Low-Loss and Low-Nonlinearity Pure-Silica-Core Fiber for Large Capacity Transmission

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This paper presents new low-loss and low-nonlinearity pure-silica-core fibers to be used for submarine and terrestrial long haul transmission systems. For large-capacity and ultra-long haul submarine systems, Z-PLUS Fiber LL with a loss of 0.162 dB/km and Z-PLUS Fiber 130 with a large effective area (Aeff) of 130 μm^2 are ideal due to their improved optical signal-to-noise ratio. For terrestrial long haul systems, on the other hand, PureAdvance-80 and PureAdvance-110 with a loss of 0.17 dB/km and an Aeff of 80 and 110 μm^2 respectively are advantageous due to their capabilities of long span length or long transmission reach.

Keywords: pure-silica-core fiber, low loss, large effective area

1. Introduction

To keep up with the exponential growth of data network traffic, large transmission capacity per a fiber is strongly needed for optical communication systems. Recent progress in the transmission capacity mainly relies on multi-level modulation techniques with digital coherent detection. However, the larger capacity transmission over long distance requires higher optical signal-to-noise ratio (OSNR)[(1)]. Although there would be several techniques to improve the OSNR, the use of low-loss and low-nonlinearity fiber would be one of the most effective solutions to improve the OSNR[(2)].

Pure-silica-core fiber (PSCF), which has been known to have inherently low attenuation[(3)], would be a promising candidate for the low-loss and low-nonlinearity fiber. Since 1980's[(4)], Sumitomo Electric Industries, Ltd. has continuously developed and proposed several types of PSCFs[(5)-(9)], including a record-low attenuation PSCF[(5)]. In fact, Sumitomo Electric has supplied PSCF products, Z Fiber and Z-PLUS Fiber for many years to submarine optical fiber cable industries by virtue of the low attenuation. However, there is a continuous need for lower attenuation and lower nonlinearity of fiber to realize further large capacity transmission over long distance. This is by no means a particular requirement for submarine applications. With the growing demand for the large volume of data traffic, OSNR improvement with low-loss and low-nonlinearity fiber would become increasingly important for terrestrial long haul applications as well.

In this paper, we first show that requirement for optical fibers have been dramatically changed to low loss and low nonlinearity. Then, we introduce Z-PLUS Fiber LL with lower attenuation and Z-PLUS Fiber 130 with lower nonlinearity as improved submarine PSCFs. Terrestrial PSCFs, PureAdvance-80 and PureAdvance-110 are also newly developed to support terrestrial long haul systems. In addition, we quantitatively discuss the impact on OSNR improvement of the low-loss and low-nonlinearity PSCFs, and present possible benefits for terrestrial long haul systems in views of the increase of span length or transmission distances.

2. OSNR Improvement with Low-Loss and Low-Nonlinearity Fiber

The needs for low-loss and low-nonlinearity fiber are rapidly increasing along with the recent progress of digital coherent techniques. In conventional systems, chromatic dispersion and polarization mode dispersion (PMD), which cause linear impairments of optical signal waveforms, have been suppressed within the optical transmission line by using dispersion shifted fiber (DSF), non-zero dispersion shifted fiber (NZDSF) or dispersion compensating fiber (DCF). On the other hand, in the digital coherent systems, chromatic dispersion and PMD are no longer obstacles because the linear impairment due to the accumulated dispersion and PMD can be equalized by a digital signal processor at the digital coherent receiver. In consequence, higher OSNR becomes the most relevant requirement for the optical transmission line, and low attenuation and low nonlinearity of fiber are strongly required to improve the OSNR.

Figure 1 shows the schematic of the OSNR improvement by low loss and low nonlinearity of fiber. OSNR at the receiver is given by the ratio of signal output power and

