TOWARDS A UNIVERSAL DESIGN FOR ROV TELEMETRY VIA FIBER OPTICS

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ABSTRACT

A brief description is presented on a current application of fiber optic technology to Remotely Operated Vehicle (ROV) design. Significant advantage is realized in terms of weight and space, EMI immunity, high bandwidth, and long length transmission capability.

Current design practice utilized a standard graded index 50/125 micron telecommunications fiber "ruggedized" with a composite armor. On-going development seeks to make this cable element small and expendable while preserving the high bandwidth and low loss nature of the fiber. To free the system designer from mechanical considerations, the cable is pre-spooled and carried and deployed by the vehicle.

Three dedicated communications channels are proposed on the single fiber by utilizing optical wavelength multiplexing.

INTRODUCTION

Historically tether cables for ROV have been based on coaxial or multiconductor designs to supply power and data transmission. Typically this approach led to the cable design dictating the entire vehicle system design. The net result is that the telemetry/cable/surface support requirements tend to be a major factor on the overall system costs. While this approach will continue to be viable for some applications, maturing fiber optic technology is providing the ROV system designer with some interesting alternatives. Fiber optics as a transmission media currently offers the ability to send real time video images over at least 50 Km without the use of repeaters. To take advantage of this media, several technological developments are being integrated which will provide a very attractive design alternative. Multiple channels can now be implemented on a single fiber via wavelength multiplexing; i.e. we can isolate different channels of information on a single fiber by transmitting each at a different wavelength and optically multiplexing and de-multiplexing the data to and from the fiber. Optical fiber manufacturing technology is now to the point where low loss, high bandwidth, and high strength fibers can be produced in continuous lengths of 10-15 Km. Single fiber cables can be manufactured with ultimate tensile strengths of 100 to 200 lb. and diameters of 0.030 to 0.040 inches. Finally, low loss optical penetrators have been developed and tested to 10,000 psi pressures.

A fiber optic cable provides high bandwidth capacity and extremely low loss which means the size and design of the cable is no longer as sensitive to the data transmission requirements. If the traditional power transmission requirement of the umbilical cable is eliminated, as is the case for battery powered submersibles, then the cable can be potentially small and expendable. The small size in turn leads to feasibility of the vehicle deploying the cable in its track. One approach to implementing fiber optics for ROV telemetry is to use a small and expendable cable as a tether link. A deployment technique has been developed allowing a vehicle to carry the cable spool and deploy the cable in its track resulting in a virtually zero cable drag operation. This deployment technique requires that the cable be precision wound with a pre-twist to form a free-standing spool. To provide a cost effective means to wind long lengths of cable, a microprocessor controlled winding machine was developed that allows automated spool fabrication. This design approach decouples the effect of cable drag, size, and length on the overall system design. However, since the cable no longer supplies energy to the submersible, applications will now become constrained by battery limitations. In energy limited applications, the system designer will have to supply a more conventional type of reuseable cable. For these situations the preferred technique for data transmission will still be optical, however. Optical transmission will generally provide advantages in weight and size of the cable and handling equipment as well as EMI immunity and high bandwidth.

To interface to the fiber, an approach will be described that utilizes multiple channels obtained by wavelength multiplexing. One channel, from the surface to the ROV, will carry command/control data. A second channel, operating in the reverse direction, would transmit status data from the vehicle to the surface. Data transmitted via these two channels is presumed to be a serial bit stream whose origin and destination are computers at each end of the cable. It is estimated that the required data rates for these channels will be in the range of 10 Kbps to 1 Mbps. Finally, a third channel would provide a high bandwidth analog channel utilizing Pulse Frequency Modulation (PFM), or another high performance modulation format, to transmit video or sonar data.

Successful demonstration of these concepts have been completed. This paper will review the results of the work to date and highlight ongoing work to further improve on performance, reliability, and standardization.

DEVELOPMENTAL APPROACH

In the first phase of development, the goal was to demonstrate overall concept feasibility. Our approach on developing a telemetry subsystem for a fiber optic media has been to create a function oriented rather than performance oriented design for the prototype. Key elements for demonstration included:

- Optical wavelength multiplexing and demultiplexing
- Utilization of PFM technique for transmission of video data
- Long fiber and cable manufacturing capability
- Reliable spooling and deployment of single fiber cable
- High pressure, low loss optical penetrators

Following the demonstration phase selected elements were identified for further work. The goal of the follow-on efforts are to develop the over-all system concept to allow for a maximum range of application; i.e. maximize transmission length, data rates, and standardize physical and electrical interfaces.

FIBER CHARACTERISTICS

Optimum transmission wavelength for low loss, silica fibers lie in the range between 0.8 - 1.6 microns. This currently represents the spectral region of lowest loss and greatest bandwidth for graded index (GI) and single mode fibers.

Figure 1 depicts the attenuation profile as a function of wavelength for a typical long length, GI telecommunications fiber.

