Towards Superior Transmission Performance in Submarine Systems: Leveraging UltraLow Attenuation and Large Effective Area

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***Abstract*—This paper expands our previous work on record-low attenuation of 0.1460 dB/km, measured on a silica-core fiber with 148 μm² effective area. We describe the technology used to achieve such low level of attenuation and quantify other span loss characteristics, such as maintaining ultralow attenuation after cabling and splice loss reduction using "bridge" fiber and tapering techniques. We also show that a superior transmission performance in submarine networks is achieved using a combination of ultralow attenuation and large effective area, and discuss the impact of span length on system performance. We finally demonstrate that the reduction in fiber attenuation provides an additional benefit of lower optimum power into the fiber, therefore, relaxing the maximum output power requirements of submarine EDFAs.**

***Index Terms*—Fiber optics communications, single-mode fibers.**

I. Introduction

A. Importance of Combination of Ultra-Low Attenuation and Large Effective Area

In 1966 Charles Kao in his seminal paper predicted that optical waveguides made with silica could achieve attenuation (α) better than 20 dB/km [1]. Four years later in 1970 Donald Keck and his colleagues experimentally showed the first silica fiber with an attenuation of <17 dB/km [2]. After this initial demonstration the progress in achieving lower attenuation in telecom optical fibers was astounding—by the time the most deployed fiber type G.652 (also known as standard single mode fiber) was specified by International Telecommunication Union (ITU) in 1984, the commercial single mode fiber products had attenuation of 0.4 dB/km at 1310 nm [3] and 0.26 dB/km at 1550 nm [4].

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Since that moment the improvement in attenuation of silica based optical fibers was less dramatic (from tens of dB/km to a fraction of dB/km) as in the first decade of optical fiber development. However, it was realized that even a minor decrease in fiber attenuation leads to a significant improvement in transmission performance, so the pursuit for lower and lower fiber attenuation continued. In addition, other fiber attributes such as effective area (A_{eff}) and nonlinear refractive index n_2) were identified as key parameters that affect overall transmission performance. For high-dispersion fiber (e.g., ITU-T G.654 fibers), the impact of attenuation, A_{eff} and n_2 can be described using a figure of merit (FOM) given below, which represents a simplified FOM from [5]

$$\mathrm{FOM(dB)} = \frac{2}{3}\left(10\log\left[\frac{A_{\mathrm{eff}}\cdot n_{2,\mathrm{ref}}}{A_{\mathrm{eff,ref}}\cdot n_2}\right] - [\alpha(dB/km) - \alpha_{\mathrm{ref}}(dB/km)]\cdot L\right) - \frac{1}{3}\left(10\log\left[\frac{L_{\mathrm{eff}}}{L_{\mathrm{eff,ref}}}\right]\right)$$

where α, A_{eff} and n_2 are taken at the signal wavelength (usually 1550 nm), L is a span length between optical amplifiers, and L_{eff} is effective length ($\approx 1/\alpha$ in linear units for long spans). This formula is devised from [5] assuming that FOM is a relative metric and shows the improvement in optical signal to noise ratio (OSNR) that a given fiber can achieve in comparison with reference fiber, therefore, EDFA noise figure and miscellaneous sources of insertion loss disappear from the equation in [5]. The use of coefficients 2/3 and 1/3 does not change the relative importance of α, A_{eff} and n_2 but ensures that the improvement in FOM can be directly translated into an improvement in Q-factor.

Fig. 1 shows the impact of attenuation, A_{eff} and n_2 on the improvement in FOM in a configuration with 65 km spans, which represents an average span length used in submarine systems (50 km—typical low, 80 km—typical high). The first notable feature on Fig. 1 is the presence of a step in FOM around the attenuation of 0.175 dB/km. This is because the reduction of attenuation < 0.175 dB/km typically cannot be achieved using SiGe fibers (with n_2 of $2.2 - 2.3 \times 10^{-20}$ m²/W, depending on A_{eff}), and silica-core fibers with n_2 of 2.1×10^{-20} m²/W should be used instead. Overall, it becomes apparent that ultra-low attenuation and large effective area (A_{eff}) are the two most important fiber

