SUMITOMO ELECTRIC TECHNICAL REVIEW

No. 96 · APRIL 2023

FEATURED TOPIC

Optical Fibers for High Fiber Count Submarine Cable Systems

Hideki YAMAGUCHI*, Yuki KAWAGUCHI, and Masaaki HIRANO

The transmission capacity of a single submarine cable has been increasing to meet the growing demand for global data traffic, requiring the continuous advancement of optical transmission systems and optical fibers. This paper discusses the submarine fiber that provides the best performance and cost efficiency for the overall system. We found that submarine fibers having a medium core area of 110 to 130 μm^2 and attenuation as low as 0.15 dB/km or less are the most preferable for the current several-hundred tera b/s cables based on digital coherent technology. The paper also discusses the prospects for optical fibers with smaller outer diameters and multi-core fibers for the realization of 1 Pb/s and beyond cable by increasing the number of optical fibers installed in the cable.

Keywords: optical fiber, pure silica core, low loss fiber, submarine fiber, multi-core fiber

1. Introduction

Global data traffic has been growing by 30 to 40% per year in line with the spread of 5G mobile communication, expansion of cloud services, and construction of data centers in respective countries (see Fig. 1).[1] To meet this growing demand, there is a strong requirement to expand the transmission capacity through a submarine cable.

In fact, submarine cable transmission capacity has been increasing in line with the advancement of optical transmission technology and optical fiber (Fig. 2).[2] Before the 1990s, a single-wavelength transmission over standard single-mode fiber (SMF) was used. Then, wavelength division multiplexing technologies (WDM, DWDM) using optical fiber amplifier (EDFA) were introduced and chromatic dispersion became the main constraint for transmission capacity, and therefore, dispersion-shifted fiber (DSF), non-zero dispersion-shifted fiber (NZDSF) and dispersion-managed fiber (DMF) were adopted.

In the 2010s, the optical signal to-noise ratio (OSNR) emerged as the main constraint factor by the introduction of digital coherent technology.*1 To improve OSNR, it is important to reduce fiber nonlinearity and transmission loss. Therefore, an optical fiber having low nonlinearity by enlarging effective area (A_{eff}*2) to 130 to 150 μm^2, and ultra-low loss (0.15 dB/km) by applying pure silica core technology was optimal. This fiber represents very high performance compared with standard SMF (A_{eff}: 80 μm^2, transmission loss: 0.18 to 0.20 dB/km).

In around 2020, transmission capacity per optical fiber almost reached the theoretical limit. Thus, space division multiplexing (SDM) technology was introduced to increase transmission capacity by increasing the number of fibers in a cable. Today, optical fibers with A_{eff} of 80 to 130 μm^2 and ultra-low loss of 0.15 dB/km are utilized mainly.

This paper discusses optical fibers suitable for SDM submarine cables from the viewpoint of total system performance and cost. It also discusses submarine fibers with a small outer diameter and multi-core fibers which are expected to contribute to further expanding transmission capacity.

