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Fiber Optics V - Equipment

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Fiber Optic Systems V - Equipment

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This series of courses are based on the Navy Electricity and Electronics Training Series (NEETS) section on Fiber Optic cable systems. The NEETS material has been reformatted for readability and ease of use as a continuing education course. The NEETS series is produced by the Naval Education and Training Professional Development and Technology Center.

Preface

This is the fifth and final course a series of five courses about fiber optic cable systems. The series covers fiber optics from basic light theory transmission to cables, connectors, testing, and signal transmission.

The complete series includes these five courses:

1. Fiber Optics I – Theory
2. Fiber Optics II – Cable Design
3. Fiber Optics III – Connectors
4. Fiber Optics IV – Testing
5. Fiber Optics V – Equipment

The first course, *Fiber Optics I –Theory*, is an overview of the technology of fiber optic cables including a description of the components, history, and advantages of fiber optic cables. This course also discusses the electromagnetic theory of light and describes the properties of light reflection, refraction, diffusion, and absorption.

The second course, *Fiber Optics II – Cable Design*, explains the basic construction of fiber optic cables including the types of cables, cable properties, and performance characteristics. The course reviews multimode, single mode step-index and graded index fibers, and fabrication procedures.

The third course, *Fiber Optics III - Connectors*, describes fiber optic splices, connectors, couplers, and the types of connections they form in systems. It includes a discussion on the types of extrinsic and intrinsic coupling losses, fiber alignment and fiber mismatch problems, and fiber optic mechanical and fusion splices.

The fourth course, *Fiber Optics IV - Testing*, describes the optical fiber and optical connection laboratory measurements used to evaluate fiber optic components and system performance, including the near-field and far-field optical power distribution of an optical fiber. This course also reviews optical time-domain reflectometry (OTDR).

The fifth course, *Fiber Optics V - Equipment*, explains the principal properties of an optical source and fiber optic transmitters, the optical emission properties of semiconductor light-emitting diodes (LEDs) and laser diodes (LDs), and explains the operational differences between surface-emitting LEDs (SLEDs), edge-emitting LEDs (ELEDs), super luminescent diodes (SLDs), and laser diodes.

It is not necessary to take the courses in sequence. However, for best comprehension it is suggested that the courses be taken in the order presented.

Introduction

This is final volume in a five-volume series on fiber optics systems. This volume is concerned with the transmitters, receivers, and the topography of fiber optic systems.

This course discusses the *equipment* used in fiber optic systems. Equipment refers to the principal properties of an optical source and fiber optic transmitters, the optical emission properties of semiconductor light-emitting diodes (LEDs) and laser diodes (LDs), and explains the operational differences between surface-emitting LEDs (SLEDs), edge-emitting LEDs (ELEDs), super luminescent diodes (SLDs), and laser diodes.

Next, fiber optic receivers are discussed. A fiber optic receiver consists of an optical detector, an amplifier, and other circuitry. In most fiber optic systems, the optical detector is a PIN photodiode or APD. Receiver performance varies depending on the type of detector used. The amplifier is generally described as having two stages: the preamplifier and the postamplifier. The *preamplifier* is defined as the first stage of amplification following the optical detector. The *postamplifier* is defined as the remaining stages of amplification required to raise the detector's electrical signal to a level suitable for further signal processing.

The final chapter in this volume reviews the topologies of fiber optic networks. Most of our discussion up to this point has referred to simple point-to-point links. A *point-to-point* fiber optic data link consists of an optical transmitter, optical fiber, and an optical receiver. In essence, all fiber optic systems are simply sets of point-to-point fiber optic links. Different system topologies arise from the different ways that point-to-point fiber optic links can be connected between equipment. The term *topology* refers to the configuration of various equipment and the fiber optic components interconnecting them. This equipment may be computers, workstations, consoles, or other equipment. Point-to-point links are connected to produce systems with linear bus, ring, star, or tree topologies. Point-to-point fiber optic links are the basic building block of all fiber optic systems.

Chapter One
Optical Sources

In volume one of this series, we learned that a fiber optic data link has three basic functions. One function is that a fiber optic data link must convert an electrical signal to an optical signal permitting the transfer of data along an optical fiber. The fiber optic device responsible for that signal conversion is a fiber optic transmitter.

A *fiber optic transmitter* is a hybrid device. It converts electrical signals into optical signals and launches the optical signals into an optical fiber. A fiber optic transmitter consists of an interface circuit, a source drive circuit, and an optical source. The interface circuit accepts the incoming electrical signal and processes it to make it compatible with the source drive circuit. The source drive circuit intensity modulates the optical source by varying the current through the source.

An *optical source* converts electrical energy (current) into optical energy (light). Light emitted by an optical source is launched, or coupled, into an optical fiber for transmission. Fiber optic data link performance depends on the amount of optical power (light) launched into the optical fiber. This course attempts to provide an understanding of light-generating mechanisms within the main types of optical sources used in fiber optics.

Optical source properties

The development of efficient semiconductor optical sources, along with low-loss optical fibers, LED to substantial improvements in fiber optic communications. Semiconductor optical sources have the physical characteristics and performance properties necessary for successful implementations of fiber optic systems. It is desirable that optical sources,

- Be compatible in size to low-loss optical fibers by having a small light-emitting area capable of launching light into fiber
- Launch sufficient optical power into the optical fiber to overcome fiber attenuation and connection losses allowing for signal detection at the receiver
- Emit light at wavelengths that minimize optical fiber loss and dispersion.
- Optical sources should have a narrow spectral width to minimize dispersion
- Allow for direct modulation of optical output power

Maintain stable operation in changing environmental conditions (such as temperature) cost less and be more reliable than electrical devices, permitting fiber optic communication systems to compete with conventional systems semiconductor optical sources suitable for fiber optic systems range from inexpensive light-emitting diodes (LEDs) to more expensive semiconductor lasers. Semiconductor LEDs and laser diodes (LDs) are the principal light sources used in fiber optics.

Operating wavelength

Fiber optic communication systems operate in the 850-nm, the 1300-nm, and the 1550-nm wavelength windows. Semiconductor sources are designed to operate at wavelengths that minimize optical fiber absorption and maximize system bandwidth. By designing an optical source to operate at specific wavelengths, absorption from impurities in the optical fiber, such as hydroxyl ions (oh^-), can be minimized. Maximizing system bandwidth involves designing optical fibers and sources that minimize chromatic and intermodal dispersion at the intended operational wavelength.

Initially, the material properties of semiconductor optical sources provided for optical emission in the 850-nm wavelength region. An 850-nm operational wavelength avoids fiber absorption loss from oh^- impurities near the 900-nm wavelength. Light sources for 850-nm systems were originally semiconductor LEDs and lasers. Currently, most 850-nm systems use LEDs as a light source. LEDs operating at 850-nm provide sufficient optical power for short-distance, low-bandwidth systems. However, multimode fiber dispersion, the relatively high fiber attenuation, and the LED's relatively low optical output power prevent the use of these devices in longer-distance, higher bandwidth systems.

The first development allowing the operational wavelength to move from 850 nm to 1300 nm was the introduction of multimode graded-index fibers.

Multimode graded-index fibers have substantially lower intermodal dispersion than multimode step-index fibers. Systems operating at 850 nm cannot take full advantage of the fiber's low intermodal dispersion because of high chromatic dispersion at 850 nm. However, the use of multimode graded-index fibers allows 850-nm LEDs to operate satisfactorily in short-distance, higher bandwidth systems.

Following the enhancements in multimode fiber design, next generation LEDs were designed to provide optical emission in the 1300-nm region. Multimode graded-index fiber systems using these LEDs can operate over longer distances and at higher bandwidths than 850-nm systems. Longer distances and higher bandwidths are possible because fiber material losses and dispersion are significantly reduced at the 1300-nm region.

Advances in single mode fiber design and construction sped the development of semiconductor LEDs and LDs optimized for single mode fibers. Single mode fibers have very low dispersion values. However, existing LEDs were unable to focus and launch sufficient optical power into single mode fibers for long-haul, very high-bandwidth communication systems. New semiconductor LEDs and LDs capable of operating with single mode fibers at 1300 nm were developed to take advantage of single mode fiber's very low value of dispersion. Additionally, LEDs and LDs operating at 1550 nm were developed to take advantage of the fiber's lowest loss.

Semiconductor light-emitting diodes and laser diodes

Semiconductor LEDs emit *incoherent light*. Spontaneous emission of light in semiconductor LEDs produces light waves that lack a fixed-phase relationship. Light waves that lack a fixed-phase relationship are referred to as *incoherent light*. Spontaneous emission of light is discussed in more detail later. The use of LEDs in single mode systems is severely limited because they emit unfocused incoherent light. Even LEDs developed for single mode systems are unable to launch sufficient optical power into single mode fibers for many applications. LEDs are the preferred optical source for multimode systems because they can launch sufficient power at a lower cost than semiconductor LDs.

Semiconductor LDs emit *coherent light*. LDs produce light waves with a fixed-phase relationship (both spatial and temporal) between points on the electromagnetic wave. Light waves having a fixed-phase relationship are referred to as coherent light. Stimulated emission of light is discussed later. Since semiconductor LDs emit more focused light than LEDs, they can launch optical power into both single mode and multimode optical fibers. However, LDs are usually used only in single mode fiber systems because they require more complex driver circuitry and cost more than LEDs.

Optical power produced by optical sources can range from microwatts (μw) for LEDs to tens of milliwatts (mw) for semiconductor LDs. However, it is not possible to effectively couple all the available optical power into the optical fiber for transmission.

The amount of optical power coupled into the fiber is the relevant optical power. It depends on the following factors:

- The angles over which the light is emitted
- The size of the source's light-emitting area relative to the fiber core size
- The alignment of the source and fiber
- The coupling characteristics of the fiber (such as the NA and the refractive index profile)

Typically, semiconductor lasers emit light spread out over an angle of 10 to 15 degrees. Semiconductor LEDs emit light spread out at even larger angles. Coupling losses of several decibels can easily occur when coupling light from an optical source to a fiber, especially with LEDs.

Source-to-fiber coupling efficiency is a measure of the relevant optical power. The coupling efficiency depends on the type of fiber that is attached to the optical source. Coupling efficiency also depends on the coupling technique.

Source-to-fiber coupling involves centering a flat fiber-end face over the emitting region of the light source. If the fiber end face is directly placed over the source emitting region, it is referred to as *butt coupling*. If the source's output light pattern is larger than the fiber's acceptance pattern, source-to-fiber coupling efficiency may be improved by placing a small lens between the source and fiber. Lensing schemes improve coupling efficiency when coupling both LEDs and LDs to optical fibers.

Semiconductor material and device operating principles

Understanding optical emission in semiconductor lasers and LEDs requires knowledge of semiconductor material and device properties. Providing a complete description of semiconductor properties is beyond the scope of this introductory manual. In this course we only discuss the general properties of semiconductor LEDs and LDs.

Semiconductor sources are diodes, with all the characteristics typical of diodes. However, their construction includes a special layer, called the active layer, which emits photons (light particles) when a current passes through the layer. The properties of the semiconductor are determined by the materials used and the layering of the materials within the semiconductor. Silicon (Si) and gallium arsenide (GaAs) are the two most common semiconductor materials used in electronic and electro-optic devices. In some cases, other elements, such as aluminum (Al), indium (In) and phosphorus (P), are added to the base semiconductor material to modify the semiconductor properties. These elements are called dopants.