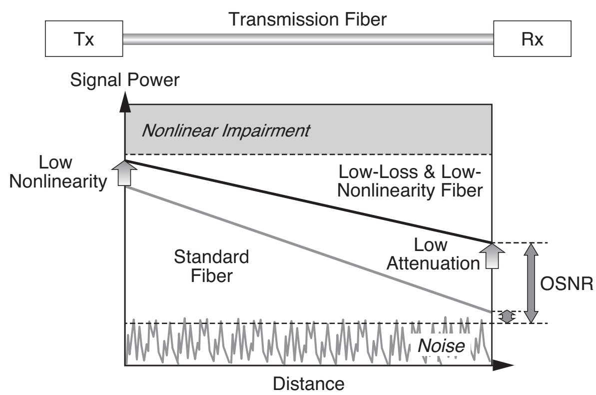


Fig. 1. Schematic of OSNR improvement by low attenuation and low nonlinearity of fiber

noise level. Lower attenuation can directly increase the output power for a fixed input power. On the other hand, the signal input power is limited by nonlinear impairment because nonlinear phenomena due to Kerr effect in fiber, such as self-phase modulation (SPM), cross-phase modulation (XPM) and four wave mixing (FWM), cause the signal distortion with high input signal power. The lower nonlinearity of the fiber allows the higher threshold of the signal input power, and then improves the OSNR.

Actually, at OFC/NFOEC2012, which is one of the largest technical conferences in the optical communication industry, all large-capacity (with a bit rate of higher than 100 Gb/s per channel) and long-distance (with a transmission distance of longer than 1000 km) transmission experiments with digital coherent detection have used the low-loss and low-nonlinearity fibers as transmission lines without in-line dispersion compensation[10].

3. Characteristics of Low-Loss and Low-Nonlinearity PSCFs

3-1 Low-loss and low-nonlinearity PSCFs

Table 1 shows the lineup of our PSCFs and their typical characteristics at wavelength of 1550 nm. Among the PSCFs listed in **Table 1**, Z Fiber and Z-PLUS Fiber have been supplied to submarine optical fiber cable industries since 1980's. Here, we introduce improved submarine PSCFs, Z-PLUS Fiber LL with lowered attenuation of 0.162 dB/km and Z-PLUS Fiber 130 with larger effective area (Aeff) of 130 μm^2 to further reduce the nonlinearity.

PureAdvance-80 and PureAdvance-110 have also been newly developed to support terrestrial long haul systems. PureAdvance-80, which is fully compliant with ITU-T G.652 recommendation, has the lower attenuation of 0.17 dB/km, while keeping the compatibility with standard single mode fiber (SSMF). PureAdvance-110 has the enlarged Aeff of 110 μm^2 to reduce the nonlinearity, and it would be suitable for longer distance and larger capacity transmission in terrestrial networks.

In the following subsections, we introduce the technologies for reduction of the fiber attenuation and nonlinearity.

3-2 Reduction of fiber attenuation

In order to reduce the fiber attenuation, it is essential to reduce the Rayleigh scattering loss that dominates about 80% of the fiber attenuation at 1550 nm. Rayleigh scattering results from the dopant concentration fluctuation and the density fluctuation of the glass composition. Therefore, the use of pure-silica glass with no dopant as the core must be the best solution to eliminate the dopant concentration fluctuation. Whereas the Rayleigh scattering coefficient and the attenuation of SSMF with GeO_2-doped core are typically 0.94 dB/km/μm^{-4} and 0.19 dB/km at 1550 nm, those of Z-PLUS Fiber are 0.84 dB/km/μm^{-4} and 0.168 dB/km, respectively. In addition, by suppressing the density fluctuation in PSCF, we have realized the mass production of Z-PLUS Fiber LL with the attenuation of as low as 0.162 dB/km and Rayleigh scattering coefficient of 0.80 dB/km/μm^{-4}. **Figure 2** shows the attenuation spectra of

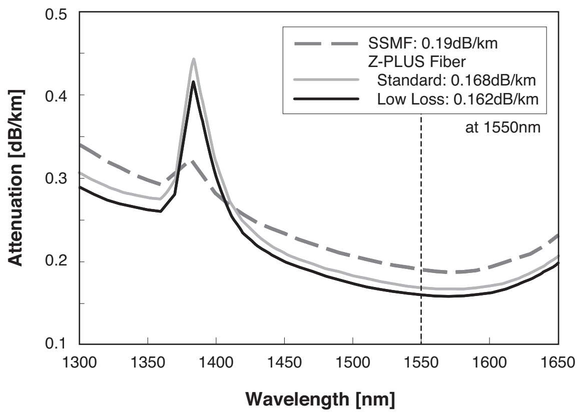
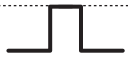
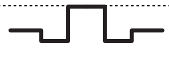
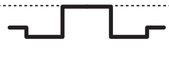
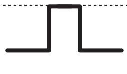
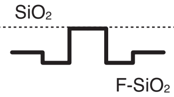


