REDUCTION OF SPLICE LOSS BETWEEN FIBERS WITH DISSIMILAR EFFECTIVE AREAS

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Abstract: We demonstrate that the use of tapering technique to achieve an adiabatic transition from large mode field (Corning® Vascade® EX3000 fiber) to smaller mode field ITU-T G.652-compliant fiber results in a reduction in splice loss, relative to a configuration where a G.652 fiber splice recipe is used. On average, a decrease from 0.29 dB (no tapering) to 0.15-0.17 dB (with tapering) was observed experimentally. Simulations using beam-propagation model show the feasibility of further splice loss reduction to 0.043 dB, by optimizing the tapers to deeper and asymmetric shapes. This loss is comparable to typical G.652-G.652 fiber splice loss.

1. INTRODUCTION

Ultra large effective area (A_{eff}) and ultra-low loss silica-core fibers are essential for long-haul submarine links. As a result of lower overall span loss and better tolerance towards nonlinear effects, such fibers allow for higher optical signal-to-noise ratios, therefore enabling longer distances, use of higher-density modulation formats, or longer span lengths/fewer repeaters.

In order to take the full advantage of large A_{eff} fiber, one also needs to ensure that its splice performance does not compromise the overall span loss. There is sometimes a perception, however, that large A_{eff} fibers suffer from higher splice loss compared to G.652 fibers. While this is true when a splice is performed between fibers with dissimilar $A_{eff's}$ (or, mode field diameters, MFDs), the majority of splices per repeater span are between two large A_{eff} fibers, for which the splice loss is actually *lower* compared to a G.652-G.652 splice [1]. It must also be noted that even though two splices must be carried out between fibers with dissimilar $A_{eff's}$ (EDFA pigtails at the two ends of transmission span) only losses arising from the second splice are important. This is because the loss at the first splice point can be compensated by increasing the output power of the EDFA, without compromising the nonlinear tolerance of transmission fiber.

In this work we perform both experiments and modelling to investigate options to reduce the splice loss between large A_{eff} to G.652 fiber. For this purpose, we use Vascade EX3000 fiber with nominal A_{eff} of 150 µm^2, representing industry's state-of-the-art level of effective area. Our experiments involving a splicer with tapering functionality show that the splice between Vascade EX3000 fiber and a G.652 fiber can be reduced to 0.145 dB. Simulations using beam-propagation model show that the splice loss can be further reduced to 0.065 dB using deeper Gaussian tapers, and to 0.043 dB, when using asymmetric taper traces. This is comparable to G.652-G.652 fiber splice loss. This means that the use of tapering can reduce the total splice loss for Vascade

EX3000 fiber to the level *below* that for a G.652 fiber.

2. MEASUREMENTS

To quantify the splice losses, a set of comprehensive statistical studies were performed with low, average, and high MFD fiber samples. For G.652 fiber we used Corning® SMF-28e+® and SMF-28® Ultra fibers – both with MFD close to an average value (Table 1).

	MFD (µm)	A_{eff} (µm^2) (Converted from MFD)
SMF-28e+ fiber (G.652)	Average: 10.46	80.6
SMF-28 Ultra fiber (G.652)	Average: 10.51	83.6
Vascade EX3000 fiber	Low: 13.61 Average: 13.80 High: 13.99	146.7 150.7 154.6

Table 1: MFDs and corresponding A_{eff}'s used in the measurements

The splices were performed using a Fujikura FSM-100P+ splicer, and the process involves stretching Vascade EX3000 fiber after the splice is performed to thin out its MFD in the vicinity of the splice point. The taper region is confined primarily to the large core fiber by controlling the offset of the arc from the splice point. Parameters such as offset, time delay of fiber pull after arc, pull speed, and pull distance were varied to minimize the splice loss [2]. A total of more than 1,000 splices were performed using the same two Vascade EX3000 and SMF-28e+ fibers to find out the configuration that yields the lowest splice loss. The optimum configuration was found when the offset position was set to 35 µm, time delay of fiber pull after arc - to 300 ms, pull speed - to 0.75 µm/ms, and pull distance - to 100 µm.

