Ultra Low-loss Pure Silica Core Fiber

Yuki KAWAGUCHI*, Yoshiaki TAMURA, Tetsuya HARUNA, Yoshinori YAMAMOTO and Masaaki HIRANO

To keep up with the exponential growth of demand for internet traffic, large capacity transmission systems applied digital coherent technologies have begun operating recently. The major challenge in such systems is to improve optical signal-to-noise ratio (OSNR). In order to improve the OSNR, optical fibers with low transmission loss and large effective area (Aeff) are in strong demand. This paper reports on a pure-silica-core fiber (PSCF) with the record-low loss of 0.149 dB/km, which is the first fiber having a loss less than 0.150 dB/km at 1550 nm. The development of Z-PLUS Fiber ULL (Aeff = 112 µm^2) and Z-PLUS Fiber 130 ULL (Aeff = 130 µm^2), both of which have an extremely low transmission loss of 0.154 dB/km on average, is also described. Exhibiting the highest fiber figure-of-merit (FOM), they will be suitable for high capacity and long haul submarine transmission systems applied digital coherent technologies.

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

1. Introduction

In order to keep up with exponential growth of global telecom traffic, high capacity submarine systems have been actively deployed based on 100 Gb/sec digital coherent technologies. A major challenge for realizing such high capacity ultra-long haul systems is to improve system optical signal-to-noise ratio (OSNR). Therefore, there is a strong demand for fibers having low loss and low nonlinearity, and various fibers have been proposed(1)-(3). Pure-silica-core fiber (PSCF), which has inherently low transmission loss, is a promising candidate for the low-loss and low-nonlinearity fiber. Since the 1980's, Sumitomo Electric Industries, Ltd. has continuously developed and proposed several types of PSCFs, including ultra low loss PSCFs. **Figure 1** shows the historical loss improvement of our research-based PSCFs (◇) and PSCF products (◆). We successfully realized ultra low-loss of 0.154 dB/km in 1986(4) and 0.150 dB/km in 2002(5). We also released several PSCF products, Z Fiber with the typical loss of 0.170 dB/km in 1988, Z-PLUS Fiber (0.168 dB/km) in 2002, and Z-PLUS Fiber LL (0.162 dB/km) in 2011. In fact, we have supplied these PSCF products for more than 20 years to submarine optical fiber cable industries by virtue of the low loss.

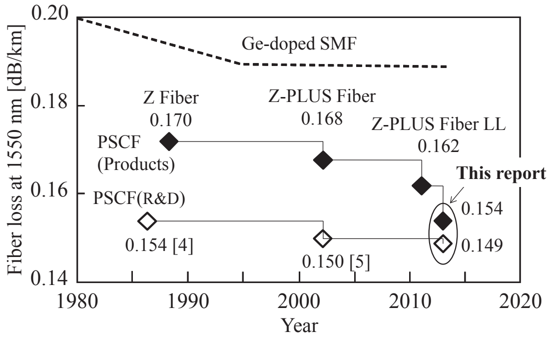


Fig. 1. Historical loss improvement of PSCFs

However, further lowering loss and nonlinearity have still been strongly demanded for realizing higher capacity transmissions over transoceanic distances. In this paper, we report the realization of PSCF with a record-low loss of 0.149 dB/km at 1550 nm. This is the first fiber having a loss of less than 0.150 dB/km at 1550 nm, 11 years after we reported the loss of 0.150 dB/km. Moreover, according to the fiber figure-of-merit (FOM) calculation(6)-(9), we show that fibers with possible low loss and appropriately enlarged effective area (Aeff) of 110 to 140 µm^2 would be optimal for submarine long haul links. Based on the results, we introduce new ultra low-loss PSCF products, Z-PLUS Fiber ULL (Z+ ULL) with Aeff of 112 µm^2 and Z-PLUS Fiber 130 ULL (Z+130 ULL) with Aeff of 130 µm^2. These new PSCFs have an ultra low-loss of 0.154 dB/km on average based on mass-production process over accumulated length of 25,000 km. Furthermore, we confirm their high mechanical reliability and environmental durability.

