A and D, may be used.

PRELIMINARY INSTRUCTIONS

Figure 1-1 shows the circuit diagram of the basic operating system. Check your power supplies to ensure that voltages are properly set before you connect them to the experimental circuit.

WARNING

AS A MATTER OF GENERAL PRACTICE, YOU SHOULD NOT LOOK INTO THE SENSOR END OF THE FIBER LINK OR INTO THE EMITTER WHILE THE POWER IS ON. THE RADIATION, AT HIGH POWER LEVELS, MAY BE INJURIOUS TO HUMAN EYES.

The system is arranged to transmit an alternating-current (ac) signal on an infrared beam. The IRED is forward-biased by the 330-Ω resistor connected to +15 V. The signal, which is ac-coupled to the IRED, modulates the dc level of the emitter. Connect one channel of your oscilloscope (vertical set at 10 mV/cm) to the output V_o (TP_3) and the second channel to TP_1. Set your function generator to a 1-kHz square wave, 0 V. Connect a 30-cm fiber cable between the emitter and the sensor. Turn on your power supplies. Close switches 1d, 2d, 3d, and 4d. All other switches must be open. Now slowly increase the generator's output so that the waveshape at V_o is approximately 1 V peak-to-peak (p-p).

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EXPERIMENT 1 Name ______________________________ Date ____________

Experimental Procedures

Answers

1. How much modulating signal p-p voltage V_{sig} is required at TP_1 to achieve 0.5 V p-p at TP_3? — 1. ____________
2. Without an input signal, how much dc voltage is across the IRED? — 2. ____________
3. Compute the dc current flow I_f through the IRED. — 3. ____________
4. From the technical data about the emitter, determine the dc power output P_o from the value of I_f computed in Step 3. — 4. ____________
5. Will the system pass a sine-wave signal? This completes your measurements. Your instructor may suggest making other measurements, such as the frequency response or pulse modulation of the IRED without the use of a dc square wave. Turn off the power. Disconnect the fiber-optic cable from the sensor, and observe the size of the center fiber. The center core is 1 mm in diameter. — 5. ____________
6. The fiber cable has the least amount of loss in the visible light range. In what range does the emitter being used produce its main light? — 6. ____________

REVIEW QUESTIONS

Complete the following statements with an appropriate word or words.

1. IRED emitters operate in the ____________ wavelength.
2. The visual spectrum ranges from approximately ____________ to ____________ μm.
3. A transducer is used to ____________ energy to another form.
4. The basic material in semiconductors is ____________.
5. A transmissive controller has the LED on one side of the object and the detector on the ____________ side.
6. In a fiber-optic system, the two end subsystems are ____________ isolated.

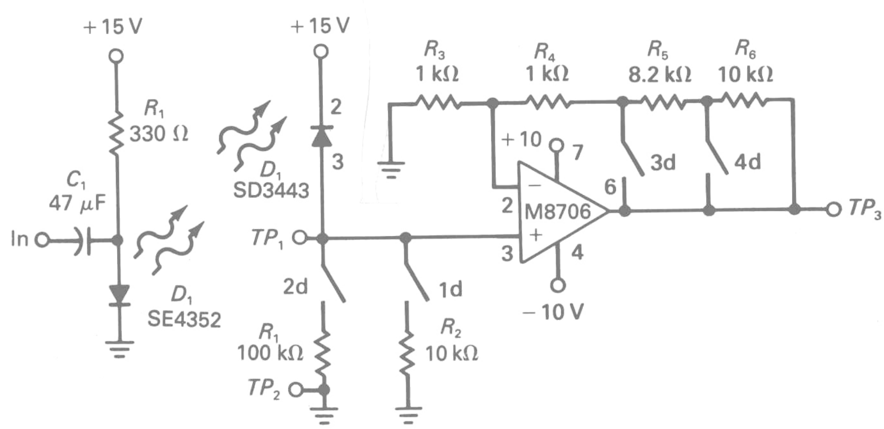

FIG. 1-1 Fiber-optic link.

7. Microwaves and radar operate ______________________ the visible light portion of the spectrum.
8. In the phototransistor detector, the input diode is ______________________ -biased.
9. The core of a fiber-optic cable is made of ______________________ or ______________________ .
10. In the basic communications system used, the IRED was the ______________________ , and the detector was the ______________________ . The cable was the transmission line.

PART

2

Optocomponents

Optocomponents fall into two general categories—light emitters and light sensors. Light emitters and sensors can be further divided into devices that operate in the visible light range and those that operate in the infrared region.

A further differentiation in the various devices involves their physical structure. Different-sized holders have been designed for different devices. Since the industry is still quite young, light-emitter sockets have not been standardized by the various manufacturers.

Light sensors are divided according to their speed of operation, frequency of operation, and ability to provide amplification. A further division relates to whether the light emitter and sensor are an integral part of one holder, such as in the optocoupler or optoisolator.

The specific application will determine whether a photodiode, phototransistor, photo-Darlington, or Schmitt trigger device is necessary. The greater the amplification of the device, the slower is its speed. In digital applications, for example, high-speed devices are generally required. If a photo-Darlington sensor is used in a high-speed data link, there is great likelihood that a trailing edge will appear in the pulses being transmitted.

Optoisolators and optocouplers are finding wide application in power control devices, where they are used in place of relays. Since the circuit to be controlled is isolated from the power source, the selection of light emitter and light sensor will depend on whether the devices are directly coupling one into the other or whether they are being interfaced by a fiber-optic cable. Should a fiber cable be used, the wavelength of light transmission for the specific cable must be taken into consideration.

The experiments in Part 2 relate to testing and evaluating various circuits which use a broad range of light sensors.