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BOL and EOL OSNR Margins in 10,000 km Pb/s DWDM Unregenerated All-Optical Lightwave Transmission Systems in the 2000 nm Band

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Abstract: We report the calculation of beginning-of-life and end-of-life (EOL) optical signal-to-noise ratio (OSNR) margins in designs of 10,000 km terrestrial and subsea Pb/s capacity all-optical (without O-E-O regeneration) dense wavelength division multiplexed lightwave systems in the 2000 nm band. Our margin analysis follows the OSNR budget tables originally designed for 1550 nm subsea lightwave transmission systems employing erbium-doped fiber amplifiers, as adapted for novel hybrid Tm-Ho-doped fiber amplifiers and hollow core fibers designed to operate in the 2000 nm region off the spectrum. Our analysis shows that ideal simulated losses of ≤ 0.0325 dB/km at 2000 nm in the novel hollow core transmission fibers are required for successful EOL system operation in the terrestrial lightwave system design, when assuming that the effective deployed loss = ideal loss + 0.030 dB/km. We discuss the implications of this analysis in the context of terminal tolerances, manufacturing and environmental impairments, Q-factor time variations, customer margins, and the anticipated aging behavior of the novel 2000 nm hollow core transmission fiber.

Keywords: thulium-doped fiber amplifier, holmium-doped fiber amplifier, 2000 nm fiber amplifier, 2000 nm lightwave system transmission, lightwave transmission system margins, beginning-of-life margins, end-of-life margins

1. Introduction

Recent reports in Tench [1] present realistic designs for all-optical unregenerated 10,000 km terrestrial and 10,000 km subsea Pb/s capacity dense wavelength division multiplexed (DWDM) lightwave systems in the 2000 nm band employing novel Tm-Ho-doped fiber amplifiers with a record 380 nm (31.6 THz) operating bandwidth and novel hollow core transmission fibers with extremely low ideal simulated losses of ≤ 0.040 dB/nm. In these designs, the beginning-of-life (BOL) optical signal-to-noise ratio (OSNR)/0.1 nm margins were calculated to be +9.0 dB for the 10,000 km terrestrial system design and +9.6 dB for the 10,000 km subsea system design, each with a total capacity of 0.161 Pb/s.

These are robust BOL margins for the designs of optically amplified DWDM lightwave systems that are completely Amplified Spontaneous Emission (ASE)-noise limited and exhibit no Q-factor degradations caused by nonlinear effects in the hollow core transmission fibers.

The question of the effects of system and equipment aging then arises, in the context of calculating the anticipated end-of-life (EOL) margins accounting for terminal tolerances, manufacturing and environmental impairments, Q-factor time variations, and customer margins, among other effects. Many analyses of these EOL margins have been conducted for existing optically amplified lightwave systems at 1550 nm with erbium-doped fiber amplifiers (EDFAs) [2, 3], but so far, there are no reports of a corresponding analysis for novel proposed fiber amplified systems employing hybrid Thulium-doped-Holmium-doped Fiber Amplifiers (TDFA-HDFA) at 2000 nm with newly developed hollow core fibers (HCFs) in this spectral region.

So the following questions then naturally occur: how do the operating margins of the 2000 nm amplified lightwave system design degrade from non-ideal effects at BOL, and what are the factors that contribute to an eventual worst-case EOL margin that will determine whether the 2000 nm system can be successfully deployed with a 25-year expected lifetime?

In this paper, we present a quantitative analysis of the BOL and EOL OSNR/0.1 nm margins in the 10,000 km terrestrial and subsea 2000 nm system designs. We show how the calculated margins depend strongly on the effective loss in dB/km of the installed HCF and also on the simulated ideal loss of this fiber. We then present HCF loss limits in dB/km for successful terrestrial and subsea system operation over 10,000 km and comment on the practical challenges of achieving this fiber loss using both today's technologies and those technologies that are expected tomorrow.

2. Analysis of BOL and EOL OSNR Margins

2.1. OSNR analysis of 2000 nm all-optical unregenerated lightwave transmission system

The analysis of DWDM lightwave systems at 1550 nm is well established. References by Carbo Meseguer et al. [4, 5] cover

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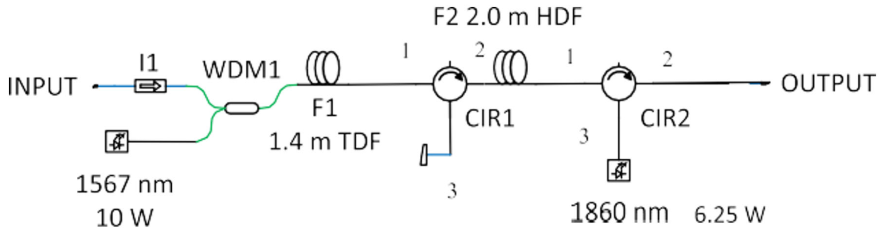
Figure 1
Schematic diagram of the hybrid TDFA-HDFA



performance predictions for future lightwave systems employing new HCFs at 1550 nm. References [5–10] outline the techniques used in today's transmission systems with EDFAs in the context of modulation format and DWDM channel allocation. References [11–16] cover the general design approaches and parameters for subsea and terrestrial lightwave system design.

