GTE Communications Transmission Systems

DEMODULATOR

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More Light on Optical Fiber Systems

The bibliography lists previous Demodulator articles that discuss Fiber Optical Transmission theory and components including Optical Fiber Cable.

This issue describes Optical Fiber Transmission Systems and discusses their advantages and disadvantages compared to other systems.

Like most communications systems, fiber optics requires a transmitter, a transmission medium and a receiver. Fiber Optics systems use a light transmitter and receiver. A glass or plastic fiber is the transmission medium.

Transmitter

A light transmitter consists of two parts, a light source and a modulator. The modulator imposes the intelligence (information) on the source. Most modulators accomplish this function by turning the light source on and off or by varying the intensity of the light.

Two kinds of light sources are suitable for fiber optic communications. The light emitting diode (LED) and the laser. Laser stands for "Light Amplification by Stimulated Emission of Radiation."

There are several types of lasers but the one most commonly used for fiber optic communications is the semiconductor laser, which is also known as an injection or junction diode laser. The LED is also a semiconductor junction diode device so, some knowledge of junction diodes is helpful in understanding the two light sources.

As shown in figure 1, junction diodes are made from two kinds of semiconductor material, a positive (P) type which has a deficiency of electrons in its atoms and a negative (N) type which has an excess of electrons in its atoms. If a positive voltage is connected to the P type material and a negative voltage is connected to the N type, "forward bias" is applied to the diode and current will flow through it. The amount of current is determined by the amplitude of the applied voltage.

Reversing the polarity of the voltage so that negative is applied to P and positive is applied to N cuts off the current flow. This is known as "reverse bias." The diode can be switched on and off very rapidly (millions of times per second) by reversing the polarity of the applied voltage.

When forward bias is applied to the light emitting diode, the electrons in the relatively-unstable, N type atoms receive energy from the battery. This extra energy allows them to cross the junction. In other words, current flows.

After crossing the junction, the electrons lose energy and enter the atoms of the P material. Some of the

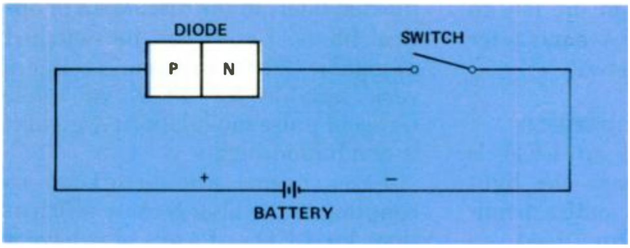


Figure 1. Junction Diode.

energy the electrons lose is emitted as light from the LED. The intensity of the light emission varies with the amount of current flowing through the junction.

Light generated by atomic action of this kind is known as luminescent as opposed to incandescent light which is generated by heating an element. Ordinary light bulbs are incandescent. Incandescent bulbs are not suitable for high speed communications.

Referring to figure 2, the semiconductor, injection laser is a junction diode with both ends polished to reflect light. One end is more highly polished than the other.

Forward bias causes the N material electrons to raise to a high energy level and move into the junction. As a high energy electron falls to a lower energy level, it emits a small burst of light. The light may strike another electron and raise it to a high energy level. When this electron falls to a lower energy level, it also emits a burst of light. These bursts of light are reflected when they hit the polished ends of the junction. A stream of light is created which moves back and forth between the ends of the junction. When these light waves reach a high enough intensity, some of the light will emerge from the least polished end of the junction in the form of a beam of light.

The frequency of the light generated by the laser is a function of the diode material and temperature. The intensity of the light increases with the current flow.

The light wave spectrum is generally expressed in wavelength rather than frequency. The shorter the wavelength, the higher the frequency. Typical wavelengths for both

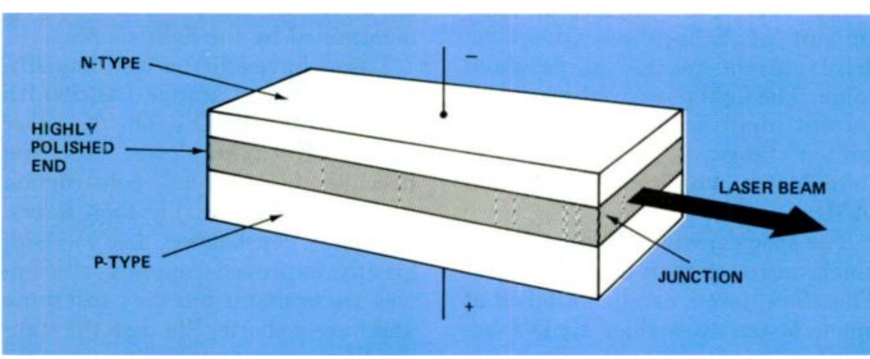


Figure 2. Semiconductor Injection Laser.

LED's and lasers are in the 800 to 850 nanometer range. A nanometer is one billionth of a meter.

LED and Laser Comparison

The emission from an LED is lambertian which means the light rays emanate over an entire hemisphere. Another term used to describe the way light emanates from an LED is "isotropic" which means the light rays are emitted at all angles. This makes it difficult to efficiently couple an LED to a fiber.

The LED output is nearly directly proportional to the current through the junction. The change in light-power output is essentially linear over a large range of input current so, LED's can be amplitude modulated.

Some LED's can be switched at rates up to 200 million a second although 50 million a second is about the fastest rate used in actual practice. Switching rates are usually stated in megabits per second; abbreviated Mbps. A megabit is one million bits or pulses.

The modulation method which switches the source on and off is called pulse code modulation (PCM). This is the modulation method commonly used in digital systems.

The laser is a threshold device. It "turns on" and provides a large amount of light-power when the drive current reaches a threshold value. The light power output versus current input is linear over a very limited range so lasers are not suitable for amplitude modulation (AM).

The spectral-width of laser light is much narrower than that of LED's. Therefore, lasers can be switched at much faster rates than LED's because material dispersion is not a problem. Material dispersion is explained later, in the discussion of optical fibers. Lasers can be switched at gigabit (Gb/s) rates so, lasers are very suitable for PCM or other forms of pulse modulation. A gigabit is one billion bits.

