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FIBER OPTICS APPLICATIONS STUDY. (U)
DEC 79 C R HOLLAND, H L DUFILO

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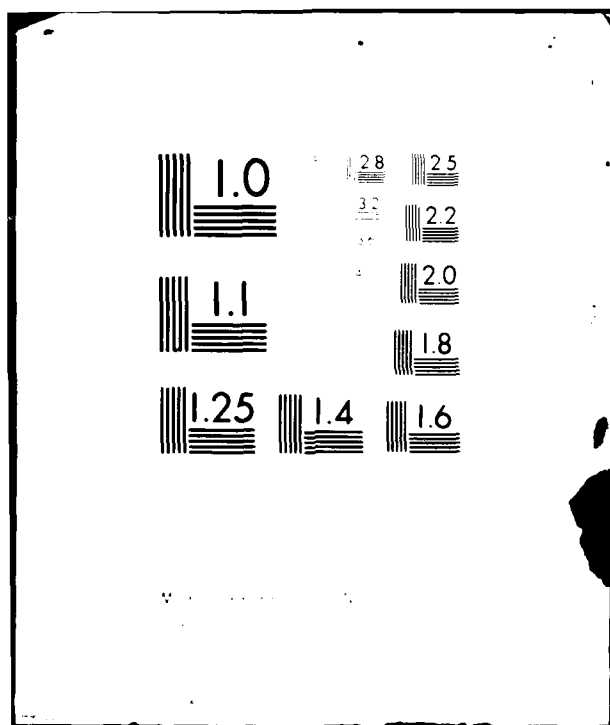
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Fiber Optics Applications Study

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Ocean Technology Division
Ocean Science and Technology Laboratory

December 1979



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EXECUTIVE SUMMARY

This study of fiber optics technology has been designed to consider the following questions: (1) What is the present (early 1979) technology state-of-the-art; (2) How might this technology be applied to improve and extend our ocean measurement capabilities; and (3) What should be our future course of action in taking advantage of this technology for ocean environmental measurements.

The first question led to consideration of a technological area that rivals electronics technology concerning the rate of development. New components having significantly improved performance and cost advantages appear almost weekly. The entire fiber optics and opto-electronics technology is growing rapidly and is on the verge of achieving a level of maturity sufficient to implement a number of measurement concepts by choosing from readily available components.

In considering the second question, we "dreamed" a bit and gave our imaginations some free reign. We found a number of ocean parameter measurements and data transmission requirements that fiber optics technology might accomplish better in terms of cost and measurement system simplicity. We also found that many present ocean measurement techniques are nowhere near full utilization of conventional copper/electronic technologies. As a result, while fiber optics (the more unknown technology) may provide improvements in ocean measurements, conventional electronics (the more proven technology) can in the majority of cases provide essentially the same performance at less development risk. There are isolated exceptions, but we could not discern any general ocean measurement area that could be exclusively answered by fiber optics. It should be noted, however, that we did not explore the acoustic requirements of the surveillance community.

What, then, about question three? It is our conclusion that utilization of the fiber optics technology can be made for many applications showing clear cost/performance advantages by using existing optics components except in the area of sensors. We further feel that the development of wide bandwidth optical data transmission cables for undersea use should be continued, but that development of an all-optical measurement system must be justified on individual requirements and that general requirements for an all-optical ocean measurement system do not yet exist from a performance or cost standpoint. We recommend continuing Navy awareness of this technology as it is being developed by industry and involvement in development of undersea optical cables, but find no specific ocean measurement system that can be recommended for development using fiber optics technology at this time.

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I. INTRODUCTION

The technology area of fiber optics and opto-electronics has experienced rapid advancements in component performance, reliability, and availability during the last few years. The major performance characteristics of wide bandwidth, high noise immunity and low crosstalk, corrosion resistance, lighter weight, and excellent signal isolation have permitted the development of greatly improved signal transmission systems and well-behaved control circuits. Having recognized the performance advantages and the rapid development of useful components, it was decided to assess the applicability of this technology to the field of ocean instrumentation and determine, as specifically as possible, those applications that would benefit the most.

Having as our purpose the assessment of fiber optics and opto-electronics as it applies to ocean instrumentation for measurements, we first acquired a detailed understanding of the present (early 1979) technology state-of-the-art. We next compared the performance of the present technology and its logical extensions to those ocean measurement requirements that have not been fully solved technically or economically. The primary purpose of this comparison has been to identify the specific ocean measurement problems that would benefit most from applied optical technology. A secondary purpose was to determine the extent of any gaps or lacks in the technology that was available for application.

In the sections that follow, the fiber optic and opto-electronic technology is described in fair detail to give the reader a reasonably in-depth appreciation of the present state-of-the-art. Potential applications of this technology to ocean measurement problems is then discussed in detail; with the final section being devoted to recommendations for future effort.

II. TECHNOLOGY ASSESSMENT

A. FIBER OPTIC CABLES

Optical fiber cables offer several distinct advantages over conventional copper wire cables. The weight of a typical fiber optic cable is approximately 26.5 g/m, while an equivalent coaxial cable, such as RG-8/u, weighs approximately 161.7 g/m. This large difference in weights does not tell the complete story, though; when the fiber optic cable is used in a marine environment it is neutrally buoyant, while the RG-8/u coaxial cable is negatively buoyant by 75 g/m. This buoyancy difference between the two types of cables becomes significant when cable lengths in excess of 1 km are used. Fiber optic cables also offer electrical isolation between sensors and receiving electronics, immunity to electromagnetic interference and noise, elimination of ground loop problems and cross talk, extremely high data transmission rates (data rates on the order of 50 m bits/sec are readily attainable over short lengths), lower signal attenuation (6 dB/km vs. 23 dB/km for RG-8/u at 10 MHz) and a high degree of resistance to sea water corrosion and galvanic action. Conversely, whenever a copper cable is deployed in a marine environment, corrective action must be taken to minimize all of the above from interfering with data collection.

Even with these distinct advantages there are still some difficult, but not insurmountable, problems associated with the use of the fiber optic cables in the ocean. The most prominent of these is the degradation of glass fiber tensile strength due to the action of water on the tips of surface flaws. When the glass fiber is under tensile stress the free hydroxyl ions are available to migrate into surface flaws, the amount of energy required to generate new surfaces within the

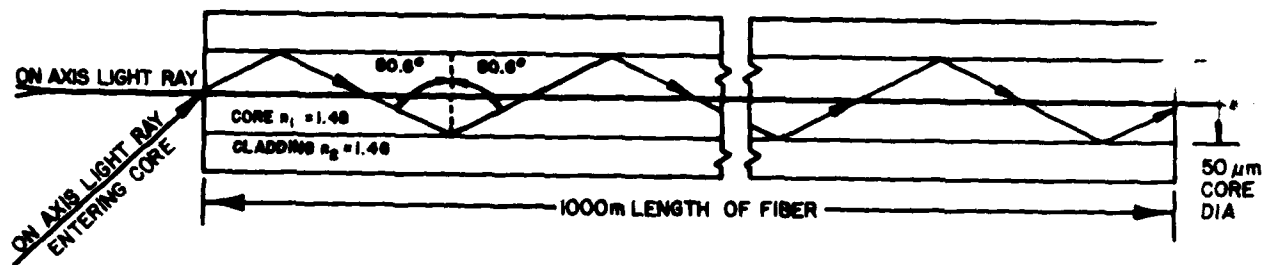
flaws is diminished and the overall strength of the fiber is reduced. This reduction in fiber strength due to the growth of macroscopic cracks with time (t) has been experimentally observed and can be calculated as $(dc/dt = (AK)^n)$ where c is the flaw size, A and n are constants, and $K = \pi \alpha C^{1/2}$ (α is the applied stress) [1,2,3]. The value for n has been experimentally determined to be around 22. If an accurate value for n can be found, it is possible to make a reasonable estimate of the lifetime of a fiber prior to catastrophic failure, because the maximum size flaw is determined during the manufacturing process and the applied stress is a known quantity. Also, the longer fibers have a greater probability of breakage with a given flaw size because the flaw distribution is such that there is a cumulative failure probability with increases in fiber length. Glass fibers are presently being manufactured with flaws smaller than $0.2 \mu\text{m}$, which allows the fibers to withstand static stresses on the order of 690 N/mm^2 (100,000 psi) without breakage. Upon exposure to sea water, the surface flaws inherent to the glass fibers grow while under stress, and the breaking strength of the fibers is reduced to a value well below the rated static breaking strength.

The reliability and useful life span of fiber optics cables are inter-related and depend on a large number of considerations such as:

- Environmental conditions
- Handling of cable during deployment and recovery
- Maximum flaw size produced during manufacture
- Length of time in water
- Working depth
- Applied stress and snap loading during operations

There have been a number of attempts to quantify the life of an optical fiber under stress by experimentally measuring the time to catastrophic failure versus a given stress. According to data gathered by Bell Laboratories [4], it appears that fibers stored in water for six months will fracture in about 10^2 minutes with an applied stress of 2760 N/mm^2 (400,000 psi). By extrapolating, it is found that with an applied stress of 1380 N/mm^2 (200,000 psi) the life of these optical fibers would be on the order of 10^6 minutes. With an applied stress of 690 N/mm^2 (100,000 psi), the probability of failure of a good quality optical fiber is generally under 5% for lengths of 1 km. As the fiber length increases, the probability of failure also increases. Based on experimental data, it would appear that an optical fiber could have a very long life if the applied stress is kept well under 690 N/mm^2 (100,000 psi) and reasonable care is exercised in the manufacture and handling of this fiber.

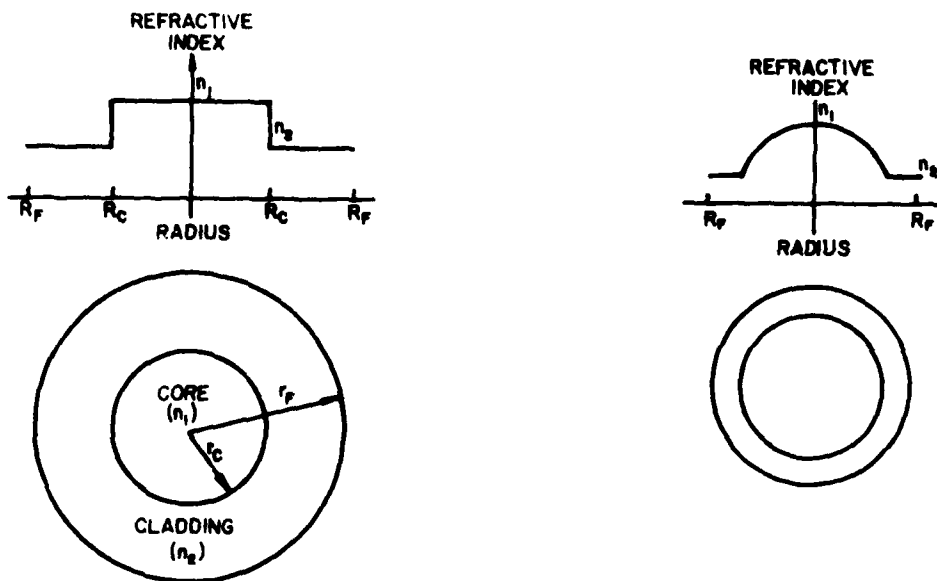
At present, the whole fiber optic industry is in a continuous state of flux, with each manufacturer attempting to produce the best fiber with the lowest price tag. The typical optical fiber consists of a core of optically transparent dielectric material with an optical index of refraction of n_1 , surrounded by a cladding material with a lower optical index of refraction, n_2 . Optical fibers are usually classified by mode type: single mode or multimode, which includes both step-index and graded-index fibers. The optical fiber represents a special case of cylindrical waveguide and can be characterized by: $V = [2\sqrt{2}\pi r (\pi \Delta n)^{1/2}] / \lambda$ where r is the core radius, λ the free space wavelength, n the average refractive index of core and cladding, and Δn the difference in refractive index between core and cladding [5,6]. When $V < 2.405$ light will propagate through the fiber in a single mode, whereas when $V > 2.405$ the propagation of light through the fiber will excite many modes, the number of which can be approximated by: $N \approx V^2/2$. Differences in the propagation characteristics of these many modes cause the appearance of a phenomenon known as modal dispersion, which is one of the more important factors contributing to bandwidth reduction in optical fibers. An example of modal dispersion in a step-index fiber is shown in Figure 1.



Reflecting back into the core each time it strikes the core-cladding interface, an off-axis light ray follows a zig-zag path 1014 m long. Compared with an axial ray, this extra 14 m produces an arrival-time difference of 69 nsec.

Figure 1. Modal dispersion of a step index fiber

As can be seen from Figure 1, an off-axis light ray travels a longer path than an on-axis light ray. This difference in path lengths between light rays traversing the optical waveguide causes bit smearing in a pulsed-data transmission system or delay distortion in an analog-modulated system. Dispersion (temporal spreading) increases with increasing fiber length and is usually expressed in ns/km for pulse transmission systems. Step-index fibers currently have modal dispersions on the order of 30 nanosec/km, while graded-index fibers can get as low as 1 nanosec/km. The construction of step-index and graded-index fibers is shown in figure 2.



The index profile takes a downward step at the core radius in a step-index optical fiber. This step divides the fiber's cross section into a central core with index n_1 and a surrounding cladding with index n_2 .

The graded-index profile tapers off parabolically with radius from its central-axis value n_1 to a lower value n_2 at the fiber radius r_1 . The cross section shows that light travels slower near the shaded center region than it does away from the center, resulting in more consistent arrival time and less modal dispersion.

Figure 2. Construction of step index and graded index optical fibers

Step-index optical fibers are constructed of a homogenous core material with an index of refraction approximately equal to 1.48 surrounded by a cladding material, with an index of refraction approximately equal to 1.46. As can be seen in Figure 2, the change of refraction index at the core-cladding interface is an abrupt step function. On the other hand, the graded-index optical fiber consists of layers of vapor deposited glass with a parabolically decreasing index of refraction from the center to the outer layer of the core. Figure 3 illustrates the path differences between graded-index fibers and step-index fibers with an off-axis light ray entering the fiber. Because of the parabolically decreasing index of

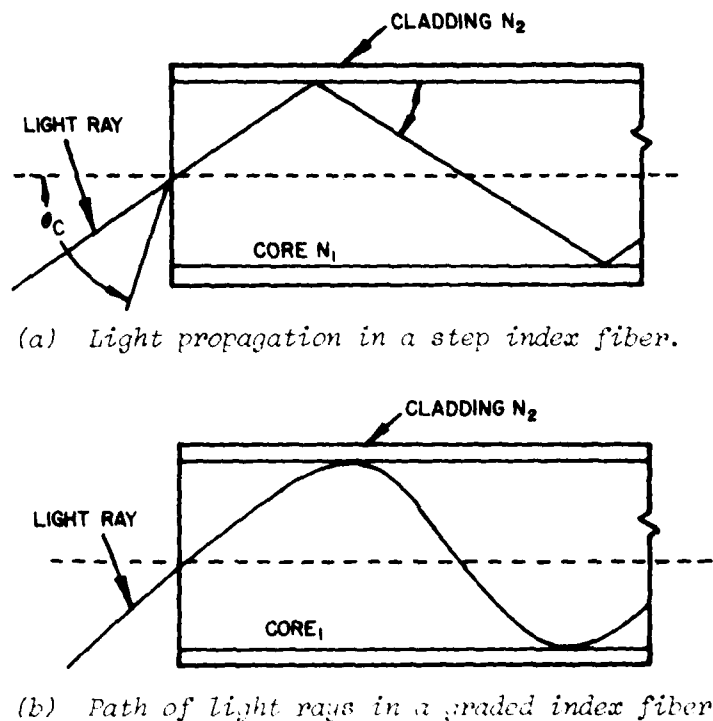
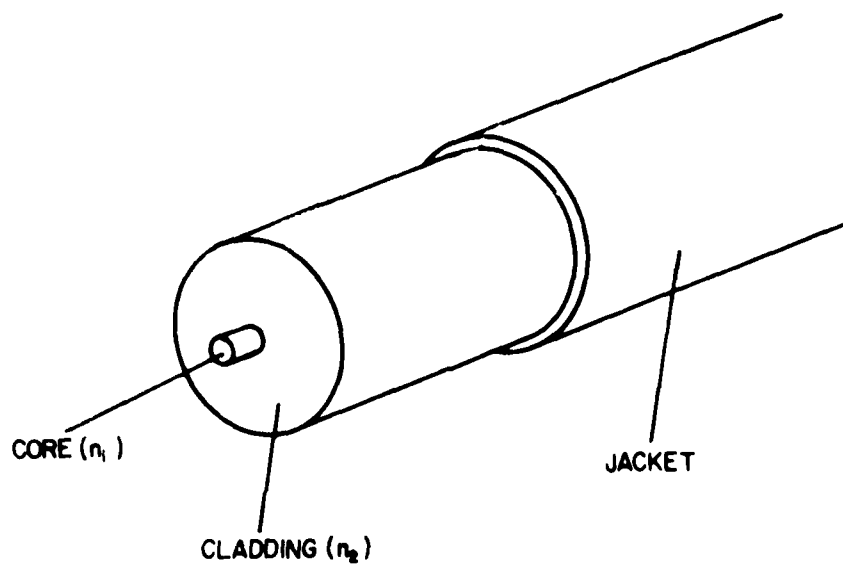


Figure 3. Comparison of off-axis path differences between graded index and step index optical fibers

refraction from the center outward, the velocity of light rays traveling through the graded-index optical fiber increases from the center outward. This produces a sinusoid-like path through the fiber and allows an off-axis ray to travel a greater distance per unit time than an axial ray, thereby decreasing the dispersion. For the ultimate in bandwidths, the single mode fiber (Fig. 4) offers bandwidths reaching into the gigabit/sec range. The single mode fiber has no dispersion because the core diameter is made sufficiently small such that $V \leq 2.405$, and there is only one mode of propagation. Since there is little modal dispersion, one might ask, why bother with step-index or graded-index fibers. As it turns out, all is not ideal with single mode fibers, either. The core of the single mode fiber has a maximum diameter of 2 to 4 μm , which makes it difficult to project light into the fiber, to splice fibers because of core alignment problems, to affix connectors to the fiber, and to detect the light at the receiving end of the fiber.

