SPLICING TECHNOLOGIES FOR DISPERSION SLOPE-MATCHED FIBERS

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Abstract: Due to significant differences in fiber core geometry and refractive index profiles between the positive and negative dispersion fibers in dispersion slope-matched systems, it is a challenge to splice both fibers together to achieve the low loss and high strength required for submarine applications. Two splicing technologies considered for joining these dissimilar fibers include bridge fiber splicing and direct splicing. The success of bridge fiber splicing has been field validated through the successful implementation of the VSNL TGN Pacific Cable System Segment G6, the first deployed system with slope-matched fibers. In this paper we discuss the development of these two splicing techniques and compare their benefits in terms of performance, implementation complexity, yield and applications.

1. INTRODUCTION

Broad-band dispersion management is important for the design of ultra-high capacity, ultra-long-haul optical transmission systems utilizing dense wavelength division multiplexing. Dispersion slope-matched fiber and cable technologies have been developed to meet this need [1]. In each fiber path of a cable system utilizing dispersion slope-matched fiber cables, the end-to-end cumulative chromatic dispersion across the transmission band is fully compensated simultaneously. Dispersion slope-matched technology not only significantly improves transmission performance but also greatly simplifies terminal designs, since minimal differential chromatic dispersion compensation is needed at the terminals. These new fiber and cable technologies were first commercially implemented in the VSNL TGN Pacific Cable System Segment G6.

Two types of transmission fiber are used in a dispersion slope-matched fiber cable system: first, a P-type fiber with positive chromatic dispersion and positive dispersion slope; and second, an N-type fiber with negative chromatic dispersion and negative dispersion slope (at 1550 nm). Both fiber types are designed for maximum effective area so performance impairments due to optical nonlinearities are greatly reduced. However, the effective area of a P-type fiber is much larger than that of an N-type fiber, and this significant difference results in a splicing challenge to achieve the low loss and high strength which are especially important for submarine applications. This challenge is also intensified by the fact that both fibers have to be designed with significantly different refractive index (RI) profiles.

Low splice loss is not only important for better system performance but also can result in lower system cost benefits by reducing the number of submerged repeaters, which continue to be one of the primary contributors to submarine system costs. For example, in a dispersion slope-matched system, a 0.2 dB splice loss reduction allows a repeater span extension of approximately 1 km. This enables a repeater savings of 1-2%, which in the case of an ultra-long haul cable system such as one across the Pacific Ocean, in which there are about 200 repeater spans, a splice loss reduction of 0.2 dB could save three repeaters or more.

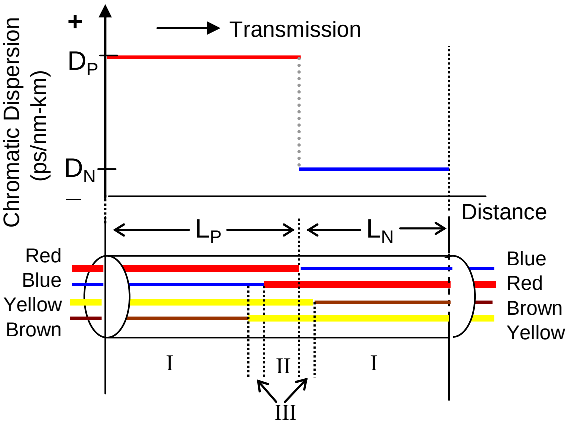

Figure 1: A typical finished transmission cable span with dispersion slope-matched fibers and its dispersion map. This cable span includes two pairs of transmission fibers. The first transmission pair is red and blue while the second transmission pair is yellow and brown. An indicative dispersion map for the first transmission path is shown with the direction of transmission indicated by the arrow. I, II, and III identify the different cable cross-section zones in which the composition of fiber types in the cable cross-section is the same: Zone I 50% P-type and 50% N-type; Zone 2 100% P-type; Zone III 50%-100% P-type and 0%-50% N-type.

Two splicing technologies have been implemented to splice P-type and N-type fibers together: bridge fiber splicing and direct splicing. In this paper we discuss both splicing technologies and identify the preferred technology and its advantages for each stage in the lifecycle of a submarine system.

2. DISPERSION SLOPE-MATCHED FIBERS AND THE SPLICING TECHNOLOGIES

Dispersion slope-matched fiber and cable technologies, along with their implementation in undersea cable systems, were discussed in greater detail in Reference [1]. A cable system utilizing dispersion slope-matched fiber and cable technologies is comprised of two types of cable spans: transmission cables and compensation cables.