Laser beams are directional so coupling to the fiber is more efficient than for LED's. Lasers also have a higher power output than LED's.

Terms used to describe laser light are "coherent" and "collimated." Coherent means that the rays are in phase and reinforce each other. The light from a truly coherent light source has only one wavelength. Collimated means that all the rays travel on parallel paths. Coherence and Collimation are ideal properties for a light source to be used in optical fiber communications. Lasers approach this ideal.

Other requirements for a light source to be used in mass communications are low cost and high reliability. In the telephone network for example, sources must be able to provide many years of continuous stable operation at ordinary room temperatures. They should also be capable of being efficiently coupled to the fiber.

Another factor which must be considered is the distance bandwidth product. This is a "figure of merit" for a system. The product is largely determined by the light source.

Lasers have a better coupling efficiency and distance-bandwidth product than LED's. On the other hand, LED's are lower cost and because of simpler construction generally more reliable than lasers. Specially constructed LED's with greatly improved coupling efficiencies are available but they cost more and have a shorter life than the standard type.

Generally speaking, LED's are

used for relatively short, limited-bandwidth systems. Lasers are required for long-haul broadband systems.

Modulators

As previously stated, the second part of a light transmitter is the modulator. Modulators used in fiber optic systems are similar to those used for microwave radio (see figure 3).

If a frequency division multiplexer is used as the modulator, it will amplitude modulate the light source to produce varying intensity light. If a time division multiplexer is used as the modulator, it will switch the source on and off at a digital rate.

A frequency division multiplexer combines information channels represented by analog signal voltages which are continuously varying in amplitude. The signals are transmitted at the same time but separated in frequency.

A time division multiplexer combines information channels represented by the presence and absence of signal voltage pulses of constant amplitude. The time position of a pulse, relative to other pulses, determines the voltage quantity it represents. The signals are transmitted at the same frequency but separated in time.

FDM signals and their component parts are referred to as analog. TDM signals and their component parts are referred to as digital. Digital signals are more commonly used for fiber optic communications systems because it is easier to detect on-off states than it is to detect variations in light intensity.

Transmission Path

The glass fibers used in fiber optical cable are very small, with typical diameters from 50 to 200 micrometers. The fiber shown in figure 4 has a cylindrical core with a uniform index of refraction. The core is encased in a concentric layer called the cladding. The cladding index of refraction is lower than that of the core.

A light ray entering the core at one end of this fiber will travel down its length and exit at the other end. This action conforms to the reflection principle of physical optics which says: When a light ray passes from one optical transmission medi-

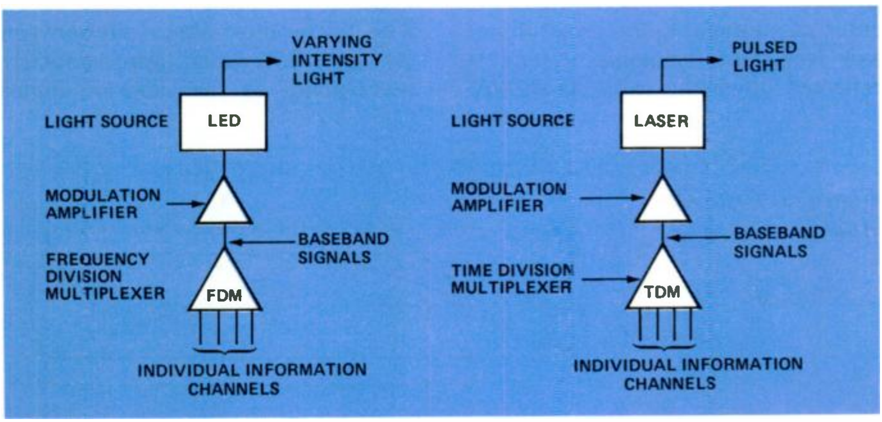
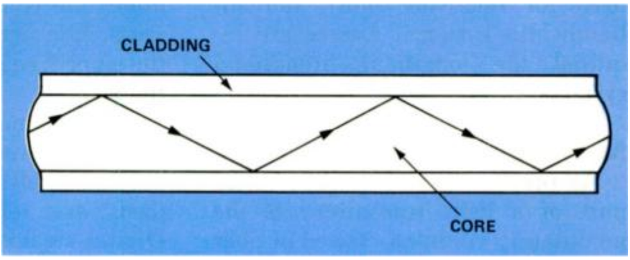


Figure 3. Modulation.

Figure 4. Optical Fiber.



um to a boundary of another medium with a lower index of refraction, the ray will be reflected back into the original medium.

This reflective action occurs over and over again as the light travels down the core. A minute amount of light intensity is lost each time reflection occurs. As the light traverses the fiber, additional losses occur, largely due to impurities in the fiber. These two factors, reflection loss and fiber loss, are the main components of attenuation per unit length of fiber.

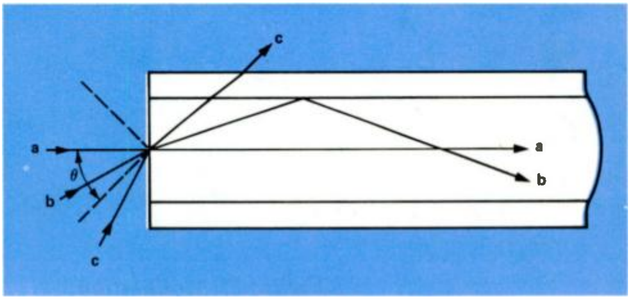
Light transmission is affected by another cable characteristic, input light acceptance.

Figure 5 shows three light rays, a, b and c entering an optical fiber. Ray a enters the fiber along the longitudinal axis and travels down the cable as shown. Ray b enters the cable at an angle to the longitudinal axis less than the angle θ and is reflected down the cable as shown. Ray c enters the cable at an angle greater than θ and escapes through the side as shown. Light rays entering the cable at angles within the cone defined by the dotted lines will propagate along the cable. Rays entering the cable at larger angles will not.