Once such optimized configuration was identified, a total of 30 splices were carried out, 10 each for the three different Vascade EX3000 fibers to the common SMF-28e+ fiber (80.6 µm^2). The average splice loss was found to be 0.145 dB, and the standard deviation was 0.019 dB. Using the same splice configuration, 10 splices were carried out between the Vascade EX3000 fiber with medium A_{eff} (150.7 µm^2) and SMF-28 Ultra fiber (83.6 µm^2). The average splice loss was found to be 0.172 dB, and the standard deviation was 0.017 dB.

The physical implication of the tapering process is the reduction of the fiber diameter (Fig. 1). This is because as the Vascade EX3000 fiber is pulled after the splice to reduce its MFD in the vicinity of the splice, the cladding diameter will naturally be also reduced (proportionally to the pull speed). Assuming pristine-glass strength (800 kpsi or 5.5 GPa) in the post-splice and post-taper glass (i.e. no defects are induced due to splicing or tapering processes), the load bearing capacity of the tapered region is reduced by a factor equal to the square of the ratio of the two diameters. If, for example, the tapered diameter is 62.5 µm, the corresponding load bearing capacity is reduced to one fourth that of the 125-µm glass. Current proof-test processes that are based on the standard fiber diameter of 125 µm would result in a much higher stress in the necked-down region of the taper. At a load that corresponds to a proof stress of 250 kpsi in 125-µm-diameter fiber, the equivalent stress increases to 1000 kpsi at the 62.5-µm tapered cross section which exceeds the tensile strength of pristine glass.

In order to resolve these difficulties, it is proposed that the tapered splice be addressed as a distinct optical component at the two ends of the transmission span with a suitable packaging design within the repeater enclosure. One such proposal could involve mounting the tapered splice to an appropriate substrate in order to prevent the load from transferring to the reduced cross sectional area.

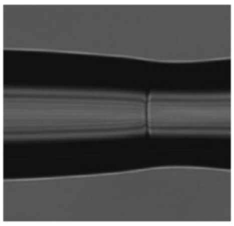

Figure 1: Example of splice using an optimized taper (SMF-28e+ fiber on the left, Vascade EX3000 fiber on the right)

Another way to reduce the MFD mismatch between the two fibers is to expand the core of a G.652 fiber by thermally diffusing the germania in the core [3]. Such process requires a specialized setup and, as a result, is somewhat cumbersome for field use. However, this process can be applied in the factory environment to fabricate EDFAs with thermally expanded core pigtails. The study of this process was outside the scope of this work.

3. MODELING

The optical signal loss at the splice joint is modeled using Beam Propagation Method (BPM) [4]. This approach allows one to take into account the actual measured refractive index profiles of the fibers on both sides of the splice, as well as the shape of the tapered index transition in the joint region. The main limitation of the BPM is that losses due to scattering at microscopic inhomogeneity and back-reflection at the joint are not modeled, however in a splice these are typically much smaller, compared to the losses due to the taper and mode-field mismatch.

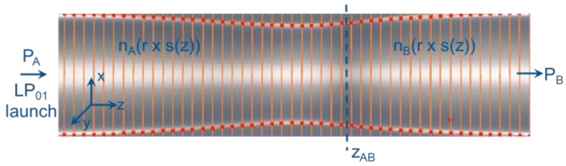

Figure 2: Tapered splice under the microscope (Vascade EX3000 fiber on the left, SMF-28e+ fiber on the right)

To model the experimentally realized splice tapers, fiber diameter $D_m(z)$ in the vicinity of the tapered splice was measured with a granularity of 10µm, as shown in Fig. 2 by the trace overlayed on the microscope image of the splice region. The normalized fiber diameter $s(z) = D_m(z)/125\mu m$, as a function of the z-coordinate along the fiber length, was used to define the refractive index profile z-dependence, scaling by s(z) the radial axis of the nominal fiber index profiles, which were measured separately using interferometric analysis technique (IFA). Thus, we consider refractive index change in the splice region due only to the geometric effect of the taper, while the effect of the dopant diffusion is not included. The BPM simulations were done by launching the fundamental LP_{01} mode of fiber A (Fig. 2) with power P_A. The optical field was propagated through the splice region and output power P_B in fiber B was recorded after it settled into guided modes of fiber B, with the splice loss computed as: $Loss[\mathrm{dB}]=-10\log_{10}(P_B/P_A)$. We verified numerically the invariance of the results with respect to the launch direction reversal, and in subsequent simulations use Vascade EX3000 as the launch fiber A (Fig. 2).