Figure 1 shows a typical finished transmission cable span comprised of two pairs of dispersion slope-matched transmission fibers. A typical dispersion slope-matched transmission fiber is comprised of P-type fibers followed by N-type fibers, referenced to the direction of transmission.

Parameters \ Fibers	P-type	N-type
Dispersion @1550nm (ps/nm-km)	20	-40
Relative Dispersion Slope (1/nm)	0.003	0.003
Cabled Fiber Loss@1550nm (dB/km)	<0.19	<0.24
Mode Field Diameter (μm)	12	6
Effective Area (Aeff) (μm^2)	100	30
PMD (ps/sqrt(km))	<0.07	<0.07
Nonlinear Coefficient n_2 (10^{-20} m^2/W)	<2.5	<3.5

Table 1: Typical values of the key optical parameters for P-type fibres

Table 1 lists typical values for key optical parameters for the P-type and N-type fibers. In a slope-matched optical system, to achieve fully compensated end-to-end cumulative dispersion across the transmission bandwidth, the key parameter is the Relative Dispersion Slope (RDS), defined as the ratio of the dispersion slope to the dispersion for a fiber. The P-type and N-type fibers are designed to have equal RDSs, which enables the complete compensation of cumulative dispersion across the transmission bandwidth. To reduce the impairments due to optical nonlinearities, the fibers are designed with high local dispersions and large effective areas so that the higher power densities required for long-haul transmission can be accommodated. This is especially important for P-type fibers, which are used at the repeater output locations. In addition to the geometric differences between the P-type and N-type fibers, there is also a significant mismatch in their refractive index profiles. Figures 2a, 2b, and 2c show typical refractive index profiles of P-type, N-type and NZDSF fibers. P-type fiber is usually designed with a step-index profile similar to standard single mode fibers. N-type fiber has an index profile similar to standard Dispersion Compensating Fibers (DCF) with a W-shape index profile that includes an α-profile center core, with α close to 1, resulting from heavy up-doping concentration in the center core and heavy down-doping concentration in the ring surrounding the center core. Both the mismatches in geometry and in the index profile make splicing P-type and N-type fibers together with low loss and high strength quite challenging. As an example, if these fibers are spliced together using conventional fusion splicing techniques, the resulting splice may have an attenuation in excess of 1dB.

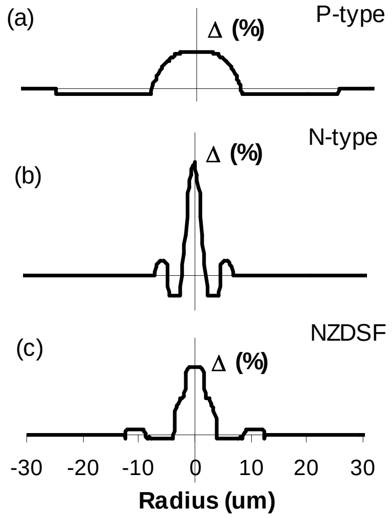

Figure 2. Typical refractive index profiles for P-type, N-type and NZDSF fibers [2-4].

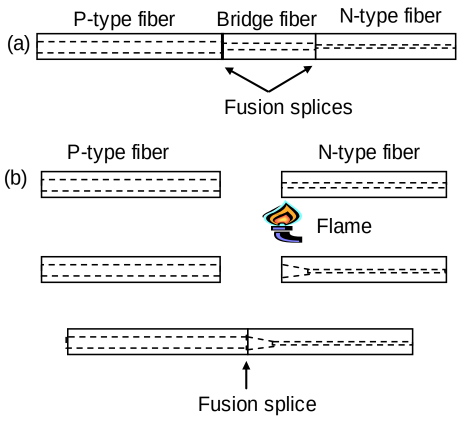

Figure 3: Simplified illustrations of bridge fiber splicing (a) and direct splicing via TEC (Thermal diffusion Expanded Core) technology

A description of the two splicing technologies developed to join P-type and N-type fibers together, bridge fiber splicing technology and direct splicing technology, follows. As shown in Figure 3a, bridge fiber splicing technology utilizes a bridge fiber which is inserted between the P-type fiber and the N-type fiber. One end of the bridge fiber is spliced to the P-type fiber and the other end of the bridge fiber spliced to the N-type fiber, with both splices performed using conventional fusion splicing techniques. To achieve low losses for both splices with minimal spectral tilt and high strength, the bridge fiber core geometry and refractive index profile should be compatible with both the P-type and N-type fibers. NZDSF fibers are typically used as bridge fibers. The use of conventional splicing techniques and “off the shelf” bridge fiber allowed this approach to quickly become commercially available, with its first application deployed in the VSNL TGN Pacific Cable System.

