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Optical communication for power system protective relaying.

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OPTICAL COMMUNICATION
FOR POWER SYSTEM PROTECTIVE RELAYING

by

Jeffrey G. Gilbert

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CERTIFICATE OF APPROVAL

This Thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering.

April 27, 1978

April 27, 1978

Advisor in Charge

Head of the Department
of Electrical Engineering

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OPTICAL COMMUNICATION
FOR POWER SYSTEM PROTECTIVE RELAYING

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ABSTRACT

Electric Utilities require reliable communication channels between extra high voltage (EHV) substations to protect interconnecting transmission lines from damage due to short circuits and phenomena such as lightning. Four types of communication channels have been used historically for this purpose:

- Pilot Wire
- Telephone Line
- Power Line Carrier
- Microwave Radio

Each alternative exhibits certain advantages with respect to capital cost, security, dependability, and available spectrum.

This thesis examines the concept of optical fibers contained within an electrical conductor utilized as an overhead ground wire as a means of communication which is cost competitive with the alternatives above, yet offering substantial performance improvements. Technical details of the concept are discussed and an economic comparison with the power line carrier alternative shows the concept to be competitive for lines up to 50 miles or less in length in the 1981 time period.

CHAPTER I

INTRODUCTION

Utilities currently select from one of four primary alternative media to communicate between extra high voltage substations: pilot wire, leased telephone lines, power line carrier, or microwave radio. Pilot wire gives the utility total control of the communication channel but is subject to electromagnetic noise and requires considerable maintenance. Leased telephone lines are somewhat less subject to power system induced noise and require no maintenance on the part of the utility, but there is no control over the lines with respect to routing and testing. Power line carrier is a popular alternative even though the available frequency spectrum is becoming crowded. Microwave communications offers many advantages, but it is very expensive to install in mountainous areas. In short, although each of these have been applied rather routinely, each has shortcomings.

Recently, optical fibers have been employed in communication applications to replace coaxial cable in linking computers, television transmitters, satellite tracking stations, etc. As the volume of fiber produced has risen, per unit length cost of fiber has decreased to the point where it may be considered for less demanding applications such as those of utilities. In order to take advantage of the properties of optical fibers, utilities must formulate a method of installing optical cables in the field at an economical cost without exposing the fiber to potential physical damage. There are two established methods of accomplishing this: burying the cable underground or stringing it overhead using a messenger cable. The former is very expensive and the latter, although somewhat lower in cost, leaves the cable susceptible to damage by lightning and other phenomena.

Current design practice for all EHV transmission lines includes utilizing overhead ground wires ("static wires") to control lightning performance. If an optical cable could be made an integral part of the static wire, it would be protected from the environment and little additional installation labor would be required of field labor forces, except at splices and repeater stations. This thesis examines the concept of optical fibers contained within metallic cable intended for use as an overhead ground wire on EHV transmission lines and attempts to ascertain both technical and economic feasibility at a future time. This discussion of the concept, problem areas, and potential solutions provides the necessary foundation upon which a prototype design program can be justified and carried out.

CHAPTER II

UTILITY COMMUNICATION ALTERNATIVES

In order to appreciate the need utilities have for reliable economic communication alternatives a brief discussion of present options which are being used is in order. The pilot wire and leased telephone circuit options will be lumped together since their primary difference lies in ownership of the facilities. Carrier current and microwave communications will be discussed separately since the problems which arise between the two are quite different, even though the relaying logic used is often the same or similar.

Pilot Wire - Leased Telephone Circuit

Pilot wire relaying circuits are divided into two classes, DC and AC. DC wire pilot relaying is for all purposes obsolete, although at one time it did find application over short distances (less than 10 miles) particularly on multi-terminal transmission lines. Because the useful distance is limited to about 10 miles and the information transmitted is also limited; DC pilot wire generally is not applied today.

AC pilot wire may require a circuit capable of transmitting 60 Hz signals only or audio tones which are typically in the range of 1.0 to 3.0 kilohertz. When distances are short (less than 25 miles) signals instantaneously porportional to power system currents are coupled to the pilot wires. For longer distances, audio tones are used for either AM or FM transmission. AM modulation involves placing a tone on the pilot wires and removing it when a "trip" condition exists. The FM scheme differs from the AM scheme in that a guard frequency, F_1, is transmitted for fault conditions and a second frequency, F_2, (the "guard frequency") is transmitted at all other times. Use of the higher frequency audio tones increases speed while the FM scheme is more secure and dependable than AM since a signal is always present at the receiver.

The primary problem common to all forms of pilot wire communication channels is their susceptibility to electromagnetic induction and ground potential rise. Both these forms of interference are worse during power system fault conditions - the time at which the communication system is needed most. The effect of induction can range from over-tripping to failure to trip for a valid fault condition. Delays in tripping are also possible. What is important is that anything but proper operation may result in damage or even collapse of the power system. Lack of control by the electric utility is a problem which has similar consequences but is restricted to leased pilot wire circuits.

Power Line Carrier

There are two basic forms of power line carrier currently being used - blocking and unblocking schemes. Because the power line acts as the communications channel and may be shorted to ground by faults on the power line being protected, the blocking scheme is used most in the United States. Stated simply, blocking schemes transmit a carrier signal during periods when no trip action is required and transmit no signal for a trip condition. The way in which power line carrier communication channels are applied and total ownership by utilities has resulted in a good performance record for this form of relaying communication. Unfortunately the capital cost for power line carrier installations is relatively high and available frequencies spectrum is limited such that not all installations which would otherwise use power line carrier will have that option available. Furthermore, proposals are currently before the Federal Communications Commission to allow radio amateurs and the military to use the power line carrier frequency spectrum. Should such a proposal be accepted the reliability of power line carrier may be questionable.

Microwave Radio

Relay logic used with microwave radio communication channels is generally the same as that used for power line carrier channels. Microwave radio, however, offers broad bandwidths for point-to-point line of sight communications. Recent advancements and solid-state technology have made microwave radio more attractive, however, the cost of repeater stations in hilly or mountaineous areas makes this alternative impractical for many electric utilities. The frequency spectrum available to utilities is adequate at present but may become crowded in future decades.

Summary

Current utility communications media options are rather limited and generally offer poor reliability or require a large capital investment. Power line carrier has demonstrated good reliability at a relatively high though reasonable cost, but limited available frequency spectrum will limit its application in the future while proposals currently before the Federal Communications Commission may seriously decrease utility confidence in existing installations. There is thus a need for a new communications alternative offering a high degree of security and dependability at cost comparable to power line carrier.

Trends and optical fiber link costs indicate optical communication will be a practical alternative in the near future. Application will be limited, however, if special messenger wires must be provided for fiber support. It would be possible to lash fiber cable to existing overhead ground wires, however, considerable labor would be required and lightning strikes might damage the fiber cable. The following chapters examine the feasibility, both technical and economic, of installing optical fibers inside overhead static wires with the objective of providing the power industry with an alternative communications media which will exhibit a reliability comparable to that of power line carrier at approximately the same cost. The advantages over power line carrier are freedom from frequency spectrum/bandwidth limitations, availability during faults, and security from external interference.

CHAPTER III

OPTICAL COMMUNICATION

Optical Cable Concepts

The potential advantages of optical wave guide communication systems became apparent during the 1960's. Some of those identified since that time are (13):

1. Optical fibers are fabricated from a non-conductive, non-inductive glass medium, typically high silica or borosilica glass. Thus, ground loops and short circuits are completely eliminated. The high heat resistance of glass materials insures safety in combustible areas.

2. Bandwidth extending into gigahertz is achievable.

3. Optical fiber wave guides are lightweight and small with outside diameters typically smaller than 200 micrometers.

4. Glass fibers are immune to electromagnetic interference and to a lesser extent, nuclear radiation.

5. Some degree of security is afforded in that the fibers are difficult to tap.

6. Typical silica type fibers have high tensile strengths which range between 4 and 10 kg. Fiber cables incorporating steel or kevlar strengthening members exhibit tensile strengths of several hundred kilograms.

