Fiber Optic Connections in the Sea

Matt Christiansen, SEA CON®/ Brantner & Associates, Inc.

Abstract

This paper provides an overview of fiber optic connector design and considerations for their use in subsea applications.

1. Introduction

1.1 Why Use Fiber Optics?

The introduction of fiber optics into subsea cables has allowed the realization of much greater rates of data communications with higher signal to noise ratios than was possible with electrical cables. Fiber optics in subsea cable systems have seen greater usage over the past few years and continues to increase. There are many applications of combined electrical and optical cable systems in use and in development today. SEA CON ® has developed and supplied connector systems combining electrical, optical and mechanical terminations (E/O/M) to many applications with unique requirements. Among those are:

a) Communication umbilicals from shore-side facilities to offshore instrumentation, and for platform to platform communications offshore.

b) SEA CON® has supplied terminations for diverse applications to commercial and scientific users.

c) 2) ROV umbilicals of many different styles have been terminated by SEA CON ® and are in use in the subsea market place.

d) 3) Downhole geophysical instruments are now turning to fiber optics for data handling.

e) SEA CON ® has supplied E/O/M cable terminations and receptacle connectors capable of operating at 20000 psi and 200°C with fail-safe open-face capability of the receptacle for guaranteed protection of the expensive instrumentation operating in these hostile environments.

f) Towed array systems deployed from ships and planes are using hybrid fiber optic connection systems to communicate with multiple sensor arrays. SEA CON ® supplied connectors used in military systems have been tested to withstand severe environmental extremes including underwater explosive shock.

1.2 What About Connectors?

In conveying power and information from control locations to subsea systems, it is most often convenient to have a means of connecting and disconnecting cables from equipment. This greatly simplifies handling, installation and maintenance tasks as well as test functions and operations. Such a connection must be quick and reliable, provide a high level of performance and be cost effective. Connectors for optical and electro-optical cables have a few special design considerations to be aware of:

a) Features of the cable construction greatly influence the design simplicity of the cable head termination. Ideally, cable and connector design should be integrated as a system for best value in performance, cost and reliability as a subsea communications conduit.

b) Each application and operating environment will define the requirements of the connector system. However, a good understanding of operating environments and the definition of performance requirements is necessary in order to design an efficient cable and connector system.

2. Connector Design

2.1 The Connector Optical Interface

The fiber optic interface is critical, termination of optical fibers into contacts requires great care in the dimensioning and tolerancing of connector hardware. Costs can be reduced by using standard commercial optical components. Standard termination techniques can be adapted to easily and reliably produce quality connection systems.

a) **Fibers** – Many types of fibers are in use in subsea cable systems. Most can be handled with similar techniques due to their common 125 micron diameter of the clad glass. Commercial fiber optic technologies support very high quality components for 125 micron fiber. Other types of fibers can be handled with specialized components using the same basic principles of operation.

b) **Optical Components –** The most basic component to the mainstream fiber optic connection today is the 2.5mm diameter ferrule and alignment sleeve. Both are available with high quality and low cost. Improvements in these components and fiber itself have made today's low loss connections possible. Zirconia ceramic ferrules are most widely used while other materials and variations of technique serve special applications. The ferrule serves to locate the end of the fiber in a precision component of convenient size for polishing and subsequent alignment to a mating fiber/ferrule.

c) **Polishing –** The fibers are polished flush to the end face of the ferrules, then the ferrules are aligned to their outside diameters in an alignment sleeve. The accuracies of these components are capable of aligning two fibers with core diameters of only nine microns such that the resultant optical loss across the junction is reliably less than -0.5 dB.

d) **Alignment –** Issues to be dealt with are physical contact of the fiber faces, concentricity and the angular alignment of the mating components. The ferrule and alignment sleeve junction has been well studied and their use understood. [1,2,3]

   Expanded beam lenses have been used in subsea connection systems. The two mating lenses do not have to touch face to face to achieve a good optical couple, this eases the accurate control of axial tolerance stack-ups in the connector manufacturing process. Unfortunately, expanded beam lenses are susceptible to high losses with angular misalignments and have the added complication of accurately positioning the end of the fiber in the focal point of the lenses.

   Newer fiber alignment technologies are emerging and SEA CON® is testing and evaluating them for the advantages they offer. These developments will allow designers to achieve greater fiber channel densities through connector systems.