In addition to the problem of modal dispersion, there are problems with signal attenuation within the fiber and input/output coupling losses. The



SINGLE MODE FIBER

$$V = \frac{2 \sqrt{2} \pi r [\pi (n_1 - n_2)]^{1/2}}{\lambda}$$

$$V \leq 2.405$$

Figure 4. Single mode fiber arrangement

attenuation of the signal within the optical fiber can be broken down into three major categories: absorption loss, material scattering loss, and waveguide imperfection loss. The absorption loss is due to material impurities, intrinsic loss, and atomic defect color centers. Material scattering losses arise mainly from intrinsic scattering of light due to thermally generated fluctuations in the index of refraction of the material and scattering due to inhomogeneities within the material. The waveguide imperfection loss is due to structural defects which occur during the manufacturing process, such as microbending and irregularities along the core-cladding interface. Much has been done to reduce the signal attenuation of optical fibers, and presently some are commercially available with attenuations as low as 2 dB/km in short lengths. There are a large number of optical fibers available with attenuations of less than 10 dB/km and a cost of less than \$2.00/m, which makes the use of optical fibers for transmission of wideband data over long distances very attractive. There are also some experimental fibers which may be commercially available in the near future with attenuation as low as 0.2 dB/km. The one big drawback to the use of long optical fiber data links is, as mentioned earlier, the tensile strength and problems associated with degradation of the fiber's tensile strength. Optical fibers are presently being produced under laboratory conditions which have tensile strengths on the order of 10^6 psi, and packaging schemes are being developed which offer considerable protection to the optical fiber, as can be seen in Figure 5. In addition, plastic optical fibers are undergoing tremendous improvements in signal transmission characteristics such that some are now available with attenuations as low as 100 dB/km. While this is still much too great of an attenuation for long data links, it is expected that within the next few years the plastic optical fibers will undergo a drastic improvement in signal transmission characteristics, such that attenuations of the order of 15 to 20 dB/km can be expected. The plastic fibers offer definite reliability and service life advantages, and make splices and interconnections much easier and less expensive. Plastic optical fibers also generally have a higher numerical aperture (NA) than the glass fibers, which decreases the input/output coupling losses. These losses, as mentioned earlier, contribute to overall signal attenuation in a data link, along with attenuation of the optical fiber itself.

The input/output coupling losses consist of losses due to fiber-source misalignment, fiber-detector misalignment, the size of the emitting area being larger than the core area of the fiber, the core area of the fiber being larger than the detector area, the light-gathering ability of the fiber, and the packing loss which occurs in multi-fiber cables. The fiber-source and fiber-detector misalignment losses are caused by the physical misalignment of the fiber and source and that percentage of the light delivered by the source is radiated into free space rather than into the fiber; conversely, at the opposite end of the link, the fiber-detector misalignment of the fiber and the detector causes a percentage of the light delivered to the end of the fiber to be radiated into free space rather than into the detector. These losses, along with the losses due to differences in the source and detector areas versus the core area, can be virtually eliminated by ensuring that the source emitting area is equal to or less than the fiber core area and the detector area is equal to or greater than the fiber core area, and the alignment at both interfaces is properly maintained under normal handling. These requirements are satisfied in most coupling configurations by using an optical fiber pigtail-light source and light detector arrangement as seen in Figure 6. The optical fiber pigtail is permanently joined to the light source or detector, thereby eliminating the possibility of misalignment and/or coupling problems due to handling. The light transmitting ability of an optical fiber is dependent upon the light acceptance cone for the fiber, which is shown in Figure 7. This light acceptance cone is a solid angle determined by the indices of refraction of the core and cladding material and it delineates the maximum angle of arriving light rays which will produce total

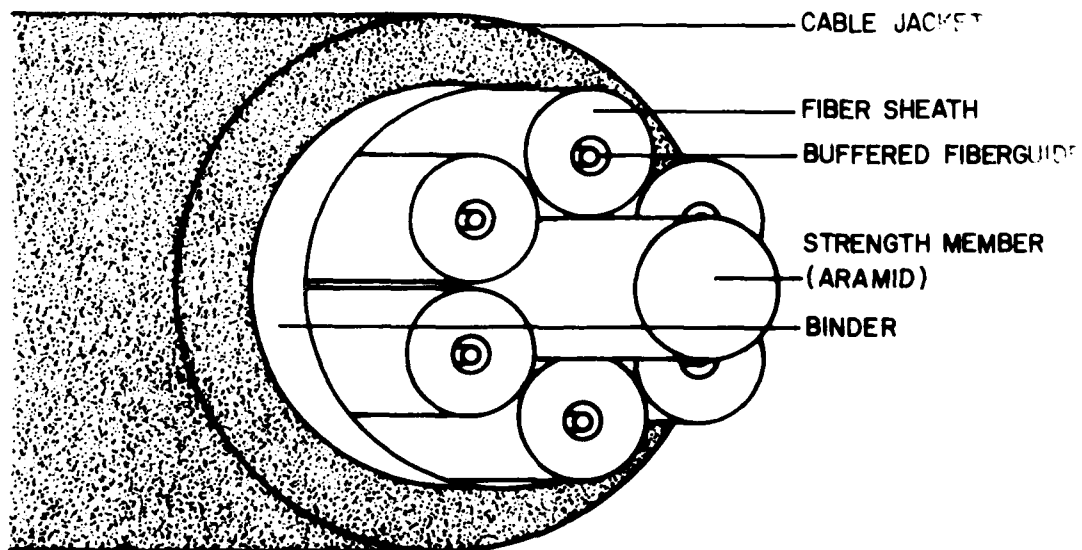
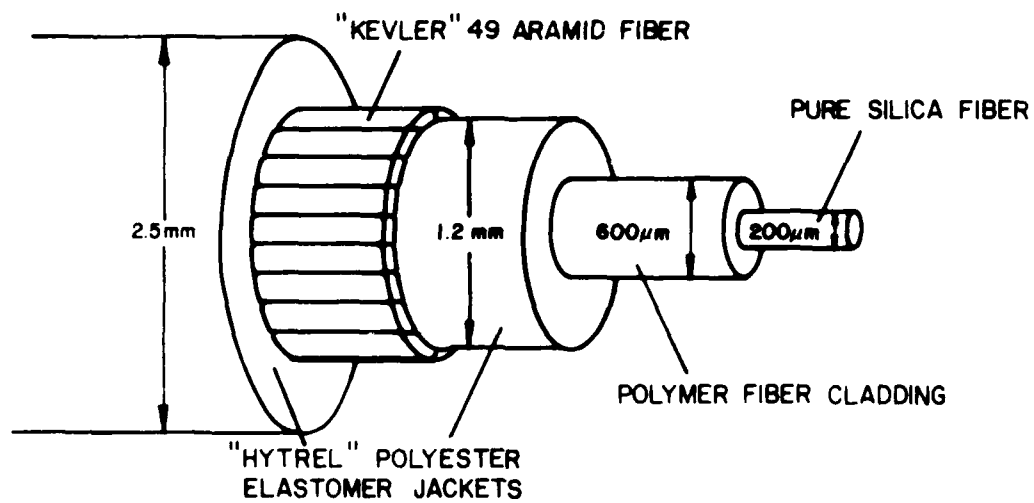


Figure 5A. Construction of typical optical fibers cables

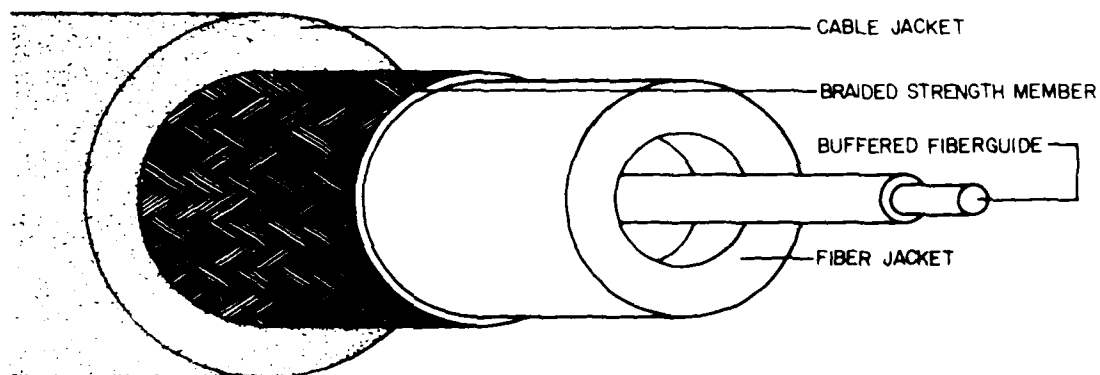
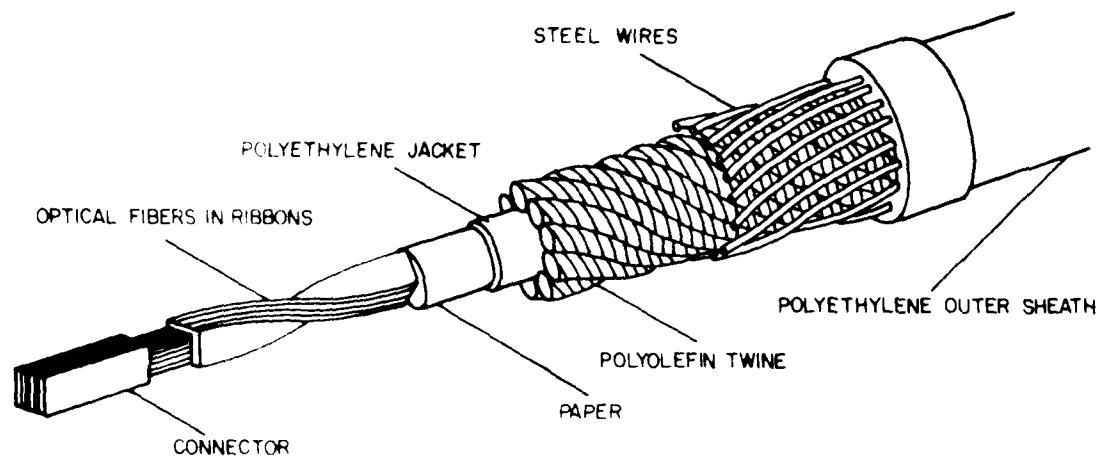


Figure 5B. Construction of typical optical fibers cables

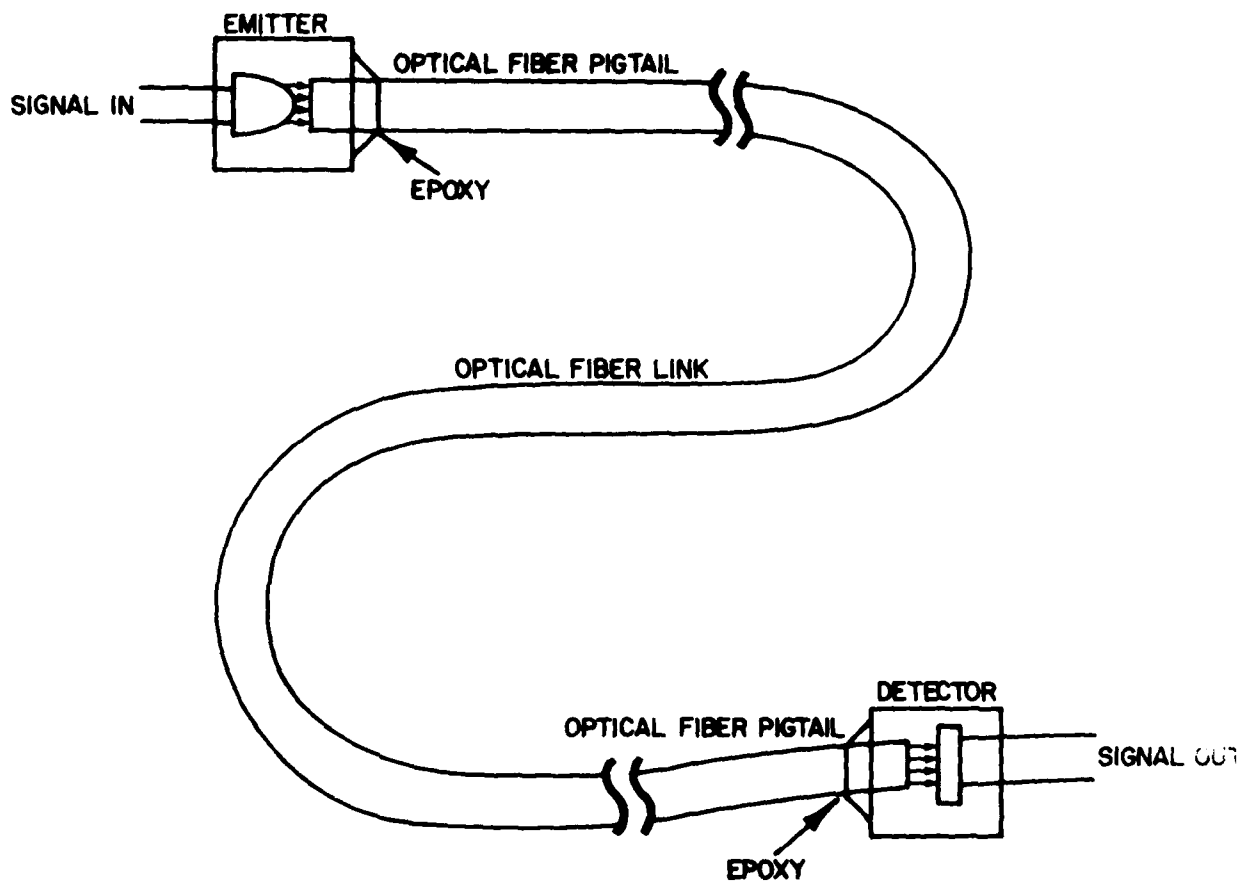
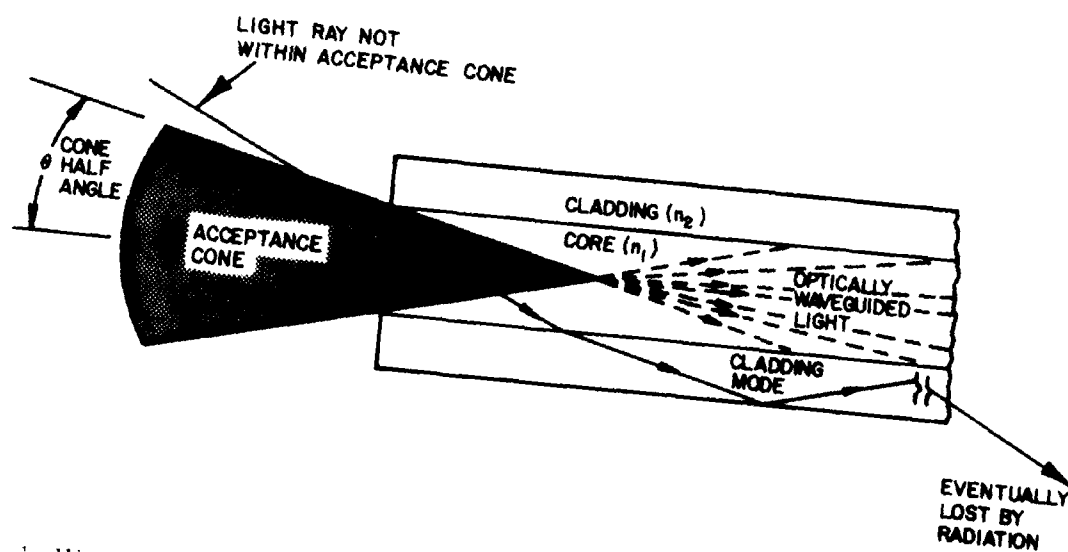


Figure 6. Typical pig-tail configurations for fiber optic light sources and detectors



A fiber's acceptance-cone half angle derives from the fiber's numerical aperture. Light projected into the acceptance cone undergoes waveguiding in the core, while rays outside the cone reflect into the cladding and are eventually lost.