2. Fabrication of Ultra Low-loss PSCF

In order to reduce fiber loss, it is essential to reduce the Rayleigh scattering loss that dominates about 80% of fiber loss at 1550 nm. The Rayleigh scattering results from microscopic non-uniformity of refractive index, due to dopant concentration and glass-density fluctuation. Therefore, the use of pure silica glass with no dopant as the core material must be the best solution to eliminate the dopant concentration fluctuation. In addition, by suppressing the density fluctuation in the glass composition, we realized a PSCF with the record-low loss of 0.149 dB/km at 1550 nm. This is the first fiber having a loss less than 0.150 dB/km at 1550 nm. Its loss spectrum is shown in **Fig. 2**, along with one of a standard single mode fiber (SSMF). The fiber characteristics are summarized in **Table 1**. To reduce the nonlinearity, Aeff has been enlarged to 135 µm^2. It is also noted that a high chromatic dispersion is preferable for suppressing nonlinear effects such as cross phase modulation (XPM) and four wave mixing (FWM). The chromatic dispersion of the PSCF is as large as 21 ps/(nm•km), which almost reaches the material dispersion of silica of about 22 ps/(nm•km). In Aeff enlarged fibers, degradation of the fiber loss due to bending losses is of concern. In **Fig. 2**, 20 km-long ultra low-loss PSCF was spooled on a bobbin with a 170 mm-diameter barrel, and there was no obvious degradation due to macro- and micro-bending losses even in a longer wavelength range. In order to improve the macro bending performance of such a large Aeff fiber, we have applied a depressed cladding index profile$^{(10)}$. The macro bending loss of the PSCF is well suppressed to a lower level than that of a SSMF, as shown in **Table 1**.

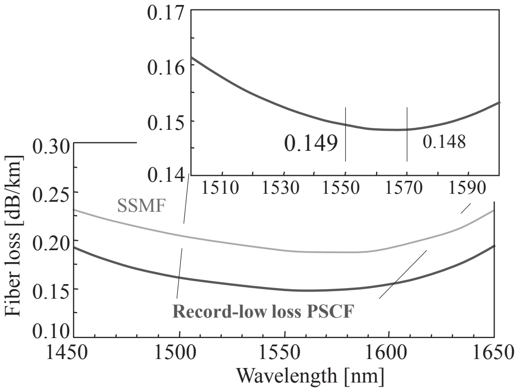


Fig. 2. Loss spectra of ultra low-loss PSCF and SSMF

Table 1. Characteristics of fabricated PSCF at 1550 nm

	PSCF	SSMF
Fiber loss [dB/km]	0.149	0.190
Aeff [µm^2]	135	80
Dispersion [ps/(nm•km)]	21.0	16.8
Dispersion slope [ps/(nm^2•km)]	0.061	0.059
Macro-bending loss (R=10mm) [dB/m]	4	7

For the ultra low-loss PSCF, we employed a ring-core refractive index profile having a center core slightly doped with fluorine, surrounded by a pure-silica ring-core, as shown in **Fig. 3**. A ring-core profile gives a better dissimilar-splice performance to a SSMF than that of a step-core profile having the same value of enlarged Aeff$^{(1)}$. **Figure 4** shows Aeff dependence of dissimilar-splice loss between a SSMF and fibers having step- and ring-core profile. For example, in fibers with the same Aeff of 130 µm^2, dissimilar-splice loss of the ring-core profile is 0.02 dB/facet-lower than that of a step-core profile.

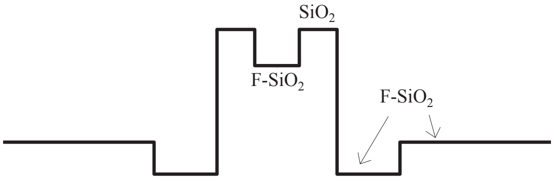


Fig. 3. Schematic refractive index profile

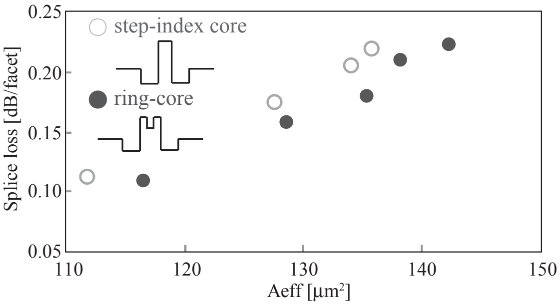


Fig. 4. Aeff dependence of dissimilar-splice loss to SSMF

3. Optimal Fiber Design Based on Fiber FOM

In this section, we analytically develop fiber figure-of-merit (FOM) that can predict the degree of improvement on Q-factor and transmission distance from the fiber characteristics in order to decide an appropriate optical fiber for large capacity and long haul transmission. **Figure 5** shows the block diagram of considered