We begin with the fundamental equation for OSNR/0.1 nm in 2000 nm DWDM optically amplified lightwave systems [1]:

$$\text{OSNR}\,(\text{dB}/0.1\text{nm}) = 60.2 + \text{TOP(dBm)} - 10\log10(\text{NSPAN}) - G(\text{dB}) - \text{NF(dB)} - 10\log10(\text{NCHAN}) \quad (1)$$

TOP = signal output power from each fiber amplifier (dBm), NSPAN = number of identical spans with fiber amplifier followed by transmission fiber, G = gain (dB) of each fiber amplifier, and NCHAN = number of DWDM channels.

The hybrid Tm-Ho-doped fiber amplifier employed in this transmission system has the optical architecture presented in Figure 1 [1].

We assume that splice losses between the hollow core transmission fibers and the silica core amplifier fibers are 0.1 dB and that splice losses between successive segments of HCFs are also 0.1 dB [17].

For the 10,000 km terrestrial system with 200 km fiber spans in Tench [1], TOP(dBm) = 33.4, NSPAN = 50, G(dB) = 10.0, NF(dB) = 6.0 (device noise figure), and NCHAN = 571. Using these values in Equation (1) yields Equation (2):

$$\text{BOL OSNR}\,(\text{dB}/0.1\,\text{nm}) = 33.0\,\text{dB for the terrestrial system} \quad (2)$$

The overall architecture of the 2000 nm DWDM lightwave transmission system is outlined in Figure 2.

As analyzed in detail in Tench [1], no nonlinear impairments exist to degrade the Q-factor derived from the OSNR in these 2000 nm DWDM lightwave systems with low-loss hollow core transmission fibers because the threshold for nonlinear effects in systems with HCFs is expected to be at least three orders of magnitude greater (> +35 dBm/channel) than the +6 dBm per channel output launch power from the wideband Tm-Ho fiber amplifiers [4, 5]. The expected effective nonlinear penalties from all effects such as four-wave mixing, Brillouin scattering, and Raman scattering are therefore equal to zero in this 2000 nm DWDM system design.

Next, we calculate degradations at BOL and also the performance penalties that lead to the final EOL margins in the worst case. Following the analysis in Rivera Hartling et al. [2], Downie et al. [3], and Bergano [16], we construct the following OSNR budget tables with an added column for margins. Here, we assume worst-case operating conditions as adapted for a 2000 nm DWDM system installed and deployed with new and unproven components and devices.

In Table 1, we have employed margins for the various OSNR penalties that are based on prior experience in the design of DWDM terrestrial fiber amplified lightwave systems, as adapted to the design of new 2000 nm DWDM systems. In these calculations, we use an effective loss of 0.05 dB/km for the HCF spans [18, 19].

Terrestrial lightwave systems at this bit rate and modulation format [1] have OSNR (dB/0.1 nm) ≥ 24.0 dB for threshold, so this 10,000 km 0.161 Pb/s DWDM system in the 2000 nm band has an EOL worst-case (EQ = equalized) OSNR margin of +4.2 dB/0.1 nm.

In this table, the line items are defined as follows [14, 15, 18, 19]:

Line 1.0: This covers allocations of the design OSNR for the transmission system, averaged over the operating spectrum.

Line 1.1: This is the effect of signal droop impairments in the OSNR caused by ASE.

Line 1.2: OSNR degradation from any reconfigurable optical add-drop-multiplexers.

Line 1.3: Decreases in OSNR resulting from extensions and/or an unrepeatered branch, as appropriate.

Line 1.4: Line 1.4 for the system is equal to the subtraction of Lines 1.1, 1.2, and 1.3 from Line 1.0.

Line 1.5: Supplier margin: Covers allocation for product variations from the manufacturing process, system deployment, normal operations, and the environment.

Line 1.6: Average system OSNR with equal input powers for each DWDM channel (flat launch conditions) at BOL. Line 1.6 OSNR = Line 1.4 – Line 1.5.