The bridge fiber splicing technique is simple and easy to implement, however the loss of a bridge splice is relatively high, since it is the sum of the losses of two fusion splices. In addition, there are other potential performance impairments which may be introduced via bridge fiber splicing, such as Multi-Path Interference (MPI), discussed later in this paper. Direct splicing technology has been developed as a solution for these shortcomings. Figure 3b illustrates the direct splicing technique, which is a fusion splice assisted with thermal-diffusion expanded core (TEC) technology [5]. In the direct splicing process, the tip of the N-type fiber is heat treated before fusion splicing with a diffuser heat source to a temperature >1000°C for tens of minutes; the diffuser heat source may be either a flame, a heat tube, or an infrared laser source such as a CO_2 laser. During the heat treatment, the dopants in the core and inner cladding diffuse into the outer cladding, and the dopants in the inner cladding diffuse into the core as well. Proper control of the heat treating process provides a refractive index profile “up-taper” along the tip, which results in a refractive index profile and core geometry at the tip of the N-type fiber that closely matches those of the P-type fiber. The last step of the direct splicing process is to fusion splice the “up-tapered” N-type fiber to the P-type fiber using a conventional fusion splicing technique. This direct splicing technique, with a single fusion splice, has the potential for reduced loss and eliminates the system impairment concerns associated with the bridge fiber splice dual splices. Such fiber tapering techniques, through physical or refractive index profile modification, have been successfully used in the fiber component industry.

3. PERFORMANCE OF SPLICES

	Typical Conventional Fusion Splice	Typical Bridge Fiber Splice	Typical TEC-assisted Direct Splice
Splice Loss (dB)	> 1	~ 0.4	~0.3
Absolute Spectral Tilt (dB/nm)	1.0E-02	1.0E-03	1.0E-03

Table 2: Losses for splices between P-type and N-type fibers by different splicing techniques

Both bridge fiber splicing and direct splicing offer performance improvements relative to conventional fusion splicing techniques for joining P-type and N-type fibers; each technique has its own advantages and disadvantages in performance and application.

3.1. Splice Losses

The bridge fiber splicing and direct splicing technologies both offer reduced splice loss and spectral tilt compared with conventional fusion splicing. Table 2 shows the typical splice attenuation and absolute spectral tilt values for current splices between P-type and N-type fibers using different splicing techniques. We can see that bridge fiber splicing and direct splicing techniques indeed enable much lower splice loss and spectral tilt. Even though the current loss differential between bridge fiber splicing and direct splicing is small, it is not insignificant, and the direct splicing technique has greater potential for achieving the lowest splice losses between P-type and N-type fibers.

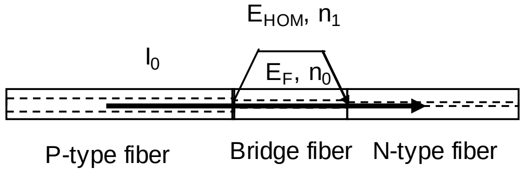

Figure 4. Illustration of MPI generation in bridge fiber splicing

To minimize splice loss, the refractive index profile transition(s) along the transmission axis must be very smooth. This has been demonstrated both theoretically and experimentally; adiabatic power transfer requires a gradual evolution of refractive index profile along the power transfer direction [6, 7]. Such a gradual index profile transition between P-type and N-type fibers is extremely difficult to achieve using conventional fusion splicing techniques. Using the bridge fiber as a “transition” fiber improves the transitions, allowing for more gradual index profile evolution between the P-type fiber and N-type fiber. The most promising approach for achieving a designed gradual transition, however, is the up-tapering of the N-type fiber refractive index profile achieved via TEC prior to direct splicing. This approach is in its early stages of introduction to commercial submarine systems. It is fully expected that splice loss improvements will be made as further experience is gained. Results from the component industry tell us that a maximum insertion loss of 0.2 dB has been achieved commercially for coupling fiber transmission into EDF core with 2x ~ 3x MFD expansion.

