FIBER OPTICS
For Non-EE Educators

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Fiber optics is a technological break-through that is having a revolutionary impact on the electronic industry and the field of medicine. Television signals can easily be carried over a single fiber, thereby opening up new possibilities for both entertainment and business purposes. Buildings can be "wired", with the almost invisible fibers, to provide internal communication services.

Much of the cabling that interconnects metropolitan telephone switching centers goes through underground ducts. Light-wave communications with their high capacity and small size not only are making better use of the existing ducts, they do not require amplifiers in manholes to boost the signals along a typical route. A growing market for optical light guides is in machine tool servo-controls where computers are calling the signals.

This paper will be a literary research on the history, development, and application of the fiber optics as it applies to the field of electronic communication. The body of the text will cover the theory of light transmission through the fiber, the types of fibers, how the fibers are drawn (made), and the typical construction of a single fiber optic cable.

HISTORY

Visual communications is not a new technology. Remember the smoke signals of the American Indians or the English built bonfires that warned of the approach of the Spanish Armada. Or how about Paul Revere's famous ride that was started by light signals in the church belfrey. A system of hilltop semaphore stations was built throughout France around 1790, and stayed in operation until it was superseded by the electric telegraph. Even today the U.S. Navy utilizes a system of flags, semaphore, and flashing lights to transmit coded messages between ships at sea. In 1880, Alexander Graham Bell invented a system in which human speech patterns were used to modulate a beam of light by vibrating a mirror. The beam was aimed or transmitted to a selinium detector whose resistance varied with the light intensity. This inturn caused a varying current in the telephone receiver (Boyle, 1977).

With the invention of the laser in 1960, coherent sources of electromagnetic radiation reached the visible region of the spectrum and attempts were made to use the laser for communication purposes. The first experiments involved light transmission through the atmosphere. However, unlike radio systems at longer wavelengths, this system was severely limited by scattering of the light beam by fog, rain and snow. Only special applications in arid regions of the world and in the vacuum of outer space seem promising. As Dr. Marcuse (1973) stated: "For reliable light communication under terrestrial conditions, some type of light waveguide is desirable to protect the light beam from atmospheric disturbances" (p. 655).

Early attempts at light guidance over long distances utilized the focusing properties of lenses and curved mirror to counteract the natural tendency of light to spread by diffraction. Such lens waveguide systems are workable, however their costs are high because of the careful alignment and controlled positioning of the lens is required (Marcuse, 1973).

Back in 1870, the British physicist John Tyndall demonstrated that light can be conducted along a curved path. He had a thin stream of water exiting from a hole in the side of a tank. A light shined into the tank will emerge at the hole and follow the downward curving stream. We have utilized this effect in illuminating fountains and in advertising displays with glass or plastic rods serving as the conductors. By 1960, a new "light pipe" was being transformed from trivial curiosity to an important optical device. Bundles of very thin glass fibers were being produced which were both flexible and transparent. Thus we had a flexible light pipe that could look around corners and see things that were hidden from view. In proposing that glass fibers had a direct application as a fiberscope for examining interior parts of the body, Narinder S. Kapany (1960), also described another use. Kapany stated that:

> It is possible to draw still thinner fibers, but they no longer act as simple light pipes. Their diameters are now comparable to the wavelength of the light, and they act as waveguides, transmitting energy in complex patterns that are no longer isolated from one another. (p. 74)

However, even though they appeared clear and transparent, losses through the fibers were huge. A bundle seven feet long only delivered 50% of the entering light (Kapany, 1960). Even high quality optical glasses used to fabricate lenses had losses of 1000 dB/km or more (Marcuse, 1973). Charles Kao at Standard Telecommunication Laboratories proposed that the high loss of most glasses was not an inherent property, but was caused by impurities. He stated in 1966 that fused silica (quartz) may have losses as low as 80 dB/km and would be a practical light waveguide (Marcuse, 1973). In 1970, the Corning Glass Works produced a fiber whose loss was measured to be 20 dB/km at the frequency of the helium-neon laser (0.6328 micrometers.) Since this breakthrough, fiber losses have steadily been reduced. The best fibers that are commercially available at the present time have loss minima of 4 dB/km (ITT advertized specifications, 1979).