Line 1.7: Penalty in average OSNR caused by pre-emphasis-based equalization under non-flat or pre-equalized gain conditions, relative to the average OSNR with flat launch conditions.

Line 1.8: Average OSNR after equalization. Line 1.8 OSNR = Line 1.6 – Line 1.7. This is the commissioning limit for average equalized performance at the beginning of life.

Line 1.9: Spectral variation of performance across the operating wavelength region, corresponding to the worst-case OSNR across the band, after equalization.

Line 1.10: OSNR penalty caused by repairs and loss and spectral aging of the system.

Line 1.11: Average OSNR when equalization has been applied, at EOL conditions. Line 1.11 OSNR = Lin3 1.8 – Line 1.10.

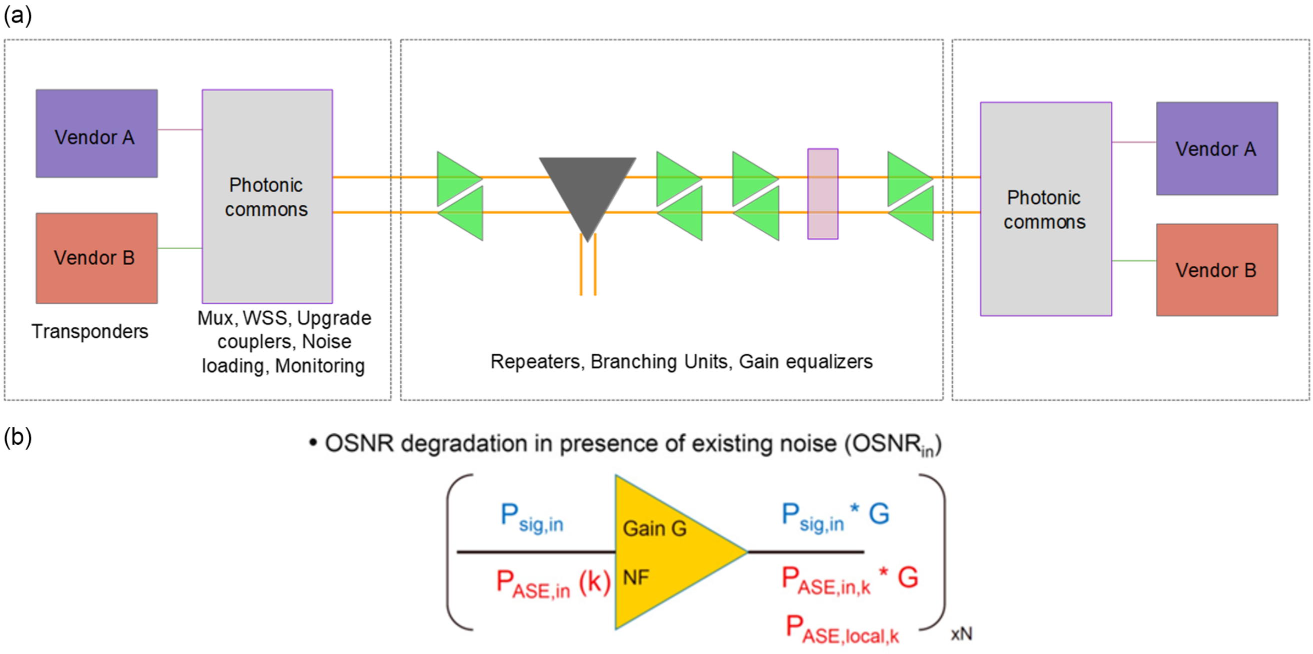
Line 1.12: An allowance for spectral variation of performance across the band. This parameter corresponds to the worst-case OSNR across the band after equalization (EQ) under EOL conditions.

We note that line 1.5 includes all expected terminal tolerance variations, as follows:

1) Optical power variations: Transmitted power, received power, and optical loss budget
2) Dispersion: Chromatic dispersion, dispersion tolerance, and dispersion management
3) Polarization mode dispersion

Figure 2

(a) Lightwave system construction for the 2000 nm DWDM lightwave transmission systems under study and (b) OSNR analysis



$$\frac{1}{OSNR_{out}} = N * \frac{1}{OSNR_{local,1}}$$

4) Other tolerances: Center wavelength, frequency offset, and duty cycle

Next, we study the subsea lightwave system with a total transmission distance of 10,000 km. Here, we select a repeater span of 100 km with amplifier gain of 5 dB and NSPAN = 100 [1]. We employ 350 nm BW fiber amplifiers with 1.0 W total output power and a noise figure of 4.0 dB as outlined in detail in the subsea hybrid fiber amplifier design in Tench [1].