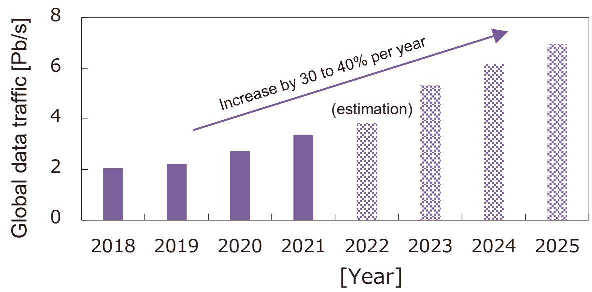

Fig. 1. Global data traffic demand

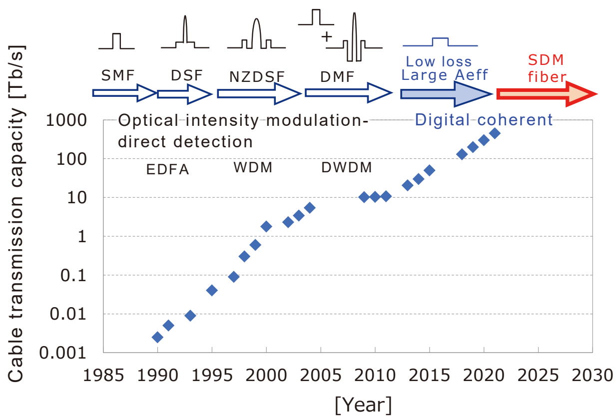

Fig. 2. Cable transmission capacity and optical fiber technology

2. Expansion of Transmission Capacity of Submarine Cables

By using Shannon's theorem,[3] the theoretical limits of the communication capacity per optical fiber and optical cable, namely, C_{fiber} and C_{cable}, are indicated by the Eqs. (1) and (2), respectively (B: bandwidth of signals, N: fiber count in a cable).

$$C_{fiber} = B \cdot \log_2 (1 + OSNR) \quad (1)$$

$$C_{cable} = N/2 \cdot C_{fiber} \quad (2)$$

To expand the transmission capacity of optical cables, it is important to 1. expand the bandwidth B, 2. improve OSNR, and 3. increase the fiber count in cable N. The details are discussed below.

2-1 Expansion of the transmission band

In general, the C-band (1,530 nm to 1,565 nm) is used as the transmission band in a submarine cable system. The possibility of using the L-band (1,565 nm to 1,610 nm) has been studied in addition to the C-band.(4) Actually, trans-oceanic submarine cables using both the C and L bands have been installed. While they almost double the band-width, they require a complicated design for optical repeater to amplify an optical signal. In addition, the effi-ciency to amplify optical signals in the L-band is lower than that in the C-band. Practical usage of the L-band is still limited, but these issues are strongly expected to be solved in the immediate future through advances in tech-nology.

2-2 Improvement of OSNR

Optical noise in an optical fiber transmission system is mainly classified into two categories: linear noise, which is caused by spontaneous emission inevitably generated in the process of optical amplification, and nonlinear noise, which is generated by the interaction between the signal light and an optical fiber.

The less amplifier gain with the higher input power to an optical amplifier, the more OSNR attributed to linear noise is suppressed. Thus, in order to suppress the linear noise, the interval between repeaters with optical amplifiers (span length) should be shortened, or the transmission loss of optical fibers should be reduced.

However, submarine repeaters are very expensive, and the span length should be extended to reduce the total cost. Therefore, a low transmission loss contributes to increasing the transmission capacity of a system and reducing the total cost. Notably, this is considered to be the most important transmission characteristic of submarine optical fibers. Sumitomo Electric Industries, Ltd. has realized the world's best low-loss fibers in terms of both R&D and mass-pro-duction products.(5)

The lower the power density of optical signals in a fiber, the lower the nonlinear noise. Thus, the larger A_{eff} is the better, however, fibers with large A_{eff} have higher bending loss. In addition, the intensity of the optical signal is constrained by the limitation of electrical power supply to optical amplification in the submarine system, from power feeding equipment at the landing station. Optimal A_{eff}, therefore, depends on the system configuration including transmission length, span length and fiber count.

Sumitomo Electric has commercialized various submarine fibers whose A_{eff} of 80 to 150 μm^2 and transmis-sion loss of 0.14 to 0.16 dB/km.(6) The company has also succeeded in formulating(7) a figure of merit (FOM) to quantify system performance by using fiber characteristics including A_{eff}, transmission loss and chromatic dispersion. Through these activities, we have contributed to increasing the performance of submarine cable systems by proposing optimal optical fibers.

