Low Loss Optical Fibers for Terrestrial Long-Haul Networks, PureAdvance

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We have developed "PureAdvance," a low-loss and low-nonlinearity pure silica core fiber complying with ITU-T G.654.E, and started supplying it for terrestrial long-haul networks. The excellent practicality of PureAdvance, including reliable terrestrial cabling, low splice loss, and stable Raman amplification, have been demonstrated for actual deployment as terrestrial links. Transmission systems using PureAdvance exhibit higher transmission performance than those with SSMF or NZDSF, making PureAdvance ideal as a transmission medium to support long-haul, high-capacity terrestrial applications including telecom trunk lines, datacenter interconnection, and transmission lines between submarine landing stations and datacenters.

Keywords: optical fiber, pure silica core fiber, low loss, terrestrial long-haul link, ITU-T G.654.E

1. Introduction

Demand for global data traffic has been increasing exponentially due to introduction of 5G service, increased use of various Internet contents, and the spread of remote work. This increasing demand has led to growing needs for high performance optical fibers that can efficiently transmit high-capacity optical signals over a long distance.

To meet such needs, Sumitomo Electric Industries, Ltd. has developed PureAdvance, a low loss optical fiber complying with ITU-T G.654.E[(1)]*[1], and started supplying it for terrestrial long-haul networks. To increase the optical transmission capacity, it is necessary to improve optical signal-to-noise ratio (OSNR). PureAdvance having low attenuation and low nonlinearity can efficiently improve the OSNR. Due to this advantage, PureAdvance can be used for the following applications.

- Terrestrial trunk lines in telecom networks
- Long-haul optical transmission systems, including transcontinental links
- Data center interconnection
- Transmission lines between submarine cable landing stations and data centers
- Repeaterless transmission systems for remote areas
- Quantum cryptographic communication systems
- Other optical transmission systems that require low loss

To apply PureAdvance to actual terrestrial links, it must meet the following requirements: practical and reliable terrestrial cabling, low splice losses between optical fibers, and applicability of Raman amplification.

In this paper, we show that PureAdvance has excellent transmission performances and meets these practical requirements for actual deployment as terrestrial links. This paper also describes expected advantages of transmission systems using PureAdvance.

2. Fiber Characteristics of PureAdvance

Figure 1 and Table 1 show the schematic refractive index profile and the fiber characteristics of PureAdvance,

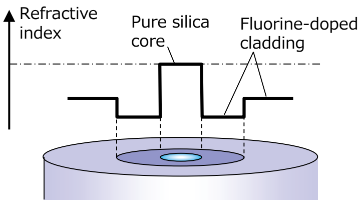

Fig. 1. Schematic refractive index profile of PureAdvance

Table 1. Fiber characteristics of PureAdvance

	PureBand (Ref., SSMF)	PureAdvance-80		PureAdvance-110	PureAdvance-125
ITU-T Recommendation	G.652.D	G.652.B	G.654.C	G.654.E	G.654.E
MFD @1310 nm	9.2±0.4 µm	Typ. 9.0 µm	-	-	-
MFD @1550 nm	Typ. 10.3 µm	Typ. 10.0 µm	Typ. 10.3 µm	Typ. 11.5 µm	Typ. 12.4 µm
Aeff @1550 nm	Typ. 80 µm^2	Typ. 80 µm^2	Typ. 80 µm^2	Typ. 110 µm^2	Typ. 130 µm^2
Attenuation @1310 nm	Max. 0.35 dB/km	Max. 0.31 dB/km	-	-	-
Attenuation @1550 nm	Max. 0.20 dB/km	Max. 0.17 dB/km Typ. 0.164 dB/km	Max. 0.17 dB/km Typ. 0.164 dB/km	Max. 0.17 dB/km Typ. 0.162 dB/km	Max. 0.17 dB/km Typ. 0.162 dB/km
Cable cutoff wavelength	Max. 1260 nm	Max. 1260 nm	Max. 1530 nm	Max. 1530 nm	Max. 1530 nm

respectively. PureAdvance features low attenuation and low nonlinearity due to the large effective area (A_{eff}). OSNR is generally dominated by two types of noise: amplifier noise, which is generated by optical amplifiers that compensate optical fiber losses, and nonlinear noise, which is generated by nonlinear phenomena in optical fibers. Therefore, suppressing the attenuation and nonlinearity of optical fibers is one of the most effective means to improve the OSNR.