Fig. 2. Attenuation spectra of SSMF, Z-PLUS Fiber and Z-PLUS Fiber LL

Table 1. Sumitomo Electric low-loss and low-nonlinearity PSCFs and their typical characteristics at 1550 nm

Application	Long haul / metro / access (reference)	Submarine			Terrestrial Long-Haul	
Product Name	PureBand	Z Fiber	Z-PLUS Fiber	Z-PLUS Fiber 130	PureAdvance-80	PureAdvance-110
ITU-T Rec.	G.652.D	G.654.C	G.654.B	G.654.B	G.652.B	G.654.B
Refractive Index Profile	Step 	Step 	Depressed Cladding 	Depressed Cladding 	Step 	Depressed Cladding 
Attenuation [dB/km]	0.19	0.170	0.168 (Std.) 0.162 (LL)	0.162	0.17	0.168
Aeff [μm^2]	80	78	112	130	80	110
n_2 [$\times10^{-20}$m^2/W]	2.34	2.2	2.2	2.2	2.2	2.2
Dispersion [ps/nm/km]	17	18.5	20.5	20.5	16	20.5

SSMF, Z-PLUS Fiber and Z-PLUS Fiber LL.

3-3 Reduction of fiber nonlinearity

The nonlinear coefficient of fiber γ [1/W/km] is given by

$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{Aeff} \quad \cdots\cdots (1)$$

where n_2 [m^2/W] is an nonlinear refractive index, Aeff [μm^2] is an effective area, λ [nm] is wavelength. From **Eq.(1)**, there would be two approaches to reduce the fiber nonlinearity. One is the reduction of n_2 to reduce the nonlinearity of the glass material itself. Another one is the enlargement of Aeff to reduce the optical power density in the core. Since PSCF generally has about 9% lower n_2 than SSMF(11), PSCF would also be preferable to reduce the fiber nonlinearity.

The enlargement of Aeff would be mainly limited by degradations of the macro- and microbending performances because the light confinement in the core becomes weaker for larger Aeff fibers. In order to improve the macrobending performances of large Aeff fibers, we have employed depressed cladding index profile for Z-PLUS Fiber, Z-PLUS Fiber 130 and PureAdvance-110, as shown in **Table 1**.

On the other hand, the microbending loss is caused by small random deformations of the fiber axis in an installed cable. We have applied a lower Young's modulus primary coating to mitigate the deformation of the fiber(8). **Figure 3** shows the measured microbending losses as a function of Aeff for fibers with the low modulus and conventional primary coatings. Here, the microbending loss was characterized by a wire mesh bobbin test with wound tension of 80 g(12). Although the microbending loss increases with larger Aeff, the lower modulus coating can significantly reduce the microbending loss compared to that with the conventional coating, as shown in **Fig. 3**. By applying the lower modulus coating, we have successfully developed Z-PLUS Fiber 130 with enlarged Aeff of 130 μm^2 while keeping the equivalent microbending performance to Z-PLUS Fiber with conventional coating that has been deployed in actual submarine cables for many years(8).

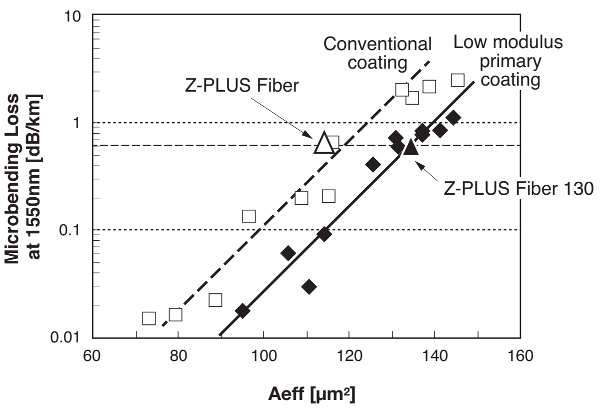


Fig. 3. Microbending loss for fibers with low Young's modulus primary and conventional coatings