For modeling, we used fibers with MFDs (A_{eff}'s) shown in Table 2 – this selection was largely determined by the availability of already measured refractive index profiles, and provided an adequate overlap with the A_{eff} range used in the experiments.

	MFD	A_{eff} (Converted from MFD)
SMF-28 Ultra fiber (G.652)	Average: 10.4	81.8
	High: 10.78	88.1
Vascade EX3000 fiber	Low: 13.47	143.9
	Average: 13.73	149.2
	High: 13.9	152.7

Table 2: MFDs and corresponding A_{eff}'s used in the measurements

The experimental taper trace optimized for Vascade EX3000 fiber to SMF-28e+ fiber splice is shown in Figure 3. We used this taper to simulate Vascade EX3000 fiber to SMF-28 Ultra fiber splice loss, for a range of A_{eff}'s given in Table 3. Dashed vertical line in Figure 3 indicates the splice point, i.e. Vascade EX3000 fiber (left) to SMF-28e+ fiber (right) transition coordinate.

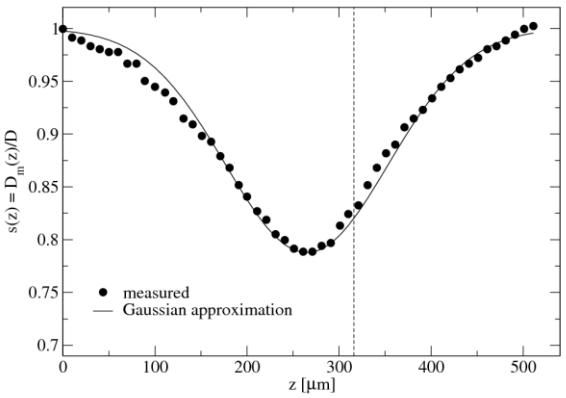

Figure 3: Radial scaling function dependence on the distance along the fiber, computed from the measured diameter variation, $D_m(z)$, normalized to the nominal fiber diameter, D = 125 μm.

The plots of the normalized optical power through the splice region, and the resulting loss are shown in Fig. 4. The simulated loss of 0.126-0.165 dB for EX3000 A_{eff}'s in the range 143.9-152.7 μm^2 and nominal value of 81.8 μm^2 for SMF-28 Ultra fiber, is seen to correlate well with the average measured loss of 0.145-0.172 dB for simular A_{eff} values. For low-A_{eff} (143.9 μm^2) Vascade EX3000 fiber and high-A_{eff} (88.1 μm^2) SMF-28 Ultra fiber, the splice loss is predicted to be as low as 0.089 dB.

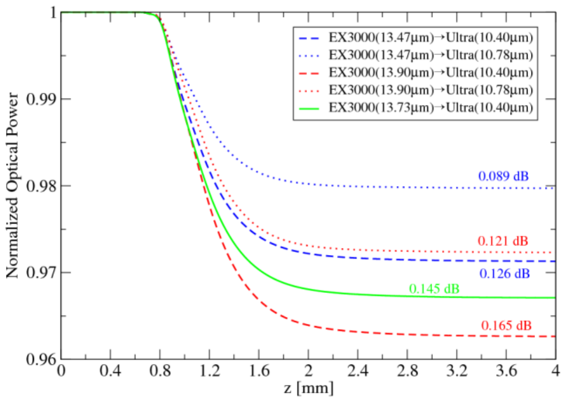

Figure 4: Simulated optical power loss across Vascade EX3000 fiber to SMF-28 Ultra fiber splice, using measured taper shape from Fig. 3.