Low attenuation of PureAdvance is achieved by applying pure silica for the core, in which most of the transmitted optical power is confined, as shown in Fig. 1. Sumitomo Electric has developed and mass-produced low loss pure silica core fibers (PSCFs) for more than 30 years and supplied them mainly for submarine optical cables. Recently, Sumitomo Electric achieved a world record low attenuation of 0.1419 dB/km(2) and realized mass-production of a PSCF having ultra-low-loss of 0.144 dB/km.(3) By applying the ultra-low-loss PSCF technologies, we have achieved low attenuation of 0.17 dB/km at the maximum and 0.162 dB/km in typical for PureAdvance.

The PureAdvance lineup consists of three types of optical fibers with different A_{eff}, as shown in Table 1. PureAdvance-80 has a mode field diameter (MFD) equivalent to that of a standard single mode fiber (SSMF). On the other hand, PureAdvance-110 and PureAdvance-125, which comply with ITU-T G.654.E, have low nonlinearity due to the enlarged A_{eff}, and these fibers must be suitable for long-haul and high-capacity transmission. It should be noted that macrobending losses of these fibers are lower than or equivalent to that of SSMF, while enlarging the A_{eff} to 110 and 130 μm^2, by applying depressed cladding index profile(4) shown in Fig. 1.

3. Applicability of PureAdvance to Terrestrial Links

3-1 Requirements for terrestrial links

A typical terrestrial long-haul optical transmission link consists of a transmitter (TX), optical cable, repeaters, regenerators, and a receiver (RX), as shown in Fig. 2. In order to apply a fiber to actual terrestrial long-haul links, the following three fiber properties will be required.

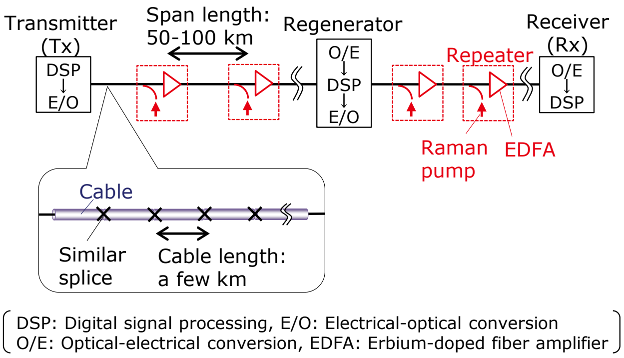

Fig. 2. Schematic diagram of terrestrial long-haul optical transmission link

- Practical and reliable terrestrial cabling
- Low splice losses between similar fibers and with SSMF/submarine optical fibers
- Applicability of Raman amplification

In this chapter, we evaluate the fiber properties of PureAdvance required for actual deployment as terrestrial long-haul optical transmission links.

3-2 Terrestrial cabling

Optical cables for terrestrial links usually accommodate higher count of optical fibers at higher density compared to submarine optical cables. In addition, optical cables would be deployed in various environments (e.g., conduits, burial, or aerial wires). Thus, applicability to terrestrial cabling for actual deployment should be evaluated. We demonstrated that PureAdvance shows good terrestrial cabling performances and high reliability. For example, we fabricated a 200-fiber count PureAdvance-110 cable with 4-fiber ribbon slotted core cable structure shown in Fig. 3, which is commonly used in Japan. We confirmed that the cable showed low typical attenuation of 0.17 dB/km or less and high reliability.(5) The cable has been supplied for terrestrial trunk lines.