The angle θ (Greek letter Theta) is known as the "maximum propagation angle." It is mathematically related to the difference between the reflective indices of the fiber and the cladding. So, the light gathering capacity of a cable can be expressed as a number, which is called the numerical aperture, abbreviated NA.

NA is equal to the square root of the difference between the square of the peak value of the reflective indices of the core and the cladding which is also equal to the sine of θ. The NA for most fibers falls between 0.1 and 0.3 which approximately corresponds to the sines of angles

Figure 5. Critical Angle.



between 5.7 and 17.4 degrees. As shown in figure 5, these are 1/2 angles. Two things to remember about light acceptance are: (1) Only the light entering the fiber at a small angle to its longitudinal axis will travel down the fiber and (2) The greater the difference between the reflective indices of the core and cladding, the larger this angle will be.

The "maximum propagation angle" is also known as the "critical acceptance angle." The reflective property of an optical fiber is also described in terms of the "critical angle" which is the maximum angle to the cladding at which a light ray will be reflected. Rays striking the cladding at a larger angle will escape through the cladding. To sum up, rays entering a fiber at an angle greater than the maximum propagation angle (i.e., striking the cladding at an angle greater than the critical acceptance angle) will escape through the cladding. These rays are absorbed by the opaque jacket which surrounds the fiber.

Optical fibers which have an abrupt change of reflective index between the core and cladding are called "step-index fibers." Step index fibers are further divided into "single-mode" and "multimode." The number of modes which can propagate along a fiber is determined by the core diameter, the numerical aperture and the wavelength. For a given wavelength, the number of modes can be decreased by reducing the diameter of the core.

When the diameter equals the wavelength, only a single mode will propagate. A single-mode, step-index cable eliminates modal dispersion, which is a limiting factor on the bandwidth of fiber optical systems.

The cause of modal dispersion is shown in figure 6, which shows the path of two rays, A and B, through a fiber.

As shown in the figure, Ray A travels a shorter path because it is not reflected as often as Ray B. Therefore, Ray A will exit the cable sooner than Ray B. As a result, light pulses, formed of rays which enter the cable at the same time, will be stretched or broadened in time as they travel down the cable.

This effect is known as "modal dispersion." Severe dispersion causes an overlap between pulses which makes it difficult to distinguish between them. Also, overlap may make it appear that a pulse is present where one is not. It is apparent that allowing more space between pulses, i.e. sending fewer pulses per unit time, could alleviate overlap. However, the information

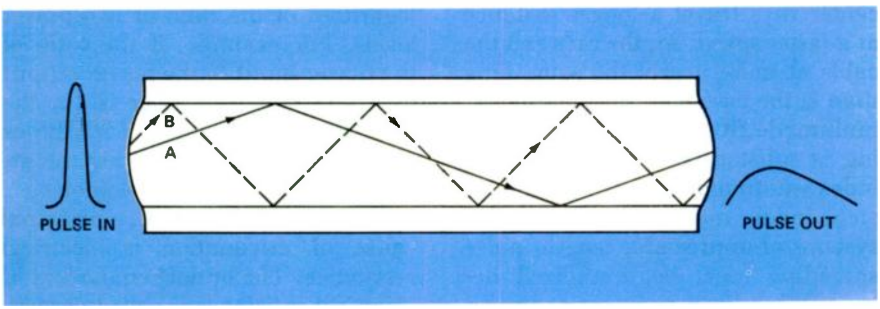


Figure 6. Modal Dispersion.

capacity (bandwidth) of the system would be reduced.

As previously stated, single-mode fiber eliminates modal dispersion. However, its core diameter is so small that it is difficult to achieve and maintain efficient coupling between a light source and a single-mode cable under other than laboratory conditions. A step-index, multimode cable has a much larger core diameter so efficient coupling can be achieved but it has the disadvantage of dispersion effects.

A compromise between the step-index single-mode and multimode fibers is the graded index fiber. This fiber provides a good coupling efficiency and reduces modal dispersion. This is accomplished by using a graded index of refraction across the fiber core instead of the uniform index of refraction used for step-index core.

The graded-index, multimode fiber has an index of refraction which is maximum at the center of the core and decreases with radial distance from the center. Because the speed of light is inversely proportional to the index of refraction of the material through which it propagates, rays traveling along the centerline will travel slower than those traveling off the centerline. The centerline rays travel a shorter distance at a slower speed. The off-center rays travel a longer distance at a faster speed, so, the rays exit the cable at more nearly the same time than is the case with the step-index, multimode fiber. The pulse spreading is substantially less for graded index multimode fiber than it is for step index multimode fiber. For systems of appreciable length, pulse spreading must be minimized because it is a limiting factor on the bit rate capacity (bandwidth). Graded index or single-mode is the fiber of choice for these systems. Figure 7 shows the modal dispersion of the three basic fiber types.

Material Dispersion

Another dispersion effect is called material dispersion. It is a result of the fact that different wavelengths of light travel at different velocities through a given medium.

Practical light sources emit light at different wavelengths. An LED may have a wavelength spread of 50 nanometers. A laser is much better in this respect. Its spread is on the order of 4 nanometers.

Material dispersion is also a limiting factor on bit rate capacity. This effect is present in all types of cable. One way it could be reduced is by a truly monochromatic light source (i.e., one which radiates light at only one wavelength). Another way material dispersion can be reduced is by using long wavelength transmission. Material dispersion approaches zero at a wavelength around 1.3 micrometers. Material dispersion is also referred to as wavelength dispersion.

Attenuation

Attenuation is another important characteristic of an optical fiber cable. Fiber attenuation is measured in decibels (dB) the same as wire attenuation. A decibel is 10 times the logarithm of the ratio of two power levels. For example, if the ratio of the power input to the power output of a one kilometer fiber is 10, the fiber has an attenuation of 10 dB per kilometer; if the ratio is 100 the attenuation is 20 dB per kilometer.