The 1.0 W output power value for the subsea hybrid fiber amplifier is constrained by the available CW power of 18 kW net and cable sheath resistance of 1.0 ohms/km for today's subsea fiber amplifier technology. A detailed analysis of the electrical powering budget for the 10,000 km segments is presented in Section 5.

Relevant parameters for the 10,000 km subsea system operation are then the following: TOP(dBm) = 30.0, NSPAN = 100, G(dB) = 5.0, NF(dB) = 4.0 (device noise figure), and NCHAN = 571. Using these values in Equation (1) yields Equation (3):

$$\text{BOL OSNR}\,(\text{dB}/0.1\ \text{nm}) = 33.6\ \text{dB for the submarine system} \quad (3)$$

Subsea lightwave systems with this bit rate and modulation format also require an OSNR (dB/0.1 nm) ≥ 24.0 dB, so this 10,000 km 0.124 Pb/s DWDM system in the 2000 nm band has an EOL worst-case (EQ) OSNR margin of +4.8 dB/0.1 nm as shown in Table 2. Here, we have employed margins for the various OSNR penalties that are based on prior experience in the design of fiber amplified lightwave systems, as adapted to the design of new 2000 nm DWDM systems. We additionally assume an effective loss of 0.05 dB/km for the HCF spans.

2.2. System context using novel hollow core fibers optimized for 2000 nm spectral band

To help interpret the values in these tables and place them into a system context, we now turn to an analysis of the predicted margins as a function of the effective loss of the transmission fiber spans in dB/km. Figure 3 shows this analysis for the 10,000 km terrestrial lightwave system with 200 km HCF spans starting with nominal loss = 10.0 dB/span. Various terrestrial and subsea lightwave system analyses that support the theory and calculations underlying Figure 3 are outlined in references [20–31].

Here, we see that the EOL margin remains above 2.0 dB (red dashed line) for effective transmission fiber losses of ≤ 0.0625 dB/km. Based on experience with deployed systems, we assign an EOL worst-case threshold of 2.0 dB as the design limit for the system at the end of life after 25 years of operation.

The situation is quite different for the 10,000 km subsea lightwave system with 100 km fiber spans as shown in Figure 4.

Here, because there are 100 spans starting with nominal loss of each = 5.0 dB and the BOL OSNR is larger than for the terrestrial system, we find that effective transmission fiber losses of ≤ 0.0775 dB/km are now required for successful operation with a 2.0 dB EOL worst-case threshold at the end of life after 25 years of operation.

We now place the results of Figures 3 and 4 into greater perspective by plotting the effective transmission loss of the HCF as a function of the ideal HCF loss as shown in Figure 5. In this plot, we assign a realistic effective loss = ideal loss + 0.030 dB/km to account for variations in large-scale manufacturing, bend losses, cabling considerations, and the effects of deploying the extremely low-loss HCFs in demanding terrestrial and subsea environments.

Following this plot, we see that the successful operation of the terrestrial system requires ideal HCF losses of ≤ 0.0325 dB/m, and

Table 1
OSNR budget table for 10,000 km terrestrial system

	Segment information	OSNR, dB/0.1 nm	OSNR change, dB	System margin, dB
	SNR (ASE)			
1.0	Design	33.0		9.0
1.1	Signal droop		0.0	
1.2	ROADM		0.2	
1.3	Terrestrial extension		0.0	
1.4	Nominal	32.8		8.8
1.5	Supplier margin		0.2	
1.6	BOL average flat launch	32.6		8.6
1.7	Pre-emphasis margin		0.7	
1.8	BOL average (EQ)	31.9		7.9
1.9	BOL worst case (EQ)	29.6		
1.10	Aging and repairs		1.4	
1.11	EOL average (EQ)	30.5		6.5
1.12	EOL worst case (EQ)	28.2		4.2

Table 2
OSNR budget table for 10,000 km subsea system

	Segment information	OSNR, dB/0.1 nm	OSNR Change, dB	System Margin, dB
	SNR (ASE)			
1.0	Design	33.6		9.6
1.1	Signal droop		0.0	
1.2	ROADM		0.2	
1.3	Terrestrial extension		0.0	
1.4	Nominal	33.4		9.4
1.5	Supplier margin		0.2	
1.6	BOL average flat launch	33.2		9.2
1.7	Pre-emphasis margin		0.7	
1.8	BOL average (EQ)	32.5		8.5
1.9	BOL worst case (EQ)	30.2		
1.10	Aging and repairs		1.4	
1.11	EOL average (EQ)	31.1		7.1
1.12	EOL worst case (EQ)	28.8		4.8

the subsea system then requires losses of ≤ 0.0475 dB/km. The best ideal result at 2000 nm so far reported for a new Double-Nested Antiresonant Nodeless Hollow-Core Fiber (DNANF HCF) is 0.040 dB/km as shown in Figure 6 (taken from Figure 3 of [16]) [18].