How low can the losses be? Researchers at the Nippon Telegraph and Telephone Public Corporation in Japan have transmitted a 800 megabit-per-second signal through 30 kilometers of continuous single-mode fiber optic cable. A laser wavelength of 1.3 micrometers was used. The overall loss of the optical cable (including the splices every 2 km) came to only 0.73 dB/km (Optical Spectra, p. 26, Nov. 1979). This agrees with the theoretical predictions showing a probable fundamental limit of 0.5 dB/km for silica fibers (Electronic Review, 1977).

Because of the 0.5 dB/km limitation, other materials are being investigated. Hughes Aircraft Company's Research Laboratories had demonstrated a polycrystalline core technique that permits fabricating IR fiber-optic waveguide. They have achieved optical transparency for the broad spectrum of 0.6 micrometers (in the visible) to approximately 35 micrometers (in the infrared.) These fibers have a loss of 0.01 dB/km and a pliable quality that allows bending them easily without damage (Electronic Review, 1977). While this performance shows what is possible with further development in improving low-loss communications links, applications in medicine are enormous. The possibility of transmitting a low-power laser beam has great significance to physicians as a highly selective cauterization instrument.

The developments for creating a light communication system has not been confined to the fiber. Although the gas laser was the key in 1960, it was big and inefficient. Plus the fact that the wavelength of the least attentuation within glass fibers is not in the visual region, but in the near intra-red. In 1962, the first "solid-state" laser was developed by two separate groups working independently. The threshold current for laser action in the solid-state devices was quite high, and very low temperatures had to be maintained (Cook, 1973).

By 1971, two new solid-state infrared lasers became promising as sources for optical fiber transmission; the neodymium-doped yttrium aluminum garnet laser (neodymium YAG laser), and the gallium arsenide laser. The neodymium YAG laser radiates at a wavelength of about 1.06 micrometers and is efficient in converting drive power into coherent light. The draw-back of this device is that once it is turned on its coherent radiation cannot be turned off quickly, so it's beam must be modulated by another device (Cook, 1973). The gallium arsenide laser is an injection-diode device made in layers of semiconducting material. This diode can be turned on and off rapidly by simple modulation of the electric current. It has only been the early failure rate that slowed their implementation into workable systems. An alternate to this as a light source is the light-emitting diode (LED). Although it is made of the same materials as the injection laser, the LED radiates a wider spectrum of light frequencies.

By utilizing only a small part of the full range of light frequencies generated by the laser, a single system could in principle simultaneously carry the telephone conversations of every person living in North America (Boyle, 1977). A few examples of existing applications are:

(1) Telephone inter-switching center communications of under 5 km (3 mi) are being converted to fiber optics. Systems in Chicago and Long Beach, Calif. have been operational for over two years.

(2) Cable TV installations in the US, UK, Germany, and Japan are incorporating fiber optics as a replacement for microwave transmission links and coanial conductors.

(3) Machine tool manufacturers are using optical fibers for various light transmission requirements and data transfer applications.

(4) Fiber optics cable systems are used for nuclear power station instrumentation. They provide isolation between primary and secondary circuits.

(5) The Navy has two ships at sea with fiber optics systems (Hirschfeld, 1978).

THE FIBER

The simplest optical fiber consists of two concentric rods of dielectric materials with different refractive indices. The geometry theory for understanding light rays is a simple one; all rays travel in a straight line. Along with this, one must understand the index if refraction. The index of refraction for any optical medium is defined as the ratio between the speed of light in a vacuum and the speec of light in another medium (Jenkins, 1976). Whenever a ray of light is incident on the boundary separating two different media, part of the ray is reflected back and the remainder is refracted (bent) as it enters the other medium. As shown in figure 1a, the reflected ray lies in the plane of incidence and on the opposite side of the normal. This relationship is known as Snell's law (Jenkins, 1976).