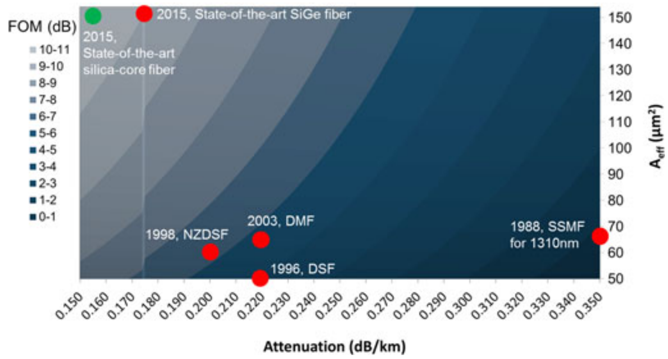

Fig. 1. FOM with respect to 0.350 dB/km fiber with $A_{\rm eff} = 67\ \mu{\rm m}^2$ in a 65 km span configuration.

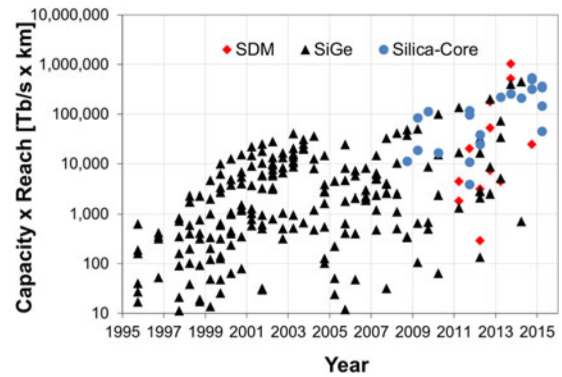

Fig. 2. Historic evolution of capacity x reach product, as reported in hero transmission experiments from OFC and ECOC postdeadline conference sessions (different colors represent SDM, SiGe, and silica-core fibers).

attributes for long-haul transmission systems, which lead to a superior transmission performance. It is remarkable that since the inception of optical fiber in submarine systems in 1988 the FOM was improved by almost 10 dB through the introduction of new generations of optical fibers [6]–[10]. Ultimately, any increase in fiber FOM results in longer reach or longer span length [11], which can be beneficial in many scenarios. Higher FOM also supports a higher bit-rate—a feature which has been historically essential for every new generation of submarine link. The trend of bringing higher data rates into the submarine links is likely to continue in the foreseeable future through the use of advanced modulation formats. It is worth noting that state-of-the art silica-core fiber provides almost 1 dB improvement in FOM relative to state-of-the-art SiGe fiber for a configuration with 65 km spans studied in this paper.

There is an additional benefit of ultra-low fiber attenuation, which leads to lower optimum launch power into the fiber, relative to generic fibers, therefore, relaxing the requirements on maximum available EDFA output power. This feature is particularly important for submarine systems, where repeaters are powered from the shores and minimization of total EDFA output power is beneficial for its reliability and minimizing requirement for the power feed.

It is also worth mentioning that over the last few years there has been a substantial interest in non-traditional fibers for space division multiplexing (SDM). Those fibers can be generally divided in two distinct categories: multi-core and few-moded fibers, where information can be transmitted over multiple cores/modes simultaneously to further increase transmission capacity. However, in terms of capacity x reach (which represents a good practical metric to determine the performance of different transmission technologies), SDM fibers have not yet provided a significant transmission improvement, according to hero experiments from OFC and ECOC post-deadline conference sessions (see Fig. 2). In addition, the complexity of SDM technology is still unclear in many areas, especially, the extent to which operational procedures and design rules need to be changed. Also, Fig. 2 suggests that hero experiments involving silica-core are surpassing hero experiments using SiGe fibers, therefore, in this paper we only focus on technology related to silica-core fibers.

In this paper we expand our previous work on record-low attenuation of an ultra-large $A_{\rm eff}$ silica-core fiber [12] measured across the C-band on both shipping and tension-free spools. The attenuation obtained on a tension-free spool mimics the benign, tension-free environment of a properly-designed submarine cable. The attenuation at 1550 nm was measured to be 0.1467 dB/km, and the lowest attenuation value was 0.1460 dB/km at 1560 nm. These results beat the previous attenuation records of 0.149 dB/km (at 1550 nm) and 0.148 dB/km (lowest within C band), reported in [13].