3.2. Multi-Path Interference (MPI)

Although the bridge fiber splicing technology offers reasonably low splice loss, it has the potential of introducing a unique performance impairment, the phenomenon of Multi-Path Interference (MPI). When there is a significant mismatch between the characteristics of the two fibers on either side of a splice, mode coupling between the fundamental mode in one fiber and Higher Order Modes (HOM), or radiant modes, in the other fiber occurs. As illustrated in Figure 4, when P-type fiber is spliced to N-type fiber through a bridge fiber, a HOM is excited at the splice location between the P-type fiber and the bridge fiber (input splice). This HOM in the bridge fiber may propagate to the splice between the bridge fiber and the N-type fiber (output splice) without being fully attenuated in the bridge fiber. A portion of this HOM in the bridge fiber may then be coupled back into the fundamental mode of the N-type fiber at the output splice (bridge fiber to N-type fiber splice) where it could interfere with the desired transmission of the P-type fundamental mode. This phenomenon is called Multi-Path Interference, and, if not mitigated by proper bridge fiber selection and length, it could degrade system performance [8]. In contrast, for direct splicing, there is no “output splice” mechanism to couple the HOM back into the N-type fiber, so MPI does not exist in splices made using the direct splicing technique.

Characterizing MPI can be done as follows. If I_0 denotes the field intensity in the P-type fiber, L the bridge fiber length, n_0 and n_1 the effective refractive indexes of the fundamental mode and HOM in the bridge fiber, respectively, then the MPI, defined as the ratio of the interference ripple to the transmitted fundamental mode power at the output splice, is given by:

$$MPI \propto \gamma \cdot \exp\left[-\left(\alpha_1 - \alpha_0\right) \cdot L\right] \cdot \cos\left[\frac{2\pi(n_1 - n_0)L}{\lambda} + \varphi(t)\right] \qquad Eqn.1$$

where λ and $\varphi(t)$ are the wavelength and phase of the signal source input into the P-type fiber; α_0 and α_1 are the attenuation coefficients for the fundamental mode and HOM in the bridge fiber; and γ is related to the product of the mode coupling between the fundamental mode and the HOM at the input and output splices. As the fast component, MPI will convert jitter in the laser source into signal high frequency noise; as the slow component, environmental changes such as temperature variation may introduce low frequency noise. To minimize system impairment due to MPI, the MPI magnitude for a bridge fiber splice should be lower than -50 to -60 dB. From Equation 1, we expect that the MPI magnitude depends on not only the properties of the bridge fiber but also on: (1) the splice losses of the input and the output splices (when the splice loss is mainly contributed by mode coupling to HOM), and (2) the bridge fiber length. Our measurements, shown in Figures 5a and 5b, demonstrate the dependencies of MPI on bridge fiber length and bridge fiber splice loss. Figure 5b shows that for lower bridge fiber splice losses, the MPI is correlated with splice loss, however, for higher bridge splice losses, MPI is not well correlated, since more and more signal is dissipated through radiation modes. These relationships enable the control of MPI by proper design of the bridge fiber. The design rules for maintaining MPI in a bridge fiber splice below the target level are:

1. Determine the loss ranges for the input and output splices.

2. Select a bridge fiber with a proper cutoff wavelength so single mode transmission is maintained within the bridge fiber.

3. Use a long enough bridge fiber so the HOM can be greatly attenuated before the output splice.

3.3. Bend Sensitivity

The bending of a splice can impact the splice loss; this effect is more prominent in the direct splice taper than in the bridge fiber splice conventional fusion splices. Currently, for a macro-bending loss allowance of 0.1 dB, a direct splice may be bent to diameters in the 100-200 mm range. In contrast, for bridge fiber splices, if we ignore the bending effect of the bridge fiber itself, the bending effect is the combined contribution from each of the two single conventional fusion splices. For example, the macro-bending loss of a bridge splice at a 50 mm diameter is normally less than 0.06 dB. To reduce the bending sensitivity of direct splices, the taper length may need to be increased in order to reduce the localized change in refractive index profile along the transmission axis. Fortuitously, the bending configuration of fiber within the undersea cable structure is relaxed and sufficiently benign so that macro-bending loss is of no concern for either type of splice within the cable.

4. IMPLEMENTATION COMPLEXITY AND YIELD

The selection of a splicing technique depends not only on the splice performance, but also on other factors such as implementation complexity, splicing environment and expected splice physical geometry. Conventional fusion splicing is a mature technology using an electrical arc heat source which is easy to control and reasonably insensitive to environmental variation. The current direct splicing TEC (Thermal-diffusion Expanded Core) technique, implemented in the fiber factory, utilizes a flame diffuser with alcohol fuel and appropriate safety measures for the fiber manufacturing environment. To implement TEC diffusion in a less controlled environment, additional safety measures would likely be required. In addition, the time required for taper diffusion, on the order of tens of minutes, directly impacts splicing time and efficiency. The splice yields for both direct and bridge fiber splices, with 200 kpsi proof test for submarine applications, are approximately equivalent to each other. The additional splicing time required for the direct splice technique, however, reduces overall direct splicing throughput. This reduction in throughput can be readily accommodated with appropriate production planning of splicing equipment and personnel, so that the performance advantages of the direct splicing technique can be exploited.