Figure 7. Acceptance cone for a typical fiber

internal reflections, thereby propagating down the fiber. Light rays arriving from outside of this acceptance cone will be absorbed by the cladding material and not transmitted down the fiber, as shown in Figure 7. The parameter which is most often used to define this acceptance cone is the numerical aperture (NA) of an optical fiber. The numerical aperture is defined as the sine of the half angle of the acceptance cone and generally ranges from 0.1 to 0.5, depending on the core and cladding materials.

The final source of input/output coupling losses is the loss associated with many fibers packaged in a common bundle. This input coupling loss is called the packing fraction loss, and is due to the illumination of many fibers in a single bundle by one light source. This loss is measured by the ratio of the total core area of all the fibers to the cross sectional area of the entire bundle (see Fig. 8).

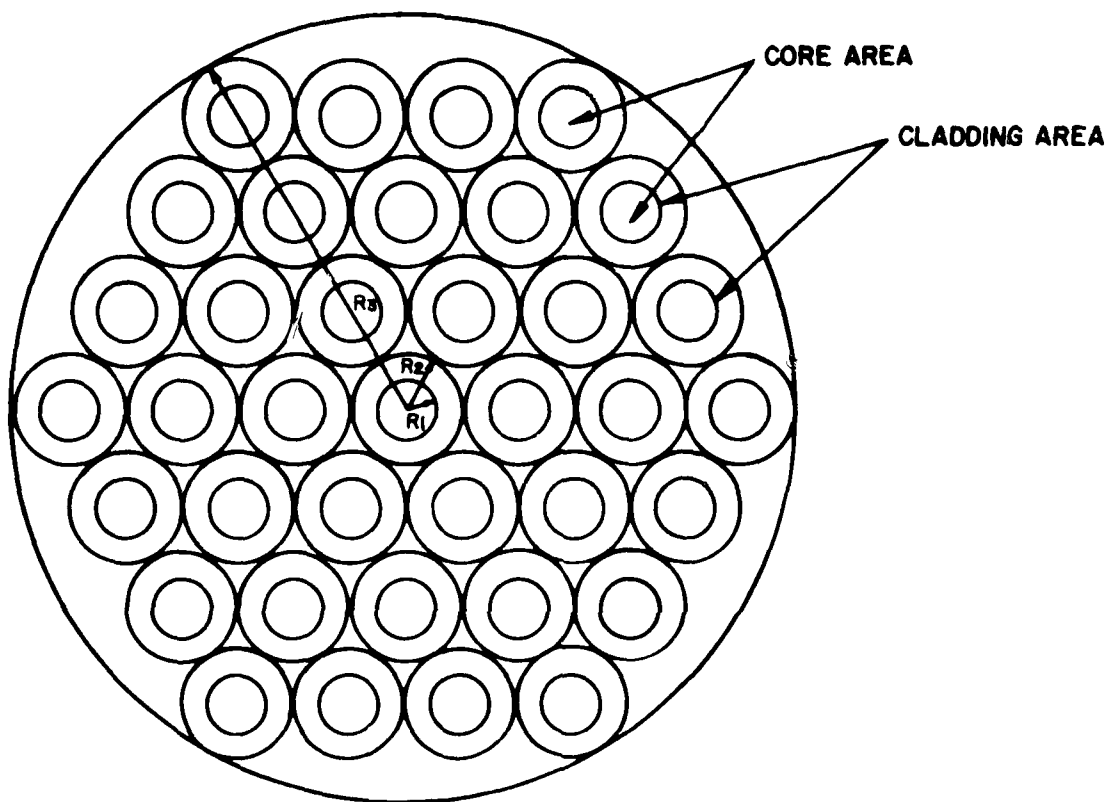
Future optical fibers will tend to be high strength (106 psi), low loss (<2dB/km), graded-index fibers; in addition, plastic step-index fibers may possibly be available with losses in the 10 to 20 dB/km range. There exists, also, a good possibility that low loss liquid-core optical fibers will be commercially available in the not too distant future. Some reported results [7,8] indicate that liquid core optical fibers with losses on the order of 0.1 dB/km are possible now. In addition to all of this, the trend toward lower prices will continue, with prices of optical fiber cables becoming less than that of comparable copper cables.

B. OPTICAL CABLE CONNECTORS

From the previous section on fiber optic cables, we see that optical signals can be transmitted over rather significant distances with reasonable loss in signal strength. But to utilize these cables one must be able to couple signals into and extract signals from the transmission cable. Couplers (optical fiber connectors) are required and can introduce additional signal attenuations which equal hundreds of meters of transmission cable; therefore, in the design of any fiber optic data transmission system careful attention must be given to the coupler design, fabrication, and installation.

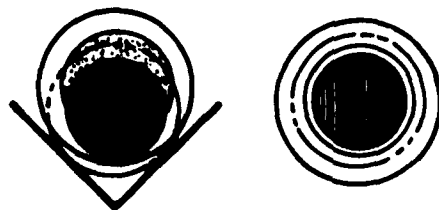
Continuous fibers derive their low attenuation values from pure materials having few light absorbing impurities and fabrication techniques that insure very few structural flaws in the final drawn fiber. When coupling two fibers together, however, one attempts to bring together two cleaved ends, which represent major mechanical flaws, into perfect alignment. Figure 9 illustrates the major alignment problems that must be solved by the selected coupler in joining two fiber cables. Assuming near perfect mechanical alignment, one must additionally consider the optical discontinuity of the parallel cleaved end surfaces. These end surfaces permit reflections to occur wherever the index of refraction changes markedly, thereby increasing signal losses and reducing the maximum operating frequency because of the creation of multimode interference. One attempt to reduce the end surface reflection problem involves the use of a liquid having nearly the same refractive index as the fiber cable and good light transmission properties. The connector body is designed to hold the fiber ends in correct alignment while submerging the ends in the coupling fluid. Figures 10, 11, and 12 illustrate some of the more popular types of fiber connector designs now on the market.

Techniques have been developed for field installation of connectors and for emergency cable patches wherein considerable additional attenuation can be tolerated without unacceptable operation degradation. In all the field installation techniques, the fiber must be cleaved so that the end face of each piece is perpendicular to the cable axis. One popular technique involves scribing of the fiber



$$\text{PACKING FRACTION} = \frac{\text{TOTAL CORE AREA}}{\text{TOTAL ARRAY AREA}} \approx \frac{N\pi R_1^2}{\pi R_3^2}$$

Figure 8. Typical bundle cross section



FIBER TOLERANCES CAN CONTRIBUTE
SIGNIFICANTLY TO AXIS OFFSET.

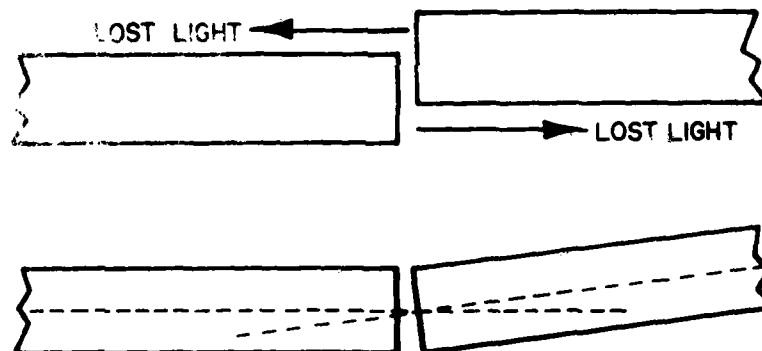


Figure 9. Typical examples of fiber misalignment

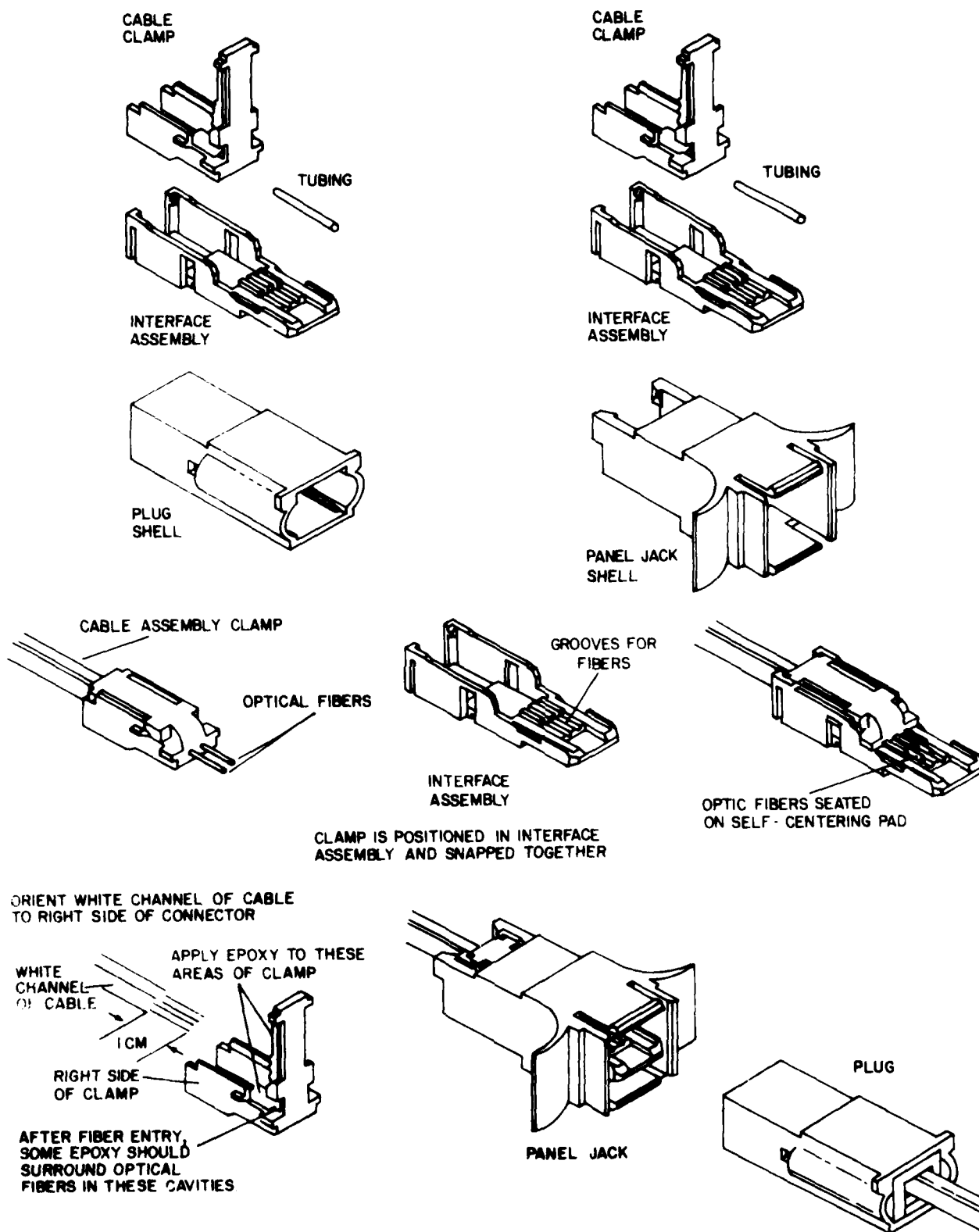
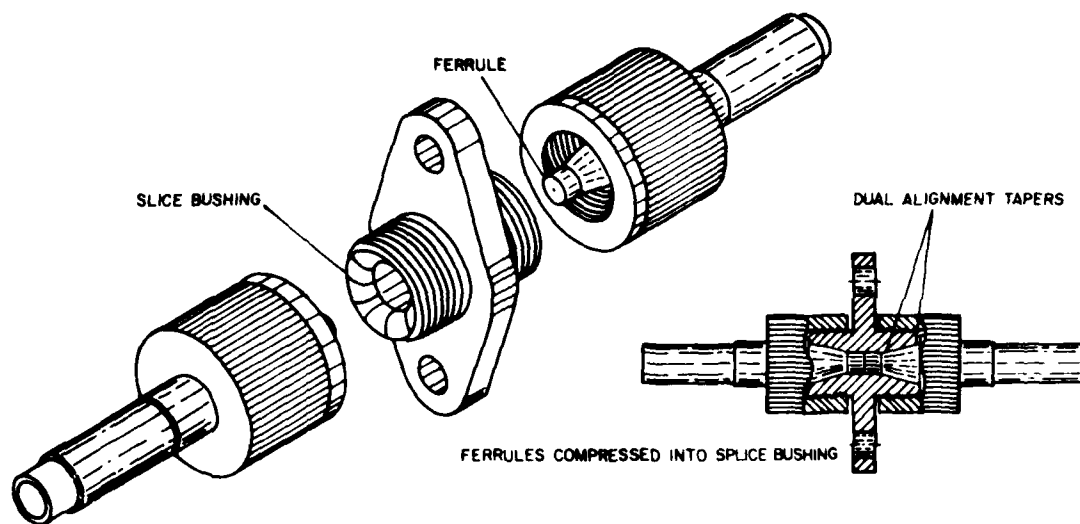


Figure 10. Optical fiber connector-clamp type



CABLE CONNECTOR

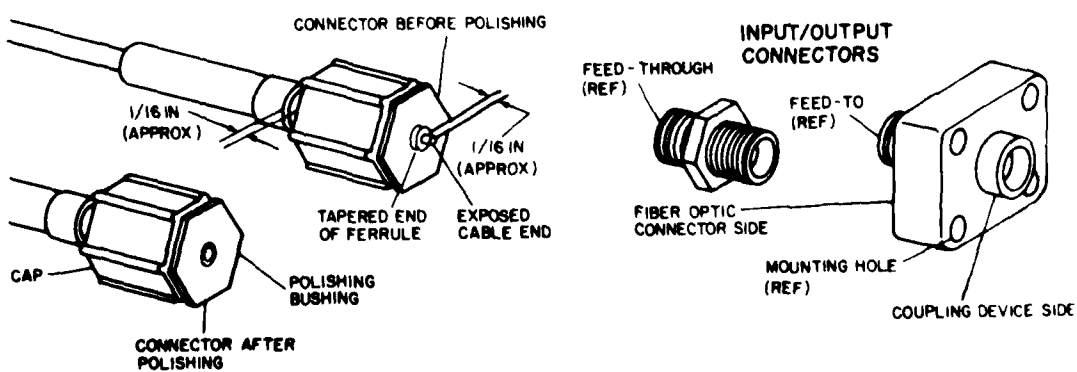
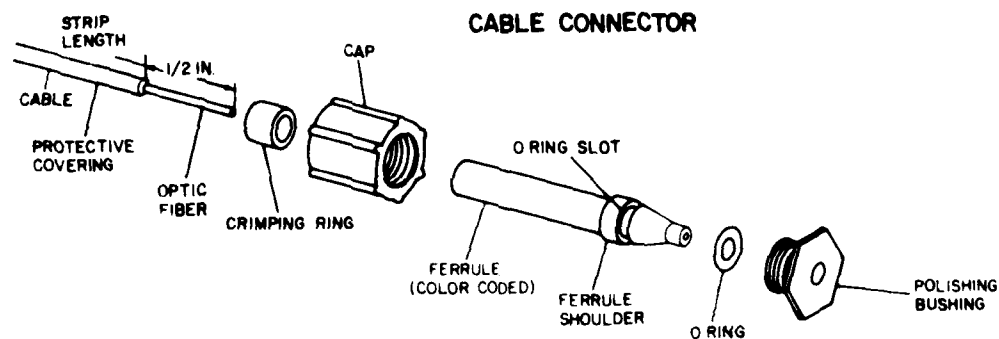


Figure 11. Optical fiber connector-ferrule type

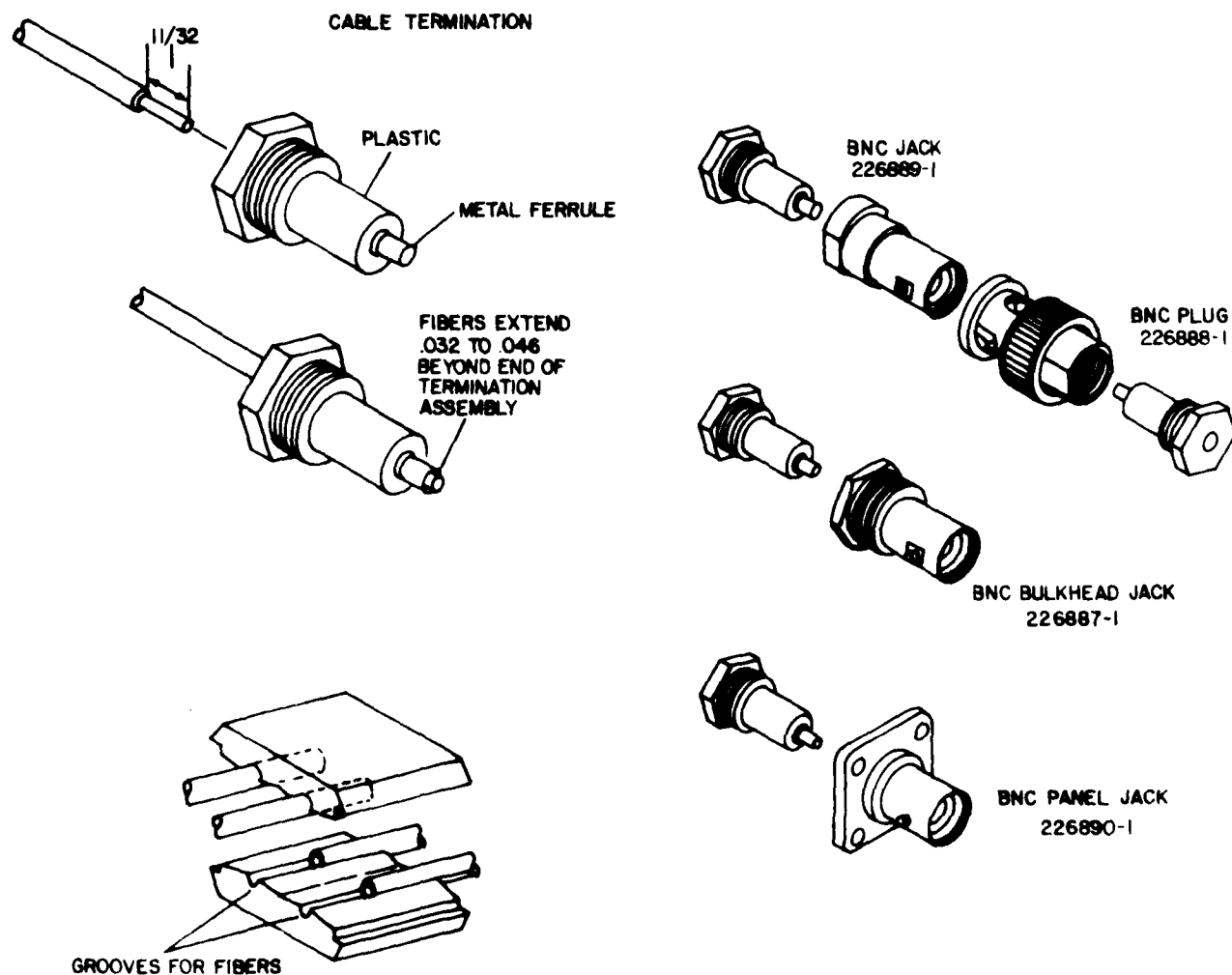


Figure 12. Optical fiber connector-BNC type

carefully with a sapphire cutter and then tensioning the strand until the stress is achieved. Properly done, this technique yields a clean perpendicular break in the strand. Next the end is polished to reduce end surface irregularities. End surface polishing has a great effect on the signal transmission scattering. To maintain correct alignment, the strand is mounted in a holder and polished on an optically flat plate using successively finer paste grits. After polishing and cleaning, the fiber strand is ready for mounting in the selected connector. Each connector has its own special procedure for receiving the polished fiber, and complete assembly instructions are supplied by the manufacturers of the more successful designs.