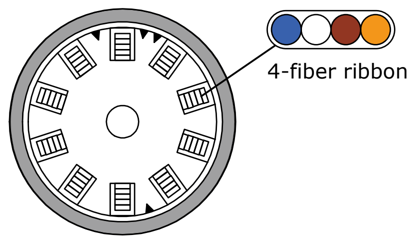

Fig. 3. 200-fiber count PureAdvance-110 cable with 4-fiber ribbon slotted core

In references (6) and (7), G.654.E optical fibers with A_{eff} of 110–130 μm^2 from several fiber manufacturers, including Sumitomo Electric's PureAdvance-110, have been cabled in 96-fiber and 64-fiber count duct and aerial loose-tube cables. The fabricated cables have been deployed in terrestrial links in China, and the good cable performances have been confirmed.(6) 400 Gb/s wavelength division multiplexing (WDM) transmissions have also been successfully demonstrated over the field-deployed cables over the distance of 430 km and 150 km.(7)

3-3 Similar and dissimilar splice performances

(1) Splice losses of optical fibers

In terrestrial links, there would be plural splices between similar optical fibers, because the cable length on a single spool is generally limited to a few kilometers. In addition, an optical fiber would be connected to repeaters at both ends of the span. Since most of pigtails employ SSMF, it is also necessary to connect the optical fiber to the SSMFs. In case an optical fiber is connected to a submarine landing station, the fiber may be directly spliced to a submarine optical fiber. Thus, it is also required to reduce the similar splice losses and dissimilar splice losses with SSMF or submarine optical fibers.

Assuming that angle tilt between optical fibers is negligibly small, the splice loss α_{sp} [dB] can be expressed by the following equation:[8]

$$\alpha_{sp}[\mathrm{dB}] = -10\log\left\{\left(\frac{2\cdot MFD_1\cdot MFD_2}{MFD_1^2+MFD_2^2}\right)^2\cdot\exp\left[-\frac{8d^2}{MFD_1^2+MFD_2^2}\right]\right\} \cdots\cdots (1),$$

where d [μm] is core misalignment between optical fibers to be spliced. MFD_1 and MFD_2 [μm] are the MFD of each optical fiber. From Eq. (1), in case of a similar splice ($MFD_1 = MFD_2$), the splice loss is dominated by both core misalignment and the MFDs. On the other hand, for a splice between dissimilar fibers ($MFD_1 \neq MFD_2$), the splice loss increases with the difference in MFDs (MFD-mismatching).

(2) Similar splice loss

Similar splice losses for dispersion-shifted fiber (DSF), SSMF, and PureAdvance-110 have been evaluated using a commercially available core aligning fusion splicer.[9] Figure 4 shows the average, maximum, and minimum splice losses for 20 splices. Calculated splice loss from Eq. (1) assuming the core misalignment d of 0.3 μm is also shown by a dashed curve. As shown in Fig. 4, the larger the MFD, the lower the splice losses. The average splice loss of PureAdvance-110 is 0.011 dB, which is 0.005 dB and 0.018 dB-lower than those of SSMF and DSF, respectively. The improvement of the splice losses may not seem very large. However, if we consider a 100 km–span link with similar splices at every 1 km (99 splices), the improvements in accumulated splice losses per span reach considerable levels of 0.5 dB and 1.8 dB, respectively.

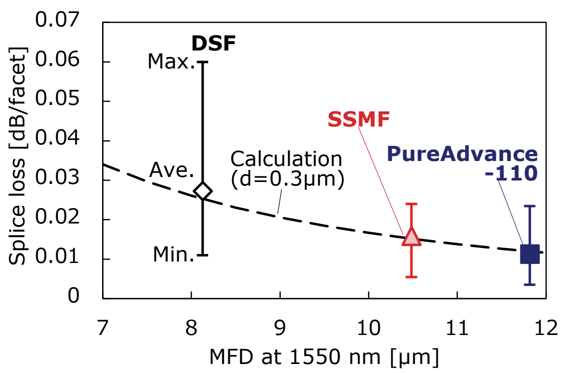

Fig. 4. Similar splice loss

(3) Dissimilar splice loss with SSMF/submarine optical fibers

Table 2 summarizes calculated splice losses between PureAdvance and SSMF/submarine optical fibers, assuming d of 0.3 μm in Eq. (1). PureAdvance-80 and PureAdvance-110 can have low splice losses with SSMF of 0.1 dB or less. In addition, PureAdvance-110 can also achieve low splice losses with all the submarine optical fibers of as low as 0.1 dB or less, because PureAdvance-110 has the small MFD-mismatching with submarine optical fibers having A_{eff} of 80–150 μm^2.