The measured shape of the taper can be approximated to first-order by a Gaussian function, as shown in Figure 3. We thus varied the width and depth of the taper trace (by maintaining its Gaussian shape) to reduce the splice loss even further. Figure 5a shows the taper traces and Figure 5b shows the associated splice loss for each trace at different values of the splice point offset from the taper minimum. In general, deeper taper traces (i.e. with more dramatic reduction in cladding diameter) were found to lead to smaller splice losses for taper lengths in the 0.5 to 1 mm range. The setting with lowest splice loss (0.062 dB) between Vascade EX3000 and SMF-28 Ultra fibers, both with average A_{eff}) was found to be when the offset between the splice point and taper minimum was set to -50 μm (minus sign reflects the fact that the taper minimum is on SMF-28 Ultra fiber side), taper width (defined as $2w_0$, where w_0 is the Gaussian width) was 325 μm, and taper depth was 55 μm (i.e. the reduction of cladding diameter from 125 μm to 70 μm). It was also found that increasing the taper width beyond ~400 μm did not lead to any improvement in splice performance. This is likely due to larger mode diffraction losses in the longer SMF-28 segments of the taper.

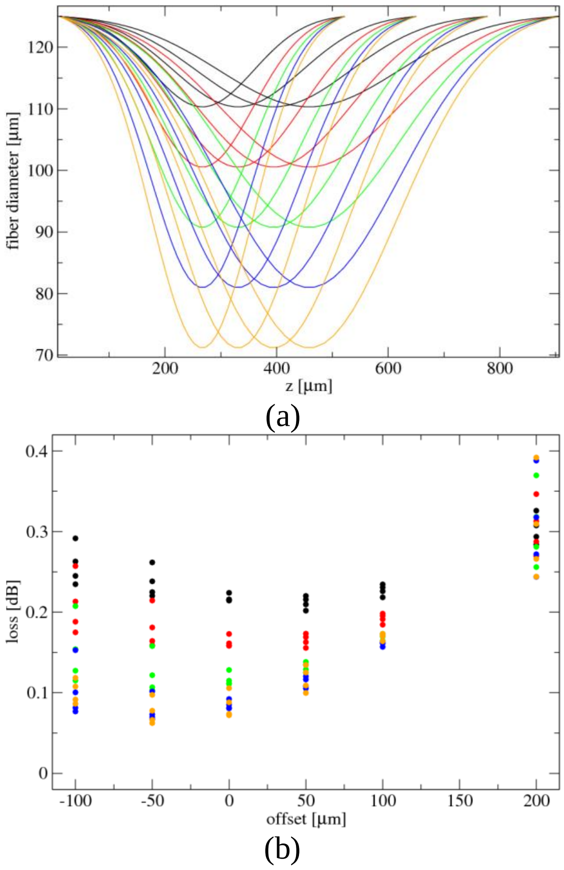

Figure 5: (a) Simulated Vascade EX3000 to SMF-28 Ultra taper traces with Gaussian shape and variable depth and width); **(b)** Corresponding computed splice losses vs. splice point offset from taper minimum.

We also considered Gaussian shaped tapers in which the parameter w_0 was set to be smaller on one side of the Gaussian curve ($w_{0+} < w_{0-}$), resulting in an asymmetric taper shape (Fig. 6a). It is worth noting that during the experiments we could not confirm that the splicer we used was capable of creating asymmetric tapers. However, we believe that such functionality can, in principle, be implemented by using different pull speeds during the splice (e.g. by linearly accelerating or decelerating pull speed). As an example, we used an asymmetric taper in the configuration with zero offset between splice point and taper minimum. Our simulations showed that asymmetric tapers can reduce the splice loss by ~0.02 dB, relative to symmetric tapers. We believe that the reason for an improved splice loss when using an asymmetric taper is due to faster transition from tapered mode of the large A_{eff} fiber to the small A_{eff} fiber, which avoids additional diffraction and leads to better mode overlap. Within the parameter ranges considered, the best splice loss achieved using an asymmetric taper was 0.043 dB.