An emergency connection can be made in a fiber cable by first cleaving and polishing each strand end. Next the ends are butted together in the middle of a piece of heat shrinkable tubing, the diameter of which is just slightly larger than the fiber strand. While keeping the fiber strands tightly butted together, the tubing is carefully shrunk. This emergency procedure provides a coupling which exhibits reasonable mechanical strength and somewhere between 2 to 10 times the attenuation of the best commercial connectors. If additional mechanical strength is desired, extra heat shrink sleeves can be placed on the cable and shrunk one at a time over the first sleeve.

In some applications, the need exists to couple signals onto a transmission line at various points along its length. Techniques are being investigated for performing this function using optical fibers and "Y" couplers, but no commercial components are available as of this writing. One technique is shown in Figure 13 and consists of typical end coupling of fibers wherein the ends are offset so that only a portion of the fiber end surface is coupled to the next fiber. The operation of this multi-coupler is straightforward and works well for short distances, but the attenuation is very high (due to poor coupling area) and becomes severe if a few such couplers are used because of the compounding of attenuation losses. With the on-going investigations into other techniques for multi-couplers and distributive coupling, it is reasonable to anticipate the introduction of commercial devices within a few months or at most two years.

C. OPTO-ELECTRONICS

Perhaps the best way to begin a discussion of the opto-electronic components for an optical communications link is with the light source. There are a large number of light sources available, but the three most widely used types are the light emitting diode (LED), the injection laser, and the Neodymium: YAG lasers. The first two sources are both semi-conductor Gallium-Arsenide (GaAs) junction devices which emit light due to the process of recombination of carriers injected across a P-N junction, while the third source is a solid state, optically-pumped, Neodymium: Yttrium-Aluminum-Garnet laser. LEDs for communication links are generally of two types: surface-emitting and edge-emitting diodes. The surface-emitting or Burrus diode consists of a double heterostructure having an active layer of GaAs sandwiched between two AlGaAs layers. In order to minimize the coupling losses, it also has a well etched into the substrate for the physical attachment of a single optical fiber pigtail (see Fig. 14). The Burrus diode provides a high radiance, reasonably fast rise time, bandwidths in excess of 50 MHz, and can be operated with a high duty cycle; the edge-emitting diode provides a much narrower source with a subsequent reduction in radiated power, but this is compensated for by the reduced coupling losses at the source-fiber interface. The injection laser, which offers several advantages over conventional LEDs, is a solid-state GaAs device with a construction similar to LEDs. Figure 15 shows the construction of a typical double heterojunction injection laser. The injection laser has a very fast rise time, which allows data rates in excess of 500 Megabits/sec; it also offers higher

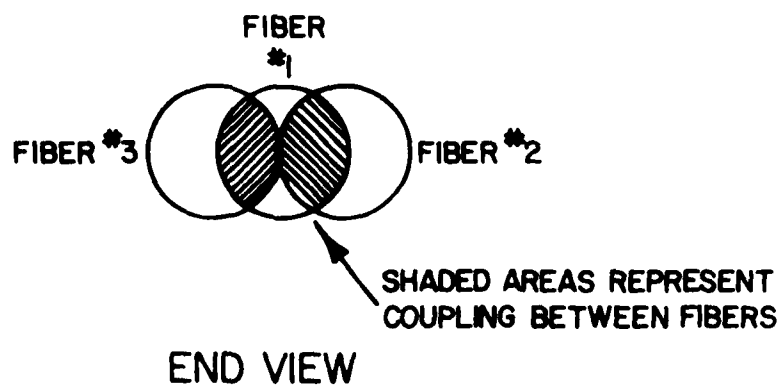
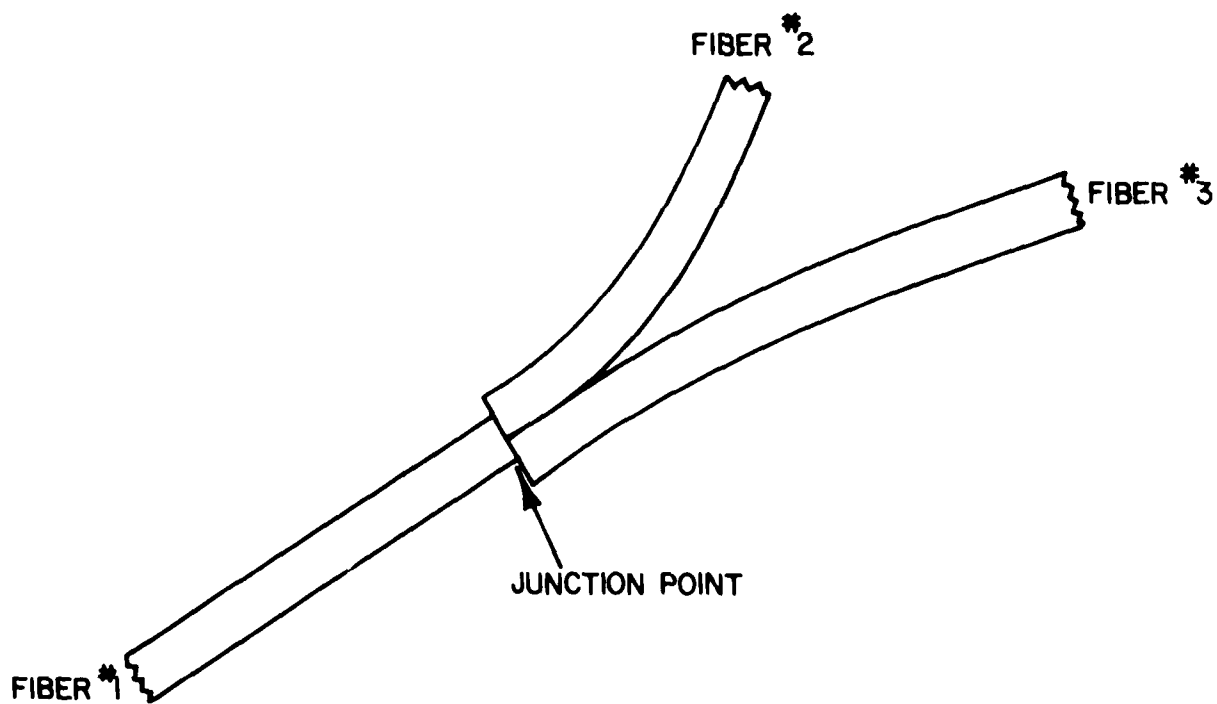
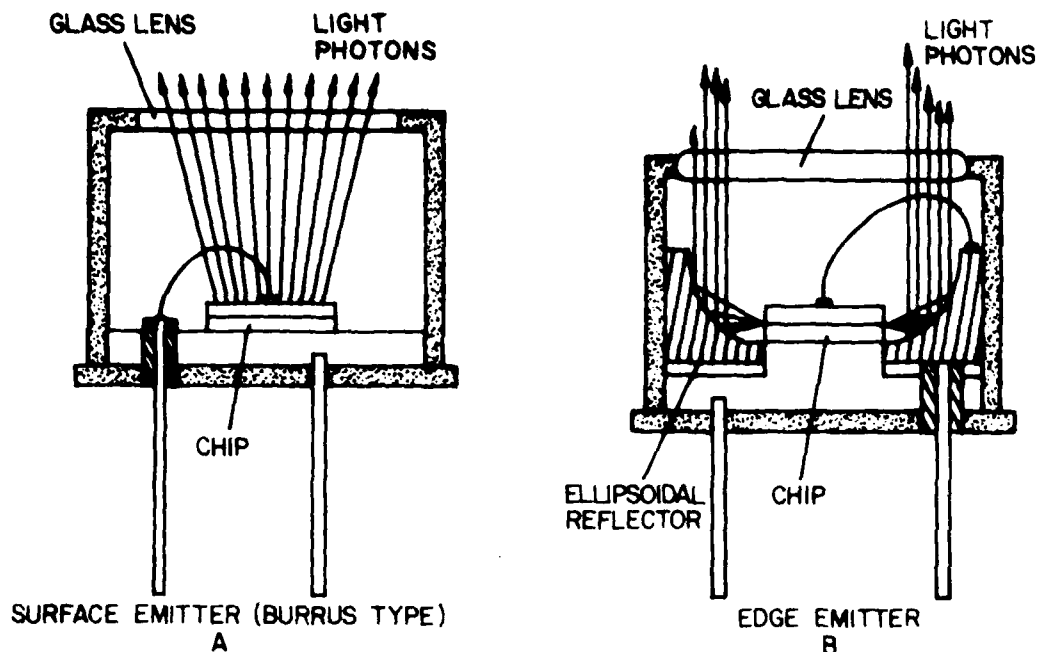
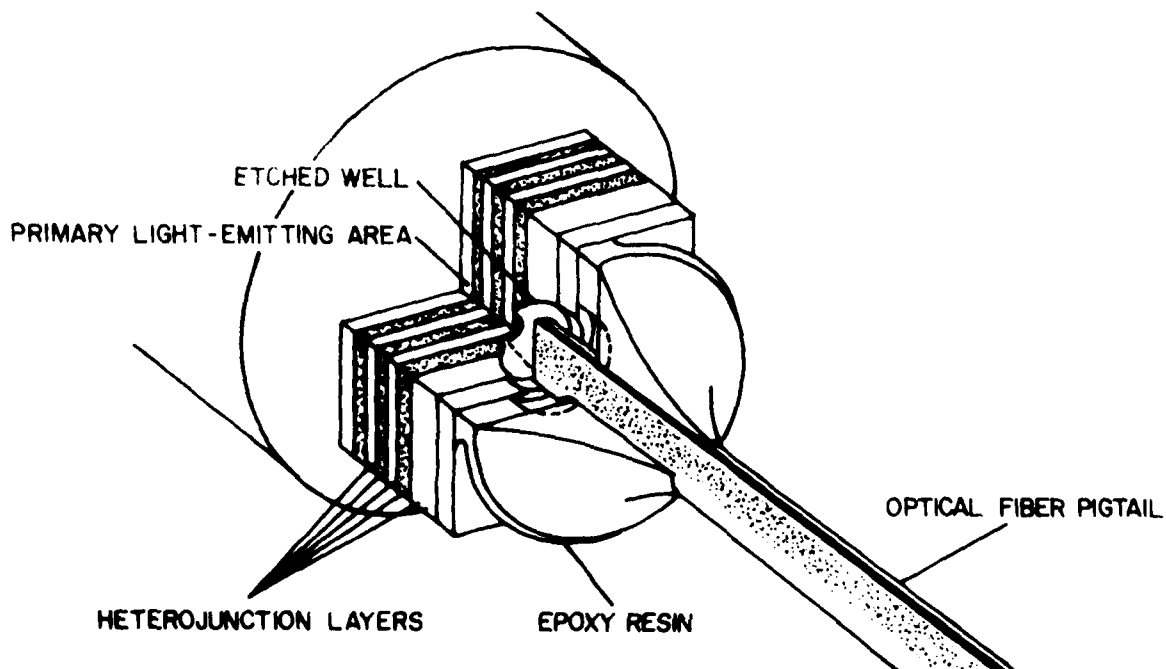


Figure 13. "Y" coupling of two fibers into one fiber

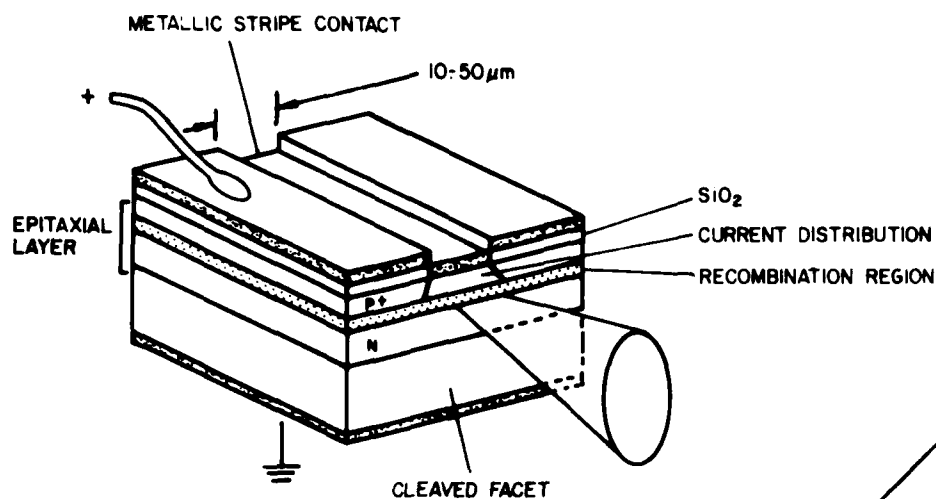


The surface emitter LED configuration (a) provides a higher intensity output than the edge emitter configuration (b), but its wide beam distribution is more difficult to couple to a fiber optic cable.



LIGHT EMITTING DIODES, which are also made from heterojunction layers, are simpler, cheaper and more reliable than lasers. They are useful where narrow bandwidths are not needed and for transmission distances where their low average power of .1 milliwatt is adequate.

Figure 14. Typical LED light source configurations



A typical double-heterojunction injection-laser diode built using GaAs offers the top performance of any semiconductor light emitter. Nd:YAG lasers top laser diodes but they require special modulators.