In a wire cable system, a principal cause of attenuation is electrical resistance. The optical equivalent of electrical resistance is called absorption which, in this particular case,

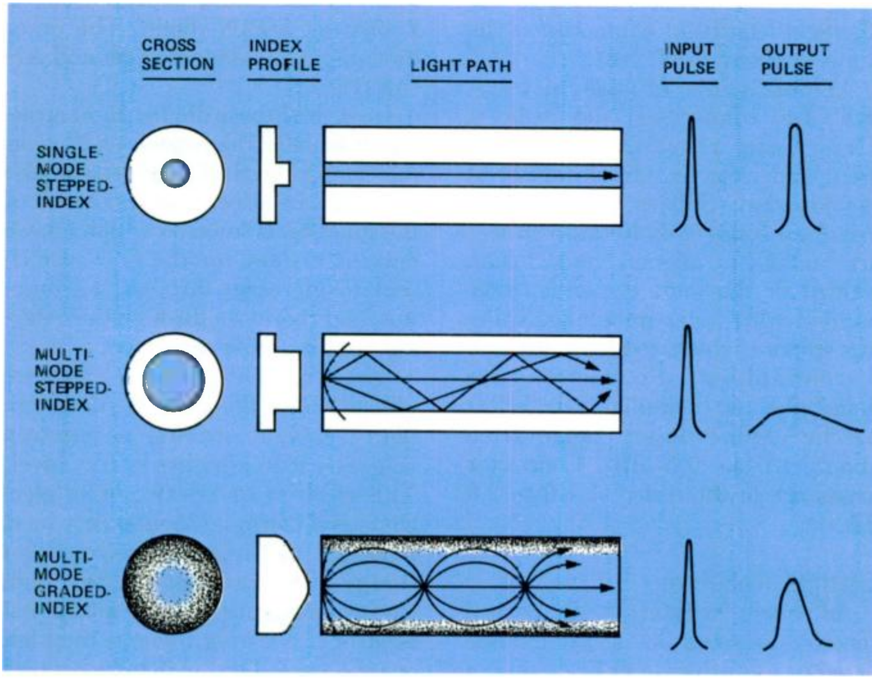


Figure 7. Pulse Spreading, Various Cables.

means the conversion of light into heat.

One cause of absorption is impurities in the core material. Impurities can be reduced by carefully controlling the core material.

Another cause of absorption loss is scattering-effect. Scattering loss results from fluctuations in the glass density and imperfections at the core/cladding boundary. Again, careful construction and quality control can reduce these losses.

Scattering loss is also inversely proportional to the fourth power of the light wavelength, so scattering losses are lower at longer wavelengths. However, efficient, cost-effective, reliable light sources and detectors are currently limited to wavelengths from about 0.8 to 1.0 micrometers. Intensive research and development efforts are underway to perfect sources and detectors which provide satisfactory operation at longer wavelengths.

Radiation losses are also present in fiber optical systems. Radiation losses result from minute bends in the fiber and from dirt or abrasions on the fiber's outer surface. Microbends often occur during cable manufacture. These can be minimized by avoiding contact between the fibers and other substances—as can dirt and abrasions. Again, careful fabrication and quality control are important.

Total cable losses vary greatly between types of cable and for different wavelengths, but usually range between 2 and 20 dB per kilometer. If the attenuation specifications are being used to judge the relative transparency between two or more cables, it is important to be sure the comparison is made for identical lengths of cable and at the same wavelength of light.

Another source of losses in a system are connectors and splices. These losses result from misalignment and reflective discontinuity at the junction. Splices have a lower loss than connectors because splices are carefully aligned and fusion welded or the joint is permanently bonded with index-matching, splicing epoxies which reduce reflection discontinuities. Connectors are detachable, so their alignment is less precise. Splice losses range from about 0.1 to 0.6 dB. Connector losses are in the order of 1.0 to 2.0 dB.

Optical Receiver

As shown in figure 8, an optical receiver consists of a photodiode detector, a driver amplifier and a demultiplexer. The following paragraphs discuss each of these parts in turn.

At the receiving end of the optical communications system, the first step in recovering the intelligence used to modulate the transmitting light source is to convert the incoming light back to electrical signals. The device used to accomplish this conversion is called a detector or demodulator. Two types of photodiodes are most useful for this purpose. One of these diodes consists of a PN junction with an intrinsic layer between the P and N regions. It is known as a PIN diode. The other diode is the avalanching photodiode (APD).

In each of these diodes, light striking at or near the junction will raise the energy level of electrons in the junction. In effect, the resistance of the junction is lowered which allows current to flow (or the flow of current to increase) through the junction and therefore through the external circuit across the diode.

The avalanche photodiode is more efficient than the PIN. As shown in figure 9, light striking an electron will raise it to a higher energy level. This electron strikes two other electrons and increases their energy level although the original electron loses energy in the process. The two high energy electrons strike additional electrons, boosting them to the high energy level. This avalanche process continues with an increasing number of electrons achieving higher energy levels.

Since higher energy electrons in the junction represent current flow, the avalanche effect causes a gain in signal power through the diode. Because they have gain, APD's have better sensitivity than PIN diodes.

The sensitivity of an optical detector is defined in terms of the minimum light input required to provide a given performance level. The performance level is stated in terms of signal to noise ratio for analog

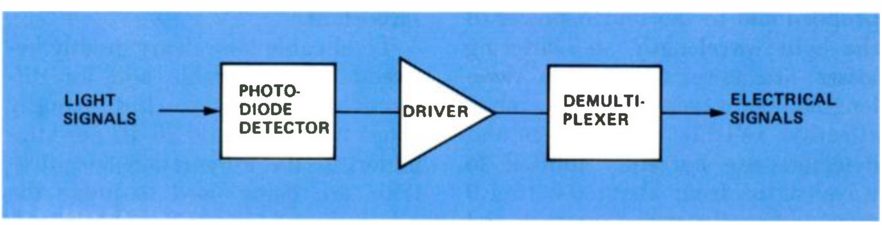


Figure 8. Optical Receiver

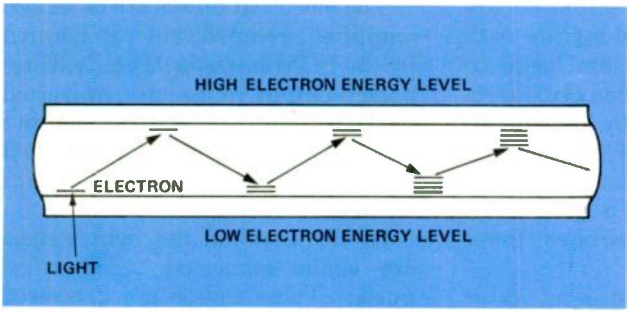


Figure 9. Avalanche Effect.

systems and in terms of bit error rate for digital systems.