Current flowing through a semiconductor optical source causes it to produce light. An in-depth description of either of the two processes by which this occurs is beyond the scope of this course. However, we discuss elementary descriptions in the following paragraphs.

LEDs generally produce light through *spontaneous emission* when a current is passed through them. Spontaneous emission is the random generation of photons within the active layer of the LED. The emitted photons move in random directions. Only a certain percentage of the photons exit the semiconductor and are coupled into the fiber. Many of the photons are absorbed by the LED materials and the energy dissipated as heat. This process causes the light output from an LED to be incoherent, have a broad spectral width, and have a wide output pattern.

Laser diodes are much more complex than LEDs. Laser is an acronym for light amplification by the stimulated emission of radiation. Laser diodes produce light through stimulated emission when a current is passed through them. *Stimulated emission* describes how light is produced in any type of laser. In the laser diode, photons, initially produced by spontaneous emission interact with the laser material to produce additional photons. This process occurs within the active area of the diode called the laser cavity. The process does not affect the original photon. The stimulated photon has many of the same properties (wavelength, direction, and phase) as the original photon.

As with the LED, not all the photons produced are emitted from the laser diode. Some of the photons are absorbed and the energy dissipated as heat. The emission process and the physical characteristics of the diode cause the light output to be coherent, have a narrow spectral width, and have a narrow output pattern.

It is important to note that in both LED and laser diodes all the electrical energy is not converted into optical energy. A substantial portion is converted to heat. Different LED and laser diode structures convert differing amounts of electrical energy into optical energy.

Light-emitting diodes

A *light-emitting diode* (LED) is a semiconductor device that emits incoherent light, through spontaneous emission, when a current is passed through it. Typically, LEDs for the 850-nm region are fabricated using GaAs and AlGaAs. LEDs for the 1300-nm and 1550-nm regions are fabricated using InGaAsP and InP.

The basic LED types used for fiber optic communication systems are the surface-emitting LED (SLED), the edge-emitting LED (ELED), and the super luminescent diode (SLD). LED performance differences help link designers decide which device is appropriate for the intended application. For short-distance (0 to 3 km), low-data-rate fiber optic systems, SLEDs and ELEDs are the preferred optical source. Typically, SLEDs operate efficiently for bit rates up to 250 megabits per second (mb/s). Because SLEDs emit light over a wide area (wide far-field angle), they are almost exclusively used in multimode systems.

For medium-distance, medium-data-rate systems, ELEDs are preferred.

ELEDs may be modulated at rates up to 400 mb/s. ELEDs may be used for both single mode and multimode fiber systems. Both SLDs and ELEDs are used in long-distance, high-data-rate systems. SLDs are ELED-based diodes designed to operate in the super luminescence mode. A further discussion on super luminescence is provided later. SLDs may be modulated at bit rates of over 400 mb/s.

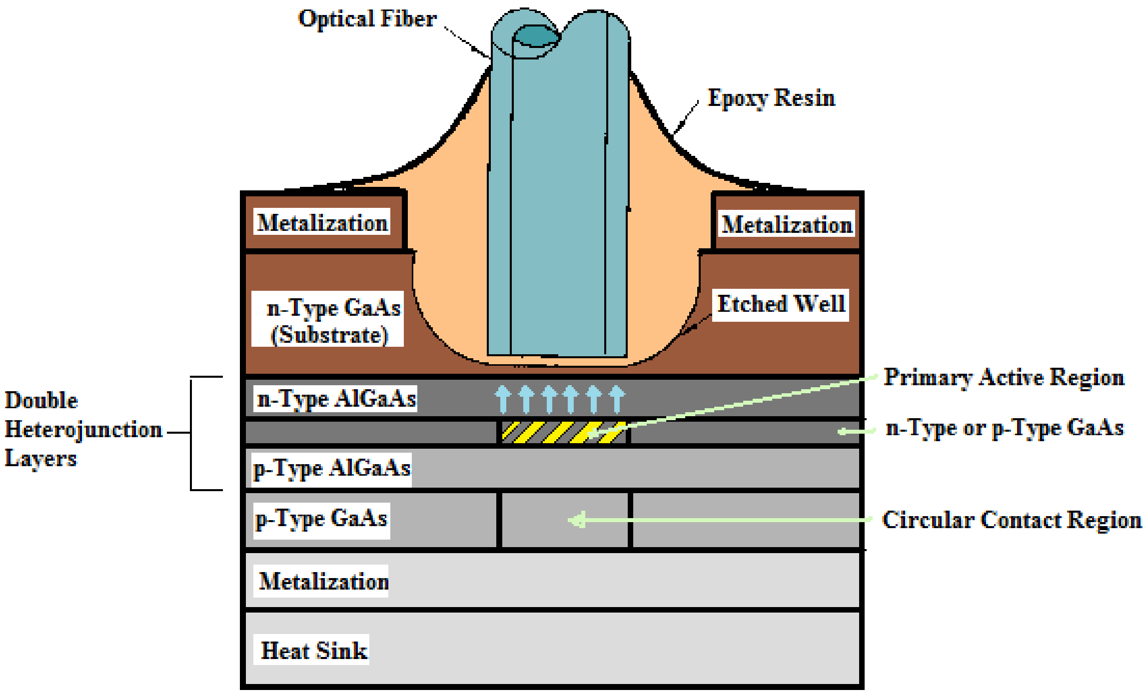
Surface-emitting LEDs

The surface-emitting LED (shown in Figure 1) is also known as the Burrus LED in honor of C. A. Burrus, its developer. In SLEDs, the size of the primary active region is limited to a small circular area of 20 μm to 50 μm in diameter. The active region is the portion of the LED where photons are emitted. The primary active region is below the surface of the semiconductor substrate perpendicular to the axis of the fiber.

A *well* is etched into the substrate to allow direct coupling of the emitted light to the optical fiber. The etched well allows the optical fiber to come into close contact with the emitting surface.

In addition, the epoxy resin that binds the optical fiber to the SLED reduces the refractive index mismatch, increasing coupling efficiency.

Figure 1. - Example of the SLED structure.

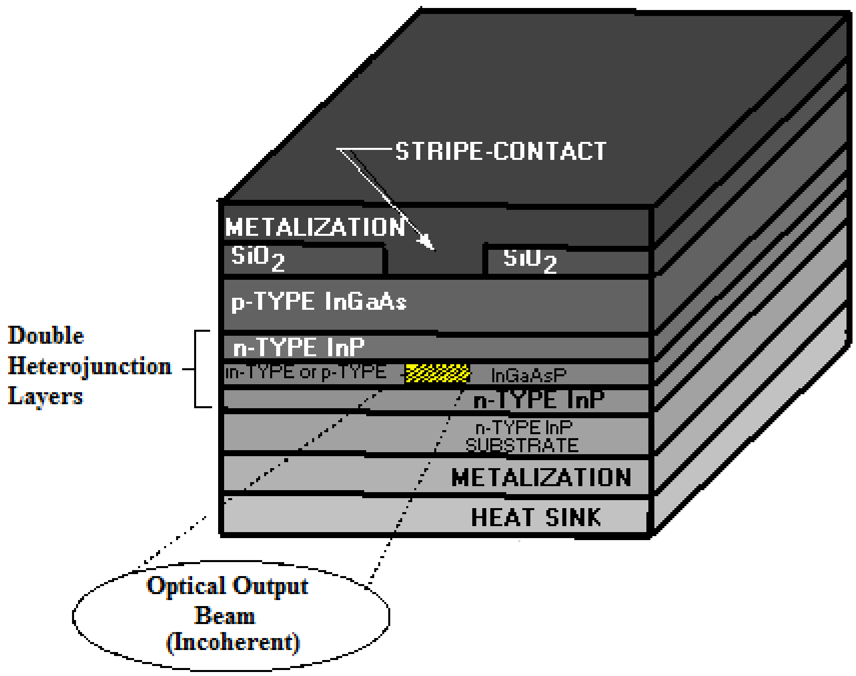


Edge-emitting LEDs

The demand for optical sources for longer distance, higher bandwidth systems operating at longer wavelengths LED to the development of edge-emitting LEDs. Figure 2 shows a typical ELED structure. It shows the different layers of semiconductor material used in the ELED. The primary active region of the ELED is a narrow stripe, which lies below the surface of the semiconductor substrate. The semiconductor substrate is cut or polished so that the stripe runs between the front and back of the device.

The polished or cut surfaces at each end of the stripe are called facets.

Figure 2. - Example of the ELED structure.



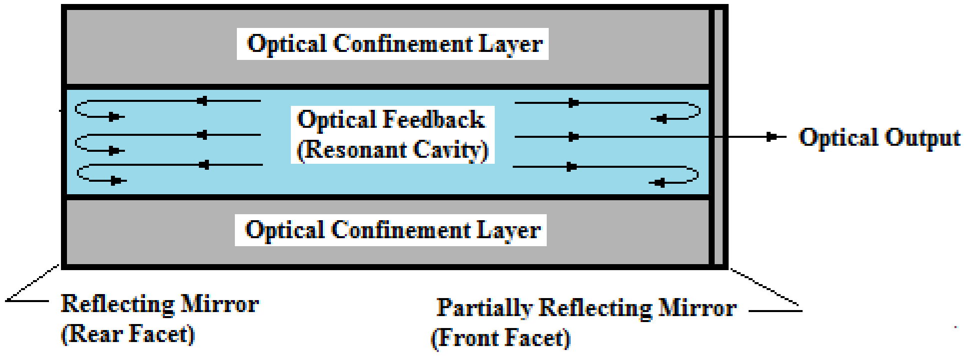
In an ELED the rear facet is highly reflective, and the front facet is antireflection coated. The rear facet reflects the light propagating toward the rear end-face back toward the front facet. By coating the front facet with antireflection material, the front facet reduces optical feedback and allows light emission. ELEDs emit light only through the front facet. ELEDs emit light in a narrow emission angle allowing for better source-to-fiber coupling. They couple more power into small NA fibers than SLEDs. ELEDs can couple er into single mode fibers for some applications. ELEDs emit power over a narrower spectral range than SLEDs. However, ELEDs typically are more sensitive to temperature fluctuations than SLEDs.

Laser diodes

A *laser* is a device that produces optical radiation by the process of stimulated emission. It is necessary to contain photons produced by stimulated emission within the laser active region.

Figure 3 shows an optical cavity formed to contain the emitted photons by placing one reflecting mirror at each end of an amplifying medium. One mirror is made partially reflecting so that some radiation can escape from the cavity for coupling to an optical fiber.

Figure 3. - Optical cavity for producing lasing.