3-4 Long haul and large capacity transmission experiments with the low-loss and low-nonlinearity PSCFs

The transmission performances of the low-loss and low-nonlinearity PSCFs have been experimentally demonstrated by several system suppliers. **Table 2** summarizes the recently-reported long haul and large capacity transmission experiments with digital coherent detection using our PSCFs. References 13 and 14 have demonstrated ultra-long haul transmissions of 100 Gb/s signals over more than 7000 km(13),(14). Here, dual polarization quadrature phase shift keying (DP-QPSK), which started commercial operations as the suitable format for 100 Gb/s line rate, has been used. The record distance of 462 km for 100 Gb/s unrepeated transmission has also been achieved(15). As a next generation signal format, DP-16-state quadrature amplitude modulation (DP-16QAM) would be a promising solution to increase the line rate to 200 Gb/s or 400 Gb/s. DP-16QAM signals have been transmitted over longer than 1200 km, indicating the feasibility of applying the format to terrestrial long haul systems(16),(17). The record capacity and distance products for unrepeated transmission have also been demonstrated with DP-16QAM format and Z-PLUS Fiber 130(18). Furthermore, our PSCF has also been used for 1 Tb/s superchannel transmission(19), which is actively studied as a future large capacity transmission technology.

Table 2. Recently-reported long haul and large capacity transmission experiments with the low-loss and low-nonlinearity PSCFs

Ref.	Fiber	Experiments
(13)	Z-PLUS Fiber	155ch × 100Gb/s DP-QPSK 7,200km Transmission
(14)	Z-PLUS Fiber 130	11ch × 112Gb/s DP-QPSK 8,500km Transmission
(15)	Z-PLUS Fiber 130	4ch × 100Gb/s DP-QPSK 462km Unrepeated Transmission
(16)	Z-PLUS Fiber 130	16ch × 224Gb/s DP-16QAM 1,280km Transmission
(17)	Z-PLUS Fiber 130	5ch × 448Gb/s dual-carrier DP-16QAM 1,230km Transmission
(18)	Z-PLUS Fiber 130	80ch × 224Gb/s DP-16QAM 240km Unrepeated Transmission
(19)	Z-PLUS Fiber	1Tb/s-Superchannel (10ch × 120G-DP-QPSK) 10,000km Transmission

4. Splice Performance of Low-Loss and Low-Nonlinearity PSCF

Whereas the enhancement of Aeff is an effective way to reduce the nonlinearity as described so far, it is noted that much larger Aeff may degrade dissimilar splice loss to SSMF unacceptably due to the larger mismatching of mode field diameter (MFD). In actual systems, both ends of a transmission fiber would be spliced to SSMF because most of pigtails of optical amplifiers and equipment are made with SSMF today. If the dissimilar splice loss to SSMF becomes larger, OSNR of the system can be degraded eventually. Therefore, dissimilar splice loss to SSMF would be also one of the important fiber properties.

We have here examined the splice loss between low-loss and low-nonlinearity PSCFs and SSMF with Aeff of 80 μm^2 by using a commercial fusion splicer with a SMF-standard setting. **Figure 4** shows the measured average, maximum and minimum splice losses for each set of 20 splices. A solid curve in **Fig. 4** shows the dissimilar splice loss calculated from the degradation of the coupling efficiency due to the MFD mismatching. As shown in **Fig. 4**, the splice loss is mainly caused by the MFD mismatching, which would be unavoidable for the larger Aeff fibers. The average splice loss for PureAdvance-110 and Z-PLUS Fiber 130 are about 0.1 dB and 0.2 dB, respectively. Meanwhile, the splice loss would be increased to more than 0.3 dB for fibers with Aeff larger than 150 μm^2. In addition, considering the loss increase due to the cabling or packaging for much larger Aeff fiber, Aeff of 110-130 μm^2 would be appropriate for practical use.