2-3 Increase in the fiber count

Due to the improvement in transmitter and receiver technologies, transmission capacity in a single optical fiber has been increasing and approaching to the theoretical limit C_{fiber}. It is therefore not easy to increase transmission capacity in fiber any further. Accordingly, an SDM cable system in which the fiber count in a single submarine cable increases is a straightforward and effective way to increase cable transmission capacity. In 2021, 48-fiber count submarine cables were put into practical application.(8)

As discussed in 2-2, an appropriate A_{eff} depends on the electrical power supply to the optical amplifier, and therefore, in a high fiber count submarine cable system, the appropriate A_{eff} becomes smaller.(9) Meanwhile, a higher fiber count increases the spatial density of optical fibers in a cable, and the bending loss of fiber shall be suppressed. Today, optical fibers having A_{eff} of 80 to 130 μm^2 are mainly used for transoceanic SDM cable systems.

3. Optical Fibers Suitable for High fiber count Submarine Cables

To discuss optical fibers applicable for constructing high-performance and cost-effective SDM submarine cable systems, this chapter states about 0.5 Pb/s cable system with 7,000 km transmission applying 48-fiber count considering electrical power supply limitation.

Figure 3 shows contour lines of span lengths as a function of transmission loss and A_{eff} calculated based on a FOM.(7) The span lengths based on the typical characteris-tics (Table 1) of Sumitomo Electric's submarine optical fiber products,(6) namely, Z Fiber LL (Z LL), PureAdvance-110 Submarine (PAd110S), Z-PLUS Fiber ULL (Z+ULL), Z-PLUS Fiber 130ULL (Z+130ULL), and Z-PLUS Fiber 150 (Z+150), were also plotted.

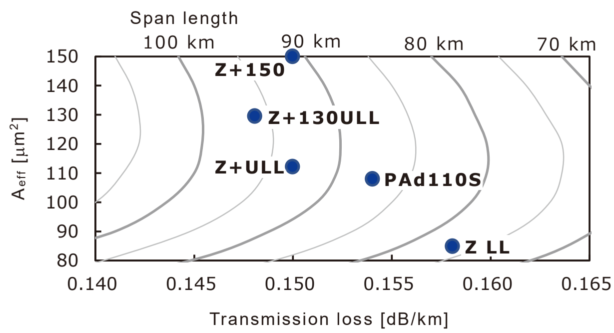

Fig. 3. Span length as a function of A_{eff} and transmission loss (Transmission distance: 7,000 km, 48 cores, Cable transmission capacity: 0.5 Pb/s)

Table 1. Typical characteristics of Sumitomo Electric's submarine fibers (at wavelength of 1,550 nm)

Fiber type	Z LL	PAd 110S	Z+ULL	Z+130 ULL	Z+150
Transmission loss [dB/km]	0.158	0.154	0.150	0.148	0.150
A_{eff} [μm^2]	85	110	112	130	150

As shown in Fig. 3, it was found that the span length is extendable when the transmission loss of optical fibers is low and A_{eff} is at an optimal value (around 110 to 130 μm^2). The longer span length means a fewer number of repeaters, which makes it possible to reduce the total cost of the submarine cable system. It should be noted that a fiber having a low transmission loss and a large diameter of the core has a high manufacturing cost in general.

Considering these points of view, to reduce the total cost while increasing the transmission performance at the SDM cable system, it is preferable to use optical fibers with low transmission loss and an appropriate A_{eff} (110 to 130 μm^2 in this case). It can be concluded that Sumitomo Electric products Z+130ULL, Z+ULL, and PAd110S are appropriate optical fibers for such SDM systems.

4. Submarine Optical Fibers in the Future

As shown in Fig. 1, the transmission capacity of submarine cables will continue to expand and it is projected to reach 1 Pb/s by around 2025. A simple way to expand the capacity is to increase the number of fiber count in a cable having an enlarged diameter, but this is accompanied by a significant increase in various costs including manufacturing, parts and materials of submarine cables, and installation due to decreased lengths of larger diameter cable loaded onto a cable-laying ship.