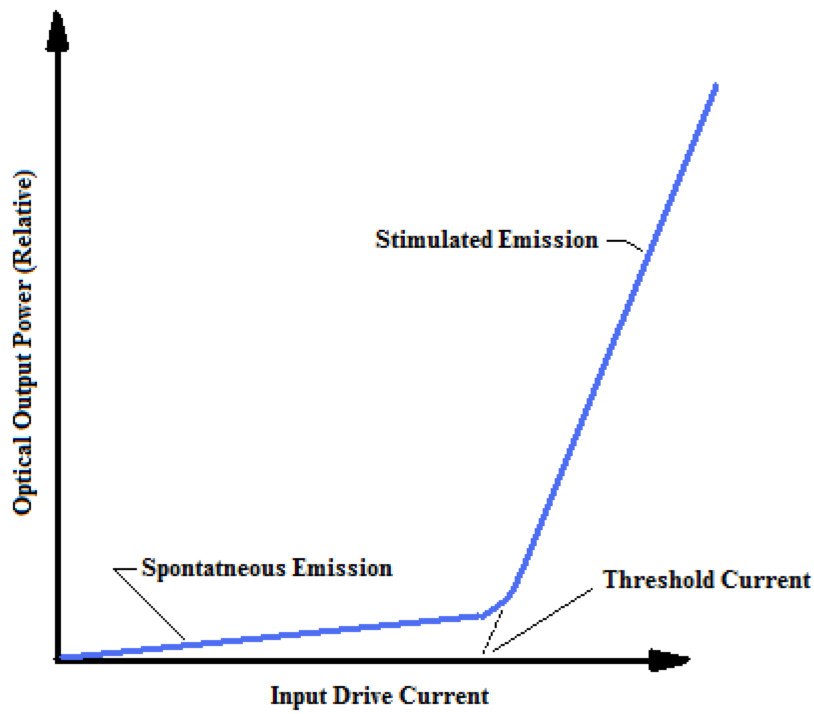


Only a portion of the optical radiation is amplified. For a particular laser structure, there are only certain wavelengths that will be amplified by that laser. Amplification occurs when selected wavelengths, also called laser modes, are reflected back and forth through the cavity. For lasing to occur, the optical gain of the selected modes must exceed the optical loss during one round-trip through the cavity. This process is referred to as optical feedback.

The *lasing threshold* is the lowest drive current level at which the output of the laser results primarily from stimulated emission rather than spontaneous emission. Figure 4 illustrates the transition from spontaneous emission to stimulated emission by plotting the relative optical output power and input drive current of a semiconductor laser diode. The lowest current at which stimulated emission exceeds spontaneous emission is the *threshold current*.

Before the threshold current is reached, the optical output power increases only slightly with small increases in drive current. However, after the threshold current is reached, the optical output power increases significantly with small changes in drive currents.

Figure 4. - The optical output power as a function of input drive current of a semiconductor laser diode.



Many types of materials including gas, liquid, and semiconductors can form the lasing medium. However, in this course we only discuss semiconductor laser diodes. Semiconductor laser diodes are the primary lasers used in fiber optics. A laser diode emits light that is highly monochromatic and very directional. This means that the LD's output has a narrow spectral width and small output beam angle.

A semiconductor LD's geometry is like an ELED with light-guiding regions surrounding the active region. Optical feedback is established by making the front facet partially reflective. This chapter provides no diagram detailing LD structures because they are like ELEDs in design. The rear facet is typically coated with a reflective layer so that all the light striking the facet is reflected into the active region. The front facet is typically left uncoated so that most of the light is emitted. By increasing the drive current, the diode becomes a laser.

At currents below the threshold current, LDs function as ELEDs. To optimize frequency response, laser diodes are often biased above this laser threshold. As a result, in an LD fiber optic system, light is modulated between a high-power level and a lower power level, but never shut off. LDs typically can be modulated at frequencies up to over 2 gigahertz (GHz). Some lasers are capable of being modulated at frequencies over 20 GHz.

There are several important differences between LDs and LEDs. One is that LEDs usually lack reflective facets and in some cases are designed to suppress reflections back into the active region. Another is that lasers tend to operate at higher drive currents to produce light. A higher driver current results in more complicated drive circuits and more heat dissipation in the device.

LDs are also much more temperature sensitive than either SLEDs or ELEDs. Increases in the laser temperature significantly reduce laser output power. Increases in laser temperature beyond certain limits result in the loss of lasing. When lasers are used in many applications, the temperature of the laser must be controlled. Typically, electronic coolers, called *thermo-electric (TE) coolers*, are used to cool LDs in system applications.

Super luminescent diodes

Super luminescence occurs when the spontaneous emissions of an ELED experience gain due to higher injected currents and reflections from facets. Super luminescent diodes (SLDs) are differentiated from both conventional LEDs and LDs. Although the output is not fully coherent, SLDs emit light that consists of amplified spontaneous emissions. The spectral width and beam angle of SLDs are narrower than that of conventional LEDs and wider than that of LDs.

An SLD is, in essence, a combination of a laser and an ELED. SLDs are similar in geometry to lasers but have no built-in optical feedback mechanism required by laser diodes for stimulated emission to achieve lasing. SLDs have structural features like those of ELEDs that suppress the lasing action by reducing the reflectivity of the facets. SLDs are essentially highly optimized ELEDs.

While SLDs operate like ELEDs at low current levels, their output power increases super linearly and the spectral width narrows at high currents. Optical gain resulting from the higher injection currents causes the super linear power increase and narrowing of the spectral width.

The advantages of SLDs over conventional LEDs include higher coupled power, narrower spectral width, and greater bandwidths. The disadvantages include nonlinear power-current characteristics, higher temperature sensitivity, and lower reliability.

Chapter Two
Fiber optic transmitters

As stated previously, a fiber optic transmitter is a hybrid electro-optic device. It converts electrical signals into optical signals and launches the optical signals into an optical fiber. A fiber optic transmitter consists of an interface circuit, a source drive circuit, and an optical source. The interface circuit accepts the incoming electrical signal and processes it to make it compatible with the source drive circuit. The source drive circuit intensity modulates the optical source by varying the current through it. The optical signal is coupled into an optical fiber through the transmitter output interface.

Although semiconductor LEDs and LDs have many similarities, unique transmitter designs result from differences between LED and LD sources. Transmitter designs compensate for differences in optical output power, response time, linearity, and thermal behavior between LEDs and LDs to ensure proper system operation. Nonlinearities caused by junction heating in LEDs and mode instabilities in LDs necessitate the use of linearizing circuits within the transmitter in some cases.

Fiber optic transmitters using LDs require more complex circuitry than transmitters using LEDs. The basic requirement for digital systems is for drive circuitry to switch the optical output on and off at high speeds in response to logic voltage levels at the input of the source drive circuit.

Because LDs are threshold devices, LDs are supplied with a bias just below the threshold in the off state. This bias is often referred to as *pre-bias*. One reason for pre-biasing the LD is to reduce the turn-on delay in digital systems.

Most LD transmitters contain output *power control circuitry* to compensate for temperature sensitivity. This circuitry maintains the LD output at a constant average value by adjusting the bias current of the laser. In most cases LED transmitters do not contain output power control circuitry. LD and LED transmitters may also contain cooling devices to maintain the source at a relatively constant temperature. Most LD transmitters either have an internal *thermo electric cooler* or require a relatively controlled external temperature. Because LDs require more complex circuitry than LEDs, fiber optic transmitters using LDs are more expensive.

Transmitter output interfaces generally fall into two categories: optical connectors and optical fiber pigtails. *Optical pigtails* are attached to the transmitter optical source. This pigtail is generally routed out of the transmitter package as a coated fiber in a loose buffer tube or a single fiber cable. The pigtail is either soldered or epoxied to the transmitter package to provide fiber strain relief. The buffer tube or single fiber cable is also attached to the transmitter package to provide additional strain relief.

The transmitter output interface may consist of a fiber *optical connector*. The optical source may couple to the output optical connector through an intermediate optical fiber. One end of the optical fiber is attached to the source. The other end terminates in the transmitter optical output connector. The optical source may also couple to the output optical connector without an intermediate optical fiber. The optical source is placed within the transmitter package to launch power directly into the fiber of the mating optical connector. In some cases, *lenses* are used to more efficiently couple light from the source into the mating optical connector.

Fiber optic transmitter packages

Fiber optic transmitters come in various sizes and shapes. The least complex fiber optic transmitters are typically packaged in *transistor outline (TO) cans* or hybrid microcircuit modules in *dual inline packages (DIPS).* These simple transmitters may require separate circuitry in the system equipment to provide an acceptable input signal to the transmitter. More complex fiber optic transmitters are available that have some or all the signal conditioning circuitry integrated into the package. These transmitters typically are packaged in hybrid microcircuit modules in either dip or butterfly lead packages, circuit cards, or complete stand-alone fiber optic converters. Stand-alone fiber optic converters and circuit cards generally contain sources in either TO cans or one of the hybrid microcircuit packages. For commercial applications, the most popular transmitter packages are the TO can and the DIP hybrid microcircuit.

Fiber optic transmitter applications

Fiber optic transmitters can be classified into two categories: digital and analog. Digital transmitters produce two discrete optical power levels. These levels are essentially on and off with the exception that some light is emitted in the off state by some transmitters. Analog transmitters continuously vary the output optical power level as a function of the input electrical signal.

<u>Digital applications</u>
Different types of fiber optic transmitters are used for different digital applications. For each specific application, the link data rate, transmission length, and operating environment influence the source type, center wavelength, spectral width, and package type chosen.

For *low-data-rate applications*, fiber optic transmitters generally use LEDs operating in either the 850-nm or 1300-nm window as their source. For the lowest data rates (0 to 20 megabits per second (mbps)), sources tend to operate in the 850-nm window. For *moderate data rates* (50 to 200 mbps), sources tend to operate in the 1300-nm window. Laser sources are almost never used in low-data-rate applications. Laser sources are only used when extremely high transmitter output powers are required in the application. The packages found in low-data-rate applications include all the package types discussed earlier.

For *high-data-rate applications*, most fiber optic transmitters use laser diodes as sources. The sources typically operate in either the 1300-nm or 1550-nm windows. Most high-data-rate applications use LDs as the optical source and operate in the 1300-nm region. Almost all 1550-nm systems use an LD as the optical source. 1550-nm transmitters are usually only used in the extremely long distance high-data-rate applications (undersea links, etc.). High-data-rate transmitters are generally hybrid microcircuit modules or complete circuit cards. Almost all high-data-rate transmitters contain power control circuitry. Depending upon the application, high-data-rate transmitters may contain TE coolers.

Analog applications

Different types of fiber optic transmitters are also used for different analog applications. For each specific application, analog signal type, transmission length, and operating environment influence the source type, center wavelength, spectral width, and package type chosen.

For *low-frequency applications*, analog fiber optic transmitters generally use LEDs operating in either the 850-nm or 1300-nm window. Typical low frequency applications are analog audio and single channel video systems. For these systems, sources tend to operate in the 850-nm window. For *moderate frequency applications*, sources tend to operate in the 1300-nm window. These types of systems include multi-channel analog audio and video systems as well as frequency modulated (FM) systems. Laser sources are almost never used in low- or moderate-frequency analog applications. The main reason for this is the added circuit complexity that laser sources require. Laser sources are only used if extremely high transmitter output powers are required in the application. Most low-frequency analog transmitters are hybrid microcircuit modules, circuit cards, or stand-alone boxes.