7. The minimum bending radius of fiber optical wave guides is less than 10 centimeters.

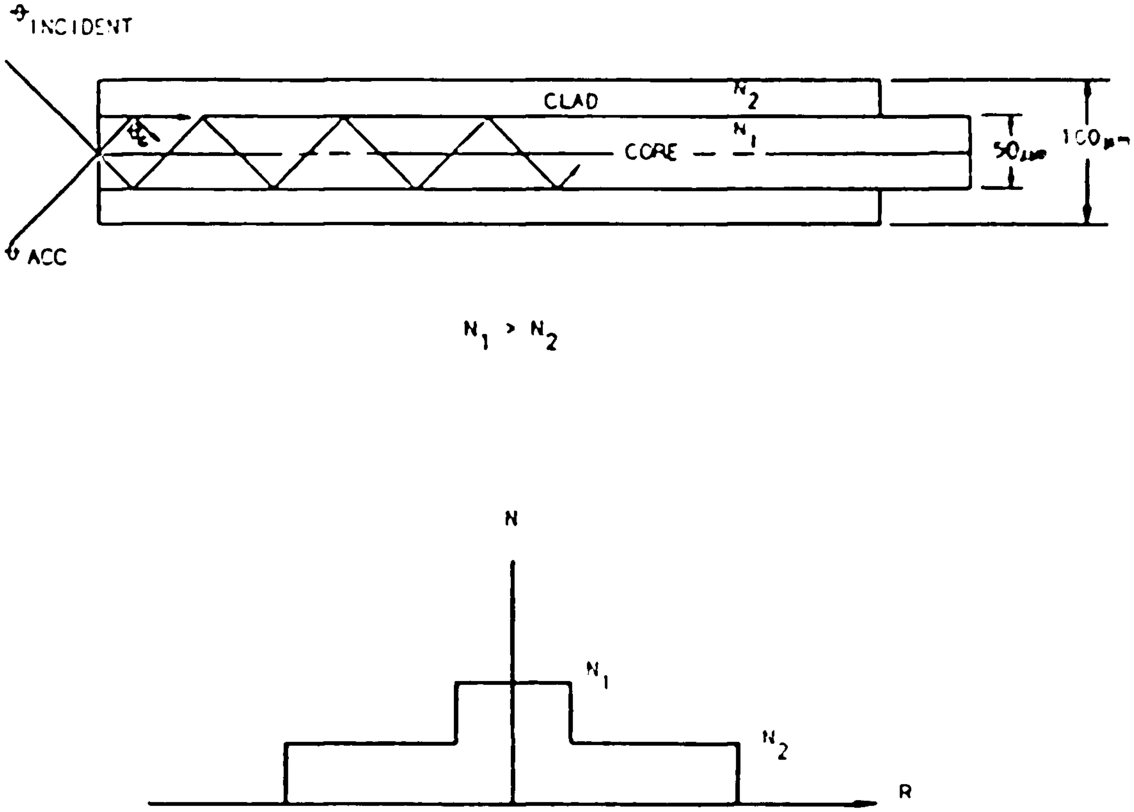
8. Glass fibers typically exhibit losses less than 20 dB/km and can be manufacturered to yield transmission losses less than 1 dB/km.

9. Optical fibers have the potential of being relatively inexpensive. Prices are expected to fall by a factor of 3 between 1977 & 1980.

Fiber Optical Wave Guides: Fiber optical wave guides can be manufactured using plastic, high silica glass, or borosilica glass. Plastic fiber transmission losses are on the order of several hundred dB/km making it unusable for long distance transmission. Fibers incorporating glass as a core and plastic as the cladding result in losses between 10 & 20 dB/km with length-bandwidth products between 10 and 15 MHz-km. Graded index glass fibers have been produced with attenuations less than 1 dB/km and length bandwidth products greater than 500 MHz-km. Finally, using single mode glass fibers, length-band width products several gigahertz-km have been demonstrated.

A single fundamental construction concept is applied for all types of fiber wave guides: the core of the fiber is created such that its refractive index is greater than that of the cladding. There are three forms of fiber wave guides which differ in their physical dimensions and the optical variation in the refractive index. These are:

1. Step-Index Multimode (Figure 1, Page 15) - dimensions of Step-Index Multimode optical wave guides are on



STEP INDEX MULTIMODE FIBER

FIGURE 1

the order of 1-100 micrometers. Guidance of rays takes place by total internal reflection at the core-clad boundary. Ray propogation can be described mathematically using Snell's Law:

$$\text{Sin } \theta_{\text{incident}} = (N_2/N_1) \text{ Sin } \theta_{\text{reflected}} \quad (4\text{-}1)$$

where N_1 and N_2 are the index of refraction of the core and cladding materials respectively. For the condition where θ reflected $= \pi/2$, Snell's Law can be rewritten in the form:

$$\theta_{\text{Crit}} = \arcsin\ (N_2/N_1) \quad (4\text{-}2)$$

Thus, rays incident at an angle $\theta>\theta_{\text{crit}}$ will be totally reflected back into the core while those incident at angles less than θ_{crit} will be partially refracted into the cladding. In the case where light energy is coupled from air into the fiber, Snell's Law may be used to compute the maximum acceptance angle for propogation. Letting θ_{ACC} be the acceptance angle and $N_2 = 1$ for air:

$$\mathrm{Sin}\ \theta_{ACC} = N_1\ \mathrm{Sin}\ \theta_{crit} \qquad (4\text{-}3)$$

or

$$\mathrm{Sin}\ \theta_{ACC} = (N_1^2 - N_2^2)^{1/2} = NA \qquad (4\text{-}4)$$

where NA is defined as the incident numerical aperture of the fiber.

Bandwidth of step index fibers is limited by modal dispersion resulting from the variation in group delay between different propogating modes. Consider two rays, one propogating straight through the center of the core and the second propogating at an angle θ_{crit}. The difference in time delay between these modes over a length L is given by:

$$t = (\frac{N_1 L}{c})(\frac{1}{\cos\theta_{crit-1}}) \qquad (4\text{-}5)$$

where c is the velocity of light in free space. This expression may be simplified to the form:

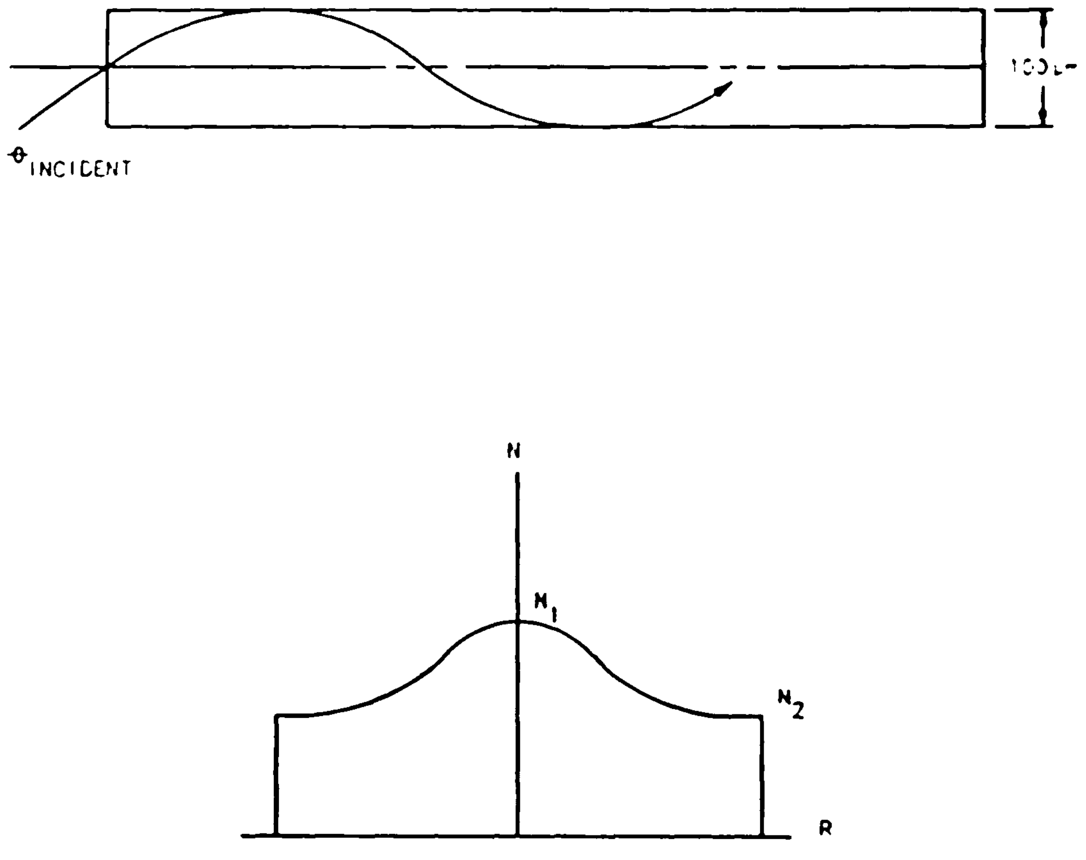
$$t = N_1 L/\Delta c, \ \Delta = (N_1 - N_2)/N_1 \qquad (4\text{-}6)$$

Substituting typical values for N_1(1.5), Δ (0.01), and c (3×10^8), $t/L = 5 \times 10^{-7}$ sec/km, which is equivalent to a data rate of approximately 2mb/sec over a 1 km length. Thus, step index multimode fiber is limited to applications requiring modest data rates. Historically, step index fiber has been less costly than other forms of fiber optic waveguides that are able to operate at a higher data rate, however, by 1980 the cost of graded index fiber will drop to the point where it is likely step index fiber will no longer be manufactured.