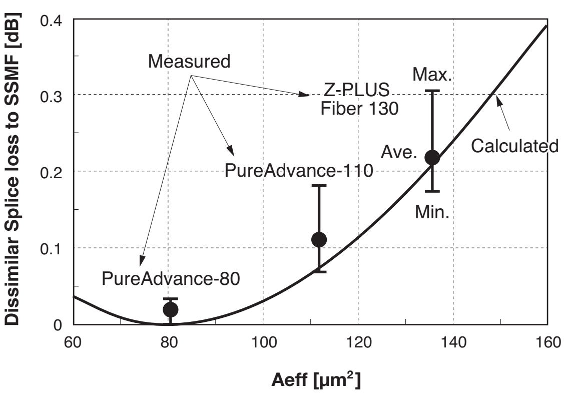


Fig. 4. Splice loss between low-loss and low-nonlinearity PSCFs and SSMF

5. Possible Benefits of Low-Loss and Low-Nonlinearity PSCFs on Transmission Systems

5-1 Impact on OSNR improvement

The amount of OSNR improvement is quantitatively discussed to compare the transmission performances of low-loss and low-nonlinearity fibers in digital coherent systems. Maximized OSNR ($OSNR_{max}$) for transmission fibers having different characteristics has been analytically formulated[20], and can be described as

$$OSNR_{\max}\,[dB] = \frac{10}{3}\log\left(|D| \times L_{eff}\right) - \frac{20}{3}\log\left(\gamma \times L_{eff}\right) - \frac{2}{3}\alpha L - \frac{2}{3}\alpha_{sp} - 10\log\left(N_s\right) + C \quad \cdots (2)$$

where D [ps/nm/km], L_{eff} [km], α [dB/km], L [km], α_{sp} [dB], N_s are chromatic dispersion, effective length, fiber attenuation, span length (distance between repeaters), dissimilar splice loss to SSMF, and the number of spans (the total distance divided by the span length), respectively. C is a non-fiber coefficient determined by the transmission system. The right side of **Eq.(2)** correspond to the effects of large dispersion, low nonlinearity, low attenuation and low dissimilar splice loss, and degradation due to accumulated amplifier noise from repeaters, respectively. It is also noted that larger chromatic dispersion would be more preferable to suppress the phase matching between signal channels and then reduce the nonlinear impairment. By using **Eq.(2)**, **Fig. 5** shows a contour map of the relative OSNR normalized to that for SSMF (α = 0.19 dB/km, D = 17 ps/nm/km, Aeff = 80 μm^2, $n_2 = 2.34 \times 10^{-20}$ m^2/W) as a function of Aeff and attenuation for a transmission link with a total distance of 1500 km and a span length L of 80 km. Here, D and n_2 are fixed to 21 ps/nm/km and 2.2 × 10^{-20} m^2/W, respectively. From **Fig. 5**, both of low attenuation and large Aeff are beneficial to increase the OSNR. Z-PLUS Fiber LL and Z-PLUS Fiber 130 are expected to have 2.7 dB and 3.1 dB OSNR improvement compared to SSMF, respectively.

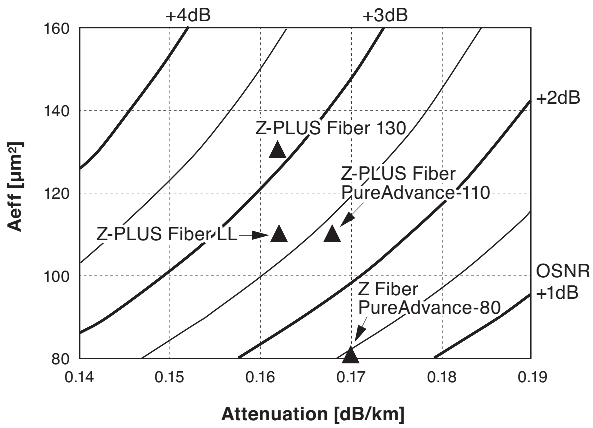


Fig. 5. Relative OSNR normalized to that for SSMF in a 1500km-reach transmission link with 80km-span

5-2 Increase in transmission distance with low-loss and low-nonlinearity PSCF

$OSNR_{max}$ in **Eq.(2)** would be directly correlated to the maximum feasible transmission distance and span length. Therefore, the maximized span length or transmission distance can be predicted from **Eq.(2)** for different fibers with a same transmission system by using the fiber parameters, such as attenuation, Aeff, chromatic dispersion, and dissimilar splice loss[20]. We calculate the impact on the increase in the maximum span length and transmission distance of PureAdvance-80 and PureAdvance-110 in terrestrial long haul systems. It is noted that the length of cable on a single spool would be generally limited to a few km in actual terrestrial transmission lines, and there would be a lot of cable splice points. Therefore, the loss increase due to the cable splice should be considered. For example, field installed cable with an average loss of 20.8 dB per 79.1 km-long span, which is equal to 0.26 dB/km, has been reported[21]. Since the typical loss of today's SSMF is about 0.19 dB/km, the loss increase in field installed cable is assumed to be +0.07 dB/km for every fiber in our calculations.