The APD is more suitable than the PIN for systems with large bandwidth requirements. However, APD's have the disadvantages of high bias voltage requirements and temperature sensitivity. These factors make it necessary to provide a regulated bias supply with voltages in the order of 100 to 400 volts. Operating at higher bias voltages may also require additional circuitry to compensate for temperature-gain variations.

The electrical output signals from the photodetector are connected to the input of a driver amplifier. The signals at this point may be either analog or digital. The amplifier design is essentially the same in either case. It is important that this amplifier be of a low noise, broadband design and that it does not load-down the photodiode.

The output of the amplifier is an exact replica of the baseband signals used to modulate the light transmitter of the distant end. These signals are passed through the demultiplexer to separate and recover the original information channels.

Comparison Optical Fiber-Wire Cable

Fiber optical cable has several advantages in comparison to wire cable. One of these is fiber's immunity to electromagnetic interference. Glass is an insulator so current cannot be induced in it from surrounding sources. Fiber cable may be run parallel and adjacent to power lines without picking up any interference. Similarly, light signals on fiber cable do not cause electromagnetic radiation. So, signals on the cable are inherently secure against eavesdropping. This is particularly important for military applications and voids the necessity for the complex encryption devices used for wire and radio communications.

A multipair fiber cable is much smaller than a multipair copper cable capable of carrying the same amount of traffic. This is an important advantage when installing cable in crowded ducts under city streets. Replacing existing copper with smaller diameter fiber cables, capable of handling a greater volume of traffic, is an attractive alternative to digging up the street and installing new duct. Also, fiber cable is more flexible and lighter weight which makes it easier to "snake" through duct. Fiber cable is also more resistant to heat and moisture than copper cable which is an advantage where ducts may be shared with steam and water pipes.

Signals are attenuated as they pass through any transmission medium. "Repeater" amplifiers are inserted at intervals along the path to overcome the signal loss due to attenuation. The distance between repeaters is determined by the path attenuation. The greater the attenuation per unit length, the more repeaters required for a given path. Lower attenuation requires fewer repeaters.

High-quality optical fiber cable has substantially less attenuation than twisted-pair or coaxial cable, so a fiber system requires fewer repeaters than either of these wire systems. The fact that a fiber system requires fewer repeaters is a definite economic advantage. However, this advantage is somewhat reduced by the fact that the fiber optical system repeater is more complex than the wire system repeater, as shown in the following discussion of figure 10.

Referring to the figure, analog signals enter the terminal and are converted to PCM signals (encoded) by the PCM channel bank (MUX). The digital signals are amplified and used to modulate the LED.

The light output pulses of the LED are carried over an optical fiber cable to the repeater input. The photodiode at the repeater input converts the light pulses to electrical pulses.

The electrical pulses are detected, amplified, retimed and regenerated by the PCM repeater. The PCM repeater output pulses are converted back to light pulses by another LED. These pulses are transmitted over optical fiber to the distant terminal.

At the terminal the light signals are again converted to electrical pulses. These pulses are processed and decoded, just as any PCM received signals, to return them to their original analog form. Signals to be transmitted in the opposite direction go through the same process.

A conventional wire cable system operates in a similar manner but does not require any of the optical components. Wire cable is used in place of the optical fiber.

In a typical system several repeaters are required between terminals. Since an optical system requires fewer repeaters, the total cost of repeaters for an optical system of appreciable length will be less than the repeater costs for a wire system of the same length. The repeater cost comparison is even more favorable when optical systems are compared to coaxial cable systems but is not so favorable when the comparison is made to microwave radio systems.

Currently, the greatest use of op-

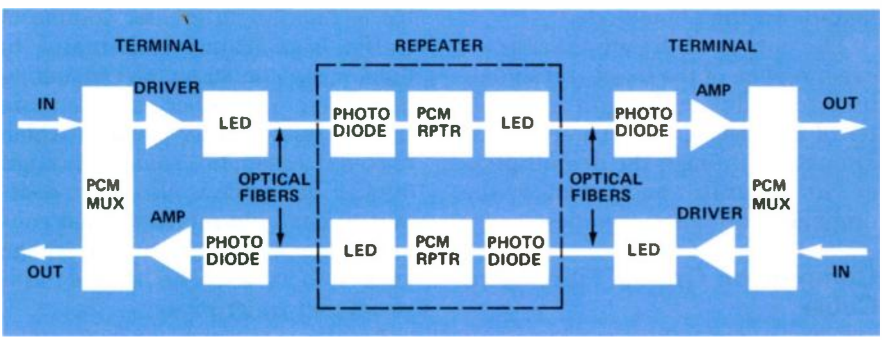


Figure 10. Optical PCM System.

tical fiber transmission is in digital trunks between telephone offices. This application has won wide acceptance by telephone companies. A substantial portion of the future requirements for high-density trunks will be filled by fiber optics rather than paired copper cable, coaxial cable or microwave radio.

Optical fiber has a greater bandwidth than wire-cable. The advantages of a wide bandwidth are that a greater volume and variety of signals can be transmitted over a wideband system. The types of signals which are transmitted over telecommunications systems, in order of bandwidth requirements are:

- Voice
- Special services
- Data; low, medium and high speed
- Television, including high fidelity music.