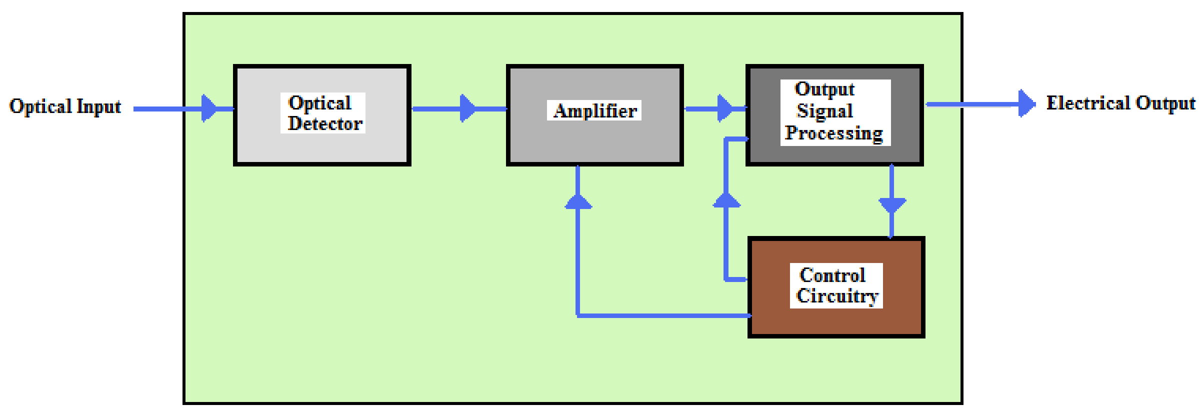
For *high-frequency applications*, analog fiber optic transmitters use laser diodes as sources. Typical high frequency applications are cable television trunk line and raw radar remoting applications. The LDs typically operate in either the 1300-nm or 1550-nm windows. 1550-nm transmitters are typically used in cable television trunk line applications. Other applications may use either 1300-nm or 1550-nm LDs. High frequency transmitters are predominately circuit cards, but some hybrid microcircuit modules are also used. All high frequency analog transmitters contain TE coolers as well as linearization and power control circuitry.

Chapter Three
Optical detectors

In the previous chapter we learned that a fiber optic transmitter is an electro-optic device capable of accepting electrical signals, converting them into optical signals, and launching the optical signals into an optical fiber. The optical signals propagating in the fiber become weakened and distorted because of scattering, absorption, and dispersion. The fiber optic device responsible for converting the weakened and distorted optical signal back to an electrical signal is a fiber optic receiver.

A *fiber optic receiver* is an electro-optic device that accepts optical signals from an optical fiber and converts them into electrical signals. A typical fiber optic receiver consists of an optical detector, a low-noise amplifier, and other circuitry used to produce the output electrical signal (see Figure 5). The optical detector converts the incoming optical signal into an electrical signal. The amplifier then amplifies the electrical signal to a level suitable for further signal processing. The type of other circuitry contained within the receiver depends on what type of modulation is used and the receiver electrical output requirements.

Figure 5. - Block diagram of a typical fiber optic receiver.



Receiver spectral response, sensitivity, frequency response, and dynamic range are key receiver performance parameters that can affect overall system operation. The choice of optical detector materials and structures determines the spectral response. Silicon (Si), gallium arsenide (GaAs), and gallium aluminum arsenide (GaAlAs) are typical detector materials used for receiver operation in the 850-nm wavelength region. Germanium (Ge), indium phosphide (InP), and indium gallium arsenide (InGaAs) are examples of detector materials used for receiver operation in the 1300-nm and 1550-nm wavelength regions.

The *receiver sensitivity* is the minimum amount of optical power required to achieve a specific receiver performance.

For digital transmission at a given data rate and coding, this performance is described by a maximum bit-error rate (BER). In analog systems, for a given modulation and bandwidth, it is described by a minimum signal-to-noise ratio (SNR). *Dynamic range* refers to the range of optical power levels over which the receiver operates within the specified values. It usually is described by the ratio of the maximum input power to the sensitivity. Before discussing receiver sensitivity, bandwidth, dynamic range, and frequency response in more detail, we discuss the main types of optical detectors used in fiber optics.

Optical detectors

A *transducer* is a device that converts input energy of one form into output energy of another. An *optical detector* is a transducer that converts an optical signal into an electrical signal. It does this by generating an electrical current proportional to the intensity of incident optical radiation. The relationship between the input optical radiation and the output electrical current is given by the detector responsivity.

Optical detector properties

Fiber optic communications systems require that optical detectors meet specific performance and compatibility requirements. Many of the requirements are like those of an optical source. Fiber optic systems require that optical detectors:

- Be compatible in size to low-loss optical fibers to allow for efficient coupling and easy packaging.
- Have a high sensitivity at the operating wavelength of the optical source.
- Have a sufficiently short response time (sufficiently wide bandwidth) to handle the system's data rate.
- Contribute low amounts of noise to the system.
- Maintain stable operation in changing environmental conditions, such as temperature.

Optical detectors that meet many of these requirements and are suitable for fiber optic systems are semiconductor photodiodes. The principal optical detectors used in fiber optic systems include semiconductor positive-intrinsic-negative (PIN) photodiodes and avalanche photodiodes (APDs).

Semiconductor photodiodes

Semiconductor photodiodes generate a current when they absorb photons (light). The amount of current generated depends on the following factors:

- The wavelengths of the incident light and the responsivity of the photodiode at those wavelengths
- The size of the photodiode active area relative to the fiber core size
- The alignment of the fiber and the photodiode

The optical fiber is coupled to semiconductor photodiodes similarly to the way optical sources are coupled to optical fibers. Fiber-to-photodiode coupling involves centering the flat fiber-end face over the photodiode active area. This is normally done directly by butt coupling the fiber up to the photodiode surface. If the photodiode active area is larger than that of the fiber core, fiber-to-detector coupling losses are very low. In some cases, a lens may be used to couple the fiber end-face to the detector. However, this is not typically done.

Semiconductor material and device properties

The mechanism by which optical detectors convert optical power into electrical current requires knowledge of semiconductor material and device properties. Semiconductor detectors are designed so that optical energy (photons) incident on the detector active area produces a current. This current is called a *photocurrent*. The properties of the semiconductor are determined by the materials used and the layering of the materials within the device. Silicon (Si), gallium arsenide (GaAs), germanium (Ge), and indium phosphide (InP) are the most common semiconductor materials used in optical detectors. In some cases, aluminum (Al) and indium (In) are used as dopants in the base semiconductor material.

Responsivity

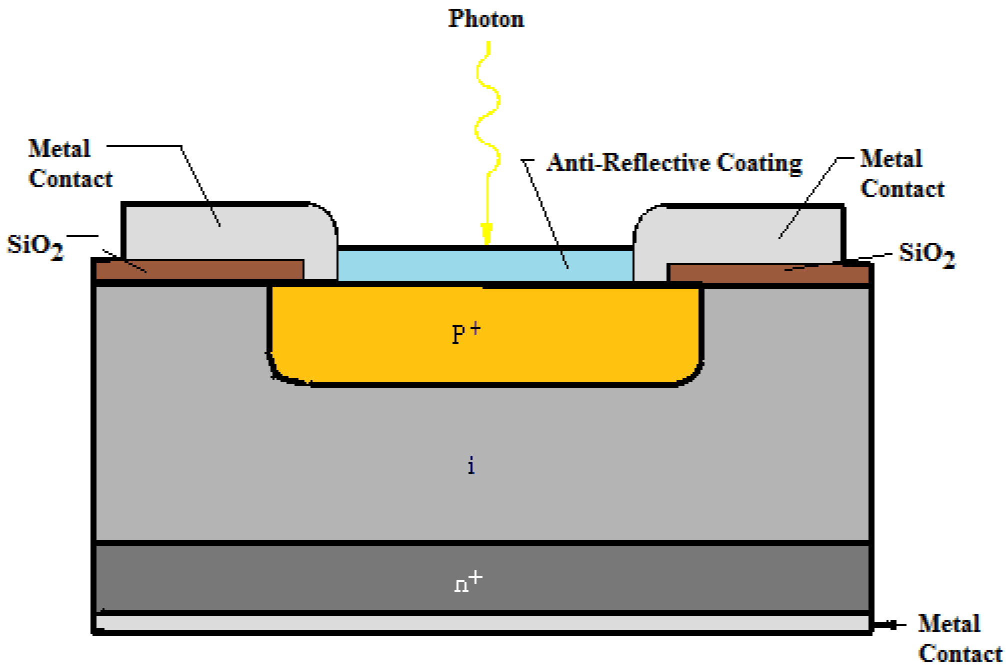
Responsivity is the ratio of the optical detector's output photocurrent in amperes to the incident optical power in watts. The responsivity of a detector is a function of the wavelength of the incident light and the efficiency of the device in responding to that wavelength. For a particular material, only photons of certain wavelengths will generate a photocurrent when they are absorbed. Additionally, the detector material absorbs some wavelengths better than others. These two properties cause the wavelength dependence in the detector responsivity. Responsivity is a useful parameter for characterizing detector performance because it relates the photocurrent generated to the incident optical power.

PIN photodiodes

A *PIN photodiode* is a semiconductor positive-negative (p-n) structure with an intrinsic region sandwiched between the other two regions (see Figure 6). It is normally operated by applying a reverse-bias voltage. The magnitude of the reverse-bias voltage depends on the photodiode application, but typically is less than a few volts. When no light is incident on the photodiode, a current is still produced. This current is called the *dark current*.

The dark current is the leakage current that flows when a reverse bias is applied, and no light is incident on the photodiode. Dark current is dependent on temperature. While dark current may initially be low, it will increase as the device temperature increases.

Figure 6. - The basic structure of a PIN photodiode.

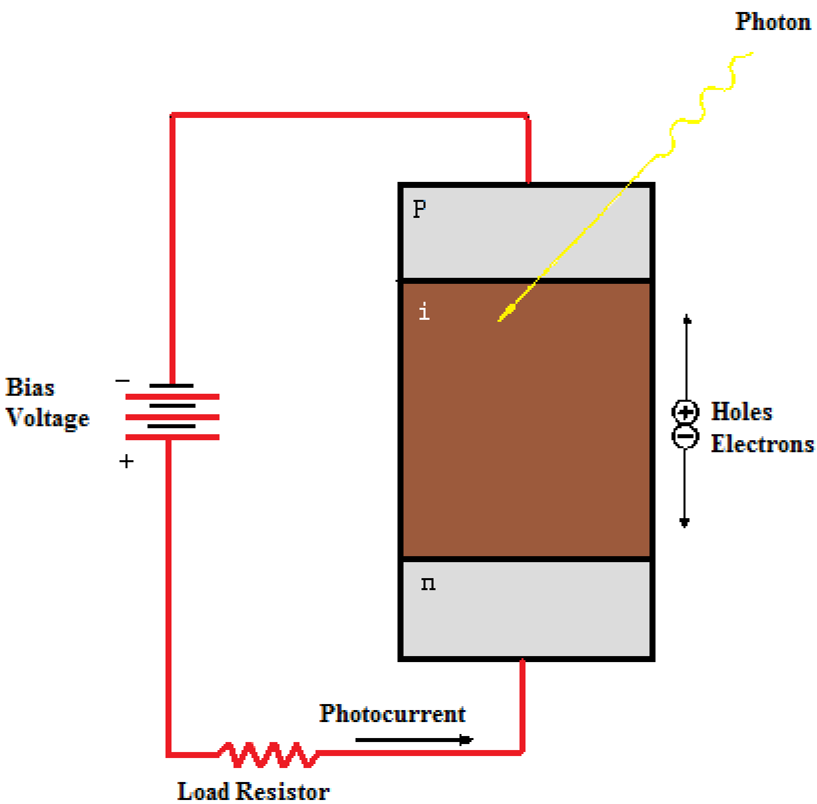


Response time

There are several factors that influence the response time of a photodiode and its output circuitry (see Figure 7).