2. Graded Index Multimode Fiber (Figure 2, page 20) - Similar in physical dimensions to step-index multimode fibers, graded index multimode fiber dimensions are on the order of 100 micrometers. The significant difference between the two is in the way in which energy is confined in the core region. The radial index distribution of graded index fiber serves to guide rays through an inherent focusing action in which "slow" rays travel faster as they move away from the center of the core greatly reducing time delay dispersion. Assuming a parabolic index profile:

$$t = NL\Delta^2/2c$$

Substituting typical values for N (1.5), Δ (0.01), and c (3×10^8), $t/L = 2.5 \times 10^{-13}$ corresponding to a data rate of approximately 4000 Mb/sec for a 1 km length. Note that this is an improvement of 2000 times the performance which could be expected from a step index fiber. In reality, bandwidth of graded index fiber is much narrower than the time

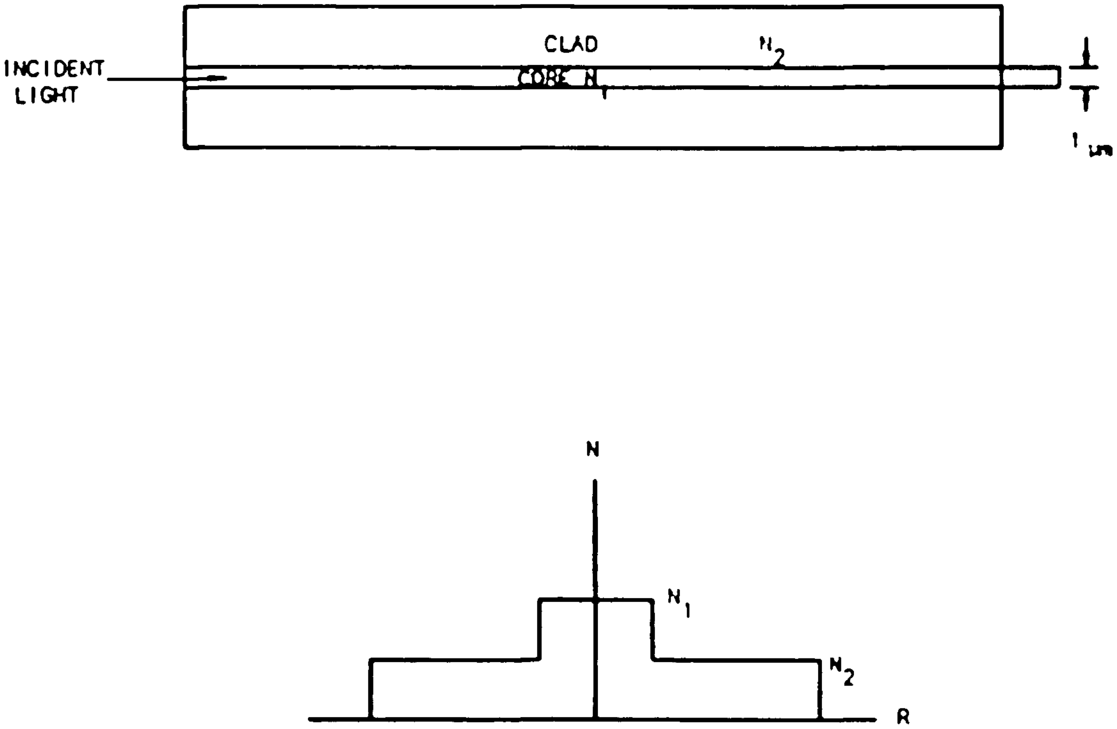


GRADED INDEX MULTIMODE FIBER

FIGURE 2

delay dispersion calculation indicates because other distortion mechanisms such as material dispersion and waveguide delay dispersion become limiting. Material dispersion results from a non-linear refractive index-wavelength relationship and is therefore proportional to the spectral width of the optical source. Waveguide delay distortion is caused by group delays resulting from waveguide dispersion for each propogating mode; it generally contributes little to total distortion. When time delay dispersion, material dispersion, and waveguide delay distortion are considered in total, data rates of several hundred Mb/sec for a 1 km length are computed. Commercial fiber is readily available for use at data rates of 400 MHz over a 1 km distance. Because moderate to wide bandwidth is achievable with production costs roughly equal to those of step index fiber, graded index fiber will be the most common type of fiber employed in future fiber optic systems.

3. Single Mode Fiber (Figure 3, page 22) - the diameter of single mode fiber is on the order of one micrometer making it very difficult to work with under field



SINGLE MODE FIBER

FIGURE 3

conditions. The small diameter, however, prohibits all modes but one from propogating, consequently there is no time delay dispersion. Total dispersion is comprised solely of material and waveguide effects and is thus controlled primarily by material properties. Material disperion is a function of the spectral width of the optical source used and the emission wavelength. Bandwidths of several gigahertz have been achieved for a 1 km distance using single mode fibers. Due to its relatively high cost and inherent handling problems, application of single mode fiber will be quite limited for many years.

Attentuation: An area of concern common to all types of fiber-optic cable is attenuation of the optical signal. There are four major factors involved:

1. Presence of hydroxyl radicals and transition metal ions (Fe^2, CU^2, Ni^2, etc.).

2. Impurities in the fiber core material.

3. Irregularities in the core-cladding interface.

4. Radiation from microbends.

Hydroxyl radicals and transition-metal ions absorb energy in specific wavelength bands; an example being the .95 micrometer absorption band associated with the hydroxyl radical. Impurities in the fiber cause scattering loss, which, for good quality fibers, is a function of wavelength raised to the -4 power (Rayleigh scattering loss). Irregularities at the core-cladding interface also result in losses due to scattering by a coupling of energy into radiation modes. Finally, bending fiber at very small radii (less than a few millimeters) also causes coupling into radiation modes. This last attenuation mechanism can result in attenuations being exceedingly high, however, careful attention during design and fabrication of the fiber cable limit this form of attenuation to acceptable magnitudes. For instance, total attenuation of 6 dB/km is a typical specification for production quantities of optical fiber at a wavelength of .85 micrometers. Attenuation less than 1 dB/km has been demonstrated in laboratory quantities (9).

Splicing: As fiber with lower attenuation characteristics becomes available, losses due to splices become increasingly significant. There are two types of splices which must be considered: permanent and connect-disconnect splices. Optical fiber is presently manufactured in lengths of less than 2 km. Thus, permanent cable splices are required for long distance applications. There are two accepted methods of making a permanent splice: (1) glue the fibers together using an index matching epoxy, or (2) fuse the fibers together using a high temperature. The latter is preferable because of its relatively high mechanical strength and low loss, however costly equipment is necessary. Whatever method is used, care must be taken to precisely radially align the fibers being joined and to insure the longitudinal axis are parallel. When such care is taken, permanent splices add a few tenths of a dB or less attenuation per splice.

Connect-Disconnect splices are currently receiving a great deal of attention. Early optical connectors were simply electrical connectors modified to accept fibers. Consequently, alignment was not as precise as is necessary to achieve insertion losses on the order of 0.5 dB or less. Several techniques for achieving good alignment and contact have been proposed and are in use. ITT employs jeweled ferrules which mate through a threaded connection for single fibers. Bell Telephone has developed a connector for fiber ribbon cable employing a grooved silicon chip insert for which a loss of 0.22 dB has been reported as well as a single fiber connector using an index matching fluid with a 0.4 dB loss. Insertion losses of this magnitude are within acceptable limits for essentially all applications. As more effort is put into this area, other techniques will no doubt be employed which will further reduce losses.

Tensile Strength: Youngs modulus for a typical glass optical fiber is approximately $7x10^5$ kg./sq. cm. while the Youngs modulus of steel is $21x10^5$ kg./sq.cm.(2). From this, one might conclude glass fibers subjected to tensile loading are 1/3 as strong as a similar steel fiber would be. This is, in fact, not the case. Steel is typically loaded to a 1% strain while glass may be subjected to loads which strain the fiber 20%. Again, however, these figures alone do not actually describe the long term relative tensile strength although, for carefully selected short lengths, glass can be subjected to tensile loads which would lead to failure in similarly sized steel wire.