Special services include health care systems such as medalert, security systems, viewdata, energy management, facsimile, teletype and telex. Figure 11 charts the ability of various transmission systems to carry the types of signals listed above.

Referring to the figure, coaxial cable systems have the greatest broadband capability. There are coaxial cable television systems in service which carry upwards of fifty TV channels. Eight video channels per fiber is the maximum achieved by fiber optics to date, although a nine channel experimental system is planned to be placed in service sometime in 1981.

Component linearity problems are the limiting factors on the fiber system. When these problems are solved, the TV channel capacity of optical fiber systems may equal or surpass that of coaxial systems. As previously stated, the optical/electrical conversion step adds to the cost of fiber systems but they have the advantage of greater repeater spacing. Repeaters are known as "trunk amplifiers" in cable television systems.

There are several techniques for transmitting video over optical fibers. The simplest method is illustrated in figure 12. The video-baseband, electronic signals are used to intensity modulate an LED.

The maximum path length is established by the light source output power, the cable loss, the photodetector sensitivity and the required signal to noise ratio of the video output signal at the receive end. Considering all these factors,

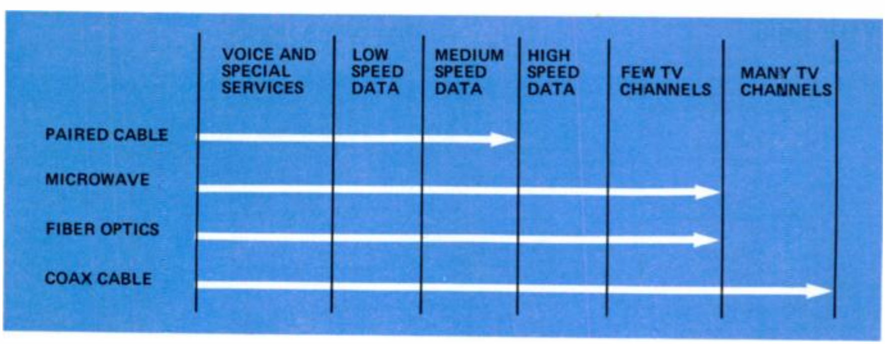
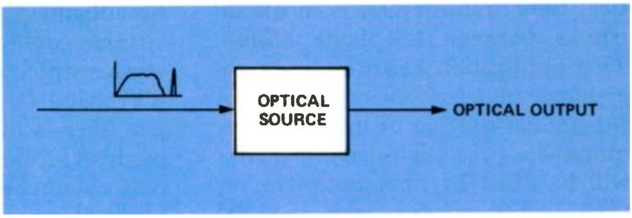


Figure 11. Broadband Capabilities.

Figure 12. Intensity Modulation.



the path loss of the optical fiber is limited to around 10 to 15 dB, which equates to a fiber length between 3 and 6 kilometers. In its most straight-forward form, this system requires an individual fiber for each video signal.

Wavelength division multiplexing (WDM) is a technique for transmitting two or more optical signals over a single fiber. Light sources operating at different wavelengths are used in systems of this type. At the transmit end, the sources' outputs are coupled to a single fiber. The outputs are separated at the receive end. If each source is modulated with a different signal, several signals can be sent over a single fiber, as shown in figure 13.

Another method for transmitting video is shown in figure 14. The light source is intensity modulated with a frequency modulated radio frequency carrier. Video signals are used to modulate the rf carrier which might be in the 30 to 300 megahertz range; corresponding to the entire television VHF band.

These frequency modulated, intensity modulated (FM-IM) systems can use a laser instead of an LED to achieve a higher signal to noise ratio than the previously described systems. The permissible path loss is around 30 dB so substantially longer paths are possible.

Several frequency modulated rf carriers at different frequencies can be combined to form a frequency division multiplexed (FDM) signal. This signal is used to intensity modulate the light source. This FM-FDM-IM process allows several video channels to be transmitted over a single fiber, as shown in figure 15.

The number of channels can be increased by using a combination of FM-FDM and wavelength division multiplexing methods, as shown in figure 16. However, the per channel receive signal-to-noise ratio is reduced each time a channel is added, so the number of channels is limited. This is true for both the FM-FDM-IM and combined FDM-wavelength division systems.

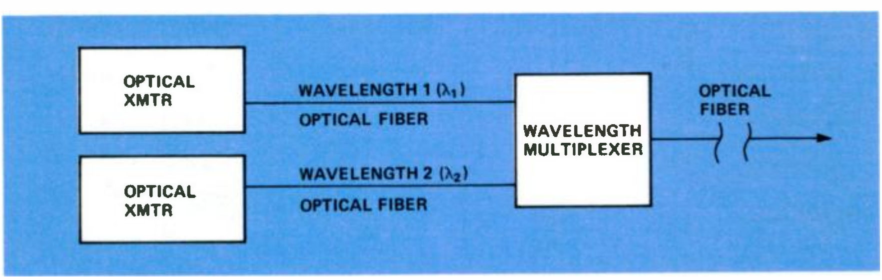


Figure 13. Wavelength Multiplexing.

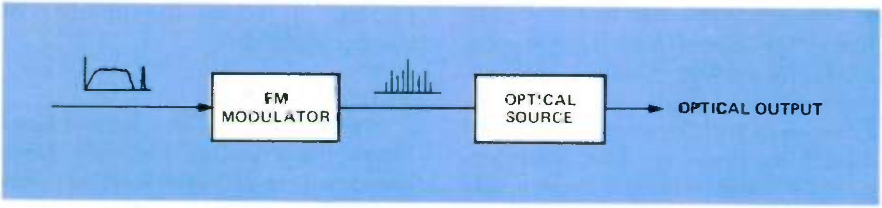


Figure 14. Frequency Modulation/Intensity Modulation.