2.2 Shells and Shell Design

The optical contacts are fitted to molded or machined connector inserts which in turn are fitted into proven connector shell designs for the keying and locating the mating contact pairs.

Working in the subsea environment involves the use of seals to exclude water intrusion into the connector internals. O-rings have always been a very reliable method to seal connector shells and can be used to seal individual optical contacts as well. Optical contacts molded into non-resilient inserts do not allow for the fine alignment necessary to achieve the highest optical performance. Contacts sitting in resilient seals retain greater compliancy and achieve better alignment.

3. Cable Design

3.1 Design Considerations

For each application the extremes of pressure, temperature, tensile load and other environmental factors need to be considered. The composition of the cable and materials of its construction dictate the means of attaching and sealing the cable to the connector shell. Operational considerations may call for the possibility of termination in field settings. Instrument specifications may call for increased levels of insulation protection in electro-optic cables. Requirements for integral armor termination or oil-filled and pressure-balanced systems will also affect the design of the cable entry.

3.2 Hybrid Electrical and Optical Cables

Subsea cables generally handle fibers in a number of ways. The fibers may be loosely bundled together in a common stainless steel buffer tube, commonly know as a “K-Tube”, often with a gel suspension to support the fibers. A variation of this is for the fibers to be embedded in a common plastic matrix helixed around a central ‘king-wire’ strength member. These elements are usually (but not always) located in the center of the cable core. Alternatively, the fibers may be individually buffered and armored with a Kevlar strength member and distributed throughout the cable core. Each of these methods lend themselves to different techniques for “breaking out” the fibers from the core of the cable. The handling of fibers in this area of the cable termination is crucial to efficient low-loss optical connections. Additionally, subsea cables often contain copper electrical conductors within the core. and may contain steel or Kevlar armoring around the cable core

4. Cable / Connector Integration

4.1 Integration

The design of an interconnection system for a cable and how it will enter into the backshell of the cable head termination must be designed as a system for best results.

4.2 The Fiber Break-Out

Once the cable is secure to the shell of the connector, the fiber itself must be broken out from the cable core and conveyed to the connection interface. Both the cable armor and electrical conductors are large and robust relative to the optical fibers requiring the fiber break-out to allow for and protect the fiber from these cable elements. The optical fiber must be reduced to the bare fiber (core and cladding) at the actual termination and the fiber immediately behind the termination must be minimally constrained so that it can adjust to movement of the termination during mating in a connector system.. The fan-out technique needs to take into account not only the protection of the fiber, but the ease of assembly and successful yield in production.

a) **Breakage –** Fiber breakage is the greatest danger. The fiber is quite strong in tension (i.e.: 100,000 psi) [4] but break very easily when bent sharply. Bending radius in the fiber path should be kept above one inch for low stress terminations to ensure long life.

b) **Bending –** Bending radii below one-half inch will result in light lost from the fiber in the area of the bend. Although a fiber will withstand such short-term bending during handling, it should be avoided**.**

c) **Microbending –** Microbends are small crimps in the fiber pathway which allow light to escape from the core and increase optical loss dramatically. Particular care must be taken to eliminate microbends in the fiber.

d) **Compliance –** In a Physical Contact (PC) ferrule termination, the two mating ferrules must come together with physical contact between the ends of the fibers for a low loss connection. Due to the aggregate tolerance of the connector components, allowance must be made to ensure that the ferrules from each side do actually meet. To accomplish this one or both sides of the connection will incorporate movement in the optical contacts, generally by use of a compliant spring to allow the contact to move axially in the mating process and to provide a reliable contact force holding the connection together. This movement of the fiber creates an excess of fiber behind the termination insert. The fiber handling must again consider any bending, stress and loss this creates in the fiber. (The split sleeve should not be over stressed)

e) **Storage –** This compliant movement of the fiber contact creates the need for a space in the back-shell of the connector for storage of excess fiber. This is most simply an air void, which requires that the connector shell be a small "pressure vessel" capable of the pressure environment in which the connector will be used. This adds additional design concern in anchoring the cable entry into the back-shell and sealing out the subsea environment. The sealing must also include the interstitial spaces of the cable to provide protection in the event that the external cable jacket is damaged, exposing the cable spaces, and potentially the back of the connector, to flooding.

f) **Re-Termination and Salvage –** Where size considerations allow this void space can be utilized to store enough extra fiber to allow re-termination of a fiber should one of the contacts be damaged. Contacts may be cleaned or re-polished but need to be cut off if the contact has been seriously damaged. Since the fibers are fixed into the contact with an epoxy it is not possible to re-use the actual contact. Storage of fiber in loops or coils comes at the cost of additional losses due to the bending of the fiber. The costs of having to remove and re-terminate all of the fibers in cable head just because one is damaged relative to the costs in additional loss and the larger connector size for stored fiber must be considered.