Table 2. List of symbols

symbol	unit	
α	dB/km	Transmission loss of fiber
α_L	1/km	Transmission loss of fiber $\alpha_L = \frac{\alpha}{10}\ln 10$
α_{span}	dB	Span loss
L_{eff}	km	Effective length(={1-exp(-α_LL)}/α_L)
n_2	m^2/W	Nonlinear refractive index
γ	1/W/km	Nonlinear coefficient (=(2π/λ)×(n_2/Aeff))
D	ps/(nm•km)	Chromatic dispersion
α_{sp}	dB	Coupling loss of fiber to EDFA $\alpha_{sp}=10\log_{10}A_{sp}$
A_{sp}	-	Coupling loss of fiber to EDFA
L	km	Fiber span length
D_T	km	Total transmission distance
N_s		Number of spans
P_{ch}	W	Launched signal power per channel
P_{ASE}	W	Accumulated ASE noise from EDFAs
P_{NLI}	W	Accumulated nonlinear noise
p_{ASE}	W	ASE noise from an EDFA
p_{NLI}	W	Nonlinear noise per span

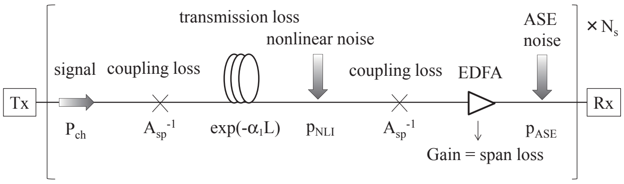


Fig. 5. Block diagram of considered link

link. We assumed a multi-span digital coherent transmission link composed of a transmission fiber, an erbium doped fiber amplifier (EDFA), and coupling losses between them(7)-(9). Symbols used for this formulation are listed in **Table 2**. In this link, signal, ASE noise, and nonlinear noise were assumed as Gaussian shape and they did not interfere each other, and therefore, the OSNR is expressed as(6)

$$OSNR = \frac{P_{ch}}{P_{ASE} + P_{NLI}} \quad \cdots\cdots (1).$$

Using **Eq. (1)**, optimal launched power (P_{opt}) and maximum Q-factor (Q_{MAX}) can be addressed as(8),(9),

$$P_{opt}\,[\mathrm{dBm}] = -\frac{10}{3}\log\left(\gamma^2 L_{eff}|D|^{-1}\right) + \frac{1}{3}\alpha L + \frac{4}{3}\alpha_{sp} + C_1 \quad \cdots\cdots (2)$$

$$Q_{\max}\,[\mathrm{dB}] = -\frac{10}{3}\log\left(\gamma^2 L_{eff}|D|^{-1}\right) - \frac{2}{3}\alpha L - \frac{2}{3}\alpha_{sp} + 10\log(L) - 10\log(D_T) + C_2 \quad \cdots\cdots (3),$$

where C_1 and C_2 are coefficients determined by a transmission system including a Back-to-Back penalty, noise-figure of EDFA, channel bandwidth, and number of channels. If we define fiber FOM as

$$FOM\,[\mathrm{dB}] = -\frac{10}{3}\log\left(\gamma^2 L_{eff}|D|^{-1}\right) - \frac{2}{3}\alpha L + 10\log(L) - \frac{2}{3}\alpha_{sp} \quad \cdots\cdots (4),$$

P_{opt} and Q_{max} can be expressed as

$$P_{opt}\,[\mathrm{dBm}] = FOM - \alpha_{span} - 10\log(L) + C_1 \quad \cdots\cdots (5)$$

$$Q_{\max}\,[\mathrm{dB}] = FOM - 10\log(D_T) + C_2 \quad \cdots\cdots (6).$$

In practical submarine wet-repeaters, EDFA output is generally limited to +16 - +18 dBm in total because of a limitation of electric power supply and broad gain bandwidth. Output per channel in an actual operation condition will be limited to -2 dBm/ch assuming 100-channel WDM transmission. Therefore, actual launched signal power may be less than P_{opt}. At an arbitrary signal power of $P_{ch} = r \cdot P_{opt}$, Q-factor (Q_R) is expressed as(8),(9)