Long term tensile strength of glass fibers is currently limited to elongations of less than 1%. When subjected to strains greater than 1%, OH ions cause microcracks to propogate across the fiber and eventually lead to mechanical failure. Manufacturers are currently researching techniques for depositing metallic film on glass fiber. Metallic films prevent water molecules (the source for OH ions) from coming in contact with the glass. Consequently, loading to strains greater than 1% will be possible in the future. One manufacturer is producing significant lengths of metallic coated fiber.

Degradation resulting from electric field gradients: During the early 70's utilities interested in applying fiber optic cables composed of glass were concerned that high electric field gradients would cause ionic alteration of the glass leading to unacceptable attenuation. Little investigation was undertaken in this area until mid-1975 when the Charles E. Carey Testing Laboratory (operated by Bonneville Power Authority) tested a 14.6 meter length of Corning 6-element fiber optic cable(11). Leakage current through the cable and light conductivity were monitored for applied potentials up to 950,000 volts AC and 750,000 volts DC under humidity conditions ranging from 60 to 100% for durations as long as 4 hours.

Although the Bonneville test did not measure light attenuation, it did demonstrate there are no gross changes in glass cable characteristics resulting from relatively high electric field gradients. Since this test was conducted, fiber optics have been applied to numerous applications where high electric field gradients exist with no apparent trouble resulting from changes in the cable caused by the electric fields.

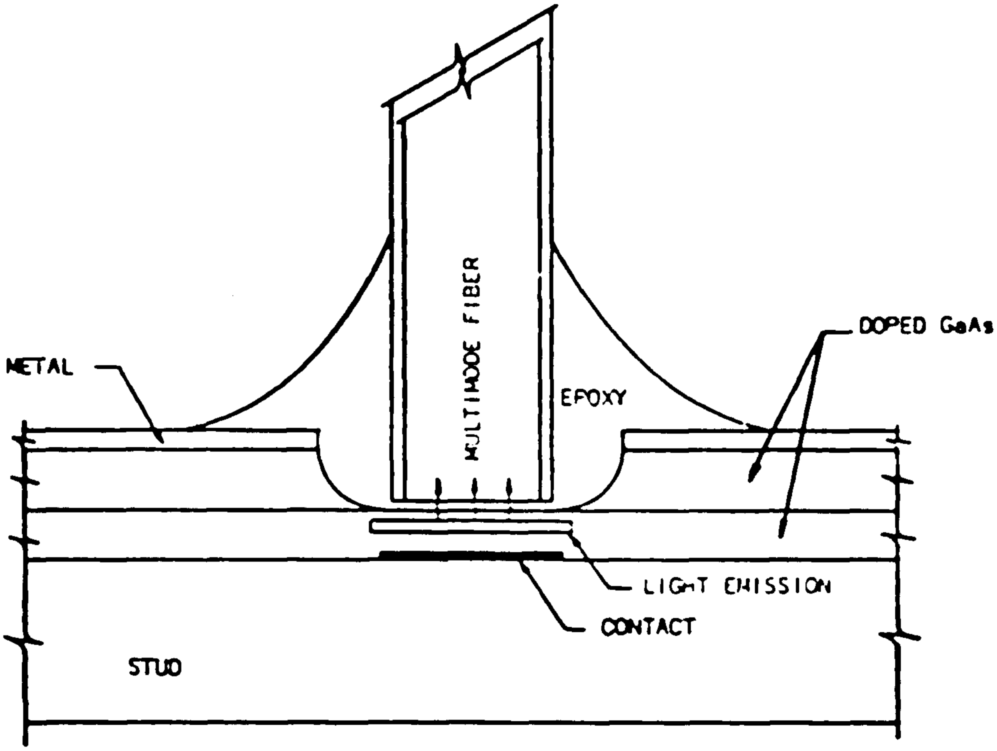
Based on the Bonneville Test and field experience since 1975, electric field gradients encountered on power system facilities do not lead to degradations of optical glass fibers and thus may be applied freely.

Conclusion: Optical cable is commercially available with loss characteristics that make it suitable for long distance data transmission at reasonable data rates. Graded index multimode optical fiber is best suited for application to power system protective relay based on bandwidth capacity, cost, and physical dimensions that can be handled with relative ease in the field. Splices in the fiber are best made by high temperature fusing of the fiber material to maintain fiber tensile strength. Connector loss, although not insignificant, will not appreciably affect system performance since only two demountable connections (one at the emitter and one at the detector) are necessary between repeaters for the relaying application.

Fiber cable installations must be limited to a strain less than 1% to insure long term mechanical integrity. Degradation resulting from electric field gradient is not a concern.

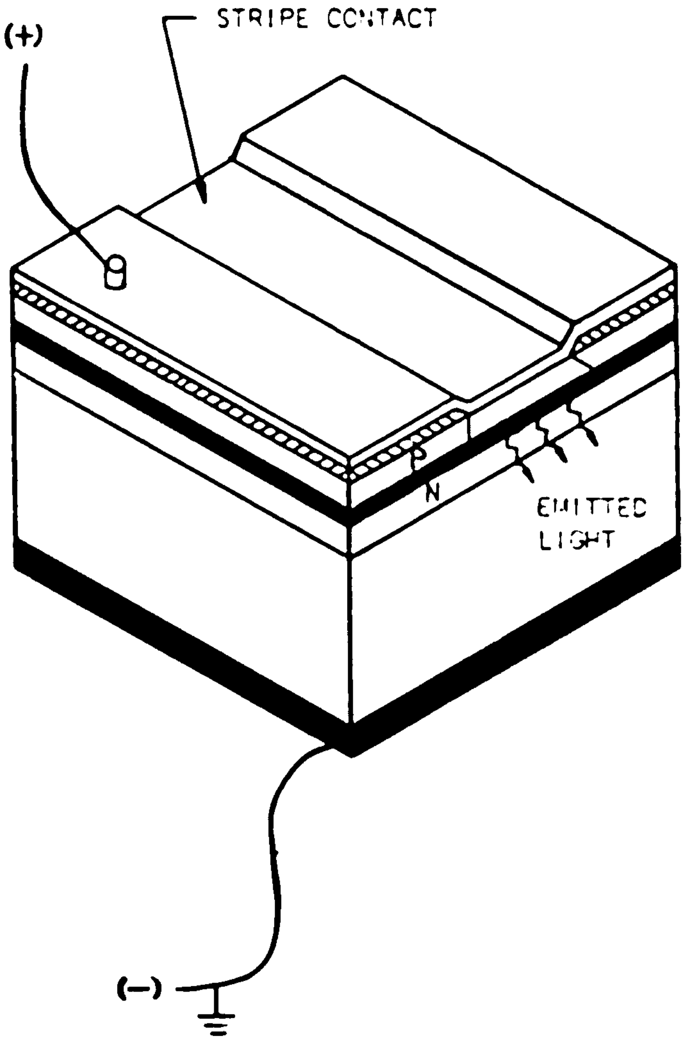
Emitters

Light Emitting Diodes: There are two configurations for high radiance LED's - the Burrus type (surface emitters, Figure 4, page 30) and the edge emitter (Figure 5, page 31). The Burrus design was originally developed by Bell Laboratories. It had the advantage of a narrow beam which can be readily coupled into an optical fiber. Edge emitters were developed by RCA and although they emit more optical power, they do so over a broader beam than surface emitters. Electrical characteristics of both devices are very similar. Output power is in the range of 1-10 milliwatts with modulation frequencies limited to approximately 200 MHz due to free carrier generation and recombination times. Emission line width varies in the range of 200-400Å. Accelerated life



BURRUS LED

FIGURE 4



EDGE EMITTING LED

FIGURE 5

testing indicates life times greater than 100,000 hours are practical(15).

LED's can be constructed using several materials, the most popular being GaAs currently because emission takes place at 9,000Å, a wavelength at which optical fibers exhibit relatively low absorption. Three important advantages of LED's in general are: (1) high reliability, (2) low cost, and (3) a relatively small output power-temperature dependence. Major disadvantages are low radiance and a broad emission spectrum which causes increased dispersion.

Laser Diodes: Laser Diodes are used in systems requiring wider bandwidth or higher coupled optical power than is available from an LED. Optical output power of laser diodes ranges from roughly 5 to 50 milliwatts with only a few dB lost in coupling to fibers. Modulation frequencies on the order of 1 gigahertz are possible while emitted line width is less than 20Å, significantly reducing dispersion in the fiber.

Just as laser diodes offer advantages over LED's, there are some disadvantages. Laser diodes must be biased to a threshhold value of current which is temperature dependent, requiring temperature stabilization circuits or an optical feedback loop. Second, the cost is greater than that for LED's. Finally, in analog applications, attention must be given to maintaining a linear output power vs. input current characteristic. This is only possible above a threshold current.