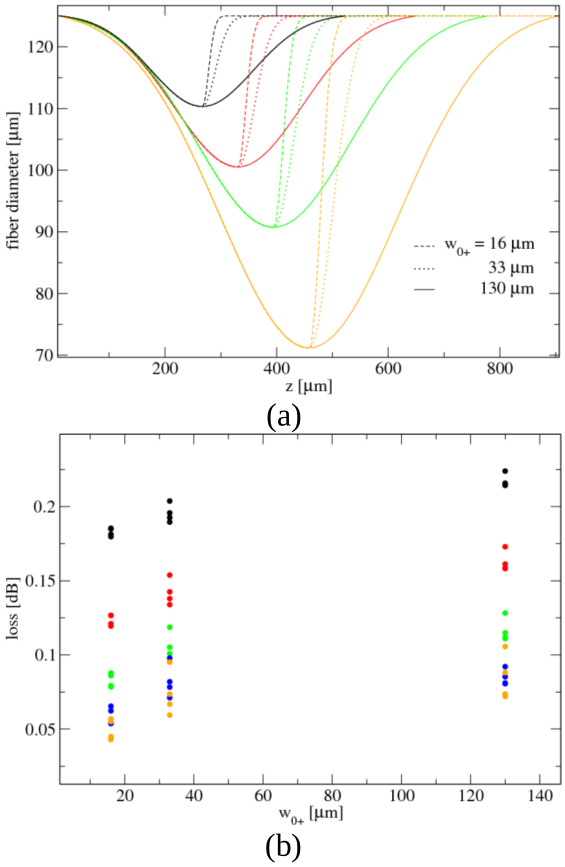

Figure 6: (a) Simulated Vascade EX3000 fiber to SMF-28 Ultra fiber taper traces with asymmetric shapes (12 curves are shown as an example); **(b)** Corresponding splice losses computed for the splice point located at the taper minimum.

4. CONCLUSION

In this work we evaluated the total splice losses when using Vascade EX3000 fiber. For the loss calculations from splices at the two repeater ends (where we assumed a G.652 fiber is used), we only took into account the loss occurring from the splice at the second repeater. This is because the loss at the first splice point can be compensated by increasing the output power of the EDFA.

Considering a realistic scenario with 80 km span, splices carried out every 10 km or 20 km, and using the experimentally obtained splice losses, the total splice loss in the case of Vascade EX2000 fiber (average A_{eff} ~ 112 µm^2) was measured to be on par with G.652 fiber (Table 3). The implication of this result is that Vascade EX2000 could be used as an effective "bridge" fiber, when splicing Vascade EX3000 to a G.652 fiber. Indeed, this use of such configuration allowed for a reduction in total splice loss to 0.26 dB for a configuration with splices every 10 km, and 0.204 dB for a configuration with splices every 20 km. An alternative to the "bridge" fiber is to use a tapering technique – a function available on some advanced fusion splicers. The use of tapering allowed for a further decrease in total measured Vascade EX3000 fiber splice loss down to 0.243 dB (splices every 10 km) and 0.187 dB (splices every 20 km).

Our simulations with a beam-propagation model showed that the splice loss between Vascade EX3000 fiber and G.652 fibers can be further reduced by using deeper Gaussian tapers to 0.062 dB. It was also shown that the use of asymmetric tapers can reduce the splice loss 0.043 dB. Overall, our modeling results show the path towards achieving *lower* total splice loss for spans constructed of Vascade EX3000 fiber, compared to the spans constructed of G.652 fiber.

dB	Same A_{eff} Splice Loss	Splice Loss at Repeater	Total Splice Loss (splices every 10km)	Total Splice Loss (splices every 20km)
SMF-28e+ fiber (G.652)	0.024	0.024	0.192	0.096
Vascade EX2000 fiber	0.017	0.065	0.184	0.116
Vascade EX3000 fiber	0.014	0.296	0.394	0.338
Vascade EX3000 fiber (w. bridge)	0.014	0.162	0.26	0.204
Vascade EX3000 fiber (w. symmetric taper)	0.014	0.145	0.243	0.187
Vascade EX3000 fiber (w. symmetric taper – modeling)	0.014	0.062	0.16	0.104
Vascade EX3000 fiber (w. asymmetric taper – modeling)	0.014	0.043	0.141	0.085

Table 3: Total splice loss for a hypothetical scenario with 80km span and splices every 10 or 20 km

5. ACKNOWLEDGEMENTS

The authors would like to thank Elli Saravanos from Corning Incorporated for useful discussions in the preparation of the paper, and Fatih Yaman for sharing details on taper parameters.

6. REFERENCES

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