TABLE I
SUMMARY OF ULTRA-LARGE AEFF SILICA-CORE FIBER UNDER TEST ATTRIBUTES

Length, km	Effective area, μm^2 (1550 nm)	Dispersion, ps/nm/km (1550 nm)	Cable cut-off wavelength, nm
22.65	148.3	20.72	1418

To fully realize the technical advantage of ultra-low fiber attenuation, it is imperative to ensure that the full ultra-low loss ecosystem of a submarine span is in place, such as, splicing and cabling. Therefore, we also showed that an acceptable splice loss can be achieved between large $A_{\rm eff}$ fiber to 1) itself, and to 2) lower $A_{\rm eff}$ fiber. The former is important since a single span between two repeaters typically consists of several shorter-length fiber reels, which are spliced together. The latter is important since large $A_{\rm eff}$ fiber sections must be spliced to the repeater ends, which typically contain lower $A_{\rm eff}$ fiber. Finally we discussed the last component of the ultra-low loss ecosystem—fiber attenuation in the submarine cable. We demonstrated that fiber attenuation is not increased during the cabling process, so that the transmission performance of a submarine link is not compromised once the fiber is cabled.

II. FIBER DESIGN AND ATTENUATION MEASUREMENT PROCEDURE

The fiber under test was an ultra-large $A_{\rm eff}$ silica-core Corning Vascade EX3000 fiber sample with attributes listed in Table I.

This fiber had a silica-core and a fluorine-doped cladding to achieve a difference in core-cladding refractive indices. As a result of elimination of GeO_2 in the core and consequent reduction of compositional Rayleigh scattering, the silica-core fiber design ensured a significantly reduced attenuation coefficient

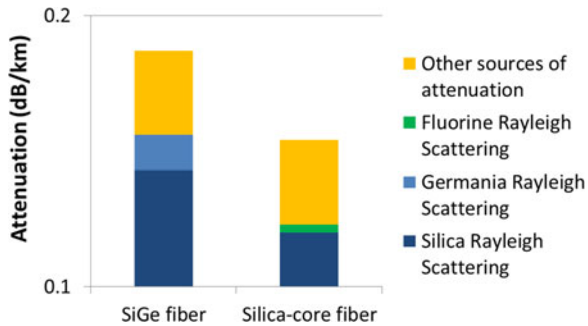

Fig. 3. Sources of attenuation of silica-core and SiGe fibers.

TABLE II
ATTENUATION OF ULTRA-LARGE A_{eff} SILICA-CORE FIBER UNDER TEST (IN DB/KM), MEASURED ON (A) LARGE DIAMETER SPOOL; (B) SHIPPING SPOOL

(A)								
1530 nm	1535 nm	1540 nm	1545 nm	1550 nm	1555 nm	1560 nm	1565 nm	1570 nm
0.1499	0.1489	0.1480	0.1473	0.1467	0.1462	0.1460	0.1461	0.1465
(B)								
1530 nm	1535 nm	1540 nm	1545 nm	1550 nm	1555 nm	1560 nm	1565 nm	1570 nm
0.1503	0.1493	0.1484	0.1478	0.1472	0.1467	0.1467	0.1467	0.1471

compared to Ge-doped fibers (see light blue bar in Fig. 3). Due to the presence of fluorine in the cladding, there is fluorine Rayleigh scattering component (see green bar in Fig. 3). However, since most of light is concentrated in the core, the fluorine Rayleigh scattering components is significantly lower than other sources of attenuation. The reduction in attenuation was also facilitated by the reduction of residual stress induced during the manufacturing process, which was achieved by matching the viscosity of the core and cladding [14] (see dark blue bar in Fig. 3). The core-cladding refractive index design was optimized for macrobend and cut-off wavelength performance and to ensure compliance with the ITU-T G654.D standard. It must be also noted that due to its ultra-large A_{eff}, the fiber did not require as much cladding index suppression as silica-core fibers with lower A_{eff}. As a result, the fiber had lower fluorine concentrations and scattering within the near-cladding.