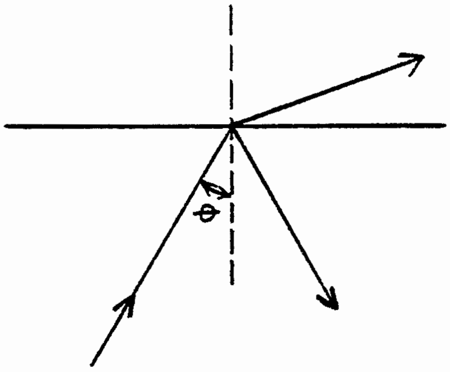

Figure 1a. SHALLOW ANGLE

If the angle between the incident ray and the perpendicular is great enough, the refracted ray will bend 90 degrees from the perpendicular as shown in figure 1b. The angle of incidence at which this occurs is called the critical angle. At angles of incidence greater than the critical angle, no light will pass into the second medium, as shown in figure 1c. Therefore, the light is entirely reflected back into the first medium and if the interface is very smooth and is protected from contamination, virtually no light is lost in this total internal reflection (Kapany, 1960).

For the simplified schematic shown in figure 2a, the core will have the highest refractive index (n_1 in figure 2b) and the cladding index will be lower (n_2 in figure 2b.) The index for air will be approximately the same as a vacuum or unity (n = 1 in figure 2b.)

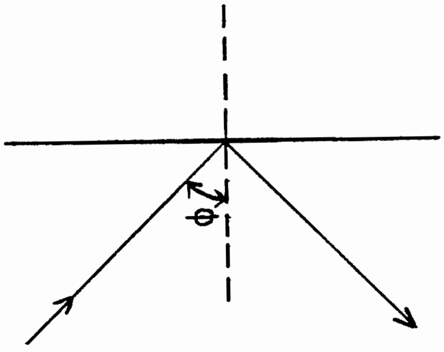

Figure 1b. CRITICAL ANGLE

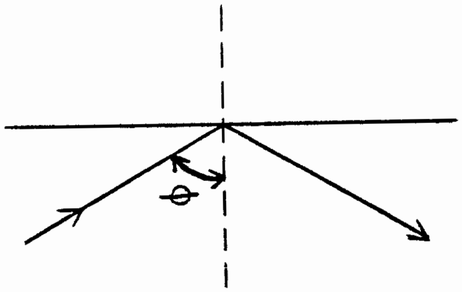

Figure 1c. STEEP ANGLE

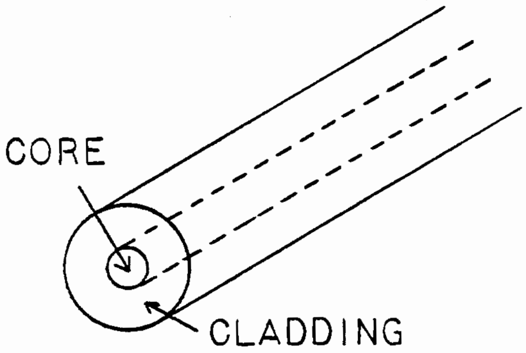

Figure 2a. Schematic of a cladded fiber

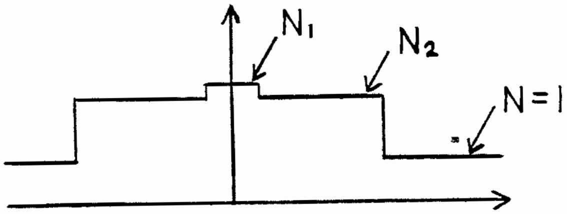

Figure 2b. Refractive index distribution

In order to understand the principle of light guidance in the fiber, figure 3 shows the cross-section of the fiber whose refractive index profile is shown in figure 2. If the angle is large enough to provide total internal reflection, then the law of reflection requires that this angle is maintained for all subsequent reflections. Rays that travel at an angle too small for total internal reflection are only partially reflected at the core-cladding boundary. These rays could travel within the cladding but this would be undesirable. If these rays were allowed to reach the detector or were re-propagated into the core, the signal would be distorted. This can be prevented by having the outer surface of the cladding covered with an absorbing material (Marcuse, 1973).