Besides attenuation, three other parameters must be considered in designing a fiber optic cable. These are length, bandwidth, and proof-test. Fiber production is a process whose yield is highly dependent on the specifications of these characteristics. Presently the manufacturing technology can produce a low loss fiber of 10 - 15 Km length proof-tested to 100 Kpsi at a reasonable cost for development work if high bandwidths (<400 MHz-Km) are not required. To get a better perspective of the yield problem, yield or relative cost of the fiber is plotted vs. continuous length with proof-test and bandwidth as parameters in Figure 2. These curves are derived from data collected in 1981 and are therefore dated but do serve to illustrate the tradeoffs involved.

DEMONSTRATION SYSTEM

To demonstrate the feasibility of the overall concept, a telemetry subsystem based on a single optical fiber cable was designed and fabricated to interface with an existing vehicle. For the vehicle, only command/control and vehicle status channels were required. The full duplex, single fiber telemetry system design is illustrated graphically in Figure 3.

Pulse code modulation (PCM) techniques are used to transmit the digital data by first converting the RS-232 signals to TTL levels and then applying a Manchester coding format. Wavelength selection for the two required channels was dictated by availability of sources and detectors in 1979. At that time 0.83 and 1.06µ wavelength LEDs and photo detectors were commercially available with the longer wavelength devices still in the experimental stage. Looking at the attenuation profile of typical graded index fiber in Figure 1, we can see the relationship of wavelength on attenuation. In a non-bandwidth limited system, maximum cable lengths are dictated by fiber losses and component insertion losses. These losses decrease the available margin available due to coupled transmitter power and receiver sensitivity, and thus directly influence maximum transmission ranges. For the demonstration system, operation at 0.83 and 1.06µ provided sufficient optical margin for transmission through the required 5 km of cable.

Use of LEDs vs. injection lasers was selected because the power output was sufficient for the cable length and because they were simpler to drive, temperature insensitive, and inherently more reliable. Data formating utilized Manchester coding to allow AC coupling at the receiver thereby allowing operation in the photovoltaic mode and improving receiver sensitivity. The receivers use silicon PIN photodetectors which operate well at the 9.6 Kbps data rate and provide sufficient sensitivity at 0.83 and 1.06µ.

To provide color multiplexing, a film of dichroic material, transparent to one wavelength and reflective to another, was sandwiched between two 1/4 pitch SELFOC lenses in a block and potted in place. To complete the assembly, three optical fibers were micropositioned into alignment as diagrammed in Figure 4 such that maximum optical coupling was achieved.

For the cable, a standard graded index (GI) optical fiber of 50/125µ geometry is used as the data transmission media. The fiber is drawn by conventional means and a protective buffer composed of silicone RTV is flow coated onto the fiber out to an OD of about 12 mils. Then a harder, non-tacky, plastic such as Nylon-12 is extruded onto the silicone layer out to a 20 mil diameter. These buffer coatings are added during the fabrication of the fiber to protect it from abrasion and microbending. The fiber yields a “weak link” strength of approximately two pounds in tension when proof-tested to a 1% strain or 100 Kpsi load specification. Developmental efforts during 1980 determined that the buffered fiber as supplied by the manufacturers had insufficient strength and stiffness for high speed deployment. To eliminate this problem “S-glass” ruggedizing was used. The S-glass armored configuration is made by laminating an epoxy resin and S-glass filaments over the original Nylon-12 jacket, increasing the OD to approximately 32 mils. The result is a cable with a minimum tensile strength of approximately 25 lb (using 1% proof-tested fiber) and an ultimate cable strength in excess of 100 lb. Figure 5 illustrates the cross-section of the cable.

A pressure penetrator design providing a watertight, low loss optical feedthru, tested to 10,000 psi was designed using SELFOC lens technology. This penetrator design, illustrated in Figure 6, developed at NOSC, was necessary because no reliable high pressure penetrator existed.

Pulse Frequency Modulation is a nonlinear analog modulation technique that has been shown to offer significant advantages over other modulation techniques for transmission of high bandwidth video signals over fiber optic cables (1). PFM efficiently utilizes available fiber bandwidth while simultaneously extending loss margin limits. The modulation technique maps signal amplitude into time differences using a train of narrow pulses. At the receiver these pulses are used to generate time information which is used to reconstruct the original analog signal. The demonstration of the PFM technique was done separately because the vehicle used did not have a video transmission requirement. Had a video channel been required, problems to be addressed would have included:

* Non-availability of sources and detectors at a third wavelength

* Lack of optical multiplexers/demultiplexers

* Crosstalk problems in laser driven PFM channel and adjacent LED driven channel

Fortunately the situation allowed for an incremental multiplexer development process. The three problems mentioned do no exist today as a result of the maturing of the technology base. Sources and detectors are commercially available at the 1.2, 1.3, and 1.55µ wavelengths allowing systems to be designed for operation at the lowest loss part of the spectrum. Duplexers have now been built and tested for the 1.3 and 1.55µ wavelengths exhibiting very low loss (< 3.0dB per channel) and high crosstalk isolation >100db) characteristics.