Table 2. Splice loss between PureAdvance and SSMF/submarine fibers

		PureBand (SSMF)	Pure Advance -80	Pure Advance -110	Pure Advance -125
MFD (Typ.) [μm]		10.3	10.3	11.5	12.4
A_{eff} (Typ.) [μm^2]		80	80	110	130
Splice loss [dB]	SSMF	0.02	0.02	0.07	0.16
	Submarine fiber				
	80 μm^2	0.02	0.02	0.07	0.16
	110 μm^2	0.07	0.07	0.02	0.04
	130 μm^2	0.16	0.16	0.04	0.02
	150 μm^2	0.28	0.28	0.09	0.03

3-4 Applicability of Raman amplification

(1) Raman gain coefficient

Although Erbium-doped fiber amplifier (EDFA) is mainly used in repeaters to amplify the attenuated optical signal power, Raman amplification is often used to assist EDFA gain, and to improve the transmission performance in terrestrial long-haul links. Therefore, applicability of Raman amplification is also required for optical fibers for terrestrial long-haul links.

Raman amplification utilizes a stimulated Raman scattering process, which is generated when pump light is propagated in an optical fiber. The gain (Raman gain) G_{Raman} [dB] is expressed by

$$G_{Raman}[dB] = 10\log\left[\exp\left(\frac{g_R}{A_{eff}}\cdot P_{pump}\cdot L_{eff}\right)\right] \cdots\cdots\cdots\cdots\cdots (2),$$

where g_R/A_{eff} [1/W/km] is the Raman gain coefficient and P_{pump} [W] is the pump power. L_{eff} [km] is the effective length given by $L_{eff} = (1 - \exp[\alpha_p \cdot L])/\alpha_p$, where α_p [1/km] is the fiber attenuation at pump wavelength, and L [km] is the span length [km].

In general, pump wavelength of Raman amplification is around 1450 nm, and it can be possibly in multi-mode region, in which the wavelength is shorter than cable cutoff wavelength of PureAdvance (λcc, max. 1530 nm). In this section, we experimentally evaluate the Raman gain and its fluctuation when the pump wavelength is shorter than λcc, to confirm the applicability of Raman amplification to PureAdvance.

Figure 5 shows the measured spectra of Raman gain coefficients g_R/A_{eff} of PureAdvance-110 with λcc of 1530

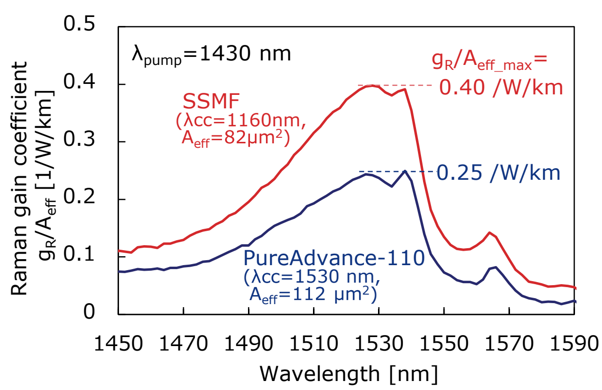

Fig. 5. Measured Raman gain coefficient

nm, which is near the maximum value in G.654.E recommendation, and SSMF with λcc of 1160 nm, as a reference.(10) The length of each fiber was 50 km, and the pump wavelength was 1430 nm. In Fig. 5, PureAdvance-110 shows the smaller Raman gain coefficient, which is about 63% (= 0.25/0.40) of that of SSMF. Here, g_R is mainly determined by the core material, and PSCF typically has smaller g_R (2.8×10^{-20} m/W for PSCF, 3.2×10^{-20} m/W for SSMF. 2.8/3.2 = 87%). In addition, A_{eff} of the fundamental mode of PureAdvance-110 is larger than that of SSMF (112 μm²/82 μm² = 137%). Since the smaller g_R/A_{eff} can be explained with only the smaller g_R and larger A_{eff} (87%/137% = 63%), no degradation due to higher order modes is observed, even though the pump wavelength is shorter than λcc.