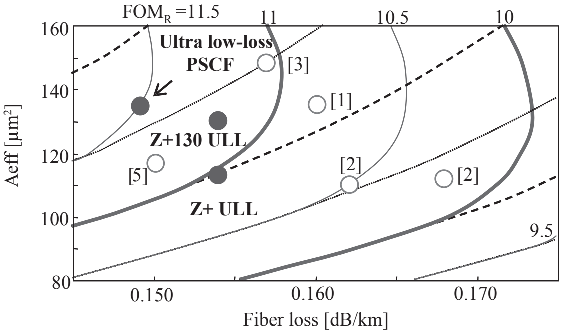
$$\begin{aligned} Q_R &= Q_{\max} + 10\log\left\{3r/\left(r^3+2\right)\right\} \\ &= FOM_R - 10\log(D_T) + C_2 \end{aligned} \quad \cdots\cdots (7),$$

where FOM_R is FOM at arbitrary P_{ch} and can be written as

$$FOM_R = FOM + 10\log\left\{3r/\left(r^3+2\right)\right\} \quad \cdots\cdots (8).$$

As can be seen from **Eqs. (4) and (8)**, FOM and FOM_R are parameters determined by fiber characteristics, span length, and launched signal power. Furthermore, from **Eqs. (6) and (7)**, improvement of Q-factor and/or transmission distance can be predicted easily when using a fiber having different FOM_R in a same system configuration. Alternatively, from **Eq. (4)**, the higher FOM_R achieves a longer span length at the same Q-factor and transmission distance. For example, a fiber having 1 dB-higher FOM_R will realize 10 km-longer span length. This can reduce the number of expensive repeaters, and therefore the total costs would be reduced in ultra long haul submarine transmission systems.

Figures 6 show iso- FOM_R lines as functions of fiber loss and Aeff at L of (a) 80 km and (b) 100 km with solid lines, along with FOM with dashed lines. In this calculation, D = +21 ps/(nm•km) and $n_2 = 2.2\times10^{-20}$ m^2/W were assumed. The coupling loss of a fiber to EDFA was calculated as dissimilar-splice loss from MFD-mismatching between the applied fiber and a SSMF(1),(11). P_{ch} was set as -2 dBm/ch when P_{opt} was calculated to be more than -2 dBm/ch using **Eq. (2)**, otherwise, $P_{ch} = P_{opt}$ (r = 1). C_1 and C_2 were set as -6.6 dBm/ch and 38.4 dB respectively fitted from 100G-QPSK-DWDM transmission experiment in(8),(9),(12). FOM_R of the ultra low-loss PSCF shown in the previous section (●) and reported fibers(1)-(3),(5) (○) are also plotted in **Figs. 6**. It is clearly found from **Figs. 6** that


(a) L=80km

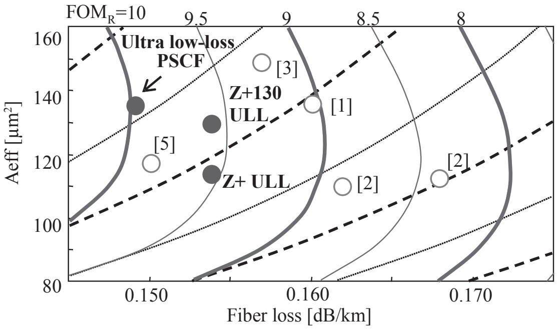

(b) L=100km

Fig. 6. Iso-FOM_R as functions of fiber loss and Aeff at span length of (a) 80 km and (b) 100 km.

the FOM$_R$ improvement is mainly depending on the lowering of fiber-loss. On the other hand, as for the Aeff, there exists an optimal value in which the FOM$_R$ becomes saturated at around 120 to 140 μm^2 for L of 80 km and 110 to 130 μm^2 for L of 100 km.

4. Productivity Verification of Ultra Low-loss PSCF

4-1 Mass production of ultra-low loss PSCF

In order to verify its mass-productivity, we fabricated ultra low loss PSCFs with accumulated length about 25,000 km. In this verification, two types of PSCFs with respective Aeff of 112 μm^2 (Z-PLUS Fiber) and 130 μm^2 (Z-PLUS Fiber 130 ULL) were designed and fabricated to maximize FOM$_R$ for long and short span lengths, respectively, as shown in **Figs. 6**. Typical characteristics of the fibers are summarized in **Table 3**. **Figure 7** shows distribution of fiber loss at 1550 nm over lengths of 25,000 km, and its averaged loss was confirmed to be an ultra-low, 0.154 dB/km. The loss distribution seems to be Gaussian in shape having its standard deviation of less than 0.002 dB/km. Other properties including Aeff, chromatic dispersion, and dispersion slope also showed good stability.