BUDGET LOSS CONSIDERATIONS

The demonstration system implements a fiber optic communications link with no inline repeaters. The maximum transmission length is therefore dictated by the available optical power margin provided by the transmitter/receiver pair and the inline losses between transmitter and receiver. Inline losses in each channel are due to connectors, duplexers, the penetrator, and the fiber losses. Of these only the fiber losses vary as a function of wavelength. Losses due to the components have been measured and typical values listed in Table I.

Table 1. Component Losses

Component	Loss	Number	Subtotal
Duplexer	1.5dB	2	3dB
Penetrator	3.0dB	1	3dB
Connectors	2.0dB	3	6dB

The loss values listed are typical values and have significant variances associated with them. In addition the cable's attenuation has shown some sensitivity to temperature and pressure changes. For these reasons a minimum safety factor of 10 dB additional insertion loss should be added to the component and cable losses for budget estimation purposes. With the component losses, cable attenuation profile, and safety factor defined, length limitations due to loss considerations are dictated by available margin.

BANDWIDTH LIMITATIONS

Another important fiber characteristic to consider in designing the cable is the fiber bandwidth specification. Given a fiber with a length-bandwidth product, P, and a baseband signal of bandwidth, B, an approximation of the maximum standoff from a bandwidth limitation is given by:

$$B = \left(\frac{P}{\sqrt{2}}\right) (L)^{-\gamma}$$

where,

L = fiber length in Km

γ = parameter reflecting degree of micro-bending typically 0.6 to 0.8 where γ decreases with increased microbending

P = length - bandwidth product specified at the 3dB optical point

The limiting length becomes

$$L = \left(\frac{P}{\sqrt{2}\,B}\right)^{\frac{1}{\gamma}}$$

As an example take a fiber with a length-bandwidth product of 400 MHz-Km. If a video signal is digitized to a bit rate of 90 Mbits/second NRZ (requires minimum of 45 MHz analog bandwidth) the fiber would be limited to a maximum length of 10 Km by bandwidth considerations alone. Use of Return to Zero (RZ) or Manchester formats would limit transmission to 4 Km. By utilizing PFM and expanding a 4.5 MHz video signal to a 32 MHz information bandwidth, transmission can be achieved over 15 Km based on fiber bandwidth limitations.

Implied in the above comparison is the assumption that the transmitter and receiver designs have adequate performance such that the fiber is the limiting factor.

CURRENT CAPABILITY

An undersea submersible has been built and operated with a 5 Km long, expendable fiber optic cable supporting full duplex communication at 9600 baud. To achieve full duplex operation on a single fiber, complimentary optical wavelength duplexers were designed and constructed for operation with 0.83 and 1.06μ LEDs as sources. The technology to Manufacture 5-10 Km length ruggedized optical cables has been demonstrated and constantly improved to provide better quality control and thus higher yields. In parallel, fiber production technology has been pushed to provide long length (10-15 Km), high strength, low loss and high bandwidth fibers on a decreasing price structure. Cables up to 5 Km in length have been precision wound using microprocessor controlled machinery and the finished spools have exhibited no additional losses due to winding. Deployment has been demonstrated from 10-60 knots with no measurable excess losses due to payout dynamics. A reliable optical penetrator design was built and tested successfully to 10,000 psi and used in an operational vehicle. Application of the PFM technique was demonstrated in parallel via laboratory breadboard operating at the 0.83μ wavelength. Advantages of this technique vs. IM and PCM approaches for video data has been verified(1). Some of these advantages include:

* Lasers can be operated in pulsed mode with no regard for linearity. This allows an approximate tenfold increase in transmitted optical signal power over IM systems using laser diodes.

* Predetection bandwidth expansion provides spread spectrum processing gain. This is achievable at modest fractional deviation.

* The receiver APD can be operated at maximum avalanche gain.

* PFM is simple to implement and inexpensive. No A/D converters or bit synchronization are needed.

Based on the results to date, it appears that a general purpose fiber optic telemetry system could be built today providing two Manchester PCM channels and one PFM channel operating on a single optical fiber cable. Such a system would require the use of dual cascaded optical wavelength duplexers on both ends of the cable. Use of two duplexers instead of one at each end will introduce the additional insertion loss of two more duplexers in two of the three channels. Operation of the PFM channel would be assigned to the 1.2 - 1.3μ region using an injection laser diode. Channel characteristics for each wavelength are summarized in Table II.

Table II. Channel Loss Characteristics

Wavelength μ	Available Margin dB	Component Loss dB	SF dB	Net Margin dB	Fiber Loss dB/Km	Maximum Length Km
0.83 LED	53	15	10	28	3.5	8
1.06 LED	45	12	10	23	2.0	11.5
1.3 Laser	53	15	10	28	1.5	18.7
0.83 Laser	73	15	10	48	3.5	13.7

As the data indicates, operation using the short wavelength LEDs would be limited to approximately 8 Km. However, if a laser operating at 0.83μ is used, the limit could be extended to over 11 Km. In order for the fiber to be bandwidth limited to 18 Km using a PFM expanded bandwidth of 32MHz, the fiber length-bandwidth product would have to be 470MHz-Km. However, if the cable is to be designed for operation over only 11.5 Km, then the bandwidth specification drops to 320MHz-Km.