This reported DNANF HCF was optimized for performance at 1550 nm, as shown in the blue curve in Figure 6, where a loss at this wavelength of 0.08 ± 0.03 dB/km was experimentally measured.

From the comparisons in Figure 5 for effective loss as a function of ideal anticipated loss, and using the assignment effective loss = ideal loss + 0.03 dB/km, we therefore see that improved ideal anticipated performance with new HCF designs with ≤ 0.0325 dB/km in the 2000 nm region is definitely required for successful operation of the 10,000 km terrestrial lightwave system studied in this paper and in Tench [1].

We also observe that if we use the assignment of effective loss = ideal loss + 0.01 dB/km as in Tench [1], we obtain the following quite different analysis shown in Figure 7.

Here, we see the dramatic impact of the dependence of effective loss on ideal loss, assuming only a 0.010 dB/km difference. Now, for terrestrial systems, the ideal loss requirement for successful operation is relaxed to 0.0525 dB/km, and for subsea systems, it is relaxed to 0.0675 dB/km.

We therefore note that the manufacturing variations, deployment variations, and aging in the DNANF HCF will have a great impact on the system margins that can be achieved in these novel 2000 nm 10,000 km DWDM lightwave system designs.

3. Discussion and Summary

The OSNR changes and worst-case scenarios after equalization listed in Tables 1 and 2 are based on experience with installed terrestrial and subsea systems, as adapted for 2000 nm DWDM systems with 350 nm (28.55 THz) bandwidth, and account for these stated effects as well as terminal tolerances, manufacturing and environmental impairments, Q-factor time variations, and customer margins. As stated in Section 2, there are no nonlinear impairments to the Q-factor derived from the OSNR in these 2000 nm DWDM lightwave systems with low-loss HCFs [4, 5].

In the analysis in this paper, we have assumed an experimentally validated PCS-64QAM modulation format at a baud rate of 32 Gbaud, which, with 25% Forward Error Correction (FEC) overhead, yields a total data transmission rate per DWDM channel of 281.6 Gb/s/carrier. We note that this represents the state of the art in high-speed modulation formats for DWDM subsea system transmission. Other

Figure 3
Calculated BOL and EOL OSNR margins as a function of effective transmission fiber loss in dB/km for the terrestrial system

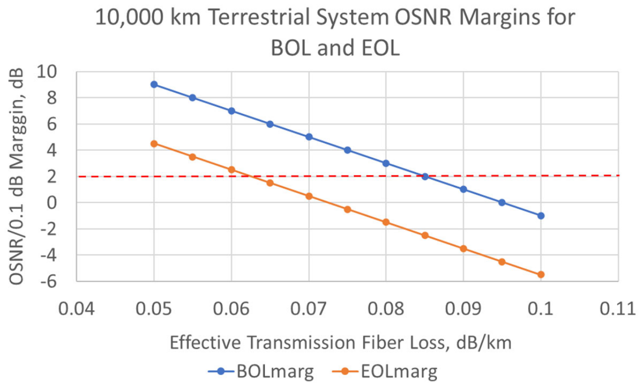
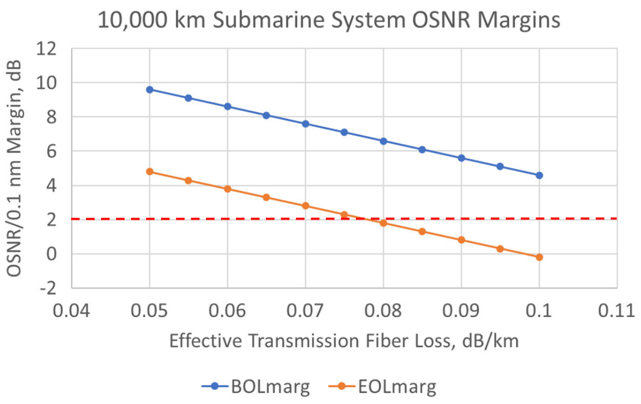


Figure 4
Calculated BOL and EOL OSNR margins as a function of effective transmission fiber loss in dB/km for the subsea system



carrier formats and modulation approaches may be considered in the future to increase the total capacity of the system.