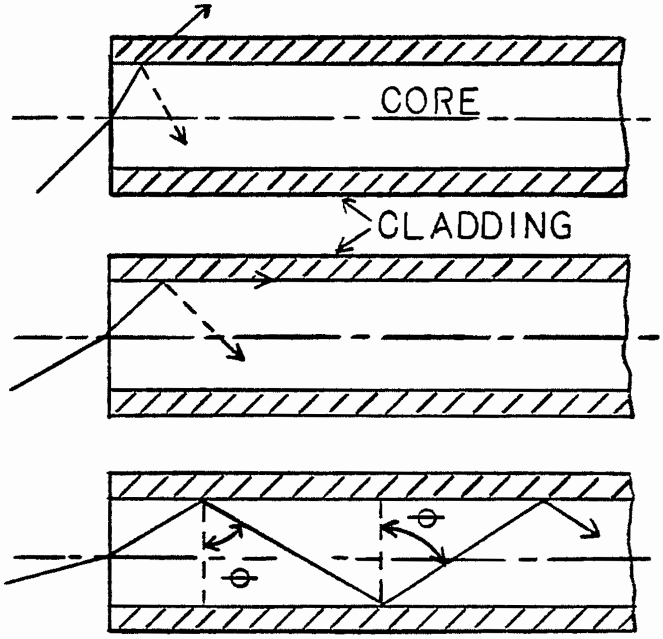

Figure 3. Snell's principle

There is an additional requirement to the fact that the angle must be larger than the critical angle of total internal reflection. The multitude of rays travelling in the core must superimpose themselves to that constructive interference results. The addition of this requirement limits the possible angles to a discrete set of values. This occurs when the dimensions of the fiber core are comparable to the wavelength of light and the fiber acts as a waveguide. The waves, or complex patterns of transmitting energy, that satisfy the requirements for guided transmission inside the core are called modes (Marcuse, 1973).

One type of fiber is the "single mode" fiber. It can be produced by either keeping the core radius sufficiently small or by restricting the refractive index difference to small values. The total number of modes that can be supported is approximately equal to:

$$2\left(\frac{a\pi}{\lambda}\sqrt{n_1^2 - n_2^2}\right)^2$$

where "a" is the core radius and is the wavelength of the radiation. Figure 4 shows the field plot of the lowest order (HE_{11}) mode. By making the fiber core 2 to 4 microns in diameter, all modes except the HE_{11}

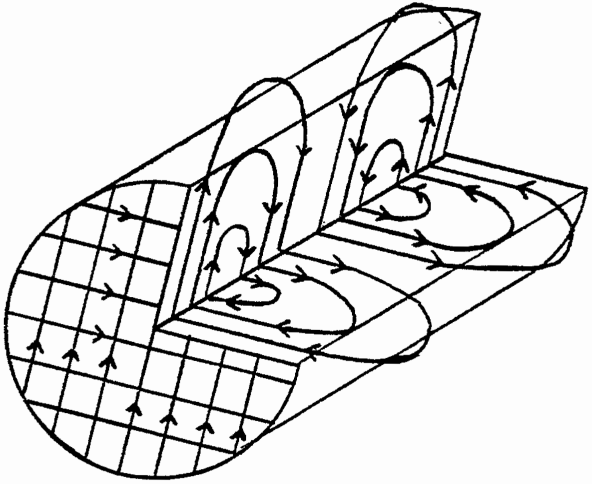

Figure 4. HE_{11} mode

mode are eliminated. For high capacity systems, single-mode operation of the fiber is desirable (Marcuse, 1973).

A "Multimode fiber" is larger in diameter (core is about 50 microns) and accepts wider angles of input light rays. Its light-gathering ability is good, but each mode travels at a slightly different group velocity (v_g.) Therefore, a short pulse of light will travel through the fiber, split up into a sequence of pulses, that arrive at the far end at different times. This dispersion has a broading effect on the pulse and this inturn reduces the bandwidth. The width of the detected pulse can be regarded at Δt, where $\Delta t = \frac{L}{c}(n_1 - n_2)$, and the pulse width will increase linearly with the fiber length. "L" is the length of the fiber and "c" is the velocity of light (Marcuse, 1973).