The construction of a laser diode is very similar to that of edge emitting LED's and materials used are the same. The significant difference between the two is that the edges of the laser diode are cleaved to create an optical cavity in which stimulated emission occurs. This optical cavity may be further defined by single or double heterojunction construction which more effectively contains optical energy. The actual construction of the device is valuable merely as background information for better understanding. What is important is device specification of optical power output, linearity, spectral width, etc.

Conclusion: Light emitting diodes are useful for low data rate applications for moderate distances. Laser diodes are suited to long distance high data rate applications by virtue of high emitted output power and radiance as well as relatively narrow spectral bandwidth. Laser diodes are presently more costly than light emitting diodes and have not yet demonstrated reliability comparable to light emitting diodes.

Detectors

There are three basic types of optical detectors used in fiber optic systems. As is generally the case, each alternative has certain advantages and disadvantages. Some basic knowledge of each type is necessary to properly design a system.

1. Silicon Phototransistors - Silicon Phototransistors are useful for low cost application requiring sizeable current gain and good temperature stability at narrow bandwidths where relatively poor signal to noise ratios are tolerable. Because of their bandwidth and signal to noise ratio limitations, silicon phototransistors are not used very widely.

2. Silicon PIN Photodiodes - Silicon PIN Photodiodes require relatively low bias voltage (2VDC) and will operate over a dynamic light level range up

to ten orders of magnitude. Optical receivers using PIN photodiodes are often thermal noise limited. Using proper circuitry, bandwidths in excess of 100 MHz are possible. The low bias requirement and flexibility of this device make it the most popular detector for fiber optic systems.

3. Avalance Photodiodes - Avalance Photodiodes offer greater sensitivity than is possible with PIN Photodiodes because they provide an internal gain which serves to reduce the effect of subsequent amplifier noise. The preceding is obtained at the sacrifice of increased shot noise, a requirement for high voltage bias (200-300 VDC) and feedback circuitry to insure minimum sensitivity to temperature and device aging. The information bandwidth of avalanche photodiodes is comparable to that of PIN photodiodes when used in conjunction with the proper control and amplification circuitry.

Conclusion: Silicon Photodiodes, although capable of high current gains and good temperature stability, do not offer sufficient bandwidth or signal to noise ratio for many applications. PIN Photodiodes are applied where nanosecond response time and wide dynamic light level range are required and a low bias source is desirable. Avalance photodiodes are useful in applications requiring higher sensitivity than is possible with a PIN photodiode where a high voltage bias supply is available.

Design Considerations For Optical Communication Links

The design of an optical link requires particular attention be given to two important areas already discussed - attenuation and dispersion or bandwidth. Keeping this in mind, the link design is begun by identifying link requirements(17):

- Required bandwidth
- Required distance
- Required signal to noise ratio (SNR) or bit error rate (BER)
- Number of splices
- Number of connectors
- Allowance for degradation
- Allowance for source and detector coupling flaws

A selection of fiber cable, source, detector, and repeater spacing can then be made. One approach to this is to select a source-detector combination and determine the maximum attenuation allowable for a given SNR for BER. Fixed losses such as splice, connector, coupling, and allowances for degradation are then subtracted to yield allowable fiber loss. A fiber cable may then be selected based on attenuation and bandwidth characteristics as well as mechanical requirements such as tensile strength. Of course this is only the first step of the design process and greater detail must be paid to specific design considerations before putting the link together. In designing a transmitter unit some specific requirements considered are:

- temperature compensation
- source aging compensation
- cost
- power consumption
- physical size
- output power vs. input voltage transfer function
- emission wavelength
- spectral bandwidth
- duty cycle

Considerations for the cable selection include:

- cost
- core size - numerical aperture attenuation tradeoffs
- dispersion
- physical size
- crush resistance
- minimum bending radius

Finally, the receiver designer must consider:

- dynamic range (sensitivity)
- DC/AC coupling
- input/output transfer function
- cost
- power consumption
- physical size

In actual practice many design decisions are made by the manufacturer of transmitter and receiver modules and fiber cable, although special requirements might limit use of the "off the shelf" modules. It is advantageous, however, to use manufacturer's standard modules whenever possible to avoid the high cost of custom design.

CHAPTER IV

ELECTRICAL CONDUCTOR

Virtually all electrical conductors used to construct electric power transmission lines today utilize aluminum alloys or a combination of aluminum alloys and steel. For that reason, the discussion of electrical conductors will consider only those types in which aluminum is present. Prior to discussion of designs employing specific materials, a more general discussion of basic mechanical design is necessary for a thorough understanding.

Conductor Concepts

A system for designating physical wire sizes was introduced by J. R. Brown in 1857. Subsequently, this system was adopted as a standard in the United States and thus is referred to as American wire gauge or AWG. The gauge is defined using given diameters and the fact that the intermediate gauge numbers form a geometrical progression. For instance, No. 0000 is defined as 1.1684 centimeters and No. 36 as 0.0127 centimeters. Thus the factor relating the ratio of successive gauge numbers can be computed as:

$$\sqrt[39]{1.1684/0.0127} = \sqrt[39]{92} = 1.1229322 \tag{5-1}$$

Wire sizes larger than No. 0000 AWG are designated in circular mils rather than in AWG. One circular mil is defined to be the area of the circle whose diameter is 0.00254 centimeters. Thus the size in circular mils expressed in terms of diameter in centimeters is simply:

$$\text{Circular Mils} = 1\text{x}10^6\text{x}(\text{Diameter}/2.54)^2 \qquad (5\text{-}2)$$

The composite size of a stranded conductor is the sum of the component individual strand sizes whether they are expressed in circular mils or AWG numbers. Most power conductors are of the concentric-lay stranded type in which the composite conductor is composed of a central core surrounded by one or more layers of wire helically laid. Where multiple layers are present, the direction of twist or lay is generally reversed in adjacent layers and all conductors in a given layer are of the same diameter. Direction of lay (right or left) is determined by the lateral direction in which the outermost layer runs across the top of the conductor as viewed axially receding from the point of observation. Stated more simply, a right lay runs clockwise away from the point of observation, while a left handed lay runs counter-clockwise. The length of either right or left hand lay is the distance measured linearly between the start of consecutive turns of the helix. Aluminum conductors generally are right-handed lay, although left-hand lay can be, and in fact has been, made. In either case, the total number of strands (N) in a conductor consisting of n lays over the core is given by:

$$N = 3n(n+1)+1$$

For one-wire core construction. (5-3)

Three-wire core construction, although seldom used for aluminum conductors, results in the following relationship:

$$N = 3n(n+2)+3 \qquad (5\text{-}4)$$

Conductor Construction

There are several ways of constructing conductors other than simple concentric lay stranding. Three common special constructions are:

- Rope lay construction - the core is concentric lay stranded construction (rather than a single solid construction) overlaid by layers of concentric-lay stranded conductor.

- Reduced diameter construction - conductor strands are trapezoidal shaped or simple concentric lay stranded, conductor is crushed to fill interstrand voids.

- Expanded construction - the core is filled with fibrous, rope, or other material or made hollow increasing the surface area to weight ratio.

Each of these is used for specific purposes such as reduction of radio noise interference, ice loading, or making the conductor more flexible.

Just as physical construction is varied to obtain desired characteristics, so is the composition of the metallic strands. Other material combinations employed in overhead conductors are:

ACSR - Electrical conductor type aluminum alloy reinforced by a steel wire core.

ACAR - Electrical conductor type aluminum conductor reinforced by high-strength aluminum alloy strands.

AW - Aluminum clad steel wire.

ACSR/AW - Electrical conductor type aluminum conductor reinforced by aluminum clad steel strands.

The process of selecting a particular material, material combination, and geometry involves optimizing size, strength, and electrical conductivity for a specific design application. Generally, ACSR, ACSR/AW, and ACAR are used as power conductors, while AW is used for overhead ground wire applications because of its high strength, relatively low cost, and adequate conductivity.

CHAPTER V

ELECTRICAL OPTICAL CONDUCTOR

Mechanical Requirements & Design

For the purpose of this study, it is assumed electrical-optical cable will be applied at the transmission class voltage of 500 KV utilized as an overhead ground wire. These assumptions are based on:

1. EHV designs generally are more demanding than lower voltage class designs.

2. The most rapid expansion of EHV facilities within eastern Pennsylvania during the next ten years will be at the 500 KV voltage level.