Therefore, small outer diameter fibers and multi-core fibers are actively studied as future submarine optical fibers that will realize a cable capacity of 1 Pb/s and beyond.

4-1 Reduction in the outer diameter of optical fibers

Optical fiber consists of a glass core and cladding through that optical signal propagates and resin coating layers that protect the glass parts. Generally, the outer diameters of the glass parts and the resin coating are 125 μm and 250 μm, respectively.

For a terrestrial cable with an ultra-high fiber count of 3,000 or more, a fiber with a small outer diameter (OD) of 200 μm is applied.[10] The 200 μm OD fiber has the same glass diameter of 125 μm and reduced coating thickness. Recently, it has been actively studied to apply the 200 μm OD fiber to submarine cable to increase the fiber-count. By reducing the OD from 250 to 200 μm, the cross-sectional area comes to be 1/1.5 and therefore, the number of fibers will be able to increase by a factor of 1.5 in a submarine cable. Thus, the application of this 200 μm OD fiber is expected as a solution to expand transmission capacity without significantly increasing the costs of submarine cables and installation as discussed above.

Sumitomo Electric developed 200 μm OD Z LL and Z+ULL fibers, and their typical characteristics are summarized in Table 2. We confirmed their high transmission characteristics, transmission loss and A_{eff} of both fibers are equivalent to those of 250 μm OD Z LL and Z+ULL fibers, respectively.

In addition to excellent transmission characteristics, submarine fibers are also required high mechanical and environmental reliability to apply long-term usage of around 25 years. The applied proof test level to 200 μm OD fibers was 1.4 GPa, which is generally required for submarine fiber and twice the level required for terrestrial fiber. For environmental tests, loss change after aging conditions including damp heat, temperature cycling and water immersion were investigated, and we confirmed that all of those results were much better than respective criteria required in the international standard of IEC 60793-2-50.[11]

Thus, we confirmed that 200 μm OD Z LL and Z+ULL have excellent transmission performance, and mechanical and environmental reliability applicable to submarine cables. These fibers are scheduled to be commercialized in 2023.

Table 2. Typical characteristics of 200 μm submarine fibers

Product name	Z LL		Z+ULL	
Outer diameter [μm]	250	**200**	250	**200**
Transmission loss [1550 nm, dB/km]	0.156[#1]	**0.156**	0.150	**0.150**
A_{eff} [1550 nm, μm^2]	85	**85**	112	**112**
Proof test level [GPa]	≥1.4	**≥1.4**	≥1.4	**≥1.4**
Loss increase [dB/km]: Damp heat test (85°C/85%RH, 30 days)	0.00 Pass[#2]	**0.00 Pass [#2]**	0.00 Pass [#2]	**0.00 Pass [#2]**
Loss increase [dB/km]: Temperature cycling test (-60°C~+85°C, 5 cycles)	0.00 Pass [#2]	**0.00 Pass [#2]**	0.00 Pass [#2]	**0.00 Pass [#2]**
Loss increase [dB/km]: Water immersion test (23°C, 30 days)	0.00 Pass [#2]	**0.00 Pass [#2]**	0.00 Pass [#2]	**0.00 Pass [#2]**

#1: Decreased from 0.158 to 0.156 dB/km. Scheduled to be commercialized in 2023.
#2: Based on the IEC60793-2-50 standard. All the test items in the table are ≤ 0.05 dB/km.