Another type of optical fiber is called a "graded index fiber". Instead of using the abrupt index distribution of figure 2, it is possible to change the refractive index continuously from a maximum value on-axis to a lower value at the boundary (figure 5a). The trajectory of the ray within the fiber follows a curved path as shown in figure 5b. The index distribution can be approximated by the equation:

$$n = n_0(1 - \frac{r^2 \mu}{a^2}).$$

The parameter (μ) determines the rate of change of the refractive index and "a" is the radius of the fiber (Marcuse, 1973).

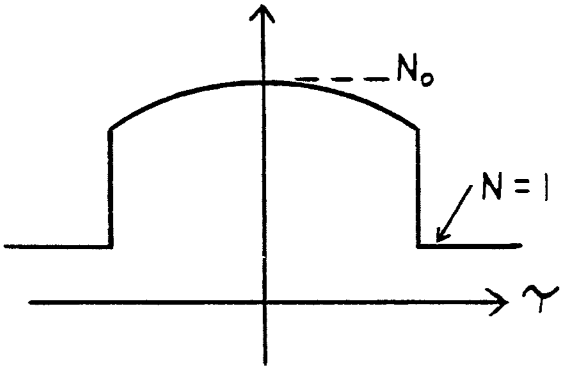

Figure 5a. Refractive for graded index fiber

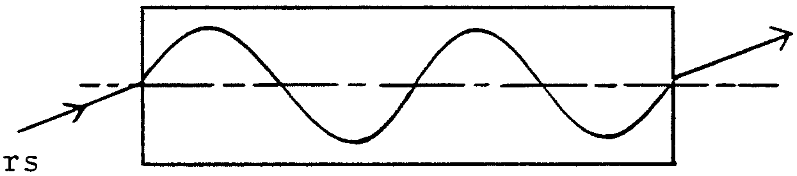

Figure 5b. Ray trajectory in a graded index fiber

A recent development in the configuration of the fibers is the double-cladded fiber or more commonly referred to as the "W-type" indexed fiber. In this configuration, the core can be increased in diameter and the intermediate clad has a large ratio to n_0. This allows a large critical angle and good light gathering capabilities. The bandwidth is determined by the index of the outer cladding. The smaller the ratio of the index to n_0, the smaller will be the number of modes existing within the fiber (Tanaka, 1976). The w-type fibers are commercially available in single-mode, mulimode, and graded-index glass fibers (ITT specification sheets, 1979). They are not available in the plastic-type fibers.