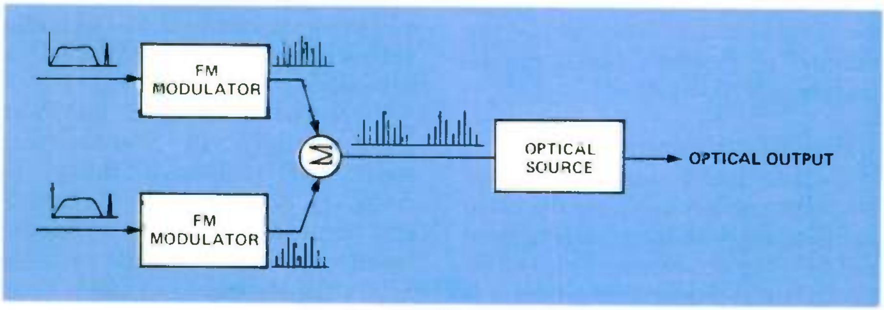


Figure 15. FM-Frequency Division Multiplexing-IM.

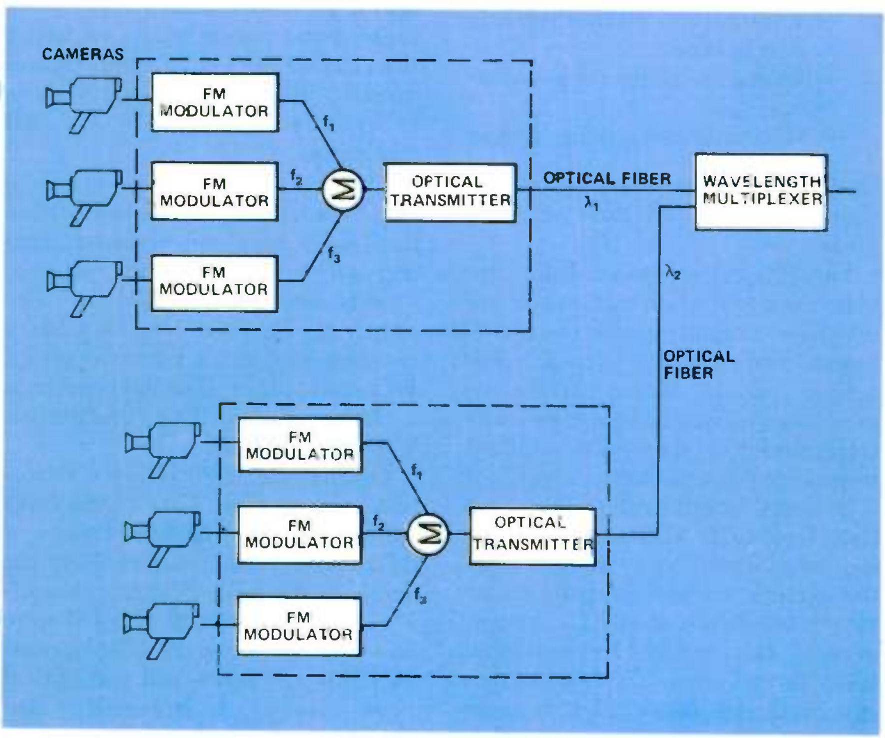


Figure 16. FDM-FM Combined with WDM.

Video channels can be encoded to form PCM signals which are used to modulate a laser. This method provides the best signal to noise ratio. Fiber span with losses in the order of 40 dB are possible. Also, repeaters can be used without appreciably degrading the signal so long-haul systems are feasible. The drawback is the large bandwidth requirements for PCM video. This limits the number of channels which can be transmitted over a fiber.

Video Applications

Remote monitoring and surveillance systems probably are the video applications with the greatest potential for fiber optics use. This is particularly true for systems where it is important to provide any of the following characteristics:

- — Immunity to electromagnetic interference
- — Immunity to electrical potential
- — Immunity to lightning strikes

Optical fiber systems are superior to wire systems in all three of these areas.

Surveillance systems usually provide black and white transmission of television signals from remotely located cameras to a control monitoring point. Transmission is generally one way although two-way transmission is sometimes required to provide camera control signals.

Systems lengths range from less than 5 up to 20 kilometers. For the shorter systems, video signals from the camera are used directly to intensity modulate an LED. Longer systems use an FM-IM modulated laser. Long systems, with a number of surveillance points, might be most economically served by using wavelength or frequency division multiplexing to reduce the number of fibers required.

Broadcast TV

Practically all of the optical fiber video transmission methods have been used for TV broadcast applications. The systems must transmit a color video signal with a 5 megahertz bandwidth plus an audio signal with a 15 kilohertz bandwidth. The audio uses a subcarrier above the video baseband.

Fiber optics are used for short links, studio to transmitter; auditorium, stadium or theater to studio, or as end links in the broadcast network. Industry standards specify a minimum signal to noise ratio of 58 dB, end-to-end for a long-haul broadcast link. Since the noise contributions of the end links are only a part of the total system noise, their performance must be better than that of the total system. Consequently, the end link signal to noise ratio specification is 67 dB minimum.

The first fiber end link to a television broadcast network was installed between a telephone company central office in downtown Tampa, Florida and Tampa Stadium. The link is 8 kilometers long and has a repeater located 6.6 kilometers from the central office. The light source is a laser diode. The modulation method is FM-IM.

During the 1980 Winter Olympics, two optical fiber video links were used to transmit signals a distance of 3.3 kilometers, from the games to the Lake Placid central office. Diode lasers and FM-IM were also used for this path. The upcoming 1984 Olympics will use optical fiber systems to transmit video signals from several locations to a Los Angeles central office. Digital transmission will be used with a line rate of 90 megabits per second.

Voice Frequency Transmission

Telephone companies define a voice channel bandwidth as 300 to 3000 Hertz. Voice channels are used to carry electrical signals analogous to conversations or data signals which have been converted to analog form.

Several methods are used to multiplex vf channels for carrier transmission over twisted pair, coax or microwave radio. As previously discussed these multiplexing systems fall into two categories; Frequency Division Multiplexing and Time Division Multiplexing. Frequency Division Multiplexing systems transmit analog signals. Time Division Multiplexing systems transmit digital signals.