FUTURE DEVELOPMENT

Operation has been limited to the shorter wavelengths (0.83 - 1.1μ) by the non-availability of sources and detectors at the longer wavelengths. These devices, designed for operation in the 1.2 - 1.6μ region, are now becoming commercially available. Because of the lower fiber attenuation at these wavelengths, losses for a given length of cable will be less. Adjustments in system operational limits should become possible due to changes in the total margin available and due to lower cable losses. It is expected that transmitter and receiver designs will be implemented at these wavelengths and data characterizing optical margin vs. signal quality for various data rates will be generated.

For the Navy, the most critical development areas are:

* Cable splicing techniques
* Cable design development

The ability to splice a ruggedized optical cable is necessary to improve the long length yield of the cabling process. The ruggedizing is achieved by passing optical fiber, S-glass filaments, and resin through a fixed-size forming die. In order to successfully produce a long length cable this imples that the S-glass and optical fiber must maintain their continuity for the entire production run. For cable lengths less than 5 Km this has not been a severe problem. However, we have not as yet been able to produce a 10 Km length. Our last attempt failed because one of 14 S-glass filaments snagged in a guideway and broke. In other production runs, bumps in the fiber buffer material have caused snags and subsequent failure. As the production lengths get longer the fabrication cycle has increased proportionately and some problems have been experienced with the epoxy resins setting up prematurely. The nature of the fabrication process requires that all aspects of the cabling process function as designed for a very long time in order to produce a long length cable. Therefore it is not surprising that catastrophic problems occur as the length is extended. In order to fabricate a long length cable with near 100% yield, we must build into the process a capability to recover from a problem by splicing sections together. The splice must maintain at minimum a 10 lb. tensile strength at 1% elongation, have a bend radius of two inches, be capable of sustaining the pre-twist torque, and most importantly must not be significantly larger in diameter than the original cable. Presently we are pursuing various approaches towards achieving this kind of a splicing capability.

Sensitivity of cable attenuation to pressure and temperature changes has been detected and is related to the physical properties of the buffer materials (2) (3). Presently it is believed that stresses due to these fluctuations produce buckling forces on the fiber resulting in microbending, a common source of propagation loss in fibers.

Cooling the cable contracts the buffer material resulting in an increase in excess attenuation. Heating the cable has the opposite effect. In some instances of heating, the excess attenuation due to cabling, as measured at room temperature, is reduced to a value close to the attenuation of the fiber before it was cabled. During heating tests of ROV cable samples, an interesting phenomenon takes place. The excess cabling attenuation decreases continually up to about 70°C but then begins to increase again. At these higher temperatures the modulus of the buffer material becomes very low. Thus, the fiber is no longer effectively isolated from the S-glass jacket. Since the cable sample is coiled in a temperature test chamber it is believed that the jacket annulus presses against the fiber, causing increases in attenuation.

Although the excess attenuation levels are small (< 0.5 dB/Km) for pressures up to 1,000 psi and temperatures of 0 to +45 degrees C. for the existing design, these losses nevertheless affect the operation over long cable lengths. Current efforts are directed at determining optimum buffer coating specifications to attain sufficient isolation for cabling stresses while minimizing sensitivity to pressure and temperature changes. The advanced cable design in Figure 5 is one example of an attempt in this direction. The Nylon-12 coating was removed from the baseline design leaving only the silicone RTV coating between the S-glass and optical fiber. Testing revealed a significant increase in attenuation of 2 dB/Km at 0.85µ. In addition the cable was much more sensitive to wide temperature variations. Discussion with the fiber production engineers has led to a new buffer coating specification calling for a different RTV coating with a thin Nylon-12 outer coating. This fiber will be cabled and evaluated next.

Should a successful splicing technique be developed and an optimum buffer coating found, a problem still remains in that the diameter of the fiber buffer must be controlled to +/-3% of the nominal fiber diameter. For our 20 mil fibers, this represents an allowable variation of +/-0.5 mil on the diameter over the entire length. Such a requirement arose because the ratio of S-glass to resin is controlled by the buffer diameter variation as it passes through the constant area orifice used for the forming die. The tight dimensional specification adds considerable difficulty to the manufacturing process when the buffer is a Nylon-12 extrusion. We have not been able to procure fibers other than in sample sizes meeting these specifications.

The requirement to produce a buffered fiber within a tight dimensional specification, results from the cabling technique. The more stringent the diameter specification, the more difficult it becomes to make the fiber and therefore is contrary with our long term goal. In order to minimize this problem, the two options we have are to modify the cabling process or alternately modify the fiber buffering process. Of the two options, modification of the buffer design is considered to be of more immediate need and is being pursued at this time.