5. TESTING [5]

5.1 What Is To Be Tested?

There are two main performance considerations for the transmission of light through an optical connector. The first is insertion loss, the light power lost through the connection. Because insertion loss is cumulative when there are multiple connections in a system, it is essential to minimize this loss. The second consideration is back reflection, the amount of light reflected back to the source from the connection interface. This reflected light can affect the laser source as out-of-phase feedback and results in a higher noise level relative to signal strength. Back reflection needs to be kept at a minimum in laser powered single-mode systems.

a) **Acceptance Testing.** Losses are present in the cable as well as the connectors and are a function of length. In a long cable system or one with many connections it is critical to keep the total loss budget low enough for the system to operate efficiently. Identification of system requirements and testing of completed assemblies ensures a successful implementation of the system in field use.

b) **In Process Testing** It is also important to monitor optical performance in-process of a cable termination in order to identify any loss increasing operation or assembly error. As these terminations can be very time consuming with a complicated cable one would not want to complete the entire termination just to find that an error in an early operation is causing excessive loss in the connection.

5.2 Insertion Loss By Power Meter

Insertion loss is measured as a decrease in light power traveling from source to receiver when adding a connection interface to a known reference system.[6] First, to establish this reference, light is passed from a laser source through a single optical reference fiber. The light power exiting the end of the fiber is collected and quantified in the light meter. This light power is the “Reference” power level and is usually tared to zero. The connection to the light source must not be disturbed once this reference level is set so that a consistent amount of light is know to be entering the reference fiber. Next, a second fiber jumper is inserted into the system between the end of the reference fiber and the light meter. The amount of light received at the meter is now reduced by the amount of light lost at this fiber connection and accounts for the loss in one standard ferrule connection.

The actual value of this loss is true for this set of connectors only though it should be representative of connections of it’s kind. This should be a low loss connection such that the terminations being used to evaluate the subject fiber optic assemblies are themselves of high quality.

A typical fiber optic cable termination assembly for subsea use will include a long length of the main transmission cable terminated to mate with a bulkhead receptacle connector. This bulkhead receptacle will have fiber pigtails on the inboard side with individual optical terminations on each fiber such as commercial “ST” or “FC” connectors. The top-side of the main cable will similarly have individual connectors on each fiber at that end. Thus the cable system to be tested is comprised of three connection interfaces. The multi-channel underwater connector must be tested together with it’s mate in order that the test be representative of the system as it will be used. The system can be accessed for measurement only at the inboard and topside fiber terminations.

In order to measure the performance of the cable system it is inserted into the aforementioned measurement setup between the reference and jumper fibers. The light power reaching the meter is now reduced by the losses incurred in the additional assembly now in the measurement system. The loss reading on the meter is representative in this case of the loss through three fiber connections. The actual amount of loss incurred at each of the interfaces cannot be individually determined by this method. The loss value read may be divided by three assuming that the three interfaces contribute equally to the total loss since they consist of essentially identical interface technology.

It should however, be considered that the interfaces in the multi-channel connector assembly may experience greater alignment challenges due to the tolerancing of multiple contacts in a single connector insert and may account for more than an equal share of the system loss. If the assumption is made that the commercial single connectors in the system (i.e. ST's or FC's) can be characterized by a demonstratively repeatable performance level, then a chosen value can be subtracted from the system loss and the remainder assigned to the multi-channel interface. In a well-designed connector with proper handling of multiple channel alignments, both methods will yield the same results.

5.3 Loss Measurement Using an OTDR

The introduction of an Optical Time Domain Reflectometers (OTDR) has made it possible to look at individual events in a fiber optic system just as electrical Time Domain Reflectometers (TDR) have done for electrical cable systems. Each feature of a cable system, such as a splice or connection will have a characteristic trace as viewed with the OTDR. The position and magnitude of each feature in a cable system can be evaluated and quantified with this instrument. In an assembly with multiple connections, each can be evaluated individually to determined it's contributing insertion loss and back reflection providing that these events are spaced far enough apart in the cable that they can be distinguished as separate events.