Low density analog systems use double sideband modulation with carriers in the 8 to 140 kilohertz range to frequency division multiplex up to 6 vf channels. High density systems use single-sideband, suppressed-carrier modulation to multiplex up to 600 vf channels.

Digital systems use pulse code modulation to time division multiplex 24 vf channels into the 1.544 megabits per second T1 carrier or 48 channels into the 3.12 megabits per second T1C carrier. Digital systems require a greater bandwidth than an analog system with the same number of channels because a signal in the general form of a sine wave must be sampled at least twice per cycle to be accurately represented digitally. For example, a signal with a 4,000 Hz bandwidth must be sampled at a rate of 8,000 times per second, minimum.

The outputs of any of the above multiplex systems can be converted to light signals for transmission over optical fibers. The low density analog carrier can be used to intensity modulate an LED in a short range FDM-IM optical system.

There is a demand for this kind of low-density system to serve as an entrance link to power generating stations. The insulating qualities of the fiber protect personnel and equipment from voltages that might accidentally be placed on the communications systems by line to ground faults. Fiber systems provide more positive isolation from these faults and are more economical than wire systems which rely on transformer or capacitor isolation devices.

These optical systems are seldom more than one or two kilometers long. The quality of the voice channels is very good. They can be used for data transmissions as well as voice.

The analog output signal from the higher density FDM system can be used to frequency modulate an rf carrier. The modulated carrier is used in turn to intensity modulate an LED or laser. The result is a high channel capacity, FDM-FM-IM optical fiber system.

There is a demand for short to medium length (up to 12 kilometer) systems of this kind to serve as links between microwave radio stations and communications centers in congested areas. There are two reasons for this demand. One reason is the limited microwave frequency spectrum. Generally, it is difficult to obtain a frequency assignment in these areas because most of the frequencies have already been licensed. The second reason is the increasing number of objections, by environmentalists and municipal authorities, to microwave antenna installations. Optical systems suitable for this purpose should be available toward the end of 1981. A possible arrangement for such a system is shown in figure 17.

The digital output signals of a PCM system can be used to modulate an LED or laser. As previously stated, PCM optical trunks between telephone offices is the largest application of fiber optics to date. However, the use of digital microwave systems is increasing and PCM optical systems could serve as entrance links for these systems. Digital microwave systems are becoming more popular, despite the higher bandwidth per channel requirements, because they cost less than FM systems when the cost of the associated multiplex and switching equipment is taken into consideration.

Data and Computer Systems

Several properties of fiber optic transmission systems make them particularly suitable for computers and data network applications. One such application may be considered as internal to a computer. The transmission distances are very short. For example, between computer components inside a cabinet or between cabinets or racks in the same room. Since the distances are so small, a directly modulated LED can be used for the transmitter and a PIN diode can be used for the receiver.

High transmission speeds and very small error rates are required. Speeds around 200 megabits per second with error rates as low as 1 part in a thousand billion (10^{-12}) are typical. The smaller space requirement of fiber in comparison to coaxial cable and the elimination of errors due to potential differences and ground loops are the principal advantages gained by using fiber in this application.

Another application for fiber optics is in inter system communications. These systems interconnect between computers and peripheral devices within the same building or between buildings or cities. Transmission distances range from less than 100 meters up to 12 kilometers.

The interconnections may be point-to-point, a looped network, a common-bus parallel arrangement or a star network. A lack of suitable coupling devices (taps) makes it difficult to establish some network arrangements. However, this problem

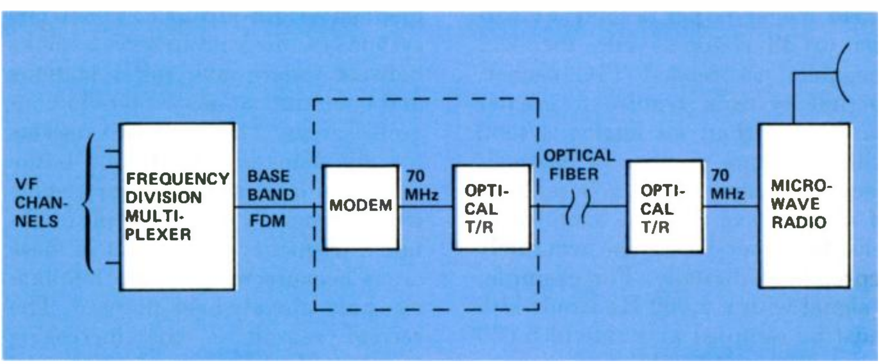


Figure 17. Fiber Optics Link to Microwave Radio.

will be solved when new taps are developed.

Data rates up to 64 kb/s are used for computer to peripheral connections. Depending upon the accuracy requirements of the specific application, bit error rate specifications vary from 10^{-6} to 10^{-9}.

The stringent space and weight limitations of aircraft, ships and submarines and their increasing use of computers and electronic devices combine to make optical fiber systems an excellent choice for these applications. The systems can be used to interconnect between component parts of computerized systems used for navigation and control and to connect these systems to remote display devices. In many ways aircraft systems are small-scale versions of the data systems previously described but aircraft systems may have greater accuracy requirements. Also they must operate in adverse environments of altitude, temperature and vibration.

An emerging opportunity for fiber optic systems lies in the area of business communications. There is a growing demand by business for an integrated communications system capable of handling all types of traffic, voice, data and video.

Such a system is technically and economically feasible. The nature of the traffic and the technology make a digital system most suitable for this application.

Since the greatest current demands for this type of system is by business, there is a requirement for a system to operate on the user side rather than the telephone company side of a private branch exchange (PBX).

The operating specifications for this system are the same as those previously described, insofar as voice and data traffic are concerned. The per channel bandwidth requirements for video signals are generally somewhat less than those for broadcast or cable television systems.

Optical fiber systems are quite suitable for small to medium sized systems of this kind. Several of these systems could be tied together by microwave radio or land lines. This kind of cluster arrangement appeals to businesses with branches in several different geographic locations.

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