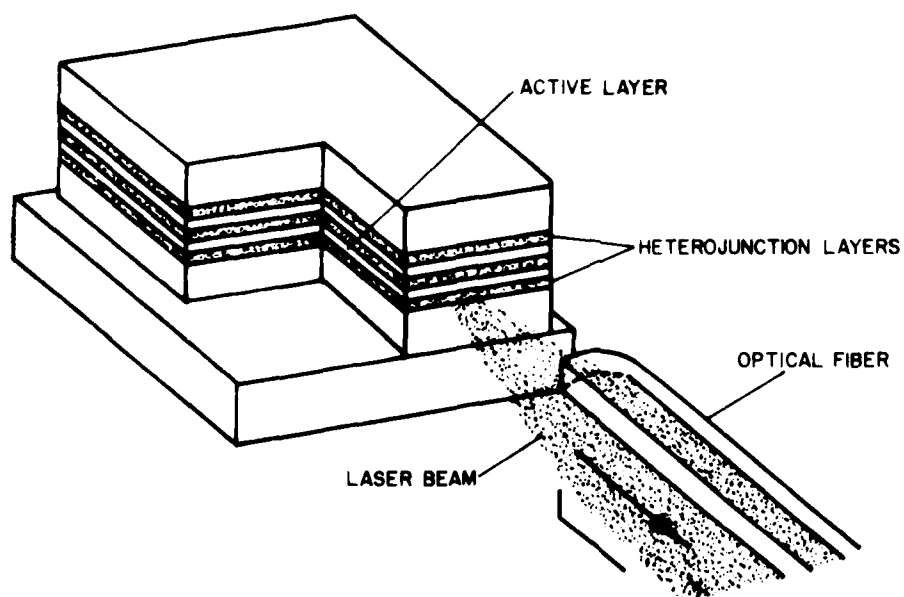
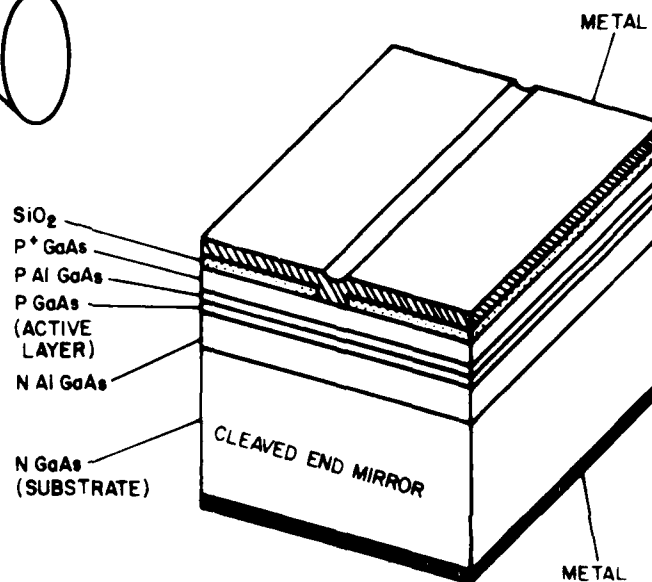
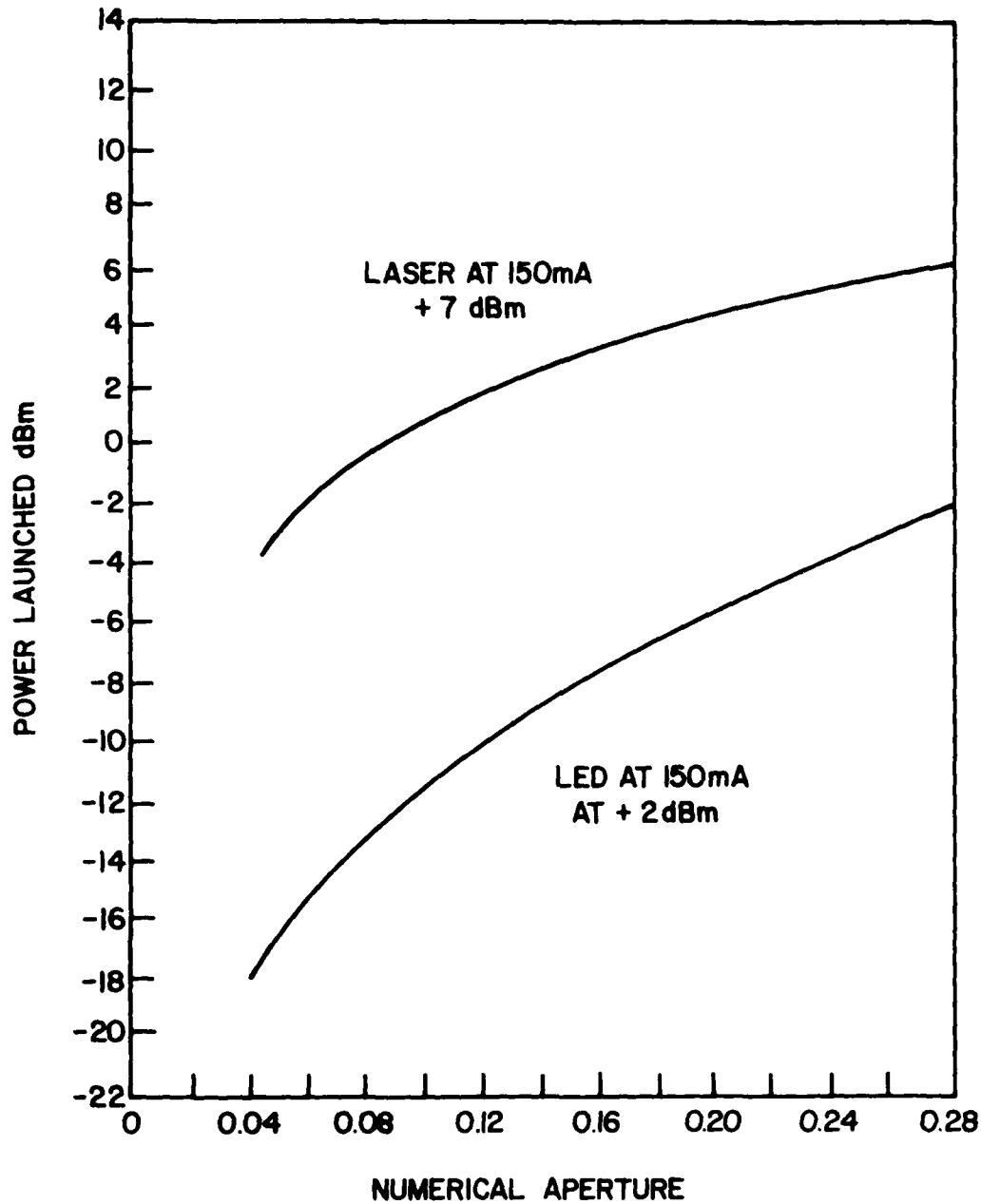


Figure 15. Typical injection laser configurations

output power, with a given input current, than currently available LEDs (see Fig. 16); the signal dispersion within the fiber from an injection laser source is much less than that from an LED because the frequency spectrum of the laser output is on the order of 10 to 15 times narrower than that of a typical LED; and the coupling efficiency of an injection laser is generally higher than that of an LED because the coherency of the output results in a very narrow beam of light being emitted by the laser, while the LED's incoherent light produces a large emission cone. The primary problem with injection lasers has been short operating life; recent literature indicates, however, that the average life expectancy of both LEDs and injection lasers is rapidly approaching 100,000 hours of operation and, because of their solid state construction, these devices are extremely rugged and their reliability is quite high. In addition, both LEDs and injection lasers can be constructed in a physically small package such that a single fiber can be effectively coupled to the source without resorting to a system of lenses or other coupling techniques. The third light source which is finding use in optical communications links, the Nd:YAG laser, offers a longer wavelength output than either LEDs or injection lasers, which means that it can operate in one of the low-loss regions of silica optical fibers and also, because of its longer wavelength, scattering losses are lower because light scattering is an inverse function of wavelength. The Nd:YAG laser also has a life expectancy on the same order as LEDs and injection lasers, but its coupling efficiency is much higher than the other two sources, as is its output power. There are some difficulties, however, with the Nd:YAG lasers; they do cost more than either LEDs or injection lasers; they cannot be directly modulated at megahertz rates, and instead require an optical modulator which is driven by the modulating signal; and they tend to be physically larger than LEDs or injection lasers.

Output power levels vary considerably, but a good approximation of the output levels for the three most common optical sources is: LEDs - 1 mW output; injection lasers - 10 mW output; and Nd:YAG lasers - 50 mW output. Prices for LED and injection laser sources range from less than ten dollars apiece for LEDs to approximately one hundred dollars each for injection lasers. Nd:YAG laser sources cost somewhat more than injection lasers.

At the other end of the optical fiber communications link is the photo detector. Photo detectors used in communications links are generally either avalanche diodes or PIN diodes. Both of these devices are extremely sensitive, solid-state devices with a very fast response time. Because of their solid-state construction, these diode detectors are also quite rugged, reasonably inexpensive, and physically small. Figure 17 demonstrates how an optical fiber pigtail is coupled to a photo detector so that coupling losses are minimized. Avalanche diodes have a built-in gain mechanism whereby an impinging photon causes an avalanche of electrons to occur, which means that the output signal levels will be significantly higher than those from PIN diode detectors. The PIN photo diodes are very good detectors for applications where the information bandwidths are in the low megahertz region and run lengths are less than 1 km. They operate at bias voltages of 100 volts or less while avalanche diodes require higher bias voltages (100-200 V) for maximum gain. Also, avalanche diodes cost five to ten times as much as PIN diodes (PIN diodes cost in the range of \$5 to \$10 apiece). Avalanche photo diodes, because of their extremely fast response times and inherent signal gain, are generally used in optical communication links where the data rates are in excess of 50 Megabits/sec and/or the incoming signal is low level. Avalanche diodes, with a bit-error-rate of 1×10^{-8} , can detect signals as low as 10-10 watt. This means that if a 10^{-2} watt injection laser is used as the source, the signal can undergo 80 dB of attenuation between the source and the detector and still be detected with a probability of error of one bit in 10^8 for a digital transmission system. For the transmission of analog signals, however, requirements are more



For the same amount of drive current, an injection-laser diode can deliver more light power to a fiber than a LED. This is because the light from the laser is totally coherent and thus passes through the cable easier.

Figure 16. Comparison of injection laser and LED output power for equal current drive

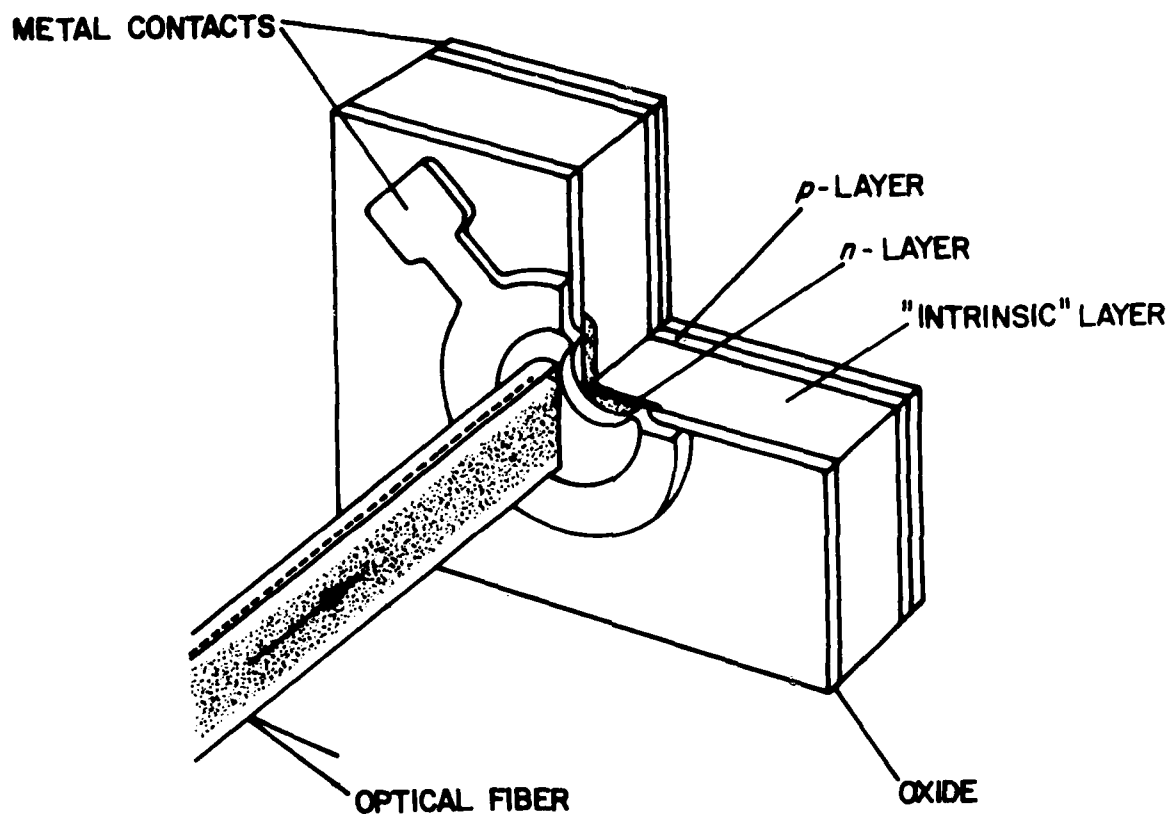


Figure 17. Typical PIN diode detector showing attachment of optical fiber

stringent because the signal-to-noise ratio must be maintained at a higher level in order to extract usable information from the surrounding noise; as the bandwidth increases, so does the inherent system noise, and a point is rapidly reached where the signal is effectively lost in the system noise unless steps are taken to ensure that the arriving signal is of a sufficient level that it can be distinguished from the ambient noise. For example, the ambient noise level in a PIN photo diode increases from 10^{-11} watt when the device is operated at 1 MHz to 10^{-9} watt when the device is operated at 100 MHz. Figure 18 compares the signal-to-noise ratios of PIN diodes and avalanche diodes versus input signal level.

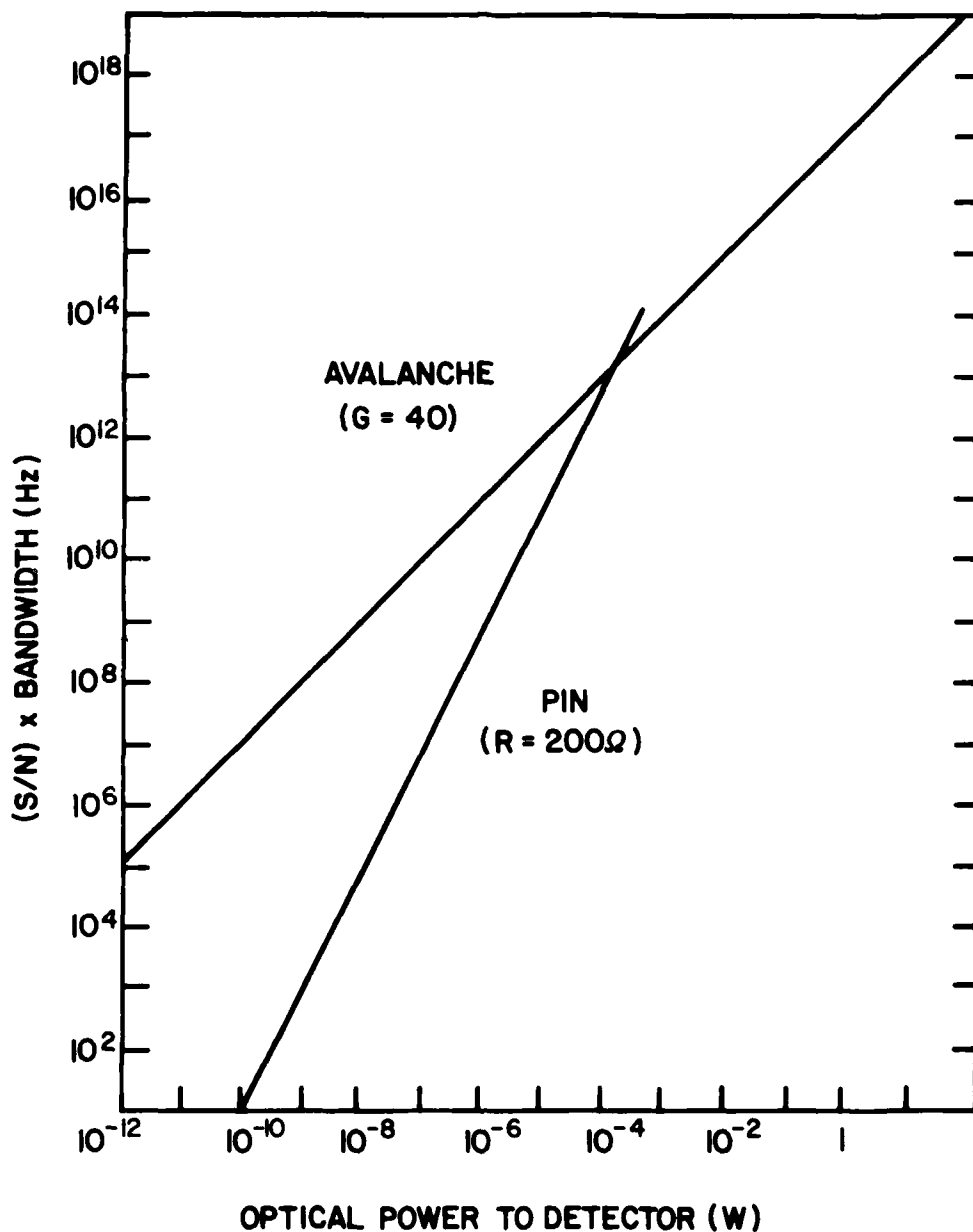
As can be seen from this brief discussion of the sending and receiving opto-electronics of an optical communications link there are many interrelated factors involved in the proper selection of components and modes of operation, such as:

- Analog or digital signal transmission
- Connecting link losses
- Maximum modulation frequency or bit rate
- Minimum signal-to-noise ratio or maximum bit-error rate
- Source level delivered into the fiber
- Source wavelength
- Source spectral width (related to material dispersion in fiber)
- Source noise
- Detector input signal level
- Detector output signal level
- Detector noise
- Detector response
- Detector cost

D. POTENTIAL OCEAN INSTRUMENTATION APPLICATIONS

Optical systems for oceanographic measurements offer the primary advantages of light weight, electrical isolation, corrosion resistance, extremely low cross talk, and large data bandwidth. In general, the sensor in an all-optical measurement system will be an optical fiber or a pair of optical fibers suspended in the water at the point of interest. This makes possible the additional advantage of having all of the system electronics, including detectors and/or sources, located remote from the measurement site, thereby reducing the sensor size and resultant distortions of the parameter or parameters to be measured. An idealized concept of an optical measurement system is shown in Figure 19. The major components of this idealized system would consist of a fiber optic sensor and connecting link, a detector and/or source, and signal processing electronics. Some examples of potential measurement systems are presented on the following pages.