The most important of these are the thickness of the detector active area and the detector RC time constant. The detector thickness is related to the amount of time required for the electrons generated to flow out of the detector active area. This time is referred to as the electron *transit time*. The thicker the detector active area, the longer the transit time will be.

Figure 7. - Schematic representation of a photodiode.



The capacitance of the photodetector must be kept small to prevent the RC time constant from limiting the response time. The photodiode capacitance consists mainly of the junction capacitance and any capacitance relating to packaging. The *RC time constant* is given by,

$$\mathbf{t_{rc} = RC}$$

Where,
t_{rc} = RC time constant.
C = Capacitance of the photodiode.
R = Resistance of the load.

Trade-offs between fast transit times and low capacitance are necessary for high-speed response. However, any change in photodiode parameters to optimize the transit time and capacitance can also affect responsivity, dark current, and coupling efficiency. A fast transit time requires a thin detector active area, while low capacitance and high responsivity require a thick active region.

The diameter of the detector active area can also be minimized. This reduces the detector dark current and minimizes junction capacitance. However, a minimum limit on this active area exists to provide for efficient fiber-to-detector coupling.

Linearity

Reverse-biased photodetectors are highly linear devices. *Detector linearity* means that the output electrical current (photocurrent) of the photodiode is linearly proportional to the input optical power. Reverse-biased photodetectors remain linear over an extended range of photocurrent before saturation occurs. Output saturation occurs at input optical power levels typically greater than 1 milliwatt (mw). Because fiber optic communications systems operate at low optical power levels, detector saturation is generally not a problem.

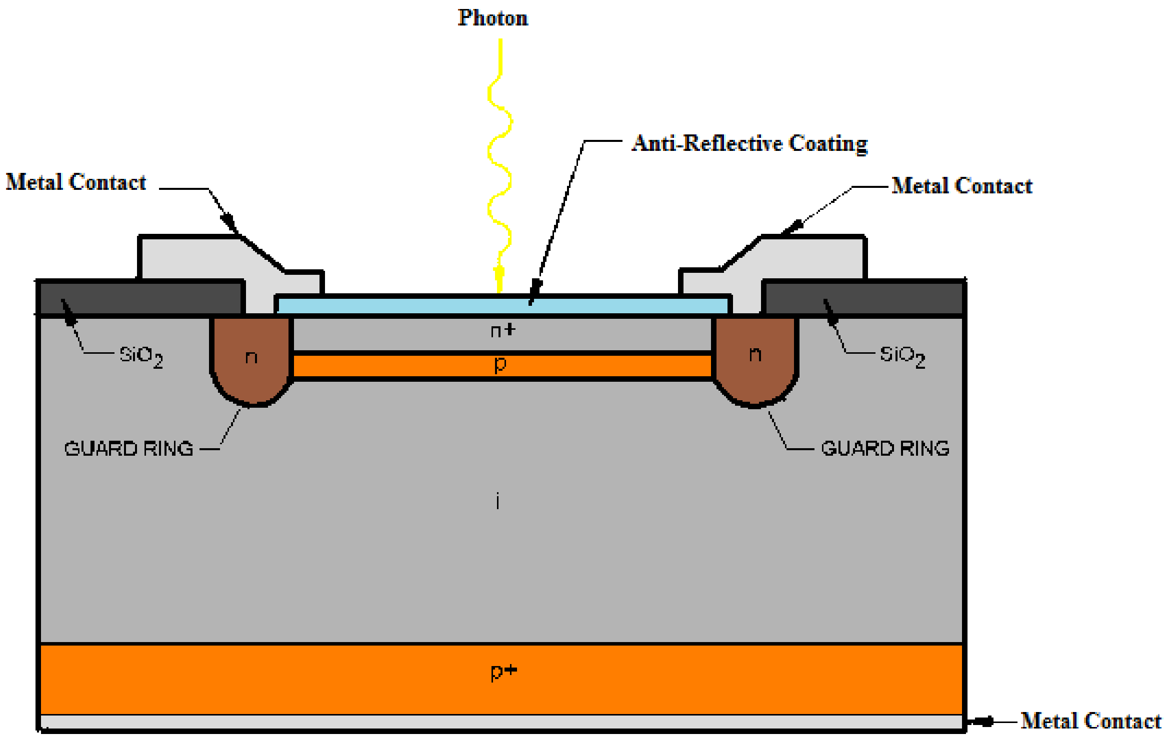
Avalanche photodiodes

An *avalanche photodiode (APD)* is a photodiode that internally amplifies the photocurrent by an avalanche process.

Figure 8 shows an example APD structure. In APDs, a large reverse-bias voltage, typically over 100 volts, is applied across the active region. This voltage causes the electrons initially generated by the incident photons to accelerate as they move through the APD active region.

As these electrons collide with other electrons in the semiconductor material, they cause a fraction of them to become part of the photocurrent. This process is known as *avalanche multiplication*. Avalanche multiplication continues to occur until the electrons move out of the active area of the APD.

Figure 8. - Basic structure of an APD.



The gain of the APD can be changed by changing the reverse-bias voltage. A larger reverse-bias voltage results in a larger gain. However, a larger reverse-bias voltage also results in increased noise levels. Excess noise resulting from the avalanche multiplication process places a limit on the useful gain of the APD. The avalanche process introduces excess noise because every photogenerated carrier does not undergo the same multiplication.

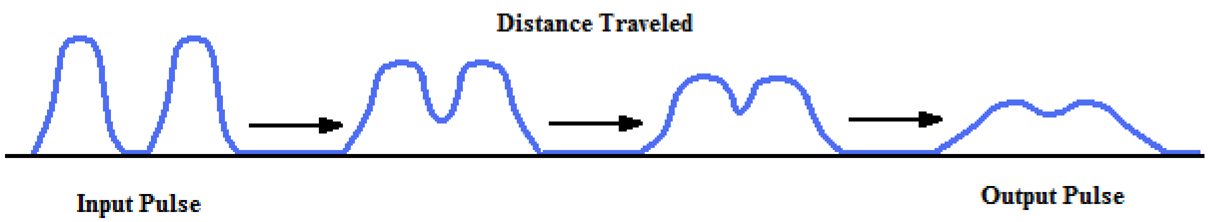
The noise properties of an APD are affected by the materials that the APD is made of. Typical semiconductor materials used in the construction of low-noise APDs include silicon (Si), indium gallium arsenide (InGaAs), and germanium (Ge).

Trade-offs are made in APD design to optimize responsivity and gain, dark current, response time, and linearity. Many aspects of the discussion provided on responsivity, dark current, and response time provided in the PIN photodiodes section also relate to APDs. The response time of an APD and its output circuitry depends on the same factors as PIN photodiodes. The only additional factor affecting the response time of an APD is the additional time required to complete the process of avalanche multiplication.

Chapter Four
Fiber optic receivers

In fiber optic communications systems, optical signals that reach fiber optic receivers are generally attenuated and distorted (see Figure 9). The fiber optic receiver must convert the input and amplify the resulting electrical signal without distorting it to a point that it cannot be used by other circuitry.

Figure 9. - Attenuated and distorted optical signals.



As stated previously, a fiber optic receiver consists of an optical detector, an amplifier, and other circuitry. In most fiber optic systems, the optical detector is a PIN photodiode or APD. Receiver performance varies depending on the type of detector used. The amplifier is generally described as having two stages: the preamplifier and the postamplifier. The *preamplifier* is defined as the first stage of amplification following the optical detector. The *postamplifier* is defined as the remaining stages of amplification required to raise the detector's electrical signal to a level suitable for further signal processing. The preamplifier is the dominant contributor of electrical noise in the receiver. Because of this, its design has a significant influence in determining the sensitivity of the receiver.

The output circuitry processes the amplified signal into a form suitable for the interfacing circuitry. For digital receivers, this circuitry may include low-pass filters and comparators. For analog receivers, this circuitry may also include low-pass filters.

Receiver sensitivity, bandwidth, and dynamic range are key operational parameters used to define receiver performance. One goal in designing fiber optic receivers is to optimize receiver sensitivity. To increase sensitivity, receiver noise resulting from signal-dependent shot noise and thermal noise must be kept at a minimum. A more detailed discussion of receiver shot, and thermal noise is provided later in this chapter.

In addition to optimizing sensitivity, optical receiver design goals also include optimizing the bandwidth and the dynamic range. A receiver that can operate over a wide range of optical power levels can operate efficiently in both short- and long-distance applications. Because conflicts arise when attempting to meet each goal, trade-offs in receiver designs are made to optimize overall performance.

Receiver noise

Noise corrupts the transmitted signal in a fiber optic system. This means that noise sets a lower limit on the amount of optical power required for proper receiver operation. There are many sources of noise in fiber optic systems. They include the following:

- Noise from the light source
- Noise from the interaction of light with the optical fiber
- Noise from the receiver itself

Because the intent of this chapter is to discuss optical detector and receiver properties, only noise associated with the photodetection process is discussed. *Receiver noise* includes thermal noise, dark current noise, and quantum noise. Noise is the main factor that limits receiver sensitivity.

Noise introduced by the receiver is either signal dependent or signal independent. Signal dependent noise results from the random generation of electrons by the incident optical power. Signal independent noise is independent of the incident optical power level.

Thermal noise is the noise resulting from the random motion of electrons in a conducting medium. Thermal noise arises from both the photodetector and the load resistor. Amplifier noise also contributes to thermal noise. A reduction in thermal noise is possible by increasing the value of the load resistor. However, increasing the value of the load resistor to reduce thermal noise reduces the receiver bandwidth. In APDs, the thermal noise is unaffected by the internal carrier multiplication.

Shot noise is noise caused by current fluctuations because of the discrete nature of charge carriers. Dark current and quantum noises are two types of noise that manifest themselves as shot noise. *Dark current noise* results from dark current that continues to flow in the photodiode when there is no incident light. Dark current noise is independent of the optical signal. In addition, the discrete nature of the photodetection process creates a signal dependent shot noise called quantum noise. *Quantum noise* results from the random generation of electrons by the incident optical radiation.

In APDs, the random nature of the avalanche process introduces an additional shot noise called excess noise. For further information on the excess noise resulting from the avalanche process, refer to the avalanche photodiode section.

Receiver design

The simplest fiber optic receivers consist of only the optical detector and a load resistor. However, the output signal of these simple receivers is not in a suitable form for most types of interfacing circuitry. To produce a suitable signal, a preamplifier, a post amplifier, and other circuitry are generally included in the receiver.

The choice of an optical detector and the design of the preamplifier help determine the operational characteristics of the receiver. Fiber optic receivers using APDs have greater sensitivity than those using PIN photodiodes.

In addition, trade-offs are made in preamplifier designs to increase sensitivity while optimizing bandwidth and dynamic range. The two basic types of amplifiers used in fiber optic receivers are the *high-impedance amplifier* and the *transimpedance amplifier*.