Buffer diameter control is a problem because the final Nylon-12 buffer layer must be extruded over the primary RTV buffer coating. Control of the extrusion feeder is difficult when the material is being fed over another layer of material because imperfections in the base surface tend to be magnified. The attempt this past year to produce a cable with a silicone RTV only buffer coating was addressed at minimizing the number of buffer layers and the cross-sectional area of the buffer materials. Since the RTV is flow coated onto the optical fiber as it is drawn, it was felt that the buffer layer would be very uniform, being a function of the RTV viscosity and the draw speed of the process. The RTV coated fibers, procured for experimental cabling did indeed exhibit greater dimensional uniformity. Fibers from International Telephone and Telegraph (ITT) were fabricated with a single layer coating and were observed to have variations typically within +/-2%. Other fibers from Sumitomo Electric were fabricated with three layers of RTV and exhibited variations within +/-4% typical. These results indicate that the flow coat process achieves a tolerance comparable to that achieved on the fiber's cladding diameter. The cladding diameter is principally determined by the draw speed of the glass through the furnace. Typically the outer diameter of the fiber can be maintained within +/-2% of nominal with worst case results of +/-5%. The implication here is that a buffer applied via flow coating will result in lower dimensional variations as compared to extruded buffer layers. However, since the RTV coatings have not been able to produce sufficient microbending isolation in our cables, new materials will be investigated. Data to date, while not conclusive, indicates the buffer should be of low tensile modulus and low shore hardness towards the center increasing as the radius of the buffer layer increases. Empirically, we have found that a buffer layer of GE-602 silicone RTV out to a diameter of 12 mils with an outer layer of Nylon-12 to 20 mils works well from a microbend isolation standpoint. As a starting point, the UV (ultra-violet) setting acrylates currently being used by some fiber manufacturers will be investigated. These materials are usually applied in a single coating with the inner volumes being of lower modulus due to a lower cure state.

To summarize, our efforts are focused at developing cable splicing techniques compatible with the S-glass ruggedizing process and improvements in the buffer design of the fibers to improve optical and mechanical performance of the finished cables. Buffer development is critical to minimizing production costs of the fiber and splicing is critical for achieving long cable lengths.

CONCLUSION

Based on a review of the material presented here, it becomes clear that the technology exists to build 10 Km fiber optic telemetry systems for ROVs with little risk. Fiber manufacturing technology has been demonstrated that can support cable lengths of this size. On-going cable development work seeks to extend the length limits and improve the quality control of the manufacturing process. As a result, cabling technology is advancing at a rate where it is expected that production lengths of 10 -15 Km will be achieved routinely in the next year. The required electro-optical components now exist and have been demonstrated and their operational limits characterized. To proceed beyond the 10 Km limit, a shift to longer wavelengths will be required and fiber and cable manufacturing technologies must be advanced to meet the longer length requirements.

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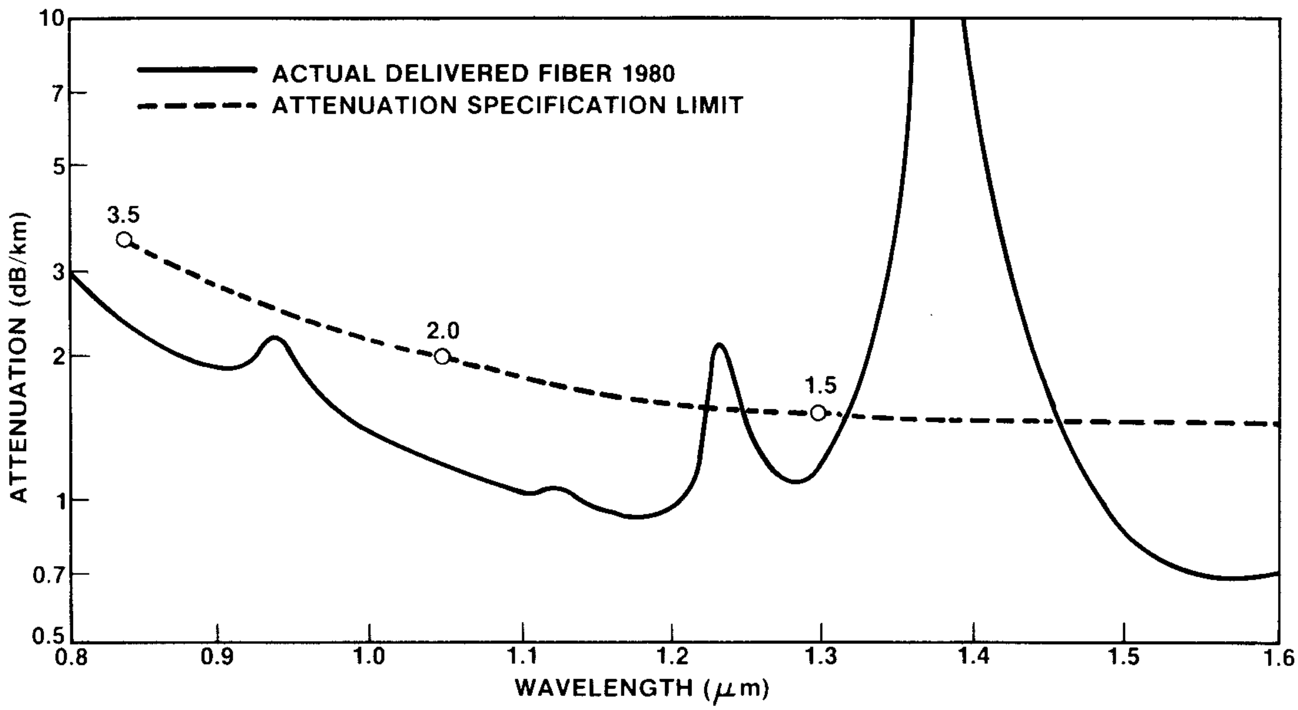
3. Tanaka, S., Yamanishi, T., and Hoshikawa, M., "Stabilization of Temperature Characteristics of Solid Coated Fiber", Technical Digest of Third Intern'l Conference, IOOC, San Francisco, CA, April 1981.