To determine fiber attenuation we used the spectral cutback measurement technique, which is compliant to the IEC 60793-1-40 standard. A measurement system consisting of a white light source, monochromator with better than 0.5 nm accuracy, modulator, and InGaAs detector was used to conduct the attenuation measurements. The system's precision is 0.001 dB or better and its accuracy was confirmed against other available industry measurement benches. The fiber measurements are summarized in Table II. The measurements were carried out over a wide range of wavelengths with the fiber under test wrapped on a (a) tension-free, large diameter spool and (b) standard diameter shipping spool. As seen from the measurement data, the lowest attenuation was achieved around 1560 nm. This was the wavelength at which the rate of attenuation increase due to infrared absorption overcomes the rate at which Rayleigh scattering is decreasing with wavelength.

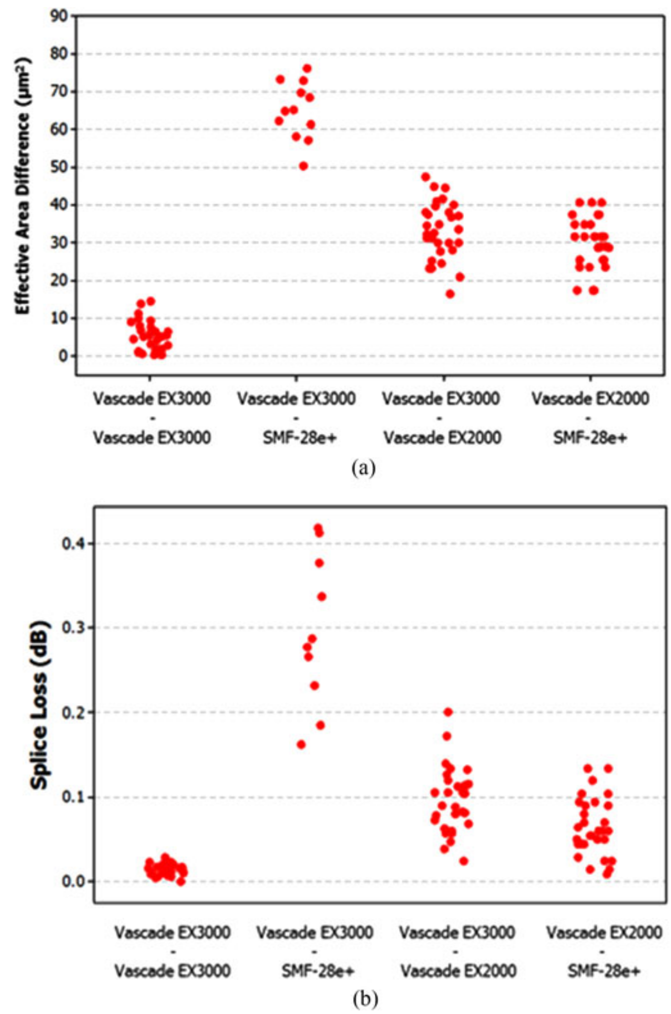

Fig. 4. (a) Effective area differences of fibers under test; (b) Statistics of splices losses for different sets of fibers.

III. SPLICING PERFORMANCE OF ULTRA-LARGE A_{eff} SILICA-CORE FIBER

To understand the splice losses, a set of comprehensive statistical studies were performed involving low, medium and high A_{eff} values of Vascade EX3000 fiber. In the first set of measurements, the average splice loss of Vascade EX3000 to Vascade EX3000 fiber was found to be 0.014 dB, which is lower than the observed average splice loss of 0.024 dB between two 82 μm^2 fibers. This is because for the same amount of radial splice offset d, the relative mode field diameter mismatch, i.e., *d/MFD* for two large A_{eff} fibers is smaller than for two 82 μm^2 fibers.