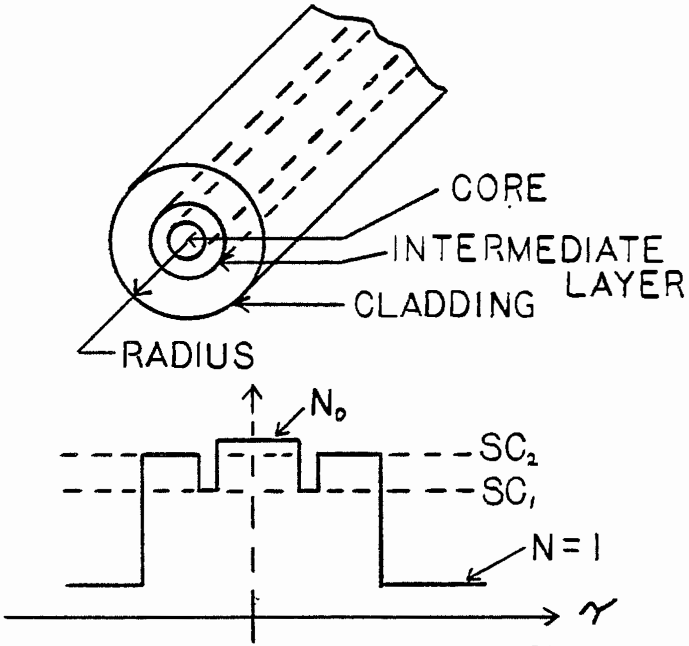

Figure 6. W-type fiber

The raw material for making glass usually is iether fused silica or a mixture of soda, lime, and more than 60% silica. To prepare the compound silicate glasses after the materials are purified, they are heated to 1500°C, stirred to achieve homogeneity, and "soaked" to remove any bubbles. The bulk glass is fine annealed, then cut into rods and tubes, are rounded, and then are highly polished. There are two basic techniques for drawing fibers with a discrete index of refraction between the core and the cladding. The first is the rod-and-tube method. A rod of glass (core material) is inserted into a glass tube (clad material) and then fed into an electric furnace. The glass fiber drawn from the end of this heated preform will have a reduction ratio of 100:1 in diameter. The second method is the "double-crucible" method. The core glass is placed inside the inner cruicible while the cladding glass is contained in the outer region. Both crucibles converge at the bottom to form a double nozzle from which the fibers are drawn (Pearson, 1971). The rod-and-tube method can be utilized in a technique comprising controlled chemical-vapor deposition. The core material or intermediate cladding material is vaporized, mixed with oxygen and passed through the tube of cladding glass. Simultaneous oxication and fusion occurs on the inner surface of the tube. The fiber emerges, it has a tensile strength as high as 500,000 psi. If nothing is done to protect the fiber, microscopic cracks will form in its skin and reduce the fiber strength to 30,000 to 40,000 psi. (Pearson, 1971). A heavy cladding helps retain the original strength, isolates the light carried in the core from the outside, and promotes easier handling.

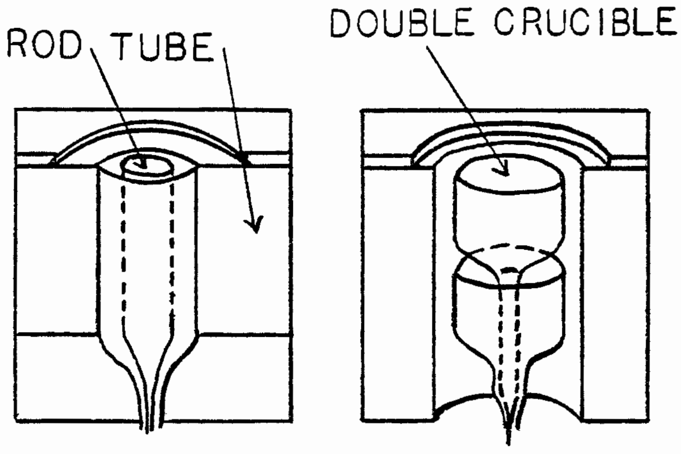

Figure 7. Fiber drawing technique

Mechanical endurance is often the chief criterion in a fiber optics system. In this respect, plastics are more flexible tougher (less likely to crack), easier to fabricate, and resist radiation better than glass. Glass, on the other hand, will withstand higher temperatures, shrinks less and is more resistant to chemicals and abrasion (Hirschfeld, 1980). A typical arrangement for a single core would be the Dupont silica-core fiber (PFX-S) with a polymer cladding and reinforced with two layers of Hytrel polyester clastomer, sandwiched around strands of Kevlar aramid (Polishuk, 1978).

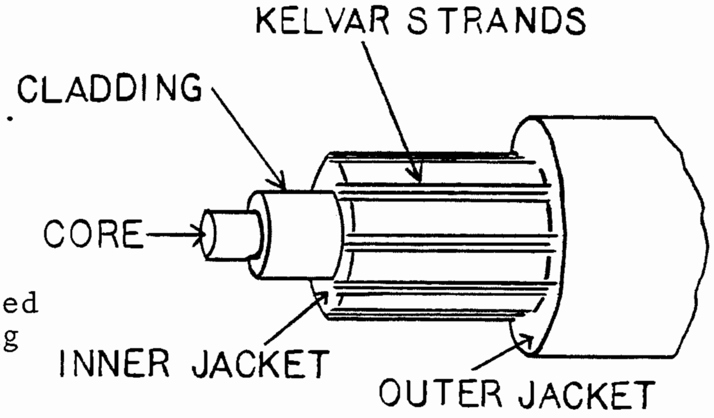

Figure 8. PFX-S type cable

The advantages of this plastic (PFX-S) fiber over glass is that plastic will more easily withstand stresses of pulling and bending. Connectors can be directly attached to the polymer without throwing the fiber off center. This means that misalignment losses will be minimized, elaborate tooling is eliminated, and crimping problems are lessened. The soft jacket of Hytrel is easily stripped and the high strength Kevlar strands will provide good strain relief between the fiber and cable.