The assignment of realistic effective loss = ideal loss + 0.030 dB/km in Figure 3 for the HCFs in Figure 5 is based on initial considerations of many factors outlined above. We can see from Figure 7 how important this assignment and analysis is for our novel systems at 2000 nm, where we assume the different values for effective loss = ideal loss + 0.010 dB/km.

We observe that HCFs with low ideal losses in the range of ≤0.0325 dB/km at 2000 nm have not yet been manufactured or experimentally studied. While the path forward to new HCFs with such low losses and ~400 nm operating bandwidth will be challenging, we note that this does not require solving physics problems but instead requires solving engineering problems. Engineering problems, time and time again, have been shown to yield to determined will and sufficient capital investment. We believe that such an approach will soon be applied to the development of the novel HCFs that are a critical part of the development and deployment of future 2000 nm DWDM lightwave transmission systems.

The subject of anticipated and predicted aging of the novel DNANF HCFs is quite topical and relevant, and we outline several initial key points here.

Early experimental studies of fiber aging behavior in installed 1550 nm DWDM subsea lightwave systems employing standard solid core silica fibers [32] indicated that for a 6500 km transmission distance, aging of the loss in the transmission fiber is approximately 0.001 dB/km over a time period of approximately three years. This report observed that the expected wavelength-dependent aging losses are largely confined to the early years of a deployed system's life and that the aging rate is expected to decrease significantly with elapsed time beyond the initial three-year period under consideration.

These early conclusions were updated and amplified by more recent studies [20, 33] covering measurements on several deployed standard subsea cables over time spans of 10–20 years and using Optical Time Domain Reflectometer (OTDR) measurements to distinguish between distributed losses along the installed cable spans and point losses in fiber splices between the spans. The experimental measurements revealed total aging losses of 0.003 dB/km over ten years for the first cable and 0.004 dB/km over 22 years for the second cable. These losses are consistent with a logarithmic trend curve for aging penalties with time. The mean data are consistent with the International Telecommunication Union-Telecommunication Standardization Sector expectations of losses of ≤0.005 dB/km over the 25-year lifetime of the subsea cable [33] and indicate that both cables may last for 75 years before reaching the upper limit in the standard. Of considerable interest is the experimental observation that the rate of aging of the losses in deployed point fusion splices is approximately 2.5 times greater than the rate of aging for distributed losses along the fiber spans. Furthermore, the aging effects in spare cables stored in a warehouse environment were remarkably found to be more than tenfold greater than the aging observed in deployed undersea cables.

The experimental studies reported in Bakhshi et al. [32] and von der Weid and Ciufo Poeys [33] lead to the following conclusions for the aging behavior of current deployed subsea fiber optic cables operating at 1550 nm.

1) Hydrogen indiffusion and microbending losses both strongly affect the loss performance of today's solid silica core fiber optical subsea cables.
2) Optimized fusion splice processes are essential to the proper functioning and minimized aging of subsea fiber optical cables.
3) The aging rate of splices is correlated to the depth of the splice boxes, indicating that water and hydrogen indiffusion may strongly affect the performance of deployed fusion splices.
4) The observed tenfold greater aging rates for spare cables stored in warehouses indicate that microbending losses, environmental conditions, and temperature variations may account for this large increase over the behavior of deployed cables.

With these conclusions for existing 1550 nm solid core silica fibers in mind, we observe that so far, no experimental results for the long-term aging of distributed and point losses in novel HCFs have been reported. Nevertheless, we can now outline the key studies and experimental measurements that need to be carried out in the 2000 nm region of the spectrum:

1) OTDR measurements of distributed and point losses in sequential fusion spliced spans [33] of DNANF or other high-performance HCFs.
2) A careful and detailed determination of microbending losses in novel HCF designs.
3) An experimental study of the effect of high optical powers [22, 23] on the aging performance of novel HCF spans and associated fusion splices.
4) A quantitative statistical/sensitivity analysis and modeling to demonstrate system robustness under real-world deployment conditions.