The high-impedance preamplifier is generally used with a large load resistor to improve sensitivity. The large load resistor is used to reduce thermal noise. Although the high-impedance preamplifier achieves high sensitivity, receiver bandwidth and dynamic range are limited. The transimpedance preamplifier uses a low-noise, high-input impedance amplifier with negative feedback. This design provides improvements in bandwidth and dynamic range with some degradation in sensitivity from an increase in noise. For more information on receiver performance and design, refer to the reference material listed in appendix 2.

Fiber optic receiver applications

Fiber optic receivers can be classified into two categories: digital and analog. Digital receivers detect the input optical signal, amplify the digital photocurrent, and reshape the signal to produce an undistorted output electrical signal. Analog receivers detect the input optical signal and amplify the generated photocurrent.

Digital applications

For most digital applications, the designs of the digital fiber optic receivers are similar. For *low-data-rate* applications, PIN diodes and high impedance amplifiers are generally used.

Receiver sensitivities are maximized by using large load resistors in the photodiode circuit. For *moderate-data-rate* applications, PIN diodes and either high impedance amplifiers with smaller load resistances or transimpedance amplifiers are used. For *high-data-rate* applications, pins or APDs are used with transimpedance amplifiers. APDs are rarely used in low- or moderate-data-rate applications unless receivers with extremely low sensitivities are required.

For each digital application, the receiver will generally contain a low-pass filter. The passband of the filter depends on the data rate of the application. The filter is used to smooth the amplified signal to remove some of the high frequency noise before the signal is further processed. The digital receiver generally contains a comparator, which reshapes the amplified electrical signal to remove any distortions introduced in the transmission process. In some cases, the receiver may also contain clock recovery circuitry, which retimes the output electrical signal as well.

Analog applications

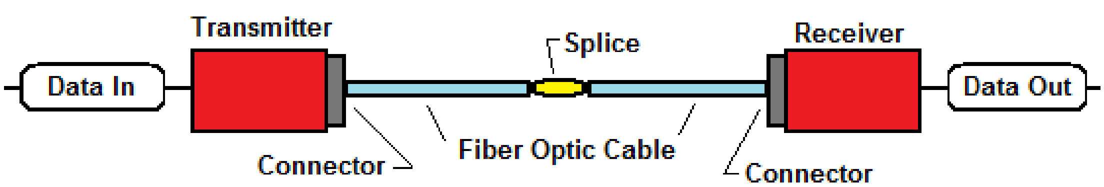
Analog receivers are similar in design to digital receivers with the exception that digital signal restoring circuitry is not used. The preamplifier and postamplifiers are designed to be more linear than those used in digital receivers in some cases.

For *low-frequency* applications, PIN diodes and high impedance amplifiers are generally used. For *moderate-frequency* applications, PIN diodes and either high impedance amplifiers or transimpedance amplifiers are used. For *high-frequency* applications, pins or APDs are used with transimpedance amplifiers. As in digital applications, APDs are rarely used in low- or moderate-frequency applications unless receivers with extremely low sensitivities are required.

Chapter Five
Fiber optic links

Most of our discussion on fiber optic data links has referred to simple point-to-point links. A *point-to-point* fiber optic data link consists of an optical transmitter, optical fiber, and an optical receiver. In addition, any splices or connectors used to join individual optical fiber sections to each other and to the transmitter and the receiver are included. Figure 10 provides a schematic diagram of a point-to-point fiber optic data link.

Figure 10. - Schematic diagram of a point-to-point fiber optic data link.



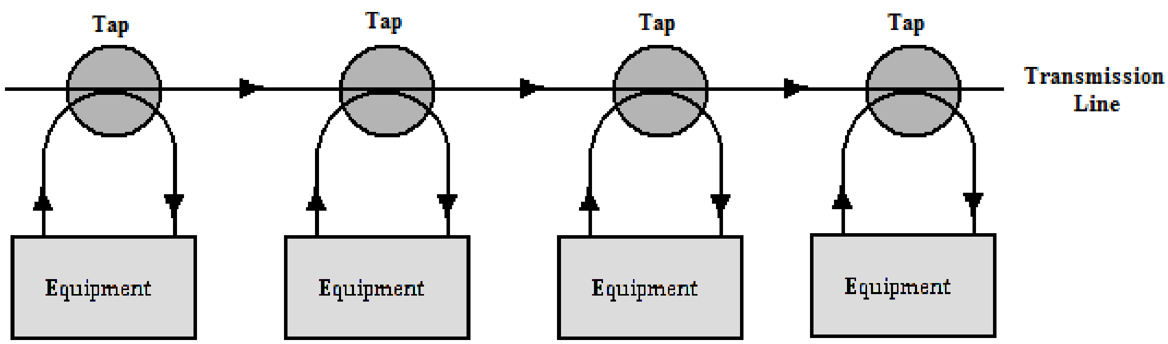
A common fiber optic application is the *full duplex link*. This link consists of two simple point-to-point links. The links transmit in opposite directions between the equipment. This application may be configured using only one fiber. If configured with one fiber, fiber optic splitters are used at each end to couple the transmit signal onto the fiber and receive signal to the detector.

All fiber optic systems are simply sets of point-to-point fiber optic links. Different system topologies arise from the different ways that point-to-point fiber optic links can be connected between equipment. The term *topology*, as used here, refers to the configuration of various equipment and the fiber optic components interconnecting them. This equipment may be computers, workstations, consoles, or other equipment. Point-to-point links are connected to produce systems with linear bus, ring, star, or tree topologies. Point-to-point fiber optic links are the basic building block of all fiber optic systems.

A *linear bus topology* consists of a single transmission line that is shared by several pieces of equipment (see Figure 11). Generally, the transmission line in a fiber optic linear bus consists of two optical lines, one for each direction of communication.

Optical taps (optical splitters) are used by each equipment to connect to each line. For each line, the optical tap is used to couple signals from the line to the equipment receiver and from the equipment transmitter onto the line. The connection between any two equipment is a simple point-to-point link that contains the optical tap for each equipment.

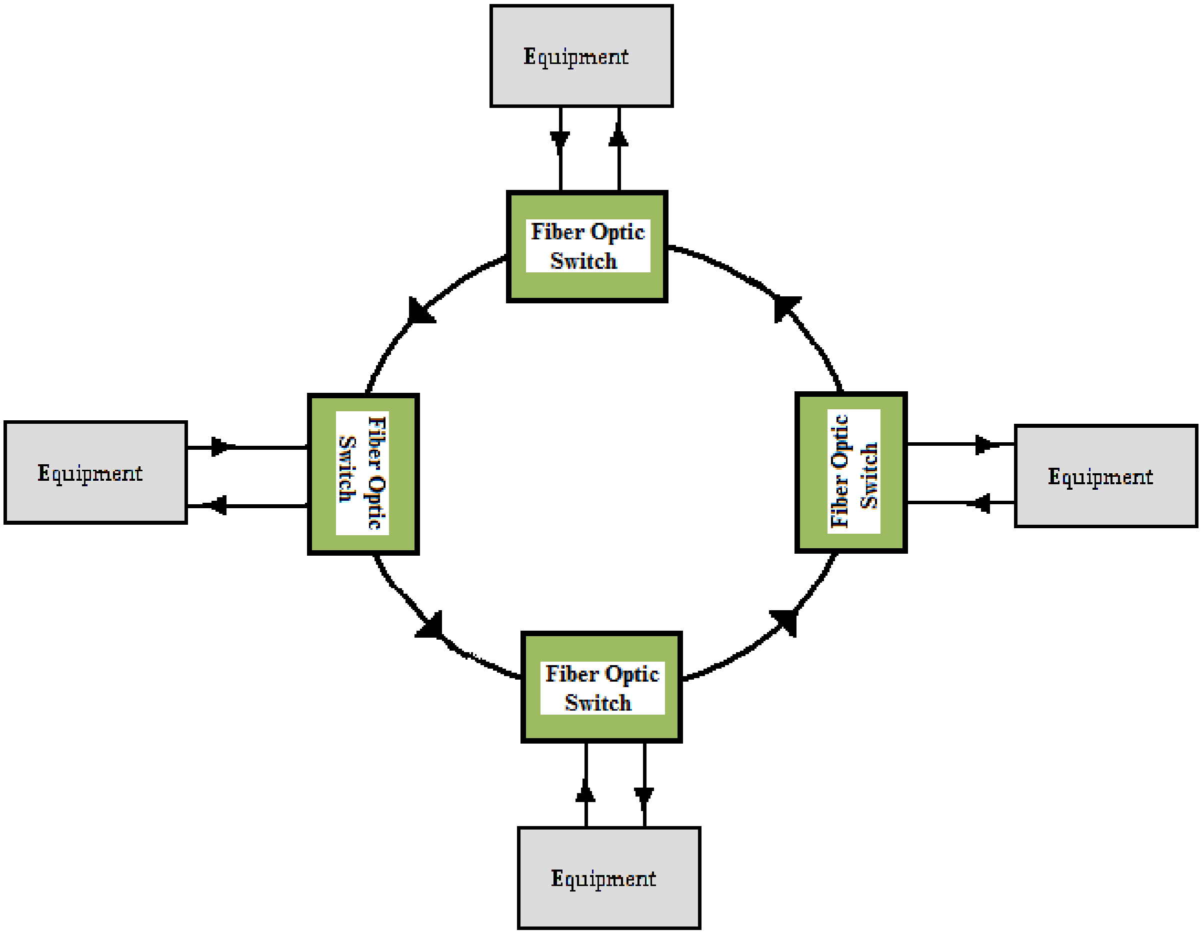
Figure 11. - Linear bus topology.



A *ring topology* consists of equipment attached to one another in a closed loop or ring (see Figure 12).

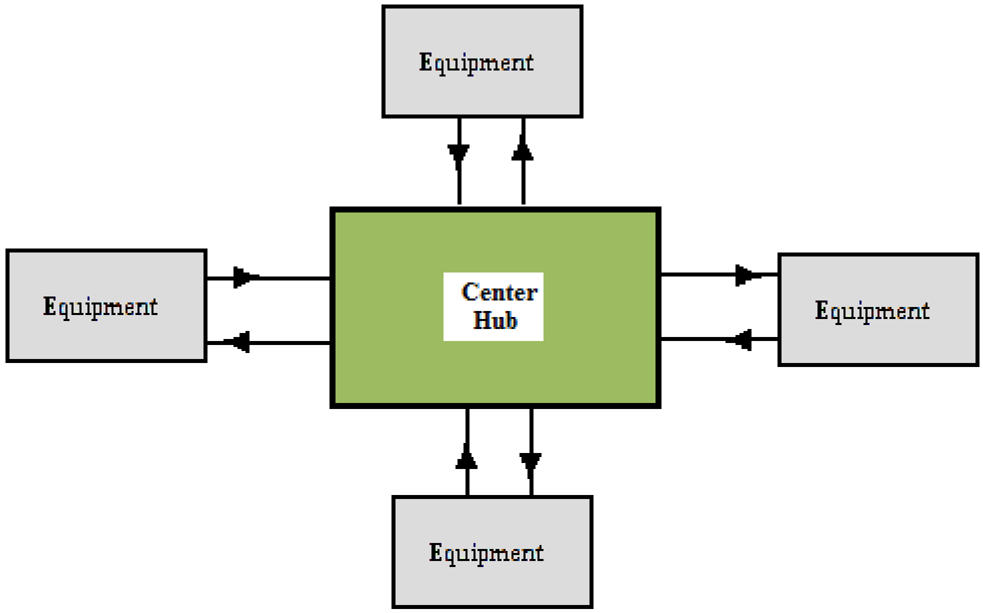
The connection between each equipment is a simple point-to-point link. In some systems each equipment may have an associated optical switch. In normal operation, the switch routes signals from the fiber connected to the previous equipment to the receiver. It also routes signals from the transmitter to the fiber connected to the next equipment. In bypass operation, the switch routes signals from the fiber connected to the previous equipment to the fiber connected to the next equipment. In each case, the connection between adjacent equipment on the ring is a simple point-to-point link through fiber, connectors, and switches.