The disadvantage for plastic-type fibers is their higher (60 to 100 dB/km) losses, or attenuation. But, the coupling losses are less because of the larger diameter core and numerical aperture. In applications of less than 100 meters of cable, the overall losses (cable plus the coupling at each end) could be lower than with glass and more economical due to the lower cost of the plastics.

SAFETY

It is very dangerous to stare directly at the free end of an optical cable excited by a GaAlAs laser or by a high radiance LED: In the case of a cable with one multimode fiber, the typical safety zone should be 1 meter when using a laser light source and 15 cm when using an LED. In the case of a single mode fiber the critical distance is approximately two to four times as large as in the multimode fiber. However, when taking into account typical values of the power level in single mode fibers, the critical distance is approximately 1 meter as well. This safety zone of 1 meter will prevent the fovea from being damaged by radiation. The tolerable power at the cornea show not exceed 5μW/cm^2 for continuous-wave (cw) operation (Timmermann, 1977).

SUMMARY

It has become increasingly common in telephony to send voice signals over cable or microwave transmission systems by means of digital pulses. To reproduce the original voice wave, which has a frequency bandwidth of 4,000 hertz, the digital system must be able to transmit 64,000 pulses-per-second. The large bandwidth of lightwave systems makes it attractive because of the increased bandwidth and in the vastly improved signal-to-noise (s/n) ratio. The major performance advantages of fiber optics in data communications are: bandwidth, noise immunity, signal attenuation, size, weight, and total electrical isolation. The obstacles associated with light transmitting systems have been eliminated. And, as the cost of copper wires and coaxial cables increase, the cost of glass and plastic fibers is decreasing.

In a great number of situations, the advantages of lightwave transmission are so important that they become compelling. Being made of a dielectric material, they provide ideal radio frequency interference/electro-mechanical interference noise immunity. They do not pick up, nor do they radiate any signal information. There is an ensurence of electrical isolation between the sending and receiving terminals, eliminating any common ground. There are no spark or fire hazards with fiber optics. In a wire system, damage to equipment can occur by shorting or grounding the wire. Also there is always the personal danger due to the voltage potentials and currents in the wires. These problems are avoided since the fibers do not conduct electrical current.

This paper presented a review of the state of the art of optical fibers and their potential use as waveguides for data communication system.

REFERENCE LIST

Boyle, W. S. Light-Wave Communications. Scientific American, August, 1977, Vol. 237, pages 40-48.

Cook, J. S. Communication by Optical Fiber. Scientific American, November, 1973, Vol. 229, pages 28-35.

Electronics Review. Hughes Fiber Shows 0.01 dB/km Loss in IR. Electronics, September 15, 1977, Vol. 20, page 44.

Hirschfeld, Fritz. The Expanding Industry Horizons for Fiber Optics. Mechanical Engineering, January, 1978, pages 20-26.

Jenkins, F. A. and White, H. E. Fundamentals of Optics. New York: McGraw-Hill, 1976.

Kapany, Narinder S. Fiber Optics. Scientific American, November, 1960, Vol. 203, pages 72-81.

Marcuse, D. Optical Fibres for Communications. The Radio and Electronic Engineer, November, 1973, Vol. 43, No. 11, pages 655-674.

Polishuk, Paul. Bright Future for Fiber Optics. Machine Design, August 24, 1978, pages 114-118.

Tanaka, T. P., Onoda, S., and Sumi, M. W-type Optical Fiber: Relation Between Refractive Index Difference and Transmission Bandwidth. Applied Optics, May, 1976, Vol. 15, No. 5, pages 1121-1122.

Timmermann, C. C. Handling Optical Cables: Safety Aspects. Applied Optics, September, 1977, Vol. 16, No. 9, pages 2380-2382.