3. Overhead ground wires are not subject to as much thermal cycling as power conductors and thus will not subject an internal fiber optic cable to as frequent stress as would power conductors.

Selecting standards used by one investor-owned public utility*, the assumptions lead to the following mechanical design requirements:

Span Length = 457.2 meters

Maximum Radial Ice Loading = 3.81 centimeters

Maximum Allowable Sag = 19.81 meters

Current design practice is to use nineteen 09 alumoweld as the overhead ground conductor installed at an initial tension of 1905 kg. When subjected to a 1.5" radial ice load at -17.8°C ambient temperature, the tension increases to 8953 kg. at a corresponding sag of 19.45 meters. Rated strength of 19/9 alumoweld is 15554 kg., thus, design tension is 56.5% of rated strength. Adhering to these design criteria requires the use of steel cable or else the cable diameter becomes unmanageable.

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*Pennsylvania Power & Light Co. - Allentown, PA

Two alternatives for a cable containing fiber optics are to use 19/9 alumoweld or 19/8 alumoweld, replacing the center strand with a fiber cable and becoming 18/9 or 18/8 conductors. The 18/9 alternative would exhibit a tensile strength greater than 14515 kg. This is not a drastic deviation from current design safety margins and should prove acceptable mechanically while being less costly than 18/8.

Use of cable consisting of eighteen 09 wires implies the diameter of the fiber-optic cable replacing the center strand is equal to or less than 0.290576 centimeters, the diameter of a solid 09 wire. It is desirable that short time tensile strength equal or exceed 227 kg. to insure that stranding may be accomplished at the normal rate with little or no modification to existing machinery. Tensile strength less than 227 kg. will increase production cost because stranding will have to be done more slowly than is normal.

Another alternative which allows for large fiber-optic cable is to use an expanded hollow conductor design. An example of one possible design is to use 24-#10 AWG/AW conductors stranded such that the hollow core has the diameter of .508 centimeters; the cable consisting of an inner lay of

9 strands and an outer lay of 15 strands. Diameter of such a cable would be 1.59258 centimeters, only slightly larger than the nominal 1.45288 centimeters diameter of 19/9 alumoweld. Breaking strengths of the two conductors should be approximately the same ignoring effects of the hollow core (which are small).

Table 1 page 48 contains detailed characteristics for three possible cable designs which all offer acceptable physical and mechanical characteristics. Figures 6 thru 8 pages 49-51 are drawings illustrating each design.

Fiber Optic Requirements & Design

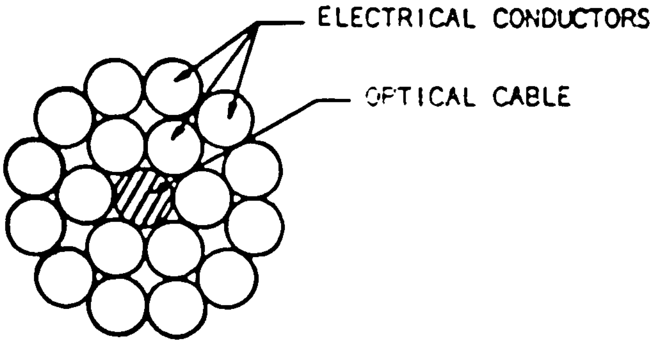
Assuming graded index fiber is used, one fiber will provide sufficient bandwidth (2200 MHz km) to meet projected requirements:

Relaying (2 channels) - 6000 Hz
Voice (1 channel) - 3000 Hz
Supervisory Control - 3000 Hz
12000 Hz

TABLE 1

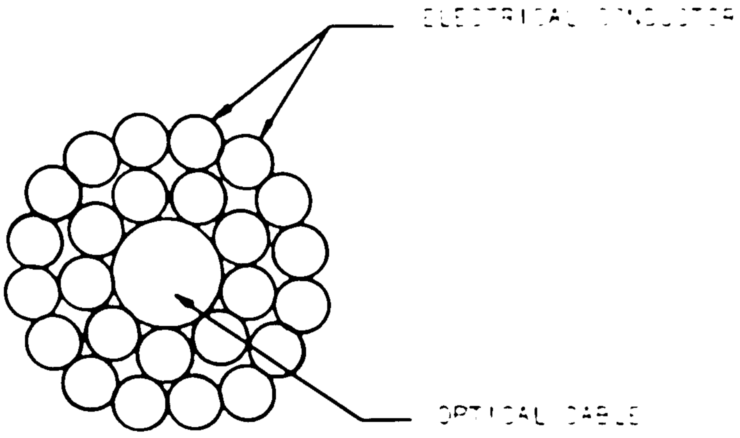
Conductor Design	Diameter Centimeters	Strength Kilograms	Core Diameter Centimeters	Weight kg/km	Cross Sect. Area CM^2	Construction
19/9	1.45288	15554	0.2905	842.3	1.261	X-6-12
27/10	1.59258	15578	0.5130	872.1	1.262	X-9-15
37/11	1.6129	14929	0.6909	834.9	1.209	X-X-12-18

X = strands eliminated



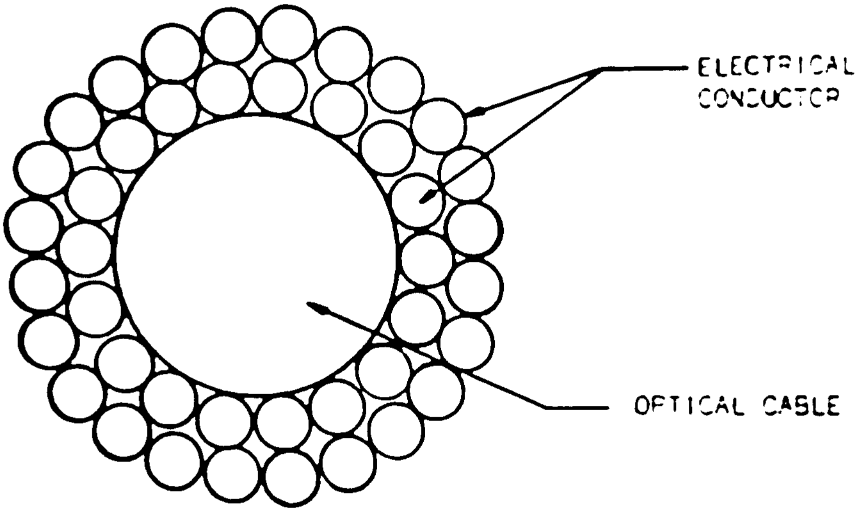
6-12/9 COMPOSITE CABLE

FIGURE 6



9-15/10 COMPOSITE CABLE

FIGURE 7



12-18/11 COMPOSITE CABLE

FIGURE 8

A single fiber is thus capable of serving in a bi-directional mode when bandwidth alone is considered, even for a large increase in existing requirements. Other aspects such as reliability and the difficulty in developing bi-directional terminal equipment requires separate fibers be employed for communication in two directions. In addition to the two fibers required for bi-directional communication, it is desirable that one additional fiber be incorporated in the fiber cable design for use as a spare in the event one of the prime fibers break due to a flaw introduced during the manufacturing process. Present costs for fiber prohibit the luxury for including extra optical fibers serving as additional backup channels, however, this concept may be economical in the future.