Figure 12. - Ring topology.



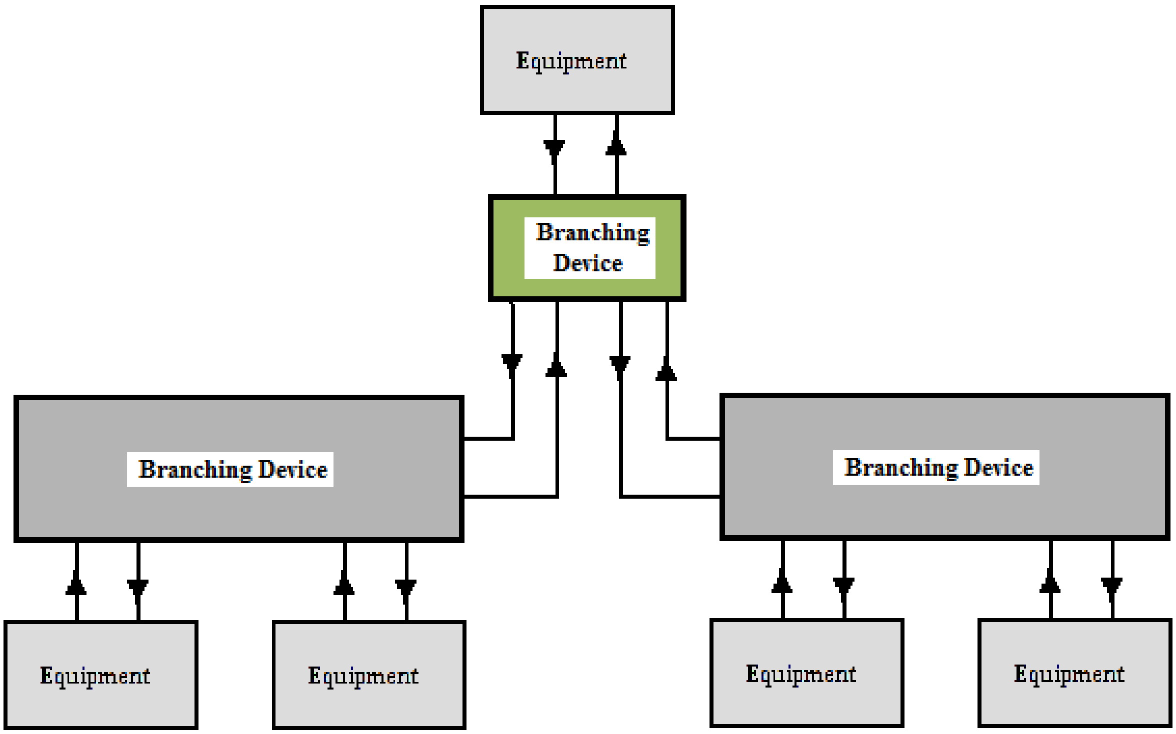
In the *star topology*, each equipment is connected to a common center hub (see Figure 13). The center hub can be a passive fiber optic star coupler or an active equipment. If the center hub is a passive star coupler, each equipment transmitter is connected to an input port of the coupler and an output port of the coupler is connected to each equipment receiver. The connection between any two equipment is a simple point-to-point link through the star coupler. If the center hub is an active equipment, the connection between any two equipment consists of two point-to-point links. Each connection consists of one link from the first equipment to the center hub and a second link from the center hub to the second equipment.

Figure 13. - Star topology.



A *tree topology* consists of a transmission line that branches, or splits (see figure 14). A tree topology may have many different branching points. At each branching point either a passive fiber optic splitter or an active branching device is used. In many cases both passive couplers and active branching devices are used within a particular system. Regardless of the branching method, each connection within the tree is a simple point-to-point link through splitters or multiple point-to-point links through active branching devices.

Figure 14. - Tree topology.



Link classification

While there are several ways to classify fiber optic links, this chapter classifies links according to the modulation type: either digital or analog. *Modulation* is the process of varying one or more characteristics of an optical signal to encode and convey information. Generally, the intensity of the optical signal is modulated in fiber optic communications systems.

Digital modulation implies that the optical signal consists of discrete levels. Analog modulation implies that the intensity of the optical signal is proportional to a continuously varying electrical input. Most fiber optic systems are digital because digital transmission systems generally provide superior performance over analog transmission systems.

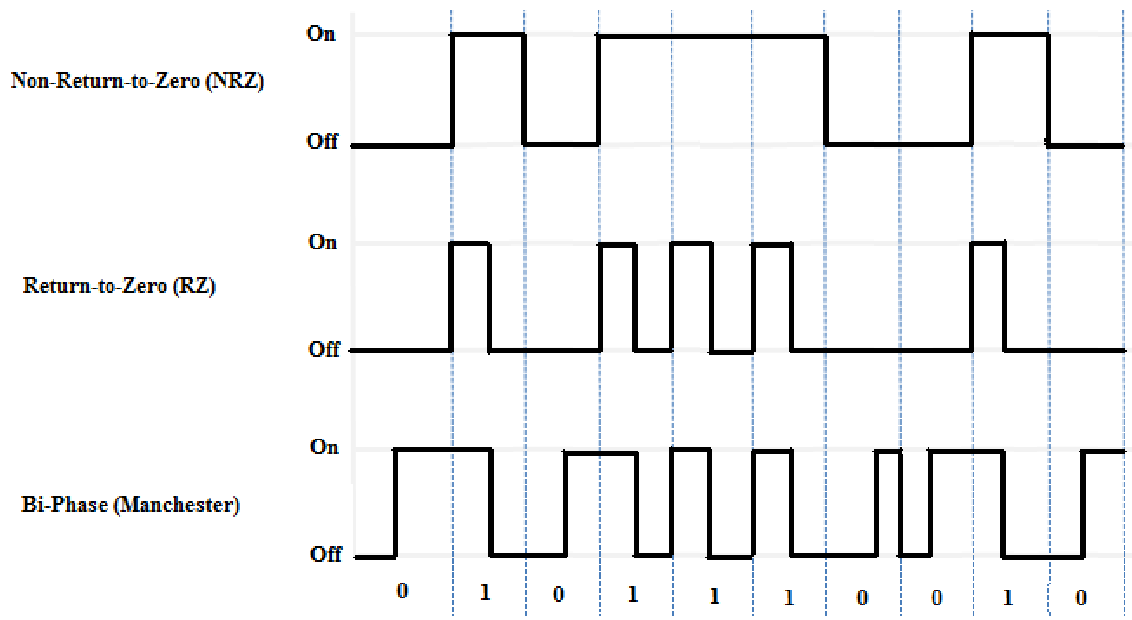
Digital transmission

A digital signal is a discontinuous signal that changes from one state to another in discrete steps. A popular form of digital modulation is binary, or two level, digital modulation. In binary modulation the optical signal is switched from a low-power level (usually off) to a high-power level. There are several modulation techniques used in digital systems, but these will not be discussed here.

Line coding is the process of arranging symbols that represent binary data in a particular pattern for transmission.

The most common types of line coding used in fiber optic communications include non-return-to-zero (NRZ), return-to-zero (RZ), and bi-phase, or Manchester. Figure 15 illustrates NRZ, RZ, and bi-phase (Manchester) encoding.

Figure 15. - NRZ, RZ, and bi-phase encoding.



NRZ code represents binary 1s and 0s by two different light levels that are constant during a bit duration. The presence of a high-light level in the bit duration represents a binary 1, while a low-light level represents a binary 0. NRZ codes make the most efficient use of system bandwidth. However, loss of timing may result if long strings of 1s and 0s are present causing a lack of level transitions. RZ coding uses only half the bit duration for data transmission.

In RZ encoding, a half period optical pulse present in the first half of the bit duration represents a binary 1. While an optical pulse is present in the first half of the bit duration, the light level returns to zero during the second half. A binary 0 is represented by the absence of an optical pulse during the entire bit duration. Because RZ coding uses only half the bit duration for data transmission, it requires twice the bandwidth of NRZ coding. Loss of timing can occur if long strings of 0s are present.

Bi-phase, or Manchester, encoding incorporates a transition into each bit period to maintain timing information. In Manchester encoding, a high-to-low light level transition occurring in the middle of the bit duration represents a binary 1. A low-to-high light level transition occurring in the middle of the bit duration represents a binary 0.

Digital transmission offers an advantage regarding the acceptable signal-to-noise ratio (SNR) at the optical receiver. Digital communications systems can tolerate large amounts of signal loss and dispersion without impairing the ability of the receiver to distinguish a binary 1 from a binary 0. Digital signaling also reduces the effects that optical source nonlinearities and temperature have on system performance. Source nonlinearities and temperature variations can severely affect analog transmission. Digital transmission provides superior performance in most complex systems (such as LANs) and long-haul communications systems. In short-haul systems, the cost and complexity of analog-to-digital and digital-to-analog conversion equipment, in some cases, outweigh the benefits of digital transmission.

Analog transmission

An analog signal is a continuous signal whose amplitude, phase, or some other property varies in a direct proportion to the instantaneous value of a physical variable. An example of an analog signal is the output power of an optical source whose intensity is a function of a continuous electrical input signal.

Most analog fiber optic communications systems intensity-modulate the optical source. In *intensity modulation*, the intensity of the optical source's output signal is directly modulated by the incoming electrical analog baseband signal. A *baseband signal* is a signal that is in its original form and has not been changed by a modulation technique.

In some cases, the optical source may be directly modulated by an incoming electrical signal that is not a baseband signal. In these cases, the original electrical signal generally modulates an electrical subcarrier frequency. The most common form of analog subcarrier modulation in fiber optic systems is frequency modulation (FM). The optical source is intensity modulated by the electrical subcarrier.

While most fiber optic systems employ digital modulation techniques, there are certain applications where analog modulation techniques are preferred.

The transmission of video using analog techniques is popular, especially for shorter distances, where costs can be minimized, and complex multiplexing and timing equipment is unnecessary. The transmission of analog voice signals may also be attractive in small, short-haul systems. In addition, fiber optic sensor systems may incorporate analog transmission. Requirements that analog transmission places on applications include high signal-to-noise ratio and high source linearity. While analog transmission can be attractive for short-haul or medium-haul systems, it is unattractive for long-haul systems where digital techniques provide better performance.

System design

Fiber optic systems can be simple point-to-point data links or can involve more complex topologies. However, it is generally necessary only to refer to point-to-point data links when discussing the process of link design. Fiber optic systems that incorporate complex architectures can be simplified into a collection of point-to-point data links before beginning the design process.

Fiber optic system design is a complicated process that involves link definition and analysis. The design process begins by providing a complete description of the communication requirements. This information is used to develop the link architecture and define the communications links. System designers must decide on the operational wavelength and types of components to use in the system. These decisions affect numerous system and link design parameters, such as launched power, connection losses, bandwidth, cost, and reliability.