4-2 Multi-core fiber

Multi-core fiber (MCF) has multiple cores in its cladding glass as schematically shown in Fig. 4. It is highly expected to increase the transmission capacity of submarine cable and actually, various studies have been conducted on the application of MCF including 2-core fiber (2CF) and 4-core fiber (4CF). Especially for 2CF submarine cable transmission, its ecosystem has been developed as schematically indicated in Fig.5. Here, optical signals are generated by the existing transmitter and propa-

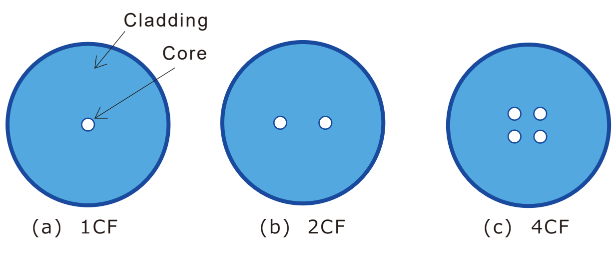

Fig. 4. Schematic cross section of a multi-core fiber

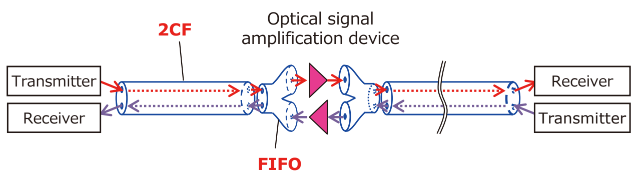

Fig. 5. Schematic diagram of a transmission system applying 2CF

gate through each core, are separated by FIFO (Fan-in/Fan-out) devices and amplified by the optical amplifier for single-core fiber (1CF), and are processed by the existing repeater. Technological hurdles are considered relatively low, and therefore, transmission system using 2CF cable is highly expected to be practical within a couple of years.(12)

The most significant difference between the characteristics of MCF and 1CF is existing of crosstalk (XT). XT is the interaction between optical signals propagating through respective cores, and becomes optical noise on the MCF transmission system. Low XT is one of essential characteristics of MCF for submarine application, and Fig. 6 shows the calculated ONSR penalty from 1CF (i.e., no XT) with transmission loss of 0.15 dB/km as a function of XT per span (80-km-long) in 2CF considering FIFO devices insertion loss (0.3 dB) and 2CF transmission losses (0.15 and 0.17 dB/km). As is found in Fig. 6, the OSNR penalty becomes higher with the higher XT, and significantly increases at XT around −45 to −50 dB.

As discussed above, in order to mitigate the OSNR penalty as much as possible, it was found that XT should be suppressed −45 to −50 dB or less. At the same time, the improvement of transmission loss of 2CF was found as another essential characteristic to construct a high-performance submarine transmission system. As can be seen in Fig. 6, when the transmission loss was reduced from 0.17 to 0.15 dB/km, OSNR improved by as much as 0.9 dB. The transmission loss spectrum of a fabricated 2CF is shown in Fig. 7, at the wavelength of 1,550 nm each core has a very low transmission loss of 0.152 and 0.155 dB/km, which is equivalent to a submarine 1CF.(12) In addition, XT of fabricated 2CF was −50 dB, low enough to minimize OSNR penalty. In conclusion, developed 2CF is considered to be applicable to submarine cables.