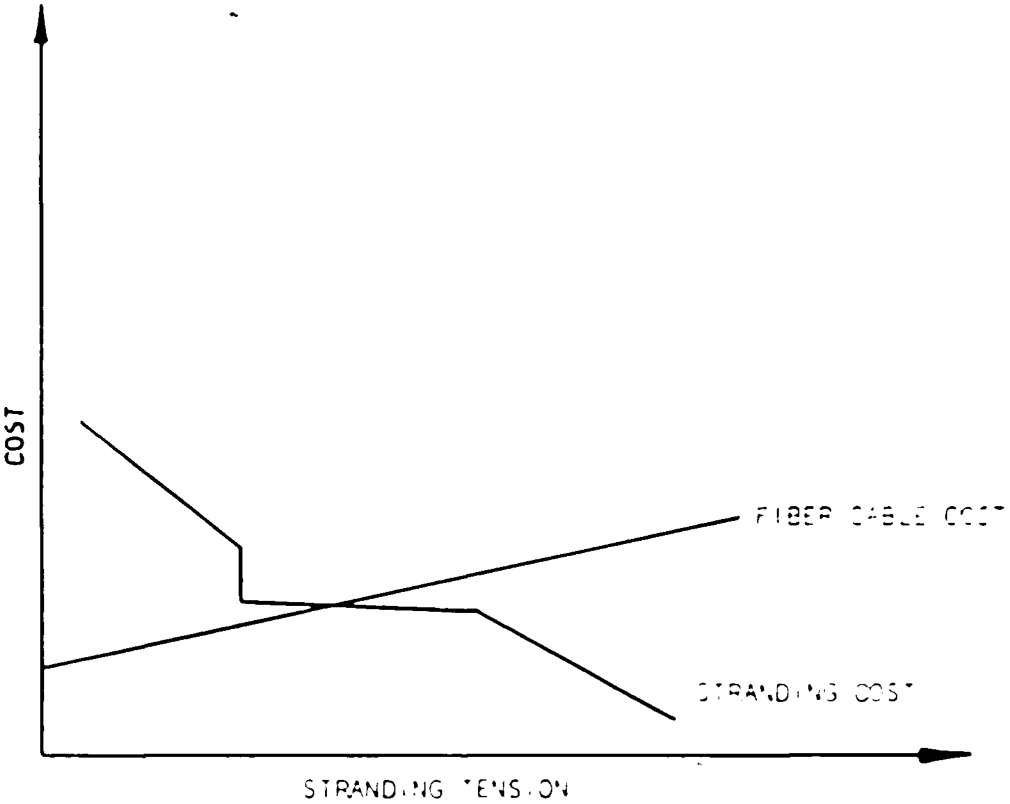
Although the tensile strength of virgin glass fibers is comparable to that of steel, production fiber cables must be designed to incorporate strengthening members which limit fiber stress because damage by drawing equipment, exposure to the atmosphere and handling of the fiber causes severe deterioration of allowable stress even though damage usually is limited by a protective coating applied to the fiber shortly after or during its manufacture. Typical coatings are: Kynar, Teflon, and Polyurethane(2). Metallic coatings, such as aluminum, are capable of protecting fibers from deterioration promoted by water molecules, however, such coatings cannot be economically applied in production quantities at present. Practically, elongation (which is proportional to fiber stress) must be limited to a few tenths of 1% for long lifetimes.

Two stress conditions must be considered in designing a fiber cable which will later become part of a metallic cable. These are:

- Cabling stress
- Loading stress

Cabling stress is imposed on the fiber cable during manufacture of the composite electrical conductor and is a function of the rate at which stranding occurs. To strand cable at a rate comparable to that at which conventional electrical cable is stranded, the fiber cable must have a tensile strength of approximately 227 kg. Stranding can be accomplished at tensions as little as an order of magnitude lower than this, however, cabling costs will increase due to the tension reduction. Conversely, the higher the tensile stress during the stranding the greater the cost of strengthening members such as steel or Kevlar. The optimum stranding tension, based on economics, may be determined graphically by plotting the incremental cost of stranding tension and strength members against stranding tension as in Figure 9, page 55. The optimum tension is that one at which the incremental costs are equal and the curves intersect.

Loading stress occurs when the composite cable is placed in service and subjected to mechanical loading, including the weight of the cable itself. Tension may range between 1536 and 8953 kg., depending upon ambient conditions for a public utility standard 500 KV line design (Table 2, page 56). Loadings to 2500 kg. for a condition of no radial ice, 1.81 kg/sq. meter wind, at a temperature of -17.78°C (bare, 1.81 kg. wind -17.78°C) can be expected frequently while the maximum design condition of 8953 kg. will occur rarely. Elongations are estimated to be .15% and .53% at 2500 and 8953 kg., respectively. Excess lengths of optical fiber must be designed into the composite cable to insure the time integral of elongation over 50 years (economic life of a transmission line) will not result in breakage of the fiber. Extreme values for the maximum loading condition are two occurrences in 50 years with a duration of 1 week for each occurrence. Procedures for precisely calculating



COST VERSUS STRANDING TENSION

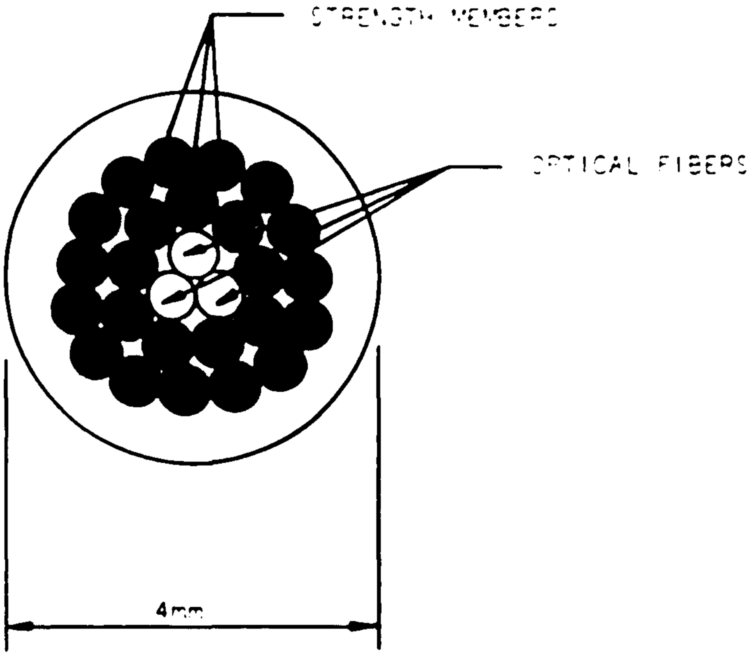
FIGURE 9

TABLE 2

Loading Condition (457.2 meter ruling span)	SAG (Meters)	Tension (Kilograms)
Bare, no wind, -28.9°C	7.56	2203
Bare, no wind, -17.8°C	7.92	2119
Bare, no wind, -1.1°C	8.47	2006
Bare, no wind, 15.6°C	8.99	1905
Bare, no wind, 32.2°C	9.54	1816
Bare, no wind, 48.9°C	10.06	1735
Bare, no wind, 100°C	11.58	1536
Bare, 19.53 kg/sq. meter wind, -17.8°C	8.08	2203
Bare, 43.94 kg/sq. meter wind, 15.6°C	9.54	2272
Bare, 122 kg/sq. meter wind, 15.6°C	11.28	3629
2.54 cm ice, no wind, -1.1°C	13.29	5946
2.54 cm ice, 39.06 kg/sq. meter wind, -17.8°C	13.78	6929
3.81 cm ice, no wind, -17.8°C	15.61	8953

expected fiber lifetime are not yet established; however, experience indicates very long lifetimes are probable if elongation is limited to about 0.1%. It is thus apparent that a minimum of a few tenths of 1% excess fiber should be incorporated into the composite cable design by winding the fiber helically.

Based on the above, a basic cable design can now be formulated. Assuming a 27/10 conductor design (Table 1, page 48) is used, the maximum allowable fiber cable diameter is 0.51308 centimeters. Practically, it is desirable that the fiber cable be of a slightly smaller diameter such as 4 mm. Figure 10, page 58 shows a potential design in which an optical fiber subunit and 0.5 mm. strength members are encased in a polyurethane jacket. If the strength members are Kevlar, strain at 226.8 kg. cabling stress is 0.71%. Use of steel strength members or lower cabling stress will of course reduce the strain. Excess fiber is incorporated into the optical fiber subunit. This is only one of essential infinite designs which are possible. It is included merely to demonstrate the concept.



OPTICAL FIBER SUBUNIT

FIGURE 10

Splicing & Termination

Splicing of the composite cable will be required for two reasons:

1. To join two pieces of cable during construction of the transmission line.
2. To make repairs of breaks in the fiber or of the entire cable.

The technique for splicing is the same for either case; however, the latter may involve locating a break in the fiber as well as difficulty in gaining access to the point of the break. The problem of access will not be discussed as this is a more or less routine problem dealt with by utilities. Location of breaks in fibers must be done using time domain reflectrometry (TDR). TDR involves transmitting a pulse down the fiber and measuring the return time. Because the propogation velocity of the pulse in glass fiber is precisely known, the technique can be extremely accurate. Extreme accuracy will be of questionable value, however, due to lack of knowledge of the tension and sag of the composite conductor. In fact, it will probably be necessary to replace a section of cable, whose length is orders of magnitude longer than TDR accuracy will dictate.

After a faulty section of cable is isolated or the end of a reel of cable is reached, splices must be made which will support at least 95% of the tensile strength of the conductors being joined. This can be accomplished by using compression splices over an area where the fiber cable is brought outside the metallic cable or, if the inner diameter of a metallic conductor is sufficiently large compared to the diameter of the fiber cable, a steel sleeve can be inserted over the fiber cable into the area where the compression will take place. In either case conventional splicing techniques can be used.

Terminations such as the end of the transmission line or at repeater stations can be handled in the same way as splices to bring the fiber into or out of the metallic conductor while connect/disconnect type connectors are used to make connections to repeaters, receivers, transmitters, etc.