(2) Raman gain fluctuation

Next, we evaluated the fluctuation of Raman gain (difference between maximum and minimum signal powers in 30 minutes) for PureAdvance-110 with λcc of 1405 nm, a fiber which has equivalent characteristics with PureAdvance-110 but whose λcc of 1531 nm is longer than the maximum value of G.654.E (hereinafter "PSCF-1531"), and SSMF with λcc of 1238 nm. The fiber length was 50 km each. The measurement setup is shown in Fig. 6 (a). The pump power and wavelength were 1 W and 1455 nm, respectively. In order to consider an extremely severe environment where the pump can easily couple to higher order modes, the fiber was cut and spliced with an intentional core offset at two places near the pump input end. The spacing between two splices was about 2 m, and the losses of the offset splices were about 1 dB. Figure 6 (b) shows the measured Raman gain fluctuation.(10) The Raman gain fluctuation of PSCF-1531 was slightly larger than that of SSMF. However, it was as small as below 0.4 dB even for the extremely severe environment with offset splices.

Reference (11) reports 400 Gb/s signals transmission over a Raman-amplified 150 km-long G.654.E optical fiber with λcc of around 1530 nm. Here, an offset splice was applied, and the ambient temperature was varied from −10 to +40°C. Even for such a severe environment, error-free and stable transmission was demonstrated over a long hour.(11) Thus, Raman gain fluctuation would be negligibly small even in such extremely severe environments.

If a part of Raman pump with the wavelength shorter than λcc propagates as higher order modes, one might concern that the Raman gain is unexpectedly degraded since higher order modes generally have much larger A_{eff} than that of the fundamental mode. Furthermore, Raman gain might fluctuate due to interferences with higher order modes. However, we have confirmed from the experimental results shown in this section that the degradation and fluctuation of Raman gain are negligible for practical use, even if the pump wavelength is shorter than λcc. Therefore, Raman amplification can be applied to PureAdvance.

(3) Transmission performance in hybrid EDFA/Raman-amplified system

In order to quantitatively evaluate the transmission performance of PureAdvance, we calculated the transmission reach in hybrid EDFA/Raman-amplified transmission systems.

The transmission reach for EDFA/Raman-amplified system can be calculated based on Gaussian noise model(12), assuming that EDFA noise, nonlinear noise, and Raman amplification noise are additive Gaussian noises.(13),(14) Figure 7 shows calculation results of the transmission reach of 200 Gb/s WDM signals for SSMF, non-zero DSF (NZDSF), and PureAdvance with EDFA-only and hybrid EDFA/Raman amplification. The span length was 100 km. Here, similar splices at every 4 km and dissimilar splices to SSMF pigtails at both ends of the span were taken into account. Raman pump power was 500 mW, and the wavelength was 1450 nm.

With EDFA-only amplification, PureAdvance-80 shows longer reach by 1.4 times compared to SSMF due to the low attenuation. PureAdnvace-110 and PureAdnvace-125 having low attenuation and low nonlinearity can achieve the further long reach of 1.9 to 2.1 times compared to SSMF.

Furthermore, with hybrid EDFA/Raman amplification, PureAdvance-110 can extend the transmission reach by 3.9 times compared to SSMF with EDFA-only. Although PureAdvance-110 with larger A_{eff} has smaller Raman gain than that of SSMF, as shown in Fig. 5, Raman amplification noise can also be reduced with larger A_{eff}. Therefore the transmission reach can be improved effectively. Meanwhile, the reach improvement from PureAdvance-110 to PureAdvance-125 would be only 1.03 times, because the