Figure 6 shows the calculated maximum span length in a 1500 km-long link transmitting 100 Gb/s DP-QPSK signals for SSMF, NZDSF (α = 0.20 dB/km, D = 4.0 ps/nm/km, Aeff = 70 μm^2, $n_2 = 2.36 \times 10^{-20}\ m^2/W$), PureAdvance-80, and PureAdvance-110. The maximum span length is decided after **Eq.(2)** assuming the Q-factor of 11 dB. We calculate the maximum span length for both with and without distributed Raman amplification (DRA). 2 dB OSNR improvement is considered for links with DRA. From **Fig. 6**, whereas the span length for SSMF is 96 km with DRA, PureAdvance-110 can increase the span length to 102 km without DRA. In addition, the span length can be extended to 119 km by combining DRA. This means the considerable increase in span length of 21 km and 44 km compared to SSMF and NZDSF, respectively.

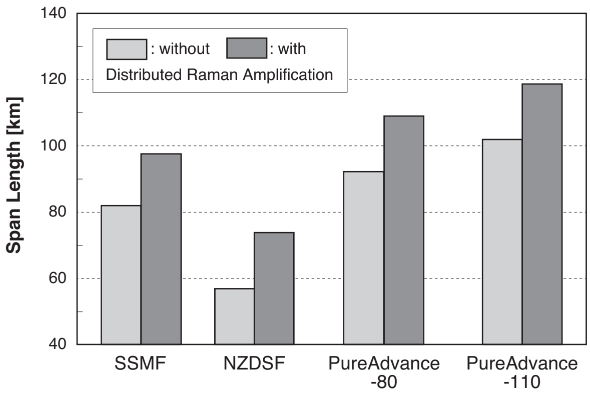


Fig. 6. Maximum span length for a 1500km transmission link with 100 Gb/s DP-QPSK format

Figure 7 shows the calculated maximum transmission distance with a fixed span length of 80 km for 100 Gb/s DP-QPSK signals. From **Fig. 7**, PureAdvance-110 can increase the maximum transmission distance to longer than 2600 km without DRA, and it can reach to 4200 km or longer by combining DRA. The distances correspond to as much as 1.7 times and 3.4 times of those of SSMF and NZDSF, respectively. From these results, PureAdvance-110 should be best suited to terrestrial long haul systems due to the capability of significant increase in span length or transmission distance.

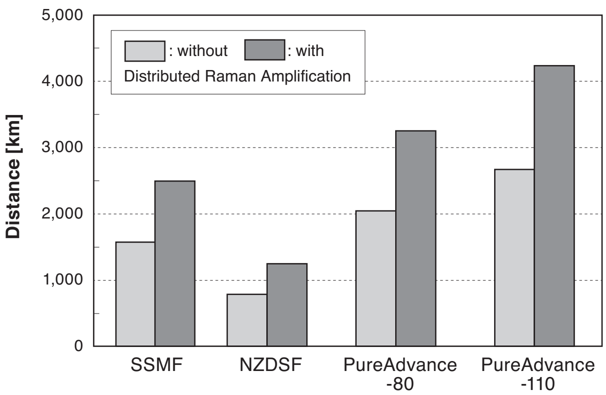


Fig. 7. Maximum transmission distance for a 80 km-span link with 100 Gb/s DP-QPSK format

6. Conclusion

We have introduced newly-developed low-loss and low-nonlinearity PSCFs for large capacity transmission systems with digital coherent detection. In addition, the possible benefits in significant increase of the span length or transmission distance have been presented based on the OSNR improvement. Low-loss and low-nonlinearity PSCFs are most promising for next generation fiber to support long haul and large capacity transmissions in both submarine and terrestrial long haul systems.

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