Sea water temperature measurements, using an optical measuring system, can be divided into two broad categories: optical path length resonator techniques and infrared (IR) emission techniques. A temperature measurement system based on optical path length resonator techniques would utilize the detection of small, thermally induced changes in optical path length as a means of measuring the temperature at various points in a column of water. This measurement system would consist of a laser source, an optical fiber link interconnecting the source with the sensor, a sensor consisting of a length of optical fiber wound on a bobbin or some other similar technique for placing a length of optical fiber in a small volume, an optical fiber link interconnecting the sensor with a detector, and a reference optical path. Figure 20 shows an elementary approach to the measurement of sea water temperature using the optical path length resonator technique. The coherent



Equal S/N ratios result when, for the given set of conditions, both the avalanche and PIN diodes receive about 160 μW incident optical power. Generally, however, for optical systems driven by LED's, avalanche diodes are recommended for analog work where bandwidths are wide and load resistances, low.

Figure 18. Comparison of signal-to-noise ratios of PIN and avalanche diode detectors

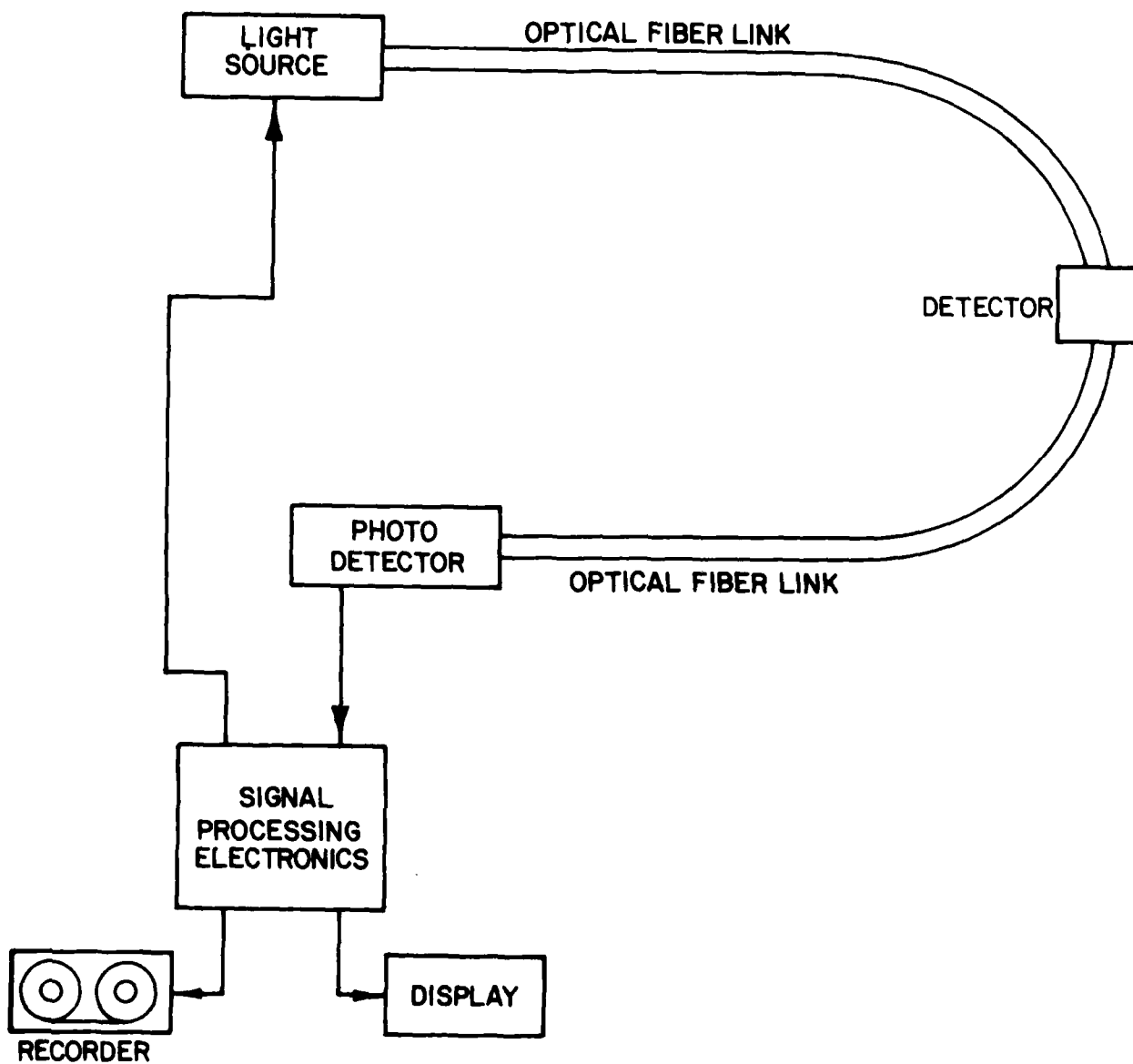


Figure 19. Idealized optical measurement system

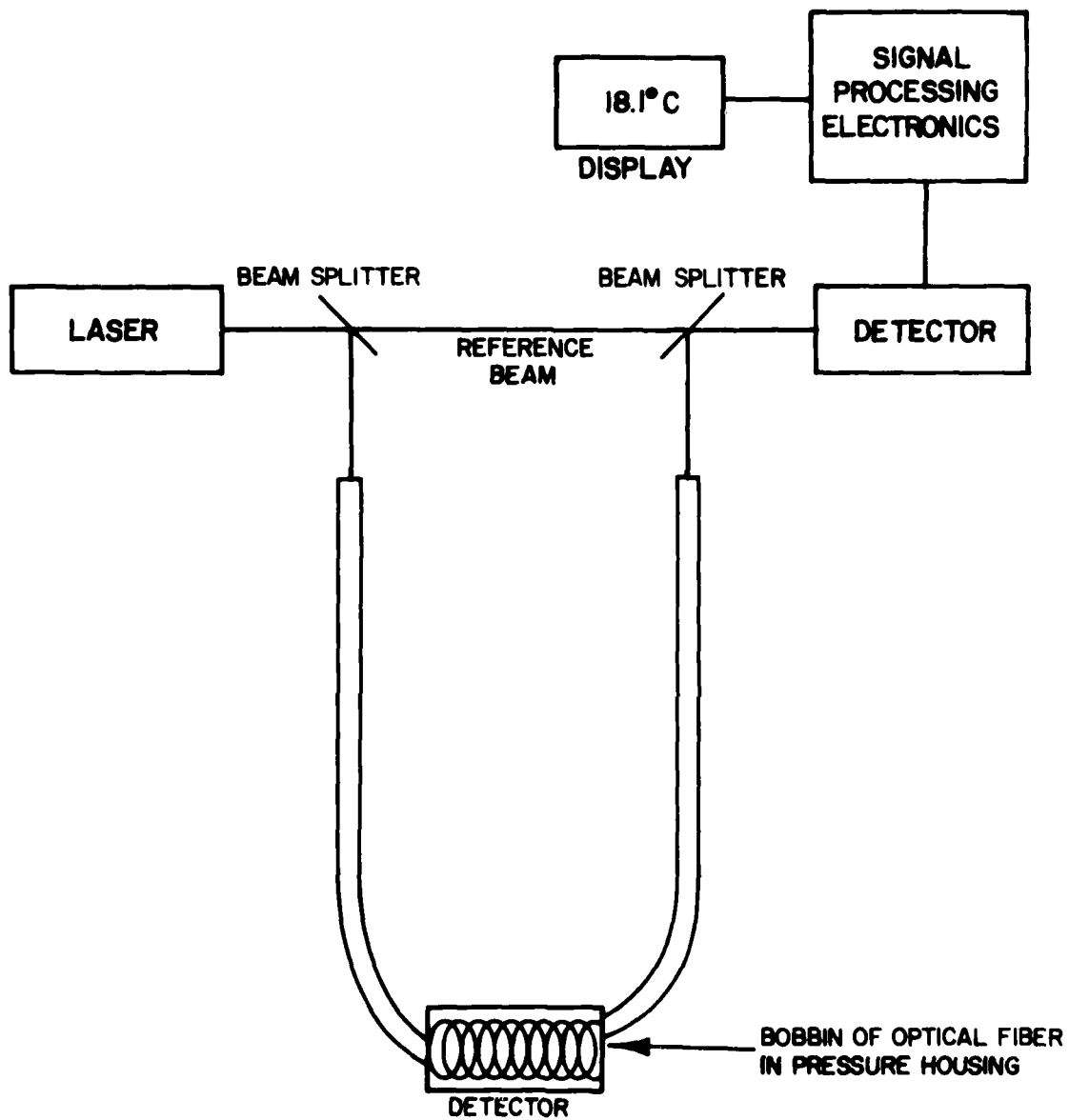


Figure 20. Temperature measurement with a laser system

light beam from the laser is split into two paths by the beam splitter, one being the reference path and the other, the sensor path. The sensor beam is coupled into an optical fiber and propagates down the optical fiber interconnecting link, through the temperature sensing element which consists of a coil having many turns of optical fiber, up the optical fiber interconnecting link, and is coupled to a detector. The reference beam is coupled to a reference detector via a known reference pathlength and the outputs from the two detectors are time correlated. The time correlator would be scaled such that its output would indicate the path length difference in terms of temperature.

The second technique for measurement of sea water temperature is based on the measurement of IR emission from thermally excited bodies. The technique would be similar to many of those developed by NASA for remote measurement of temperature of other planets in our solar system. A basic system is shown in Figure 21. A single optical fiber is required for each measurement point and an IR detector is required for each optical fiber. As the drawing shows, an N station array would consist of N optical fibers which are optically coupled to the surrounding sea water so that they collect impinging IR radiation and conduct it to the surface where it is detected by N IR detectors. The outputs from these IR detectors would be properly scaled so that they are in terms of temperature.

Sea water density measurements are of increasing interest to oceanographers and represent an area where fast, accurate measurement would be of definite benefit to the U. S. Navy. Sea water density is related to the salinity, temperature, and pressure at the location that the measurement is made. It appears that opto-electronic systems capable of accurate, in situ measurement of all three parameters would be a welcome addition to the oceanographic instrument arena. The potentials for optical measurement of temperature, having already been discussed, will not be mentioned further.

Optical measurement of salinity is based on measurement of the sea water's index of refraction, and numerous small, hand-held optical refractometers are commercially available which utilize this principle. One possible scheme for the measurement of salinity using fiber optics and opto-electronics is shown in Figure 22. A monochromatic light source is coupled into an optical fiber, which conducts the light to the location where the measurement is to take place. The beam of light is coupled out of the optical fiber through a volume of sea water and the refracted light is then coupled to an optical fiber bundle for conduction to an array of detectors. The outputs from these detectors are processed through electronic signal conditioning circuitry and then displayed or output to some recording media. This displayed information would be the measured index of refraction, a direct function of salinity, of the seawater at the measurement site.

Pressure measurements utilizing optical fibers and opto-electronics would require an approach similar to that used in one of the temperature measurement schemes. Figure 23 demonstrates this approach. A coherent beam of light is coupled from a laser source to a pair of optical fibers, which then conduct the light to the pressure sensor. The pressure sensor consists of an optical fiber coil exposed to the ambient pressure of the surrounding seawater and an identical optical fiber coil which is enclosed in a pressure housing. The coil, which is enclosed in the pressure housing, is a reference coil, and it allows small changes in the propagation of light through the sensing coil to be detected. It also allows the cancellation of temperature-related effects so that the net change in propagation conditions is due to pressure. The output from the pressure sensor is coupled to a pair of optical fibers which conduct the light to a pair of detectors. The outputs from the detectors are electrically combined and the difference between