Figure 5
Effective transmission fiber loss as a function of ideal simulated hollow core fiber loss, in dB/km, for effective = ideal + 0.03 dB/km

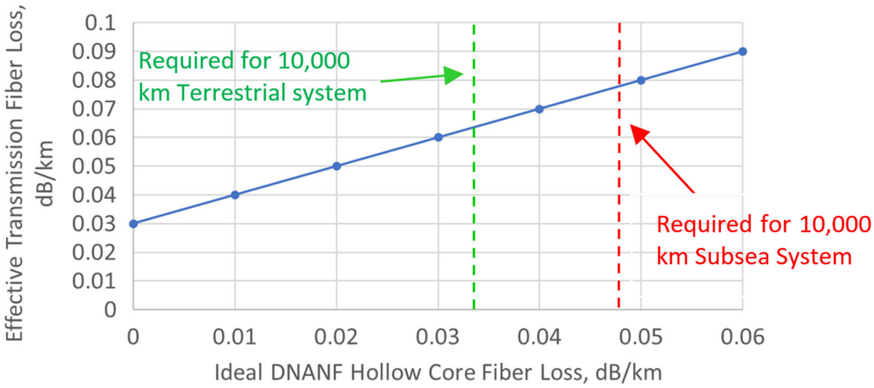


Figure 6
A plot for new DNANF hollow core fiber designs targeted at the 1550 nm band. Total predicted loss for an ideal HCF is in the dashed red curve, and 1550 nm experimental measurements for a newly manufactured fiber are plotted in blue. The loss of standard pure silica Single Mode Fiber is shown as a dashed black curve

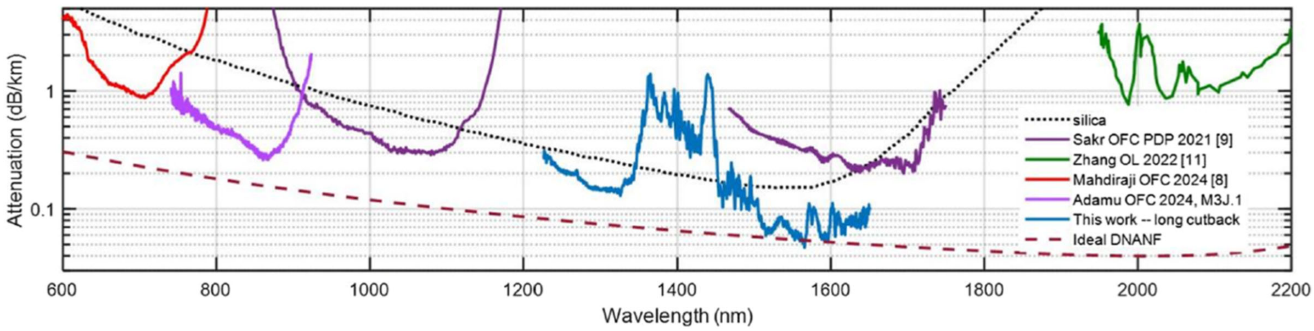
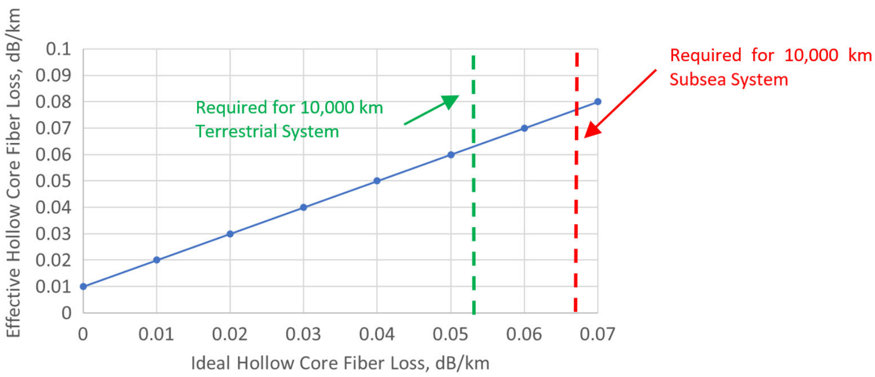


Figure 7
Effective DNANF fiber loss vs. ideal hollow core fiber loss for effective = ideal + 0.01 dB/km



Point 3) is novel and also of considerable interest and importance because the optical power levels in future lightwave transmission links using HCFs can easily be several orders of magnitude greater than in today's repeatered and unrepeatered fiber system designs [1–3, 22, 23]. Point 4) has not yet been published for 2000 nm and is of considerable relevance to the final design parameters of the novel 2000 nm lightwave system. This statistical/sensitivity analysis will first require significant aging data on the novel 2000 nm HCFs that are currently under development in many venues.

We finally note that the analysis in this paper is theoretical because the novel hybrid 2000 nm fiber amplifier designs and the novel 2000 nm low-loss HCF designs have not yet been experimentally measured in the laboratory. We expect the experimental performance of the first prototypes of these novel designs to be reported within the next 6–12 months. For this reason, experimental validation of the analysis presented here is outside the scope of this work.