TEST CONDITON: APPARATUS : GRATING TYPE MONOCHROMETER
SPECTRAL WIDTH : 2 nm
LAUNCHING NA : APPROX 0.20
LENGTH : 5058 m

Figure 1. Attenuation Profile for Graded Index 50/125μ Fiber

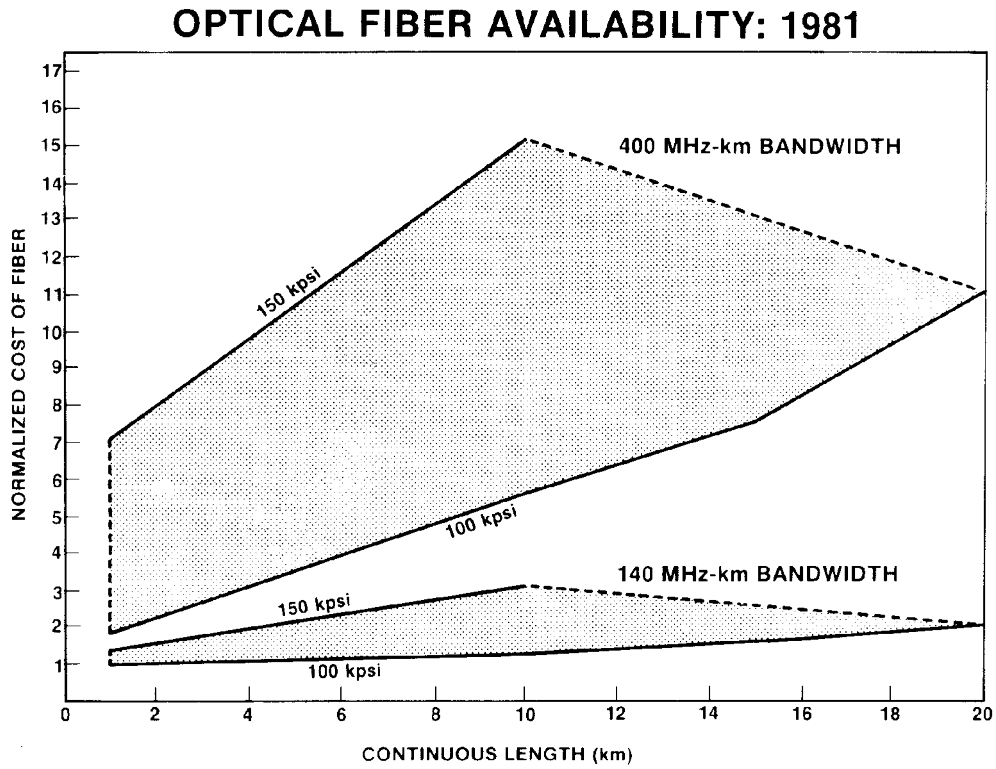


Figure 2. Fiber Yield

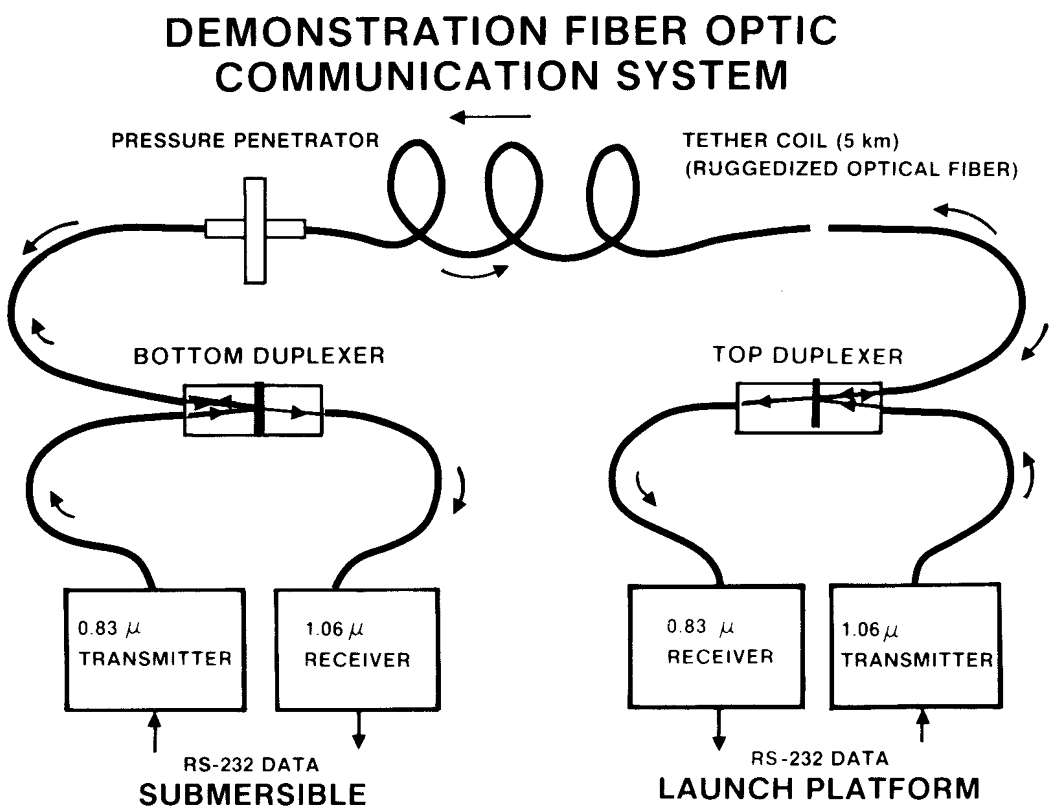


Figure 3. System Design

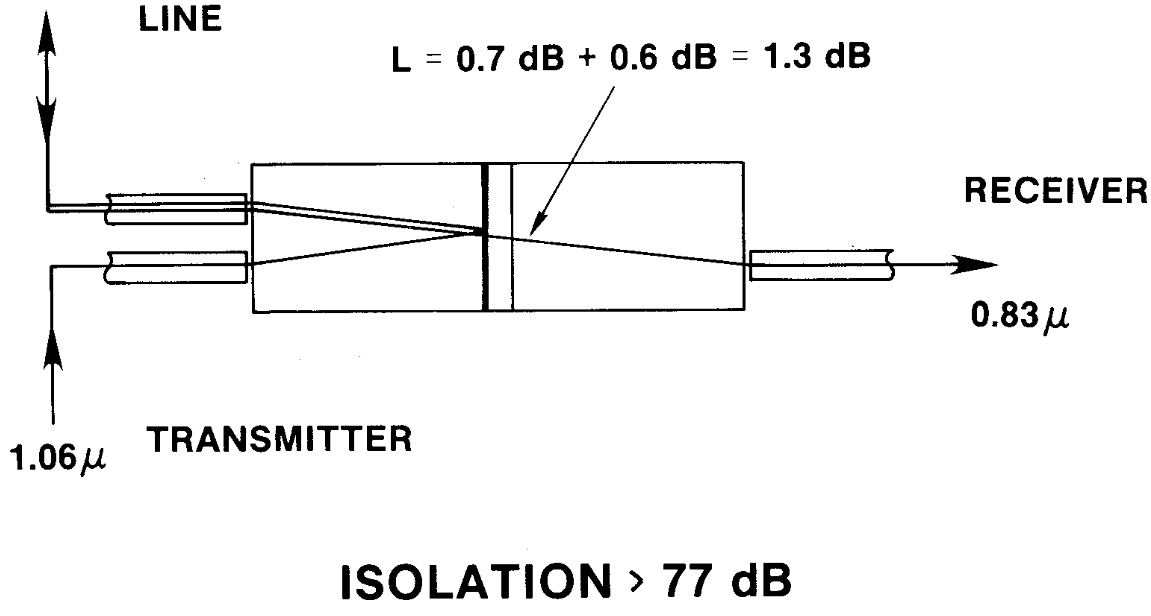