We then measured the splice losses between Vascade EX3000 and lower A_{eff} fiber, for which we chose Corning SMF-28e+ fiber with an average nominal A_{eff} of 82 μm^2. By using low, medium and high A_{eff} values within the production distribution of both fiber types, the average splice loss was determined to be 0.296 dB. It must be also noted that this value is lower than the splice loss of 0.308 dB predicted by frequently used formula (1) [15], even when the radial splice offset is neglected in formula:

$$\alpha_d = -10log\left[\left(\frac{2W_1W_2}{W_1^2+W_2^2}\right)^2 \times \exp\left(\frac{-2d^2}{W_1^2+W_2^2}\right)\right]. \quad (1)$$

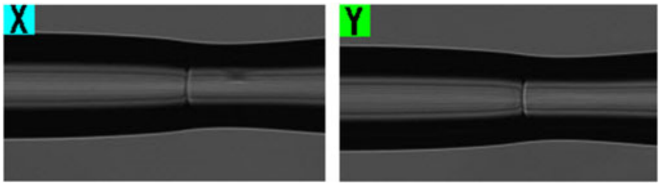

Fig. 5. Image of splice using a tapering technique (X and Y reflect different viewing angles).

In Eq. (1), $2W_1$ and $2W_2$ are mode field diameters (A_{eff} is proportional to $(2W)^2$) of the two fibers, d is the radial splice offset, and α_d is the splice loss.

One of the ways to minimize splice loss is to use a "bridge" fiber, i.e., the fiber with an A_{eff} somewhere between Vascade EX3000 fiber and SMF-28e+ fiber. For this study we chose Corning Vascade EX2000 fiber with an average nominal A_{eff} of 112 μm^2 as a "bridge" fiber, and performed a set of splices from Vascade EX3000 to Vascade EX2000 fiber, and Vascade EX2000 to SMF-28e+ (also using low, medium and high A_{eff} for all fiber types). The average splice losses were found to be 0.097 and 0.065 dB, respectively (i.e., 0.162 dB in total). These results suggest that having two splices to the "bridge" fiber yields a lower overall splice loss than having a single splice between two fibers with substantially dissimilar A_{eff} values. We also investigated tapering a Vascade EX3000 fiber with low (146.7 μm^2), medium (150.7 μm^2) and high (154.6 μm^2) A_{eff} during a direct splice to SMF-28e+ fiber ($A_{\text{eff}} = 83\ \mu\text{m}^2$) to achieve a reduction in splice loss due to a better mode field match with an adiabatic transition from the large mode field to the smaller mode field diameter. The splice was performed using a Fujikura FSM-100P+ splicer. The process involves stretching the large core diameter fiber after the splice is performed. 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. An example of such splice is shown in Fig. 5. In this test 30 splices were carried out, 10 each for the three different Vascade EX3000 fibers to the common SMF-28e+ fiber, and the results are shown in Fig. 6. The average splice loss was found to be 0.145 dB, and the standard deviation was 0.019 dB.

IV. Cabling Performance of Ultra-Large A_{EFF} Silica-Core Fiber

While this may be counter-intuitive at first, the attenuation of an optical fiber in a submarine cable can be (and in many cases, is) lower than the attenuation on a fiber shipping spool. The main reason is due to the presence of bends placed on the fiber when wrapped on a shipping reel, which is the result of the winding tension applied when the fiber is spooled to provide a stable package for storage, shipping, and processing. The applied tension compresses the fibers within the pack, which results in subtle bends at fiber crossover points generating signal loss. When the fiber is properly cabled, such bends naturally disappear, and the true intrinsic attenuation of the fiber is realized.

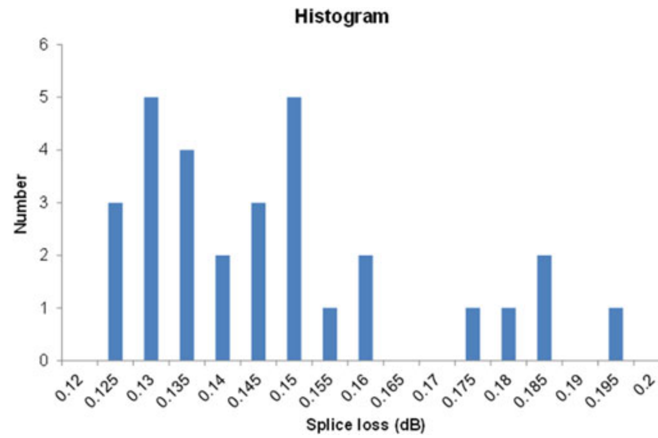

Fig. 6. Distribution of splice losses between Vascade EX3000 fiber with low, medium and high A_{eff} to SMF–28e+ fiber (directly spliced to each other using tapering technique).