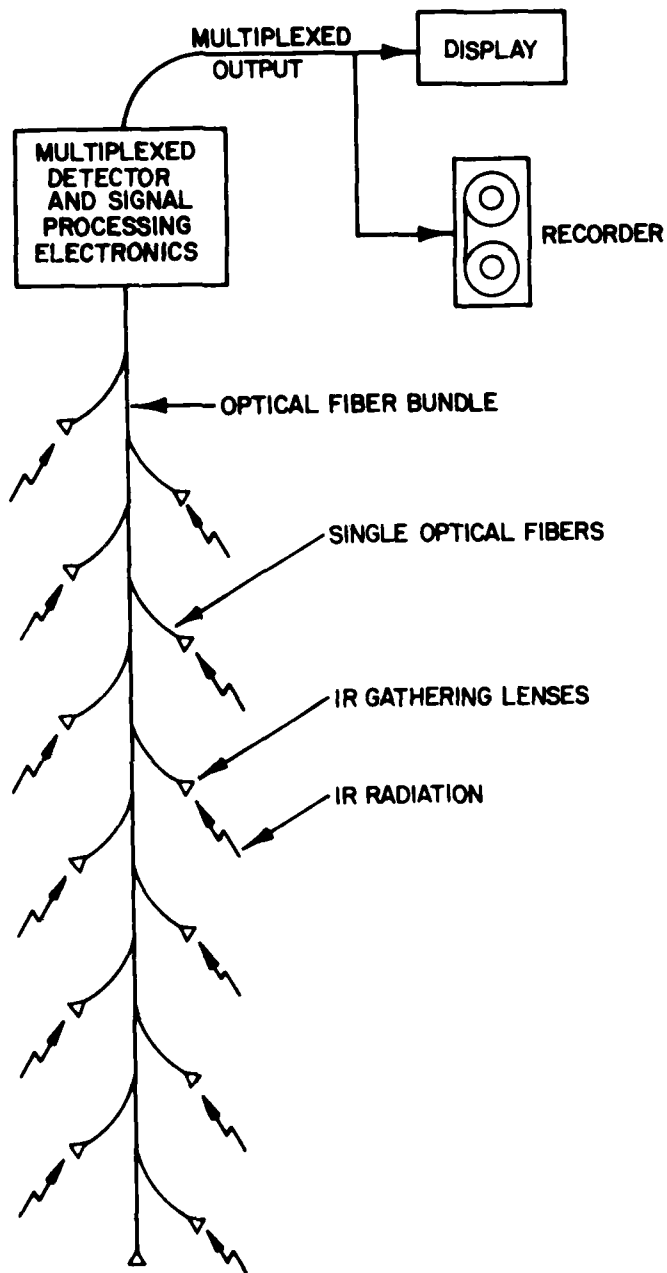


Figure 21. Black-body radiation measurement

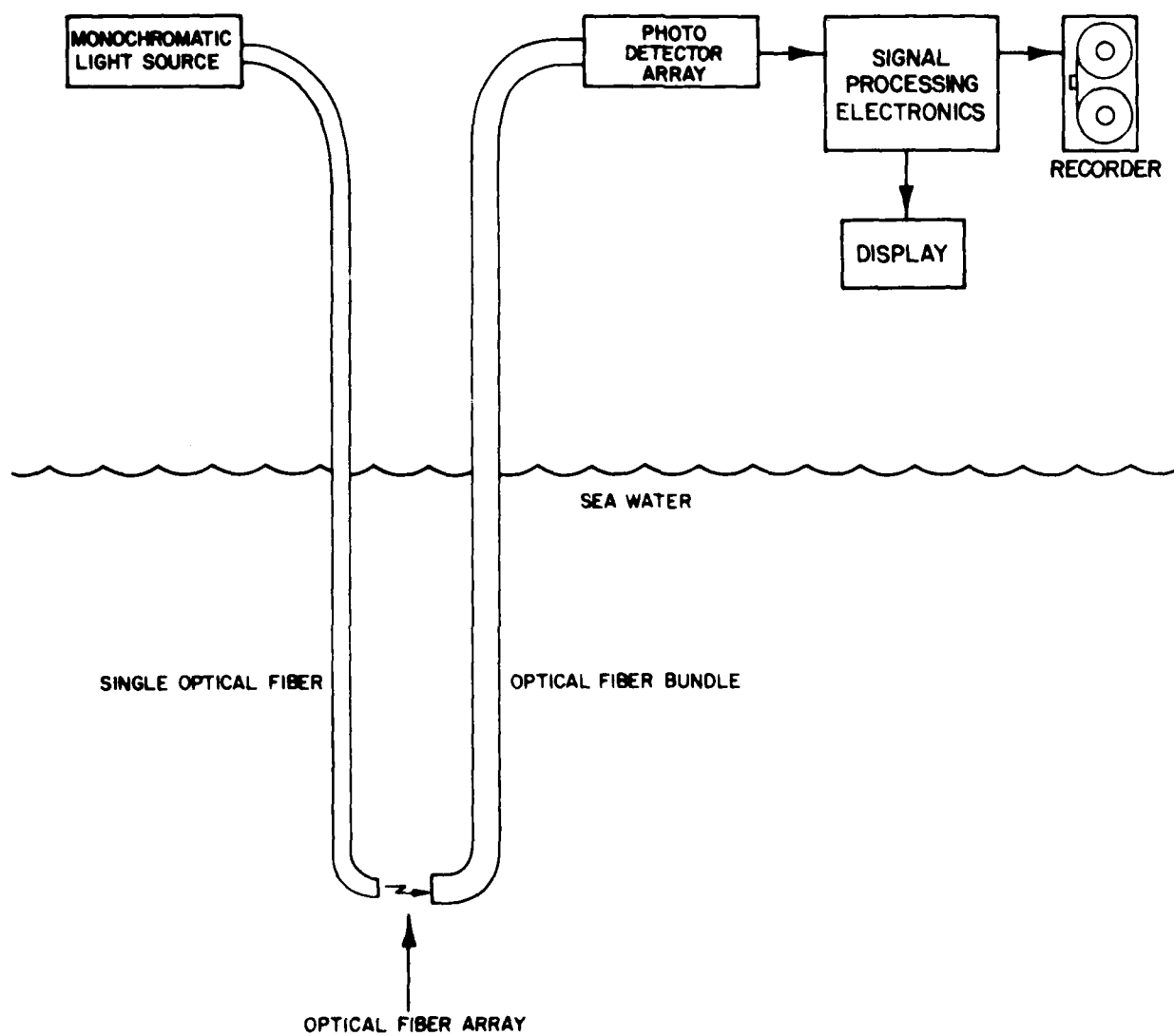


Figure 22. Index of refraction based salinometer

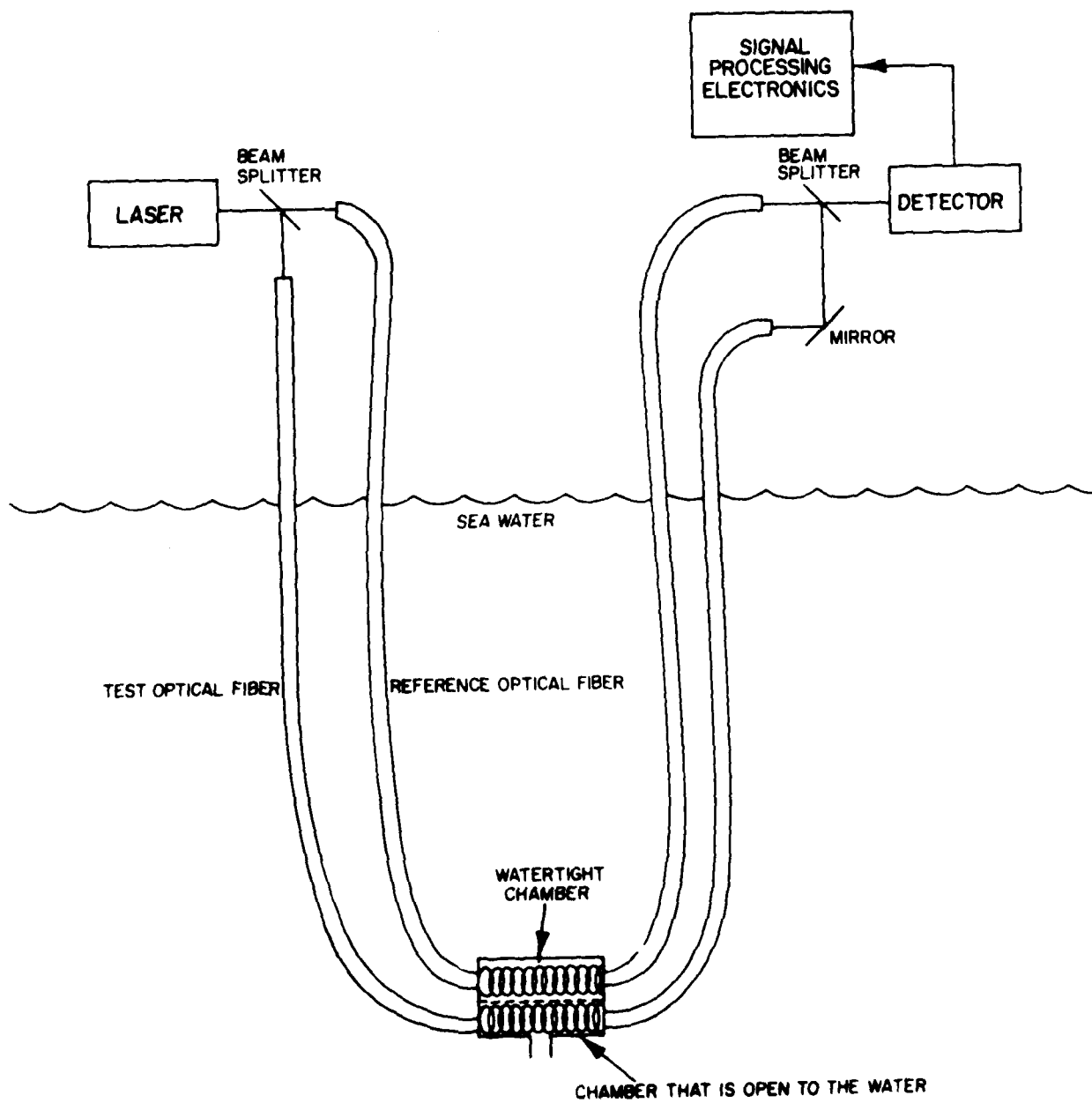


Figure 23. Optical pressure measurement system

the reference leg and the sensing leg, which represents raw pressure, is electronically processed and displayed or recorded in useful engineering units.

The outputs from the above mentioned systems (temperature, salinity, and pressure) can be processed in order to obtain density. There are several algorithms which have been developed for this purpose and many of the currently available microprocessors lend themselves quite readily to this task.

Another area of interest to oceanographers is the measurement of ocean currents and associated turbulence and eddies. Recent advances in the field of laser velocimetry have demonstrated that optical methods can be used to detect very low velocity movements in a fluid. It appears that extremely accurate current magnitude measurements might be possible by using an approach similar to that shown in Figure 24. A laser source injects a beam of coherent light into an optical fiber for conduction to the site where the water current is to be measured. The beam is split into two coherent beams of light, which are then intersected in such a manner as to produce stable interference patterns in space and in time. The interfering beams of light are coupled into a fiber optic cable and conducted to an optical detector. The output from this detector is processed and the velocity of the water moving through the region of beam interference is extracted and displayed and/or recorded. There are other possible configurations for laser velocimeters in the measurement of ocean currents, and each configuration will have to be evaluated and rated on its performance before any one configuration is decided upon. Optical arrangements have also been suggested and tested which allow the three components (X, Y, and Z) of a current to be detected, thereby allowing optical detection of current velocity and direction with a single sensor.

The optical measurement of turbidity and particle size is not a new technique; there are a number of turbidimeters and nephelometers in use throughout the oceanographic community. However, the advent of optical fibers and inexpensive, rugged, solid state laser sources bring a new dimension into the measurement of turbidity and particle size. Figure 25 shows how a laser velocimeter can be configured in order to obtain information as to the total number of particles and the size distributions within the volume of seawater examined. The set-up is essentially the same as that shown in Figure 24 for the current measurement, but the signal processing electronics are different. One company, Spectron Development Laboratories, Inc., has developed an instrument for measuring particle size and distributions which is based on the combination of two optical techniques. This instrument uses both a particle sizing interferometer and a method of measuring scattering intensity ratios. These combined methods allow the measurement of particles suspended in a field over two decades of size range. Some work is also being performed in the area of differentiating organic particulate matter from inorganic by means of optical scattering techniques.

Another application for laser velocimeters and optical fibers is in the area of sound detection. Within the U. S. Navy, the lead laboratory for this research is the Naval Research Laboratory (NRL). Optical hydrophones depend upon small changes in the light propagating properties of an optical fiber, brought about by an impinging acoustic wave front. These small changes in propagation properties are sufficient to cause a phase modulation of a laser beam being transported within the optical fiber. Figure 26 demonstrates the basic elements of optical hydrophone. The output from the laser source is coupled into an optical fiber and is conducted to the sensing element, which consists of a bobbin of optical fiber. The phase modulated output from the sensing element is conducted to a detector by means of an optical fiber, and the detector output is demodulated and the acoustic signal recovered. The practical detection limit for optical hydrophones appears to be approximately 160 dB re 1 μ Pa [9].