Figure 4. Optical Duplexer Design

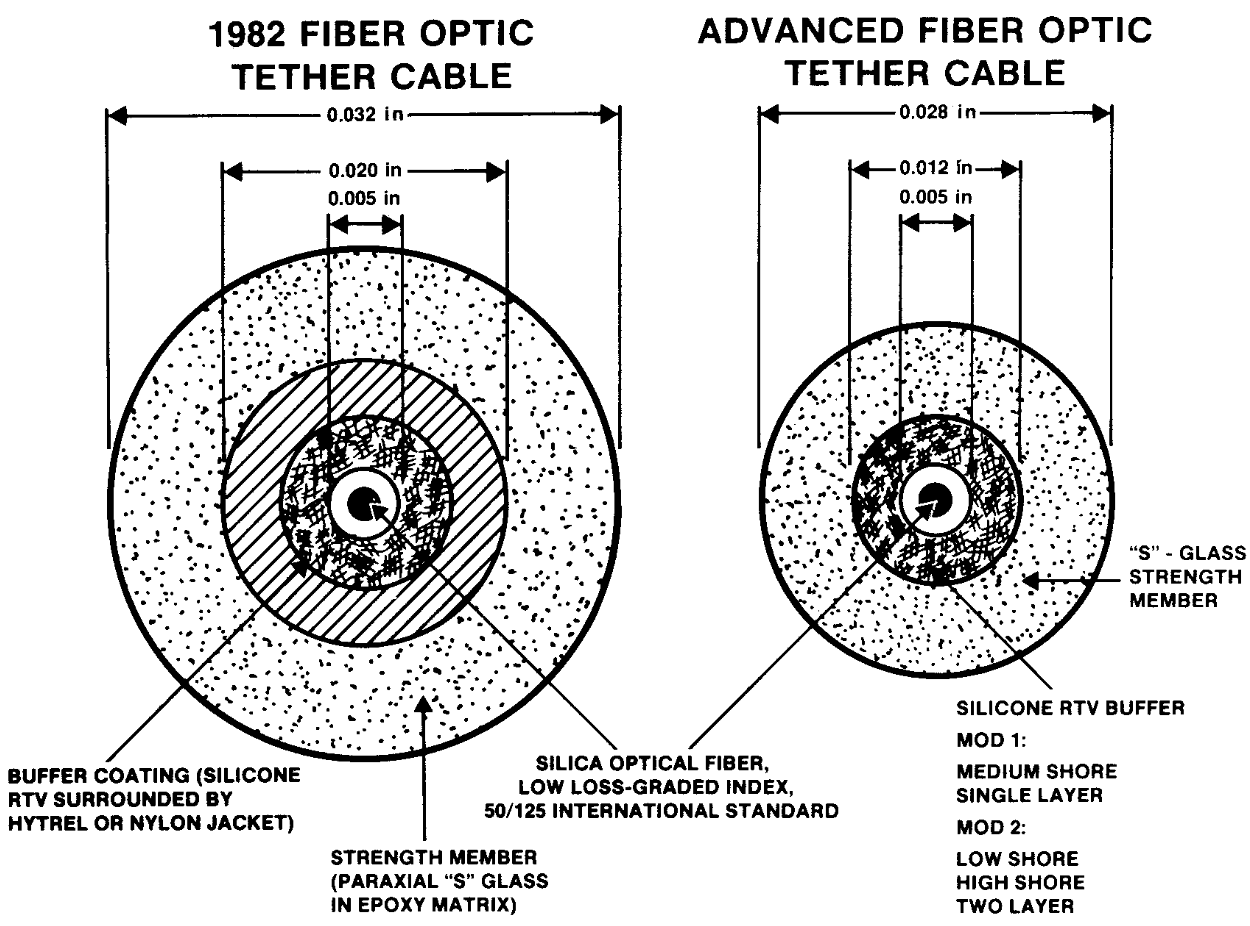


Figure 5. Cable Design

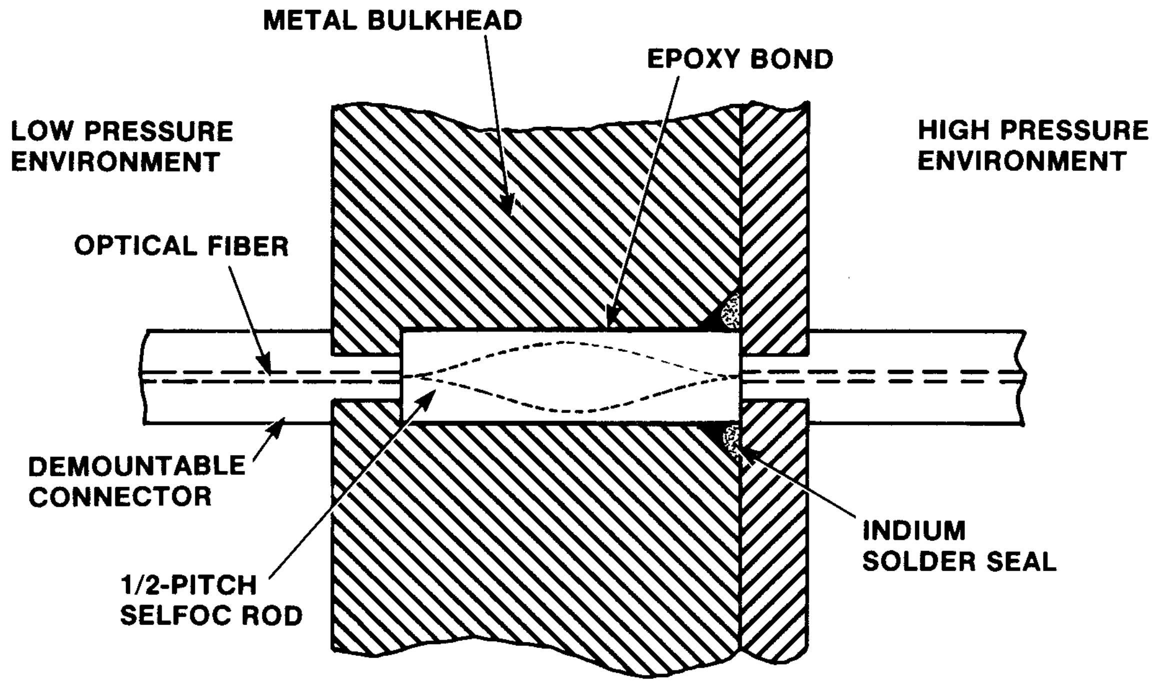


Figure 6. High Pressure Optical Penetrator