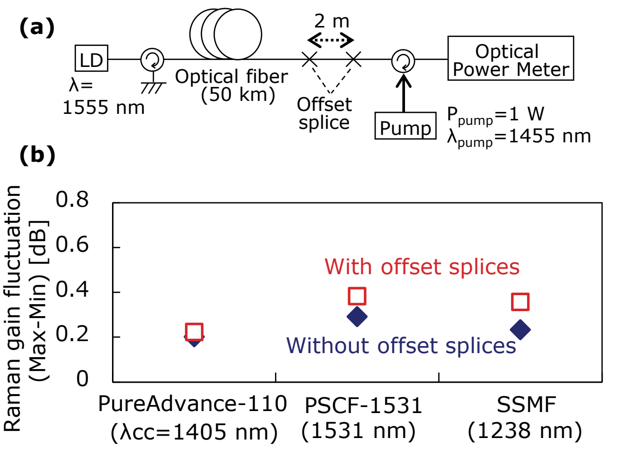

Fig. 6. (a) Measurement setup and (b) results for Raman gain fluctuation

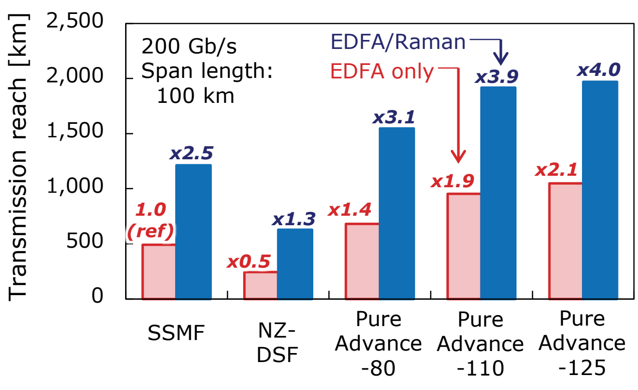

Fig. 7. Transmission reach for PureAdvance

Raman gain is significantly reduced for PureAdvance-125 with further large A_{eff}.

PureAdvance-110 should be the most practical and ideal optical fiber for actual terrestrial long-haul links due to practical and reliable terrestrial cabling, low loss splices between similar fibers and with SSMF/submarine fibers, and the high transmission performance in EDFA/Raman-amplified systems, as discussed in this chapter.

4. Advantages of Systems Using PureAdvance

This chapter discusses expected advantages of transmission systems using PureAdvance-110 for three use cases by calculating the transmission reach based on the Gaussian noise model.[(12)–(14)]

4-1 Use case 1: Reduction in the number of repeaters in ultra-long-haul 100 Gb/s transmission system

We consider that 100 Gb/s WDM signals are transmitted over an EDFA-only amplified ultra-long-haul optical transmission link with the reach of 5,000 km, as shown in Fig. 8. If SSMF is used for this system, all the span lengths should be 80 km or less to achieve error-free transmission over the 5,000 km-reach (i.e., the required number of repeaters is 62). On the other hand, by applying PureAdvance-110 having low attenuation and low nonlinearity instead of SSMF, eight repeaters can be skipped while keeping the equivalent signal quality (i.e., length of eight spans can be extended to 160 km). By reducing the number of repeaters, costs for repeater itself, power supply, and maintenance of the facilities can be reduced.

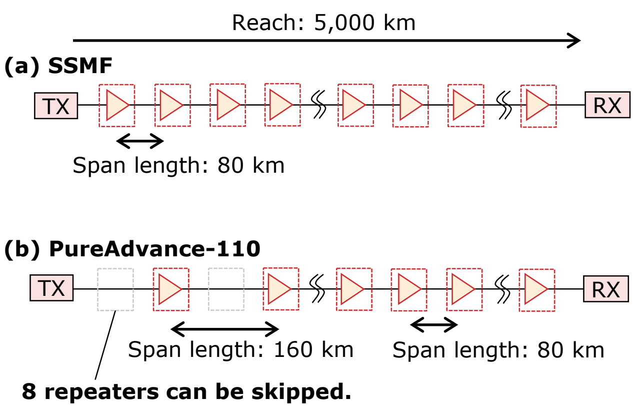

Fig. 8. Use case 1: Ultra long haul 100 Gb/s transmission system (Reach: 5,000 km, Repeater: EDFA only)

4-2 Use case 2: Reduction in the number of regenerators in 400 Gb/s transmission system

Figure 9 shows another use case where WDM signals with the higher bit-rate of 400 Gb/s are transmitted between cities 1,200 km away from each other. Since bit rate and the transmission reach are generally in a trade-off relationship, the reach for SSMF would be limited to 430 km for 400 Gb/s transmission. Therefore, two regenerators will be required to transmit over the distance of 1,200 km for SSMF. On the other hand, PureAdvance-110 can transmit