Splicing of optical fibers can be accomplished in several ways, as described in Chapter III, page 25. Because only a few splices will be needed between repeater stations, use of index matching epoxy to glue fibers together is feasible although care must be taken to ensure mechanical strength is maintained. One means of achieving acceptable strength is to glue a length of tubing over the splice area then tie the cable strength members together by compression type clamps or gluing. Such methods for splicing and repair of fiber cables are well established in the industry.

Link Design

Design of fiber optic links is a straight-forward calculation of input power and losses. The following is a link design utilitizing parameters which would be typical for this application.

ASSUMPTIONS:

1. Repeater spacing - to be determined.

2. Required link bandwidth - 2 megahertz

3. Required signal to noise ratio - 40 dB

4. Source type - laser diode (power output including coupling = -2 dBm)

5. Detector type - PIN photo diode (sensitivity including coupling = -52 dBm)

6. Fiber - graded index

    a. Loss = 5 dB/km

    b. Bandwidth = 20 megahertz-km

    c. Connector loss - 1 dB/connector

    d. Splice loss - 0.5 dB/splice

    e. Allowance for degradation - 6 dB

    f. Excess power margin - 5 dB

CALCULATION:

Laser output	-2 dB
Receiver sensitivity	-52 dB

Allowable link loss		50 dB
Connector loss (2@1 dB)	2 dB	
Splice loss (10@0.5 dB)	5 dB	
Degradation	6 dB	
Excess margin	2 dB	
Total		15 dB
Allowable fiber loss		35 dB
Maximum repeater spacing	35/5 = 7 km	
Fiber bandwidth	20/7 = 2.8 Mhz	

Note that rise times for this system need not be looked at further since the rise times for injection lasers and avalanche photodiodes are on the order of a few nanoseconds and rise time of the fiber is adequately fast. Had a calculation been necessary the total system rise time would have been computed by determining the square root of the sum of the squares of the component rise times.

Thus, using current technology, repeater spacings of 7 km are practical and 10 repeater stations would be required for a typical 80 km transmission line. If very low loss (1 dB/km) wide bandwidth fiber were used, the repeater spacing might be increased to about 20 km with a corresponding reduction in the required number of repeater stations. A penalty for the resulting increase in reliability and lower repeater cost is much higher fiber cost. Industry trends may make the use of very low loss fiber economical within a decade.

There is one electrical portion of the fiber optic link which deserves special attention - the repeater power supply. There are several alternative sources of power:

- Solar cells
- Radioactive sources
- Wind power
- Induced power from insulated ground wires

Any of these could be made to work; however, the last appears to be most attractive. Unlike the other alternatives, no storage device is required; power is available whenever the line is energized. The Hydro-Quebec Institute of Research has designed and tested this type of power supply for microwave repeaters and found reliability to be excellent. Power outputs of 5 kw/km of insulated ground wire were demonstrated indicating only one insulated span would be required to power a fiber optic repeater station.

CHAPTER VI

ECONOMIC EVALUATION OF POWER LINE CARRIER VS. EOC

If the concept of an optical cable contained in an electrical conductor applied as an overhead ground wire is to be used in practice, it must be economically competitive with alternative communication media. The most commonly applied method of communication on a public utility (Pennsylvania Power & Light) power system considered at the 500 KV transmission voltage level is power line carrier. Because many installations of power line carrier have been made, the cost for installing a typical system is readily available. Estimates used by the public utility (PP&L) Bulk Power Engineering Department are approximately $60,000 for one terminal bi-directional dual transfer trip or $120,000 for the complete communication system including engineering, drafting, material and construction costs. This cost can be expected to escalate at roughly 8.5% per year.

While power line carrier costs are escalating, fiber optic system costs are falling and will continue to fall as technological improvements are made and quantities produced increased. Projected costs for fiber optic system components in 1981 are as follows (22,23,27):

Graded index fiber	\$300/km
Transmitter, Receiver (INC.MUX.)	\$2500
Repeater	\$2000
Connectors	\$10
Splices	\$5

For a 80 km, three fiber link using a 7 km repeater spacing the total material costs is estimated to be \$144,000. Engineering and Drafting will add another \$10,000 to this cost. Incremental cabling costs are expected to \$15,000. Finally, the repeater power supply cost is estimated at \$500 per station. Thus, the total cost of a fiber optic system will be about \$174,000, ignoring any incremental installation costs for the cable. The corresponding figure for power line carrier is $(1.085)^3$ x 120,000 or \$153,275. The difference in installed costs is less than 15%-a cost which may prove acceptable in light of problems associated with power line carrier. Note also that fiber optics will be more cost competative for shorter links at earlier points in time and longer links at later points in time. The point here is not in the magnitude estimates but rather in the fact that fiber optics will be cost competitive.

CHAPTER VII

CONCLUSIONS

It is now technically and will be economically feasible in the future to manufacture a composite fiber optic cable and electrical conductor used as an overhead ground wire on a 500 KV transmission line to replace other forms of communication channels such as power line carrier. Installed cost of a typical system will be roughly $174,000 in 1981, less than 15% greater than the power line carrier alternative. Reliability will be dictated by repeater design, but will be acceptable using the redundant channel available. Key areas which must be given attention in designing a system are:

- Ensure loop losses are less than available power for fiber optic link.
- Ensure system rise time is sufficient for desired bandwidth.
- Ensure optical cable and electrical conductor are mechanically compatible by using reinforcing materials in the fiber cable and employing a

helical design for non-metallic coated fiber or using a metallic coated fiber.

- Use of a splicing technique for electrical conductors which does not damage the fiber optics. This can be accomplished by bringing the fiber out of the metallic conductor in the region of the splice or protecting the fiber with a steel tube inserted in the area of the splice.

Although current utility practices do not require more than roughly 6,000 Hz bandwidth and near term projections are 12,000 Hz, a graded index fiber is recommended for use in the electrical conductor. Graded index fibers provide sufficient bandwidth for applications such as video monitoring at little or no incremental cost over step index fiber. Laser diodes are recommended as emitters and avalanche photodiodes as detectors to maximize repeater spacing. Light emitting diodes and PIN photodiodes are currently more reliable and less expensive but exhibit less light output and lower sensitivity. The concept of three fiber channels will ensure a channel is always available in one direction. A two fiber channel design will be acceptable with the advent of bi-directional repeaters and directional couplers.

Mechanical requirements dictate the electrical conductor be steel, coated with aluminum or copper to insure low electrical resistance. The core of the conductor must be expanded to 0.5 centimeters or greater to contain an optical cable reinforced with Kevlar or steel wire if non-metallic coated fiber is used. Use of metallic coated fibers results in a smaller diameter fiber cable which may be used to replace the central strand of a 19/9 electrical conductor. Costs for production quantities of metallic coated fibers will determine which approach is used.

There are several advantages which will make the concept of optical fibers contained in electrical conductors desirable:

- Optical fibers contained in electrical conductors will be protected from lightning and other atmospheric phenomenon.

- There is little additional knowledge or effort required of personnel who string the conductors apart from optical fiber splicing.

- The utility has complete control over the communications media.

- Wide bandwidths can be made available for functions such as video security monitoring, supervisory control, or ultra high speed relaying.

- The system can be customed designed to the degree of security and reliability felt to be needed.

- The communications channel is immune to electrostatic and electromagnetic interference as well as nuclear radiation.

These and other less significant features of optical fibers contained within electrical conductors applied as overhead ground wires are likely to encourage electric utility companies to apply this concept in the future.

CHAPTER VIII

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BIOGRAPHY

The author was born in Allentown, PA on March 3, 1950, the son of George T. and Dora E. Gilbert. He graduated from William Allen High School, Allentown, in 1968 and was admitted to Lafayette College, Easton, PA, in the Electrical Engineering curriculum in September of that year. During his four year enrollment, he was employed by the Pennsylvania Power & Light Company for a total of six months in a summer employment program as a Cadet Engineer. During this time, the author was accepted as a member of Eta Kappa Nu. Upon graduation from Lafayette in 1972, he accepted a position with the Pennsylvania Power & Light Company as an engineer in the Electrical Research Section of the Bulk Power Engineering Department. In 1975 he was promoted to the position of Project Engineer-Bulk Power Engineering Development. In 1976, he was licensed as a professional engineer in the Commonwealth of Pennsylvania.

The author enrolled in the graduate school at Lehigh University where he worked towards a Master of Science degree in Electrical Engineering shortly after his full-time employment at PP&L.

In 1972, he married the former Carol L. Beam of Allentown, PA. After living in Allentown for five years, they moved to Orefield, PA where they now reside.