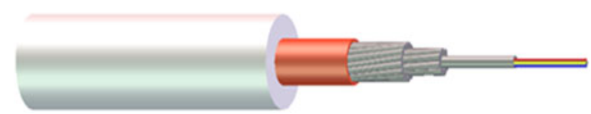

Fig. 7. Schematic diagram of submarine cable.

TABLE III
Fiber Attenuation (On A Shipping Spool) And Cabled Attenuation Values (At 1550 N·m) For Eight Fibers Under Test

	Fiber 1	Fiber 2	Fiber 3	Fiber 4	Fiber 5	Fiber 6	Fiber 7	Fiber 8
Fiber attenuation (dB/km)	0.156	0.153	0.157	0.158	0.155	0.155	0.160	0.156
Cabled attenuation (dB/km)	0.155	0.153	0.157	0.158	0.154	0.153	0.160	0.154

Well-designed submarine cables ensure that negligible strain and ultra-low pressure are applied to the fibers in normal operation conditions. The Alcatel-Lucent OALC4 cable, used in this study, consists of a core structure that isolates fibers from mechanical stresses. This is achieved with a design in which fibers lay freely in a steel tube. The fibers are housed in a jelly-filled steel tube surrounded by two layers of steel wires that form a protective vault against pressure and external aggressions, and provide tensile strength. This vault is then enclosed in a hermetically sealed copper tube and insulated with a layer of polyethylene, necessary for deep sea cable applications (see Fig. 7). As shown in Table III, for four out of eight fibers under test, the attenuation decreased after cabling by 0.001–0.002 dB/km, and for the other four fibers remained unchanged.

V. Implications for Submarine EDFA Power Requirements

There are two aspects of submarine systems that make them different from terrestrial systems: 1) power for repeaters (EDFA amplifiers) is provided from the two shores [16], and 2) the reliability of EDFAs must be very high [17]. As a result, there

TABLE IV
OPTIMUM LAUNCH POWER PER CHANNEL, AS A FUNCTION OF NUMBER OF WDM CHANNEL (FOR THE LINK DESCRIBED ABOVE)

Number of WDM λ's	1	10	40	80	100	125	150
Optimum Pin per λ (dBm)	−0.2	−1.95	−2.45	−2.65	−2.7	−2.8	−2.8

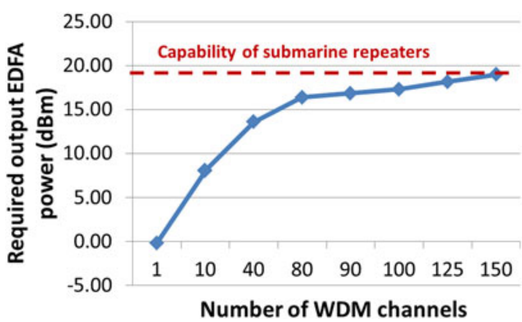

Fig. 8. Total required power of EDFA as a function of number of WDM channels for Vascade EX3000 fiber. Red line shows the maximum output power of a typical submarine EDFA.

is a strong drive to keep the maximum output EDFA power low—today this power rarely exceeds 19 dBm [18]. As the number of wavelength division multiplexing (WDM) channels per fiber continues to grow in the search for higher capacity, the maximum required EDFA power must increase to support amplification of additional wavelengths.

To study the impact of varying number of WDM channels on required output EDFA power, we modeled a configuration involving Vascade EX3000 fiber (typical values: 0.157 dB/km attenuation, 150 μm^2 A_{eff}, 20.7 ps/nm/km dispersion, 2.1×10^{-20} m^2/W n_2) over a 10 000 km link with 50 km repeater spans. The modeling was carried out using a Gaussian-noise analytical model, where nonlinearity is approximated using an additive Gaussian noise, statistically independent of ASE noise [19]. The system was assumed to be operating at 32 GBd with a PM-QPSK modulation format, resulting in the overall bit-rate of 128 Gb/s, including forward error correction overhead. EDFA noise figure was set to be 6 dB.