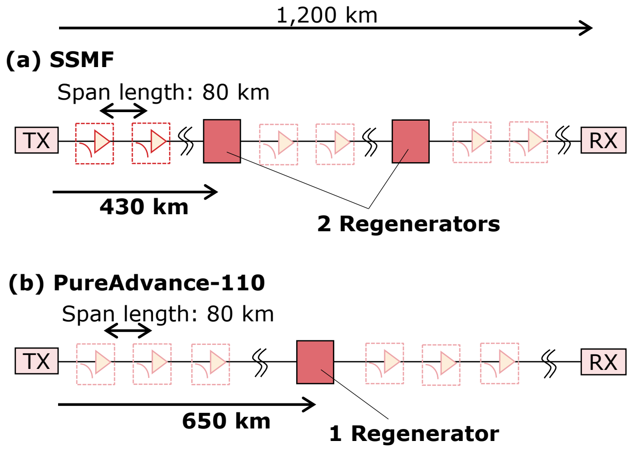

Fig. 9. Use case 2: 400 Gb/s transmission system (Reach: 1,200 km, Repeater: EDFA/Raman)

400 Gb/s signals over 650 km, and can skip one regenerator. Therefore, the costs and power consumption of regenerator can be eliminated. In addition, latency due to the regenerator can also be reduced.

4-3 Use case 3: Elimination of regenerator at submarine cable landing station

Conventionally, most submarine optical cable systems are terminated at landing stations and the signals are transmitted to terrestrial networks after regenerated at the landing stations. On the other hand, recently, there are growing needs for seamless connection to inland data centers by eliminating the regenerator at a landing station.

As shown in Fig. 10, we here assume that 150 Gb/s optical signals are transmitted through a transoceanic submarine optical cable with the distance of 10,000 km, span length of 80 km, cable attenuation of 0.152 dB/km, and A_{eff} of 130 μm^2. The signals are then transmitted through a 120 km-long terrestrial cable of SSMF or PureAdvance-110 from the landing station to an inland data center. If SSMF is used for the terrestrial cable, the transmission reach would be limited to 95 km, because the signals already deteriorate significantly due to the ultra-

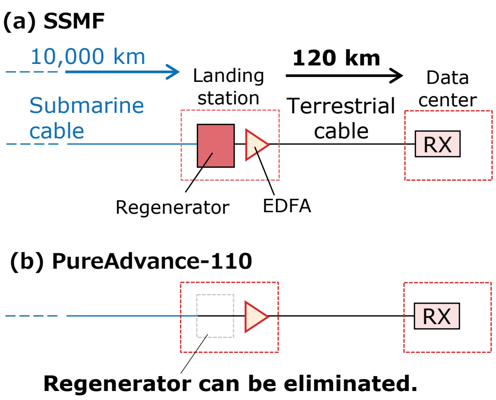

Fig. 10. Use case 3: Transmission between Submarine landing station and data center (150 Gb/s, Submarine cable: 10,000 km, 80 km-span, Terrestrial cable: 120 km unrepeated)

long haul transmission in the submarine cable. Therefore, regenerator would be required at the landing station to transmit signals to the data center. On the other hand, PureAdvance-110 can transmit the deteriorated signals over 120 km without regenerator at the landing station. Therefore, seamless connection between international data centers can be realized, and the system costs and latency can be reduced.

5. Conclusion

Sumitomo Electric has developed and started supplying PureAdvance, a low-loss optical fiber for terrestrial long haul networks. PureAdvance is an ideal fiber for terrestrial long-haul links because it has high transmission performance and excellent practicality including practical and reliable terrestrial cabling, low splice losses, and stable Raman amplification. Transmission systems using PureAdvance can reduce the number of repeaters or regenerators, and the total system cost can be reduced.

Sumitomo Electric will continue to develop low-loss optical fiber technology and mass production technology to offer products that meet the needs of society.

Technical Term

*1 ITU-T G.654.E: ITU-T (International Telecommunications Union Telecommunication Standardization Sector) is a United Nations agency that develops international standards for ICT infrastructure, known as ITU-T recommendations. G.654 is an ITU-T recommendation that describes cut-off shifted fibers and cables. G.654.E is one of the subcategories, and describes the optical fibers and cables to support 100 Gb/s and beyond 100 Gb/s digital coherent transmission systems in terrestrial deployments.

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