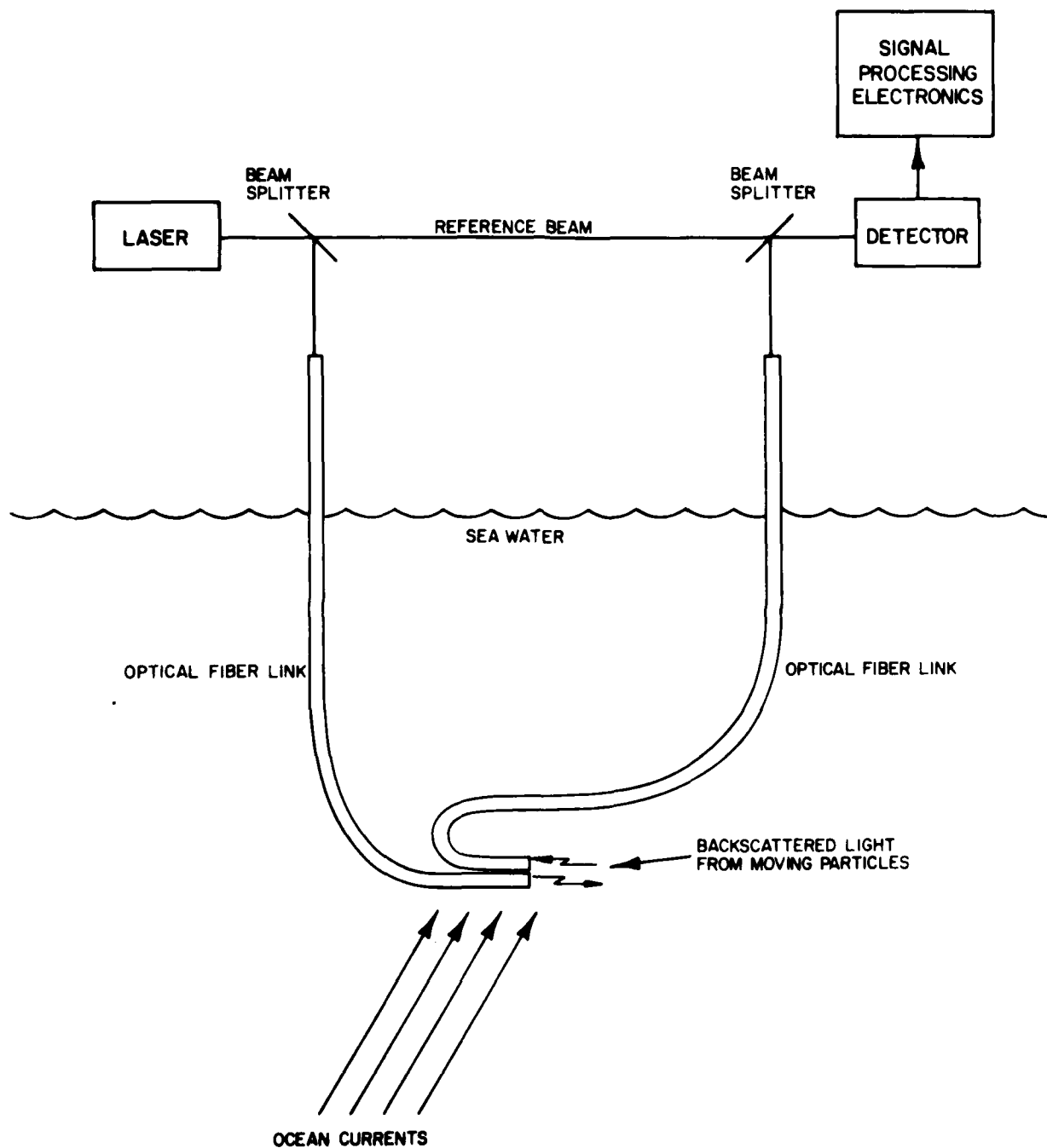


Figure 24. Measurement of ocean currents with an optical system

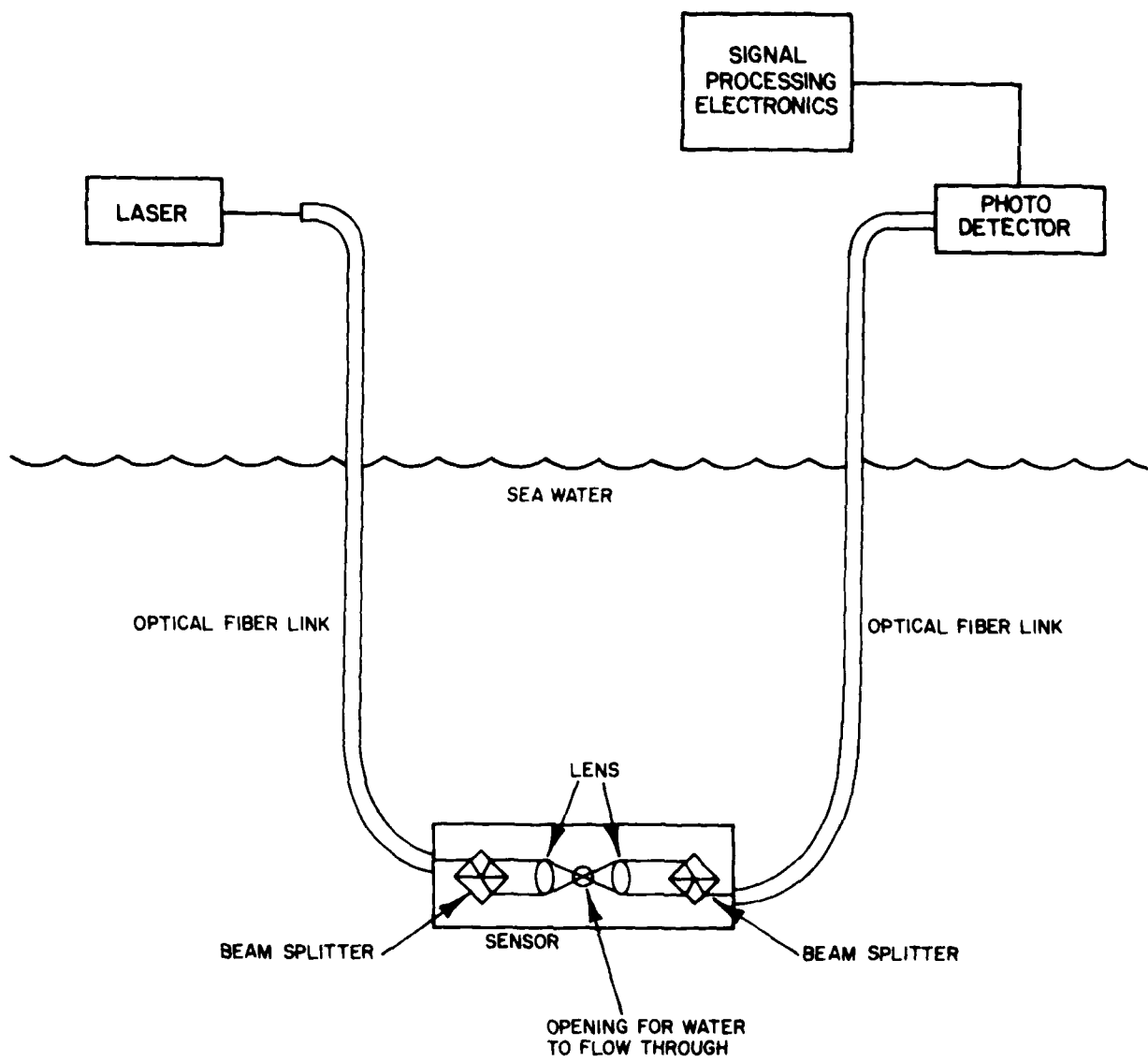


Figure 25. Optical particle counting system

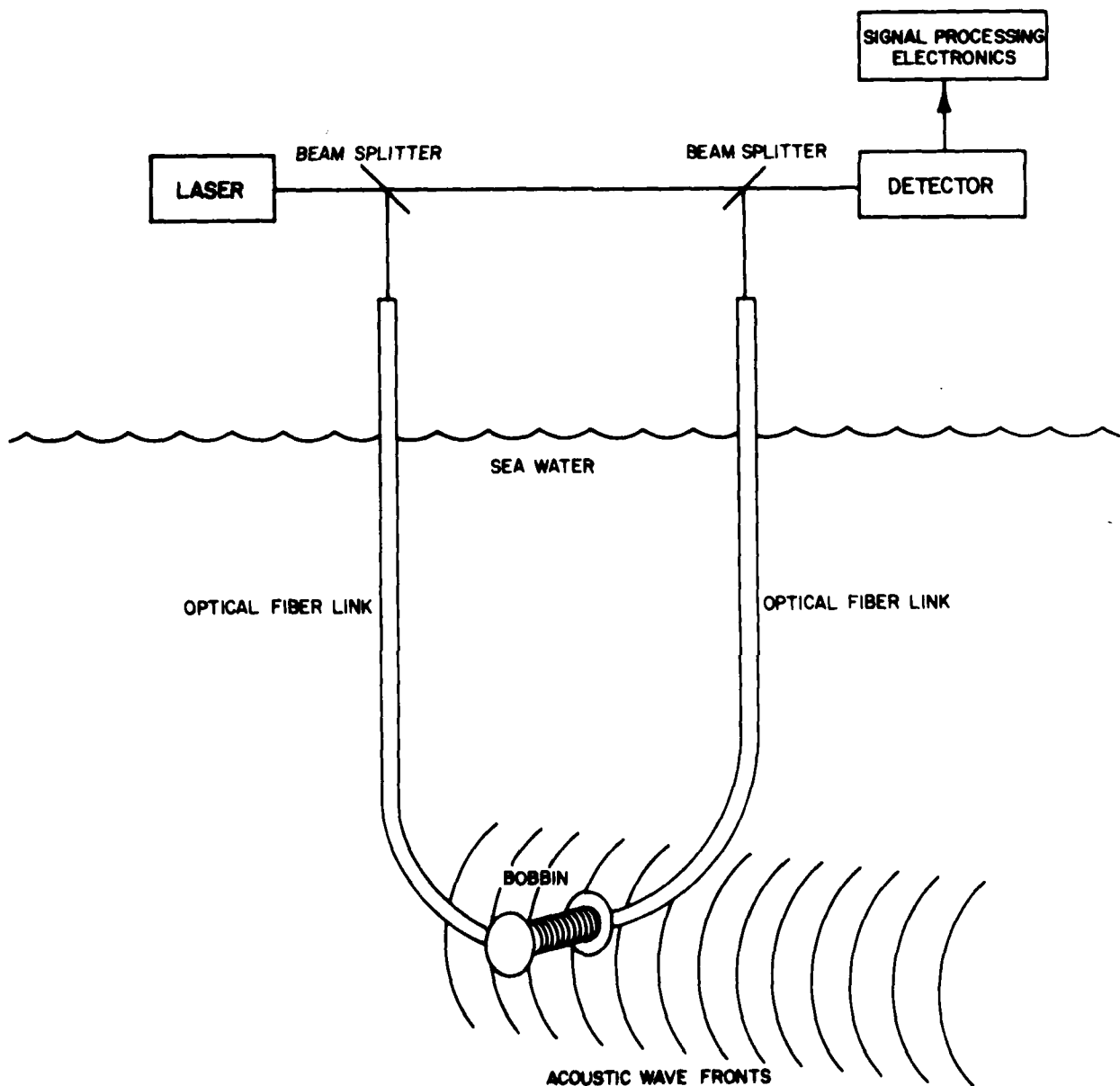


Figure 26. Fiber optic hydrophone

Bioluminescence and ambient light levels are rather easily measured using a detection system similar to that shown in Figure 27. A fiber optic bundle is used to conduct light from the location or locations of interest to the detector. The output from the detector can be displayed and/or recorded for more detailed analysis. An "N" element array would consist of "N" optical fibers and either a multiplexed detector scheme or "N" detectors. A system of lenses would be utilized at the sensor end of the array in order to increase the light gathering power of a single optical fiber. The advantage of a multi-element array such as this is the ability to obtain real time data through a large volume of water. A fiber optic array with a multiplexed detector represents a potentially low cost means of obtaining real time information about ambient light levels in the water column and also would allow a more comprehensive look at bioluminescence.

Subsea optical magnetometers capable of detecting changes in the earth's magnetic field are instruments of potential interest to the Navy. One possible means of accomplishing this measurement is shown in Figure 28. The output from the laser is passed through a linear polarizer and then is conducted, by means of an optical fiber, to the point where the magnetic field measurements are to be made. The sensor is a coil of optical fiber which uses the Faraday effect to measure magnetic fields. The Faraday effect, as its name implies, was discovered by Michael Faraday in 1845. This phenomenon is the rotation of the plane of polarization of a light wave by an applied magnetic field. This means that a light wave which is polarized in the vertical plane and then conducted through a longitudinal magnetic field by some light-conducting medium will undergo a rotation of its polarization vector. The amount of rotation was found to be proportional to the applied magnetic field strength and the distance the light travels through the medium, as shown by the relation:

$$\theta = VH\ell$$

where θ is the angle of rotation in minutes of arc, V is the Verdet constant in minutes of arc per gauss per centimeter of path length, H is the applied magnetic field strength in gauss, and ℓ is the pathlength through the light-conducting medium in centimeters. From this relation, it can be seen that in order to obtain large angles of rotation of the polarization vector in a weak magnetic field, a very long light-conducting medium is required. Optical fibers could lend themselves to this application because long lengths can be wound into fairly compact coils, thereby furnishing a long pathlength for the detection of weak magnetic fields.

The output from the sensor would be conducted to a detector and signal processing electronics, where the amount of rotation is detected and the applied magnetic field is computed. The potential advantages of an optical magnetometer are simplicity and reasonably low cost. The components used in this system would be components which could be used in other optically based oceanographic instruments; therefore, it would not require special development effort.

As can be seen from the above mentioned examples of applications of fiber optics and opto-electronics, there is quite a bit of similarity between the elements of most of the systems. This lends itself to the possibility of designing and constructing a universal oceanographic measurement system based on a laser source, optical fiber interconnecting links, a passive optical sensor and necessary support optics, a detector, and microprocessor-controlled signal processing electronics. The different signal processing algorithms would be preprogrammed in

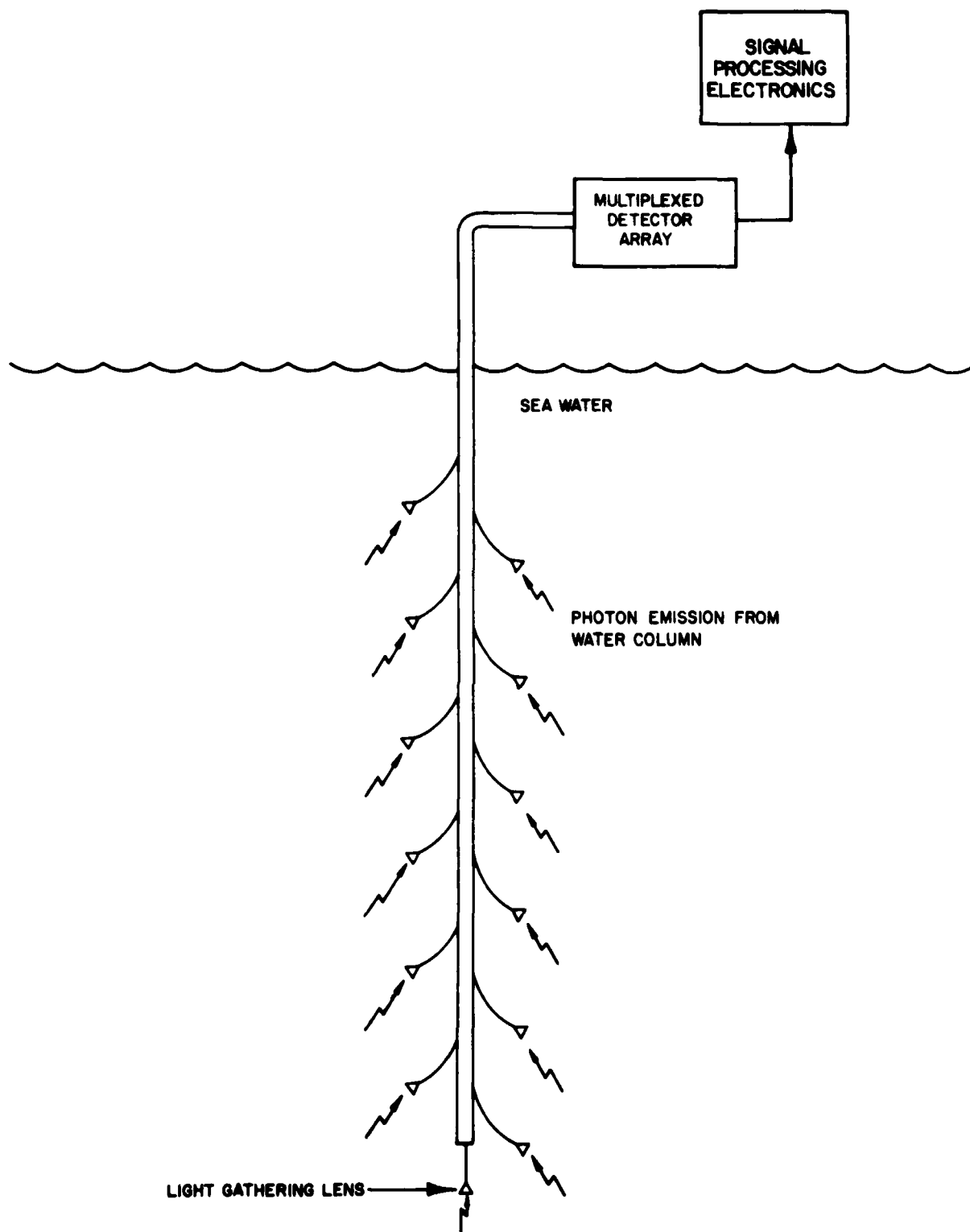


Figure 27. Fiber optic photometer

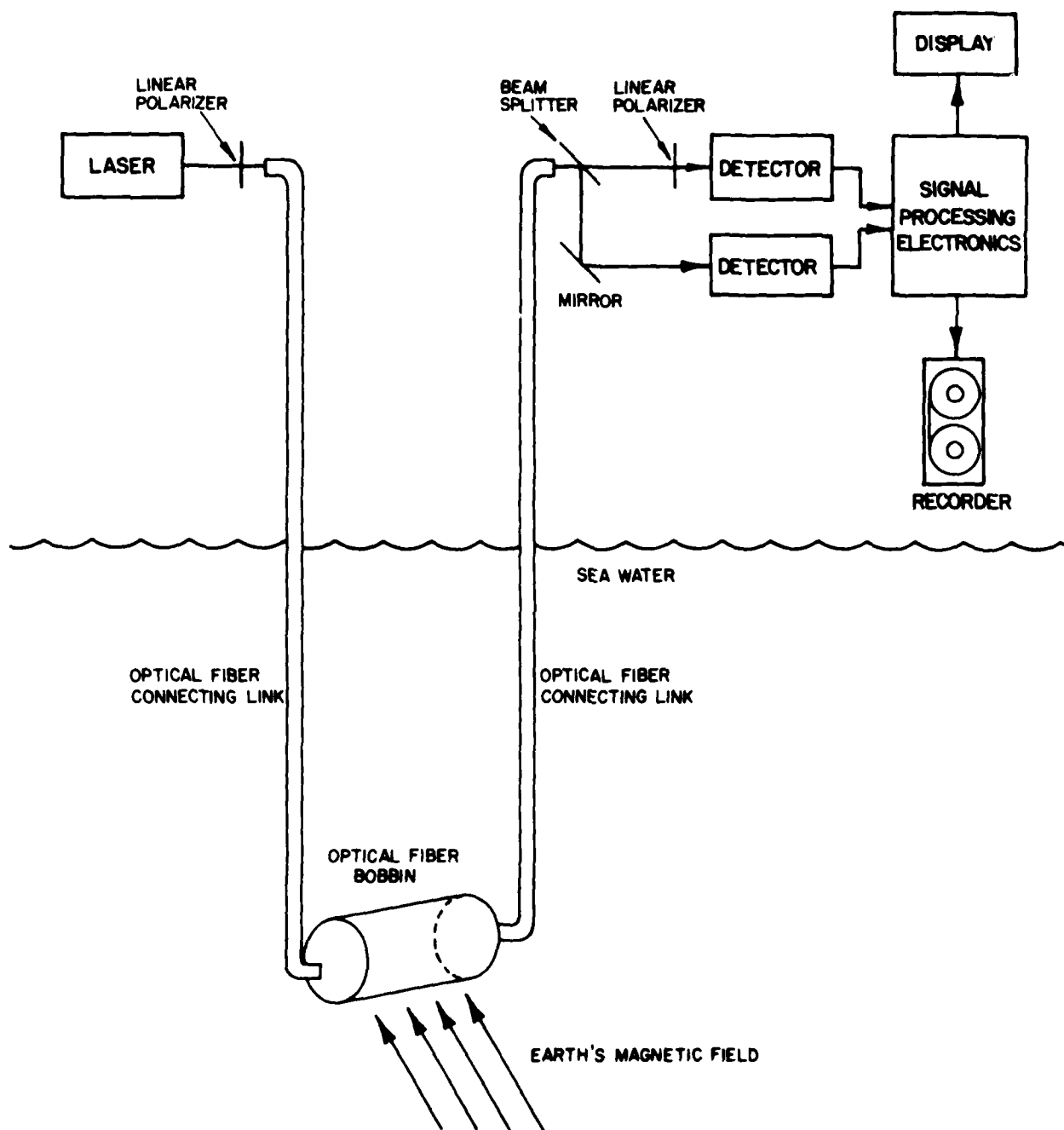


Figure 28. Optical magnetometer

Read-only-memories (ROM's), which could be plugged into the microprocessor control electronics in order to implement a particular algorithm. This would allow one system to make a variety of measurements with the only system changes being in the microprocessor firmware.

III. RECOMMENDATIONS FOR FUTURE EFFORTS

By now, the reader has a better appreciation for the fiber optics and opto-electronics technology and the many design considerations that must be employed in order to properly apply this (or really any) technology to solving a measurement problem. Fiber optics offers the widest signal bandwidth for data transmission of any presently known technology, but rarely is this capability required in making ocean measurements. Fiber optics coupled with opto-electronics provide excellent noise immunity, low crosstalk, and signal isolation, all of which can be advantageously used in the design of ocean instrumentation. The lack of corrosion and low in-water weight in potential fiber optics cables offers significant advantages over copper electromechanical cables for ocean data collection, provided the present stress problems can be solved. Probably the most important near-term task for ocean applied fiber optics is the development of reliable undersea optical cables.

What, then, should be the near term evolution with fiber optics and opto-electronics technology? The designers should carefully consider those attributes of the technology which, if applied, would result in increased performance and reliability, being always mindful of the probability that unforeseen problems always turn up when one attempts a new application. Having carefully considered the following question: Do all the necessary components exist to fully apply the optical technology to required ocean measurement problems?; we find that in the majority of cases they do, with the singular exception of optical tow cables. This means that optical fiber technology can very likely be applied now and the benefits of lower cost, signal isolation, immunity to electromagnetic interference, and higher data rates can be achieved immediately without the necessity of developing a number of key components.

What about the long-term outlook for fiber optics and opto-electronics applications? The technology is expanding rapidly, at a rate somewhat comparable to the present electronics revolution. Components are reflecting the efforts to standardize, and costs in these sectors are dropping. As the technology gains wider acceptance, and that step is assured, available components will increase in functions and number, while costs should continue to decrease. What then, about the all-optical measurement systems? There is little doubt that many show good potential, but in many cases, suitable all-optical sensors and optical-to-electrical power converters are all but lacking. It is doubtful that optical sensor development will be rapid, since the industry is not concentrating efforts in this area. As the cost and/or availability of copper becomes critical, all-optical sensing and data transmission systems may become sufficiently attractive to warrant optical sensor development. The special case user who greatly desires an all-optical system because of unique requirements must be prepared to justify and expend the necessary research funds to accomplish the optical sensor development. With the possible exception of underwater acoustics, we have not found any general class of ocean measurement requirements that appear to gain sufficient performance advantages over conventional techniques to justify large expenditures of research funds for sensor developments at this time.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The study of fiber optics technology has been designed to consider the following questions: (1) What is the present (early 1979) technology state-of-the-art; (2) How might this technology be applied to improve and extend our ocean measurement capabilities; and (3) What should be our future course of action in taking advantage of this technology for ocean environmental measurements. The first question led to consideration of a technological area that		

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rivals electronics technology concerning the rate of development. New components having significantly improved performance and cost advantages appear almost weekly. The entire fiber optics and opto-electronics technology is growing rapidly and is on the verge of achieving a level of maturity sufficient to implement a number of measurement concepts by choosing from readily available components.

In considering the second question, we "dreamed" a bit and gave our imaginations some free reign. We found a number of ocean parameter measurements and data transmission requirements that fiber optics technology might accomplish better in terms of cost and measurement system simplicity. We also found that many present ocean measurement techniques are nowhere near full utilization of conventional copper/electronic technologies. As a result while fiber optics (the more unknown technology) may provide improvements in ocean measurements, conventional electronics (the more proven technology) can in the majority of cases provide essentially the same performance at less development risk. There are isolated exceptions, but we could not discern any general ocean measurement area that could be exclusively answered by fiber optics. It should be noted, however, that we did not explore the acoustic requirements of the surveillance community.

What, then, about question three? It is our conclusion that utilization of the fiber optics technology can be made for many applications showing clear cost/performance advantages by using existing optics components except in the area of sensors. We further feel that the development of wide bandwidth optical data transmission cables for undersea use should be continued, but that development of an all-optical measurement system must be justified on individual requirements and that general requirements for an all-optical ocean measurement system do not yet exist from a performance or cost standpoint. We recommend continuing Navy awareness of this technology as it is being developed by industry and involvement in development of undersea optical cables, but find no specific ocean measurement system that can be recommended for development using fiber optics technology at this time.

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