4. Summary

In summary, we have reported the calculation of BOL and EOL OSNR margins in 10,000 km terrestrial and 10,000 km subsea 0.162 Pb/s capacity all-optical (without O-E-O regeneration) DWDM lightwave systems in the 2000 nm band. Our analysis follows the standard OSNR budget tables, as adapted for the 2000 nm band, for calculating margins for open cable lightwave system design. We show that an ideal anticipated loss of ≤ 0.0325 dB/km at 2000 nm in the novel hollow core transmission fibers is required for successful EOL system operation in the terrestrial lightwave system designs and that ≤ 0.0475 dB/km ideal loss is needed for the subsea lightwave system designs, assuming effective fiber loss = ideal loss + 0.03 dB/km. Considerations of aging behavior for distributed and point losses in standard solid core silica and novel HCFs are outlined, and future experimental measurements needed for the 2000 nm HCFs are detailed. The low ideal losses employed in our system analysis will require an HCF design that is optimized for 2000 nm instead of 1550 nm. We expect rapid progress in the development of new low-loss HCFs optimized for both of these important spectral regions.

5. Detailed Analysis of Electrical and Optical Power Budgets for 10,000 km Subsea Fiber Amplifier Cable Links at 2000 nm

The analysis in this section is based on the technical descriptions and outlines of powering of subsea fiber optic cables in Carbo Meseguer et al. [4, 5] and Inada [34]. We begin with a cable length of 10,000 km, span lengths of 100 km, and NSPAN = 100. We assume that the total DC power supply capacity is 18.0 kW, the current in the cable is 1.00 A, and the cable resistance is 1.0 ohms/km.

In this system, the voltage drop across the cable sections between the fiber amplifier repeaters is 10,000 km × 1.00 ohms/km × 1.00 A = 10.0 kV. Therefore, 18.0 kV – 10.0 kV = 8.0 kV is available for all of the 100 fiber amplifier pairs, yielding 80 V for each repeater pair, which at 1.0 A DC current means that 80 W is the total DC power available for each repeater pair. Following the outlines in Inada [34], we see that 10% of this power is used for laser pump diode control circuits and 10% is allocated for an electroding margin in the cable. This means that 80 W × 0.80 = 64.0 W is available to power each fiber amplifier repeater pair.

As described in detail in Tench [1], the hybrid 2000 nm subsea fiber amplifiers are pumped with 1190 nm semiconductor laser pump sources. Data for commercially available 1190 packaged pumps can be found in the link in the data availability statement. We find that each 1190 nm packaged pump has 700 mW fiber-coupled output power for a typical drive current of 1.70 A and a typical drive voltage of 1.6 V. The maximum drive current is 2.0 A, and the maximum drive voltage is 1.8 V. Therefore, we assume that the total maximum electrical power required to drive each packaged 1190 nm pump source is 3.6 W. No power for the Thermoelectric Cooler option in the laser package is required because of the advantageous temperature environment for the deployed subsea cable.

We now employ polarization multiplexing of two packaged pumps to provide 1.4 W of 1190 nm pump power to each of the four available pump input ports in the design of the out-of-band pump hybrid 2000 nm fiber amplifier repeater presented in [1]. This means that a total of 5.6 W of 1190 pump power is used for the operation of the hybrid fiber amplifier, with a corresponding 8 × 3.6 W = 28.8 W of electrical power consumption. Since each repeater incorporates a pair of fiber amplifiers (for left-to-right and right-to-left data transmission), we then find that the projected electrical power consumption for each fiber amplifier pair is 57.6 W. This means that 57.6 W/64.0W or 90% of the available electrical power is allocated for the overall architecture, indicating that our design choices are valid with a 10% margin available.

For the 2000 nm fiber amplifier pumped at 1190 nm, the quantum defect is 1190 nm/2000 nm = 59.5 %. Based on published results for Ho and Tm fiber amplifiers, we anticipate a total power conversion efficiency of 30% with selected low-loss input and output signal isolators. Therefore, the total 2000 nm optical output power available from each fiber amplifier repeater is 5.60 W × 0.595 × 0.300 = 1.00 W = +30.0 dBm, which is the value used in the subsea system margin calculation of Section 2.1.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by the author.

Conflicts of Interest

The author declares that he has no conflicts of interest to this work.

Data Availability Statement

Data for the 700 mW 1190 nm fiber-coupled PM-packaged pump diode are openly available at https://www.innolume.com/fabry-perot-laser-diodes/fiber-coupled-single-mode-laser-diode-at-1195nm-5/. Other data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Robert E. Tench: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

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