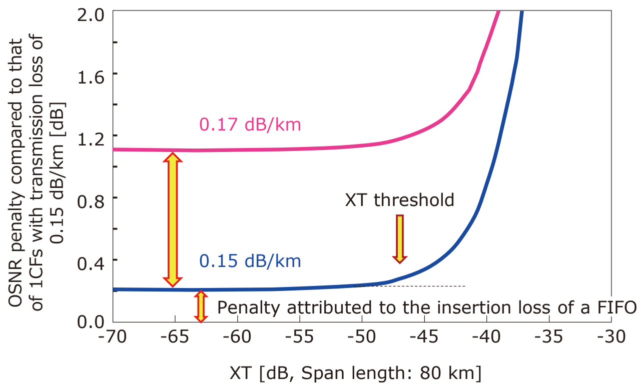

Fig. 6. OSNR penalty of 2CF compared to that of 1CF

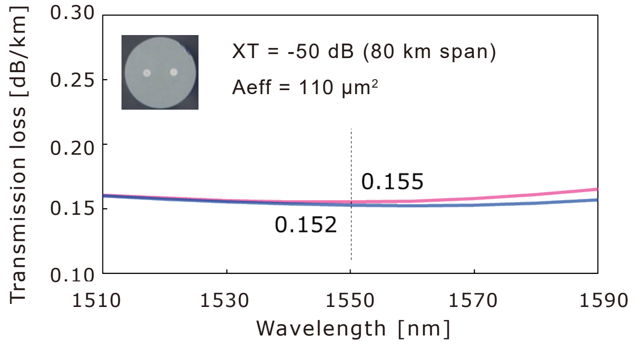

Fig. 7. Wavelength characteristics of 2CF transmission loss

5. Conclusion

We theoretically confirmed that submarine optical fibers with A_{eff} of 110 to 130 μm^2 and transmission loss of 0.15 dB/km are appropriate for compatibly realizing high-performance and low-cost high fiber count submarine cable systems. We also demonstrated that ultra-low loss 200 μm outer-diameter fibers and 2-core fiber are applicable to 0.5 to 1 Pb/s transoceanic submarine cables in the near future.

Sumitomo Electric will contribute to the development of the global information society by continuously offering submarine fibers derived from its sophisticated design and manufacturing technologies to realize large-capacity submarine cable systems of Pb/s and beyond.

Technical Terms

*1 Digital coherent technology: This is a communication protocol using light intensity and phase. Optical signals are converted into electric signals at the receiving end for signal processing. The distortion of optical signals can be equalized by electrical processing to enable large-capacity communication.

*2 Effective area (A_{eff}): This is an index which indicates the spread of optical power distribution which propagates through an optical fiber. The larger the A_{eff}, the lower the power density of the propagated light, making it possible to suppress the non-linear effect.

References

(1) W. Nielsen et al., Industry Report, Issue 11, Submarine Telecoms Forum, Inc (2022)
(2) S. Grubb, “The future of fiber optic innovation: Part IV,” Light reading Dec/8 (2021)
(3) C. E. Shannon, “A Mathematical Theory of Communication,” Bell Syst. Tech. J. Vol.27, Issue3, pp. 379-423 (1948)
(4) J. X. Cai et al., “70.4Tb/s Capacity over 7,600 km in C+L Band Using Coded Modulation with Hybrid Constellation Shaping and Nonlinearity Compensation,” OFC 2017, Th5B.2 (2017)
(5) T. Hasegasa et al., “The First 0.14-dB/km Ultra-low Loss Optical Fiber,” SEI TECHNICAL REVIEW, No. 86, pp.18-22 (2018)
(6) https://global-sei.com/fttx/optical-fibers/z-fiber/
(7) T. Hasegawa et al., “Optimal Fiber Design for Large Capacity Long Haul Coherent Transmission,” Optics Express, Vol.25, No.2, pp.706-712 (2017)
(8) NEC corporation, “NEC qualifies 24 fiber pair subsea telecom cable system” (Mar. 19, 2021) https://www.nec.com/en/press/202103/global_20210319_04.html
(9) K. Balemarthy et al., “Optimum Fiber Properties and Pair Counts for Submarine Space Division Multiplexing”, Suboptic2019, OP18-2 (2019)

(10) F. Sato et al., "Ultra-High-Density Microduct Optic Cable with 200 mm Freeform Ribbons for Air-Blown Installation," SEI TECHNICAL REVIEW, No.89, pp.17-21 (2019)
(11) International standard IEC 60793-2-50 (Dec. 2018)
(12) M. Hirano, "Subsea MCF Advances," ECOC2022, Tu4B (2022)

Contributors

The lead author is indicated by an asterisk (*).

H. YAMAGUCHI*
• Assistant General Manager, Optical Fiber & Cable Division

Y. KAWAGUCHI
• Ph.D.
Assistant General Manager, Optical Communications Laboratory

M. HIRANO
• Group Manager, Optical Fiber & Cable Division