Each event results in a deflection of the OTDR trace with an amplitude relative to the magnitude of the event. Measurement of the event is made relative to the baseline of the trace. Two events spaced close together may overlap each other on the trace and cannot be evaluated individually. The speed of the electronics in the OTDR limit the linear resolution of the instrument with higher priced (faster) instruments having greater ability to resolve separate events in a shorter span of fiber. Instruments in the $30,000 range generally report resolution to tens of meters but will require separations an order of magnitude greater in order to have good baselines from which to make measurements of event performance.

As such the OTDR has limited usefulness in evaluating short cable assemblies. This disadvantage can be overcome by fusion splicing into an assembly to avoid having to "look through" a relatively high loss event to see another event behind it. A very low loss fusion splice will typically result in a minimal deflection of the trace such that the baseline disturbance is shortened, allowing more closely spaced events to be evaluated. Testing by this method adds extra time and handling to the deliverable system, and therefore increased cost, but is invaluable in understanding the actual system performance .

5.4 Return Loss Measurements

Optical return loss is another parameter critical to many fiber optic systems, especially high-powered single-mode systems, and is increasingly included in connector specifications. Each discontinuity and imperfection in a fiber channel will reflect a certain amount of light back along the fiber to the light source. Fiber connections are inherently reflective interfaces but quality terminations can minimize reflectance to acceptable levels. Reflectance is greatly influenced by the quality of the polish in a ferrule termination, machine polishers have a demonstrated ability to achieve reliably low reflection terminations (<-45dB).

Angled Physical Contact (APC) terminations have angled interfaces (i.e.: 8 degrees from perpendicular) and effectively reduce return loss by reflecting light back at an angle to the axis of the fiber core such that it is lost from the fiber before it travels back to the source. APC connections require keyed ferrule alignments in order to match the angled ferrule faces. This is most easily accomplished in a single channel connection and adds complication to multi-channel connector systems.

Back reflection is reported as a power level relative to the incident power level at the source. Most OTDR's are capable of evaluating this parameter with a little care in the operational set-up.

Absolute values cannot be obtained if the receiver amplifiers are being saturated by the returning signal. Good results can be obtained when working with initially low reflective events by reducing the incident output power or pulse width and increasing averaging time in the signal analysis. The problem of linear resolution of the OTDR limits the ability to evaluate closely spaced reflective events.

Fusion splices are generally very low reflective events. By splicing in long lengths of launch fibers and lengths of fibers beyond the event to be evaluated (to separate it from launch and end-of-fiber events) accurate return loss measurements can be made. There are lower priced meters marketed for return loss measurements which utilize “mandrel wrapping” to extinguish light before and after an event to characterize it’s reflectance. While these instruments are useful in evaluating the first event encountered beyond the meter source, as in single fiber jumpers that can be serially disconnected, they do not lend themselves to measurement of the typical specialized multi-channel underwater optical connector. It would be possible to utilize these meters by fusion splicing into the fiber assemblies where compatible with the deliverable system requirement though it is generally not desirable to deliver assemblies with included fusion splices as these splices are more prone to failure due to physical damage than the parent fiber would be.

6. Conclusion

The completed connector assembly is a system for conveying information and power from one location to another through an environment hostile to both of these commodities. The connector transitions the mechanical, electrical and optical properties of the cable into an instrument body while protecting the system from the subsea environment. Subsea communications with optical systems have benefits and are available for use today. Using fiber optics in the sea adds a few considerations to established connector technologies. SEA CON® has evaluated these considerations and successfully incorporated them into proven connector designs resulting in reliably high quality connections. As the use of fiber optics increases and expands into new areas, connector technology will follow, contributing to the advancement of subsea technology.

REFERENCES

1. Fiber optic insertion loss measurements...how they relate to system use, Ronald Cooper, AMP Inc. 1983
2. Fiber Optic Connector Splice Losses: The Laboratory vs. the Real World, Ronald Cooper, AMP Inc. 1981
3. Understanding Fiber Optics, 2nd Ed.. Jeff Hecht , Sam’s Publishing, 1993
4. Corning SMF-28 Single Mode Optical Fiber, Product Information PI1044, Corning Incorporated, 1996
5. Technicians Guide to Fiber Optics, 2nd Ed., Donald J. Sterling, Jr., Delmar Publishers, 1993
6. Siecor OTS-100 Optical Power Meter. Siecor Corporation, 1994