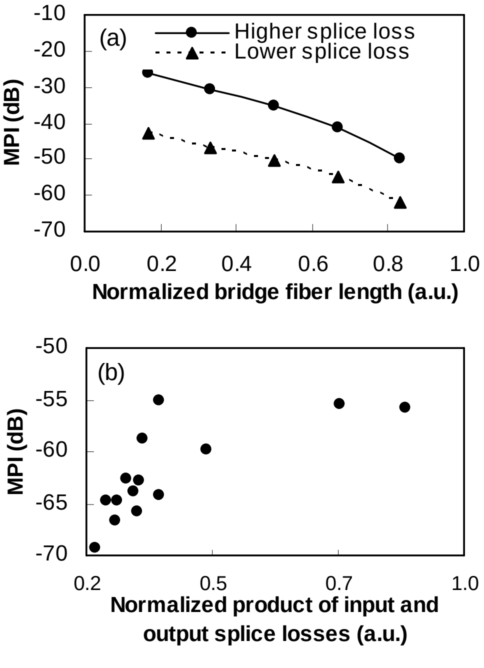

Figure 5. Measured dependences of MPI on bridge fiber length (a) and bridge splice loss (b).

5. APPLICATIONS

Throughout the life cycle of a submarine cable system, there is an on-going need for splicing between P-type fiber and N-type fiber, beginning with fiber set manufacture, through cable manufacture and system assembly, and finally system deployment and maintenance. The direct splicing technology and the bridge fiber splicing technology each have their own advantages; these advantages allow selection of the optimal splicing technique for each stage of system life.

For fiber set manufacturing, due to the large volume of splices which can impact overall system performance, splice performance is critical. In this stage, direct splicing is the preferred technology. Direct splicing has the potential for the lowest splice loss and eliminates concern about MPI impairments. The higher bending sensitivity of direct splices does not become an issue, since ultimately these direct splices are packaged within the benign cable structure in which macro-bending losses are not a concern. The controlled environment of the fiber factory is an excellent location in which to perform the TEC-assisted direct splicing technique.

For cable manufacture and system assembly, fiber splicing can be required for the construction of cable-to-cable joints. In these cases, the fiber splices are coiled within a joint box with a bending diameter of approximately 50mm. This coiling greatly minimizes the effects of bridge fiber splicing-induced MPI, since the bending of the bridge fiber itself greatly increases the HOM attenuation. Thus, a much shorter bridge fiber may be used in order to allow multiple fiber coils within the space of the joint box. Based upon our experience in constructing the VSNL TGN Pacific Cable System, the incidence of cable factory jointing requiring P-type fiber to N-type fiber splicing is quite low, and thus the slightly higher loss of the bridge fiber splicing technique does not impact overall system performance. These conditions allow the selection of the bridge splicing technique, utilizing simple, conventional fusion splicing processes, for cable jointing at the cable factory.

Cable jointing is also required aboard ship for deployment and maintenance purposes. Simplicity and speed are important considerations for shipboard splicing. In these instances, bridge fiber splicing is the preferred technology. The shipboard splicing environment is somewhat more challenging, and thus the use of standard fusion splicing processes with short bridge fibers, without the need for a TEC process necessary for direct splicing, make bridge fiber splicing the technology of choice.

6. CONCLUSIONS

Both the direct splicing technology and the bridge fiber splicing technology are being used to join P-type and N-type fibers in commercial submarine cable systems utilizing dispersion slope-matched fibers. Direct splicing technology has system performance advantages, while bridge fiber splicing offers simplicity of implementation. Direct splicing is the technology of choice for fiber set manufacture where large numbers of splices are made in a well-controlled environment. These splices reside in the benign submarine cable structure, where their more bend-sensitive taper is not subjected to macro-bending. For cable-to-cable joint splicing of P-type fiber to N-type fiber, both in the cable factory for system assembly and in the field for deployment and maintenance, bridge fiber splicing is the preferred technology. Bridge fiber splicing can be readily implemented in these environments since it utilizes simple, conventional fusion splicing processes. Fiber coiling within the joint box eliminates concerns related to Multi-Path Interference (MPI), and the small number of these cable joints in a system allow the somewhat higher splice loss to be accommodated without system impairment.

7. ACKNOWLEDGEMENTS

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