Once a system design has been formulated, each link is analyzed to determine its viability. Link analysis involves calculating each link's power budget and rise time budget. Calculating a *power budget* involves identifying all the sources of loss in the fiber optic link. These losses and an additional safety margin are then compared to the difference between the transmitter output power and the receiver sensitivity. The difference between the transmitter output power and the receiver sensitivity is referred to as the *available power*. If the sources of loss plus the safety margin are less than the available power in the link, the design is viable.

Calculating the *rise time budget* involves calculating the rise times of the link transmitter and the optical fiber. The composite optical transmitter/fiber rise time is referred to as the *fiber exit rise time*. If the fiber exit rise time is less than the maximum input rise time specified for the link receiver, then the link design is viable.

If a proposed link design is not viable, the system designer will reevaluate various decisions made earlier in the system design. These re-evaluations may include using a different transmitter or receiver or may involve redesigning the physical configuration of the link. Because there are many variables involved in link design and analysis, it may take several iterations before the variables are combined in a manner that ensures link operation.

Summary

The following is a summary of a few of the key terms and ideas presented this course.

A *fiber optic transmitter* is a hybrid electro-optic device. It converts electrical signals into optical signals and launches the optical signals into an optical fiber.

An *optical source* converts electrical energy (current) into optical energy (light).

The principal light sources used in fiber optics are semiconductor light-emitting diodes (LEDs) and laser diodes (LDs).

Semiconductor LD's emit coherent light. Light waves having a fixed-phase relationship are referred to as coherent light.

Semiconductor LED's emit incoherent light. Light waves that lack a fixed-phase relationship are referred to as incoherent light.

The *relevant optical power* is the amount of optical power coupled into the fiber. It depends on the angle over which the light is emitted, the size of the source's light-emitting area relative to the fiber core size, the alignment of the source and fiber, and the coupling characteristics of the fiber (such as the NA and the refractive index profile).

Source-to-fiber coupling efficiency is a measure of the relevant optical power.
Silicon (Si) and gallium arsenide (GaAs) are the two most common semiconductor materials used in electronic and electro-optic devices. In a semiconductor device, *photons (light)* are emitted when current flows through the active area.

Spontaneous emission occurs when photons are emitted in a random manner. Spontaneous emission produces incoherent light.

Stimulated emission occurs when a photon interacts with the laser material to produce additional photons.

A light-emitting diode (LED) is a semiconductor device that emits incoherent light, through spontaneous emission, when a current is passed through it. The basic LED types used for fiber optic communication systems are the *surface-emitting LED (SLED),* the *edge-emitting LED (ELED),* and the *super luminescent diode (SLD).*

In *surface-emitting LED's (SLEDs),* the size of the primary active region is limited to a small circular area of 20 m to 50 m in diameter. The active region is the portion of the LED where photons are emitted. SLEDs usually emit more total power into the air gap at the fiber interface than an ELED, but they do not launch as much power into the fiber. SLEDs also tend to emit power over a wider spectral range than ELED.

Edge-emitting LED's (ELEDs) emit light in a narrow emission angle allowing for better source-to-fiber coupling. They couple more power into small NA fibers than SLEDs. The polished or cut surfaces at each end of the ELED active stripe are called facets.

Super luminescence occurs when the spontaneous emissions of an ELED experience gain due to higher injected currents and reflections from facets.

Super luminescent diodes (SLDs) are similar in geometry to lasers but have no built-in optical feedback mechanism required by laser diodes for stimulated emission to achieve lasing. Although the output is not fully coherent, super luminescent diodes (SLDs) emit light that consists of amplified spontaneous emissions. The spectral width and beam angle of SLDs are narrower than that of conventional LEDs and wider than that of LDs.

The advantages of SLDs over conventional LEDs include higher coupled power, narrower spectral width, and greater bandwidths. The disadvantages include nonlinear power-current characteristics, higher temperature sensitivity, and lower reliability.

A *laser* is a device that produces optical radiation using stimulated emission rather than spontaneous emission. Laser is an acronym for light amplification by the stimulated emission of radiation.

The *lasing threshold* is the lowest drive level at which the output of the laser results primarily from stimulated emission rather than spontaneous emission.

The *threshold current* is the lowest current at which stimulated emission exceeds spontaneous emission.

A *laser diode* is a semiconductor diode that emits coherent light by lasing. The LD’s output has a narrow spectral width and small output beam angle.

Transmitter output interfaces fall into two categories: optical connectors and optical fiber pigtails.

Fiber optic transmitters using LDs require more complex circuitry than transmitters using LEDs.

Because LDs are threshold devices, LDs are supplied with a bias just below the threshold in the off state. This bias is often referred to as a pre-bias.

The least complex *fiber optic transmitters* are typically packaged in transistor outline (to) cans or hybrid microcircuit modules in dual inline packages (DIPS).

More complex *fiber optic transmitters* typically are packaged in hybrid microcircuit modules in either dip or butterfly lead packages, circuit cards, or complete stand-alone fiber optic converters.

Fiber optic transmitters can be classified into two categories: digital and analog.

Digital transmitters modulate the fiber optic source between two discrete optical power levels. These levels are essentially on and off with the exception that some light is emitted in the off state by some transmitters.

Analog transmitters continuously vary the output optical power level as a function of the input electrical signal.

For *low-data-rate applications* (0 to 20 mbps), fiber optic transmitters generally use LEDs operating in either the 850-nm or 1300-nm window.

For *moderate-data-rate applications* (50 to 200 mbps), fiber optic transmitters generally use LEDs operating in the 1300-nm window.

For *high-data-rate applications*, most fiber optic transmitters use laser diodes as sources.

Laser sources are almost never used in low- or moderate-frequency analog applications because LED sources require much less complex circuitry.

A *fiber optic receiver* is an electro-optic device that accepts optical signals from an optical fiber and converts them into electrical signals. A typical fiber optic receiver consists of an optical detector, a low-noise amplifier, and other circuitry used to produce the output electrical signal.

Receiver spectral response, sensitivity, frequency response, and *dynamic range* are key receiver performance parameters that can affect overall system operation.

Receiver sensitivity is the minimum amount of optical power required to achieve a specific receiver performance. For digital transmission at a given data rate and coding, this performance is described by a maximum bit-error rate (BER). In analog systems, for a given modulation and bandwidth, it is described by a minimum signal-to-noise ratio (SNR).

Dynamic range refers to the range of optical power levels over which the receiver operates within the specified values. It usually is described by the ratio of the maximum input power to the sensitivity.

A *transducer* is a device that converts input energy of one form into output energy of another.

An *optical detector* is a transducer that converts an optical signal into an electrical signal. It does this by generating an electrical current proportional to the intensity of incident optical radiation.

The semiconductor *positive-intrinsic-negative (PIN) photodiode and avalanche photodiode (APD)* are the principal optical detectors used in fiber optic systems.

A *photocurrent* is generated when photons are absorbed by a photodiode.

Responsivity is the ratio of the optical detector's output photocurrent in amperes to the incident optical power in watts.

Dark current, or reverse-leakage current, is the current that continues to flow in the photodetector when there is no incident light.

The *response time* of a photodiode and its output circuitry depends primarily on the thickness of the detector active area and the detector RC time constant.

The *transit time* is the time it takes electrons to travel out of the detector active area.

The *RC time constant* is defined by the capacitance (c) of the photodiode and the resistance (r) of the load.

A *high-speed response* requires short transit times and low capacitance. However, any change in photodiode parameters to optimize the transit time and capacitance can also affect quantum efficiency, dark current, and coupling efficiency.

Detector *linearity* means that the output electrical current (photocurrent) of the photodiode is linearly proportional to the input optical power.

An *avalanche photodiode (APD)* is a photodiode that internally amplifies the photocurrent by an avalanche process.

In APDs, a large *reverse-bias voltage*, typically over 100 volts, is applied across the active region.

Avalanche multiplication occurs when accelerated electrons collide with other electrons in the semiconductor material, causing a fraction of them to become part of the photocurrent.

Trade-offs are made in APD design to optimize responsivity and gain, dark current, response time, and linearity.

The *response time* of APDs accounts for the avalanche build-up time in addition to transit time and RC time constant.

The *preamplifier* is defined as the first stage of amplification following the optical detector.

The *postamplifier* is defined as the remaining stages of amplification required to raise the detectors electrical signal to a level suitable for further signal processing.

Receiver sensitivity, bandwidth, and dynamic range are key operational parameters used to define receiver performance.

Noise is the main factor that determines receiver sensitivity.

Receiver noise includes thermal noise, dark current noise, and quantum noise.

Thermal noise is the noise resulting from the random motion of electrons in a conducting medium.

Shot noise is noise caused by current fluctuations due to the discrete nature of charge carriers.

Dark current noise results from dark current that continues to flow in the photodiode when there is no incident light.

Quantum noise results from the random generation of electrons by the incident optical radiation.

The *high-impedance preamplifier* provides a high sensitivity, but limits receiver bandwidth and dynamic range.

The *transimpedance preamplifier* provides improvements in bandwidth and dynamic range with some degradation in sensitivity from an increase in noise.

PIN photodiodes are used as the detector in most applications.

Avalanche photodiodes are only used in high-speed applications and applications where detectors with extremely low sensitivities are required.

A basic *point-to-point* fiber optic data link consists of an optical transmitter, optical fiber, and an optical receiver.

The term *topology* refers to the configuration of various equipment and the fiber optic components interconnecting them.

A *linear bus topology* consists of a single transmission line that is shared several pieces of equipment.

A *ring topology* consists of equipment attached to one another in a closed loop or ring.

In the *star topology*, each equipment is connected to a common center hub. The center hub can be a passive fiber optic star coupler or an active equipment.

A *tree topology* consists of a transmission line that branches, or splits.

Fiber optic links are classified according to the modulation type: either digital or analog. *Digital modulation* implies that the optical signal consists of discrete levels.

Analog modulation implies that the intensity of the optical signal is proportional to a continuously varying electrical input.

Modulation is the process of varying one or more characteristics of an optical signal to encode and convey information.

A *digital signal* is a discontinuous signal that changes from one state to another in discrete steps.

Binary, or two level, digital modulation is a popular form of digital modulation.

Line coding is the process of arranging symbols that represent binary data in a particular pattern for transmission. The most common types of line coding used in fiber optic communications include non-return-to-zero (NRZ), return-to-zero (RZ), and bi-phase, or Manchester.

Digital transmission offers an advantage regarding the acceptable SNR at the optical receiver.

An *analog signal* is a continuous signal that varies in a direct proportion to the instantaneous value of a physical variable.

Most *analog fiber optic communications systems* intensity modulate the optical source.

In *intensity modulation*, the intensity of the optical source's output signal is directly modulated by the incoming electrical analog baseband signal.

A *baseband signal* is a signal that is in its original form and has not been changed by a modulation technique.

Fiber optic systems that have complex architectures can be simplified into a collection of point-to-point data links.

Link analysis involves calculating each link's power budget and risetime budget.

Calculating a *power budget* involves identifying all the sources of loss in the fiber optic link. These losses and an additional safety margin are then compared to the difference between the transmitter output power and the receiver sensitivity.

Calculating the *rise time budget* involves calculating the rise times of the link transmitter and the optical fiber.

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