First, the optimum launch power (defined as the launch power at which the Q-factor is at its maximum) per channel was determined for several number of WDM channels (see Table IV). It is apparent that the increase in number of WDM channels causes an increase in inter-channel nonlinearity, resulting in lower optimum power per channel. The change in optimum launch power is highest for small number of WDM channels, and is reduced for large number of WDM channels, as the effect of inter-channel nonlinearity becomes saturated. To calculate the total required output power of EDFA the optimum launch power is multiplied by the number of channels (i.e., power in dBm summed with $10 \times \log_{10}(N)$, where N is number of WDM channels), and the results are plotted in Fig. 8. The graph shows that even for 150 WDM channels, representing the maximum practical number of channels that could be jammed into C-band, using Vascade EX3000 fiber the required output power of EDFA is within the 19 dBm capability of submarine repeaters.

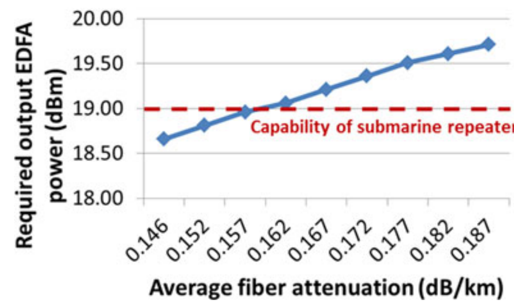

Fig. 9. Total required optical power of EDFA as a function of fiber attenuation. Red line shows the maximum output power of a typical submarine EDFA.

In addition to OSNR performance improvement, the reduction in fiber attenuation also enables lower optimum launch power into the fiber, therefore, reducing the required output power of submarine EDFA for a fully loaded C-band system (see Fig. 9). For example, for a 150 μm^2 fiber in a configuration with 150 Nyquist WDM channels over 10 000 km and 50 km spans, the reduction in attenuation by 0.02 dB/km corresponds to the reduction in total required EDFA output power by 0.5 dB. This leads to an important conclusion—an increase in EDFA output power due to large number of channels in the C-band can be partially offset by using fibers with lower attenuation.

VI. CONCLUSION

In this paper record-low attenuation of 0.1460 dB/km at 1560 nm and 0.1467 dB/km at 1550 nm for a 148 μm^2 Vascade EX3000 fiber was demonstrated. Such ultra-low level of attenuation was achieved using silica-core technology, and a design which matches the viscosity of the core and cladding. Other components needed to achieve ultra-low loss submarine span, such as splicing and cabling, were also studied.

Average splice loss between two ultra large A_{eff} ($\sim$150 μm^2) silica-core fibers was measured to be 0.014 dB, which is lower than for two G.652 fibers. The reduction in splice loss when splicing two fibers with dissimilar A_{eff} values ($\sim$150 and $\sim$82 μm^2) using a $\sim$112 μm^2 "bridge" fiber was also quantified. Even though the use of such "bridge" fiber required two splices, the overall average splice loss was decreased from 0.296 to 0.162 dB, as compared to a direct Vascade EX3000 to SMF-28e+ fiber splice. The possibility to reduce direct Vascade EX3000 to G.652 fiber splice losses was also studied using a tapering technique, which provides a better mode field match with an adiabatic transition from the large mode field to the smaller mode field. The average achieved splice loss using tapering technique was 0.145 dB.

In terms of cabled transmission performance, for four out of eight fibers the cabled attenuation was found to be 0.001–0.002 dB/km lower than the attenuation on the fiber shipping spool. This is because a properly design submarine cable represents a more benign environment for optical fiber compared to the case when fiber wrapped on a shipping reel fiber and is exposed to bends—a result of a applied winding tension. Such bends naturally disappear when the fiber is cabled. As part of our study we observed a reduction in attenuation by 0.0004–0.0007 dB/km when the fiber was rewound from the standard diameter shipping spool to a large diameter measurement spool to mimic fiber behavior in a cable.

Finally, we evaluated the transmission performance of ultra-low loss and large A_{eff} fibers—both in terms of FOM, and required EDFA output power. It was observed that a combination of ultra-low attenuation and large A_{eff} always enables a superior transmission performance. We also showed that the reduction in fiber attenuation provides an additional benefit of lower optimum launch power per channel, therefore, reducing the total required power of the EDFA (0.02 dB/km reduction in attenuation decreased the total required EDFA power by 0.5 dB).

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