Table 3. Typical characteristics of fabricated PSCF at 1550 nm

	Z-PLUS Fiber ULL	Z-PLUS Fiber 130 ULL
Fiber loss [dB/km]	0.154	0.154
Aeff [μm^2]	112	130
Dispersion [ps/(nm•km)]	20.6	20.7
Dispersion slope [ps/(nm^2•km)]	0.061	0.061

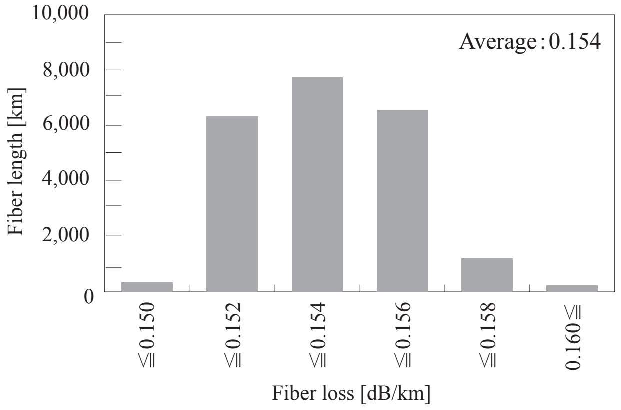


Fig. 7. Fiber loss distribution over 25,000 km

4-2 Micro-bending loss sensitivity

It is generally known that micro-bending loss sensitivity is degraded in Aeff-enlarged fibers. Therefore, reduction of the micro-bending loss is required for installing Z+130 ULL into practical submarine cables. A resin coating system with low Young's modulus in a primary layer was applied on the fabricated PSCFs in order to realize a good micro-bending loss performance$^{(13)}$. **Figure 8** shows micro-bending losses for fibers having different Aeff with conventional and low modulus primary coatings. The micro-bending loss was characterized by a wire mesh bobbin method at winding tension of 80 gram-force$^{(14)}$. As can be seen from **Fig. 8**, micro-bending loss is dramatically reduced by applying the soft primary coating. Micro-bending loss of Z+130 ULL with the soft primary coating is the same level as one of Z-PLUS Fiber with the conventional coating, which has been utilized for many years in actual submarine cable systems. Therefore, Z+130 ULL would be applicable for practical submarine cables.

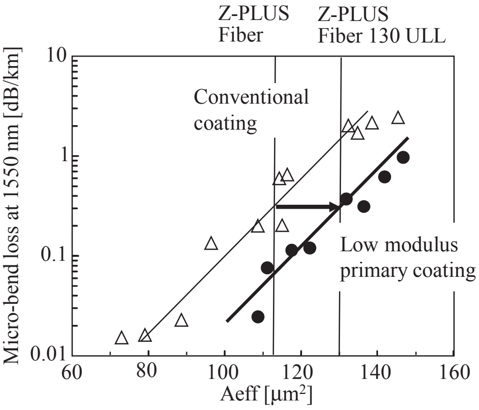


Fig. 8. Micro-bending loss for fibers with low Young's modulus primary and conventional coating

4-3 Environmental and mechanical performances of ultra low-loss PSCF

Finally, we conducted environmental and mechanical tests according to IEC60793-2-50 including the damp heat, dry heat, temperature cycling, water immersion, tensile strength, stress corrosion susceptibility, fiber curl, and proof tests. The PSCFs exhibited excellent stabilities in all tests, which show high reliability and durability practicable for a submarine cabling. For example, **Fig. 9** shows the fiber loss change during damp heat test at a temperature of 85˚C and a relative humidity of 85%, in which measurable degradation was not confirmed.

In addition to the IEC tests, we also conducted hydrogen aging test in order to verify long term reliability in submarine environment. **Figure 10** shows a spectrum of loss change after the hydrogen aging test, where the fiber was exposed to hydrogen partial pressure of 1 atm at room temperature for 4,000 hours. Measurable degradation was not observed in the wavelength of 1400-1600 nm, and it is found that the PSCFs have the excellent stability with the hydrogen exposure.

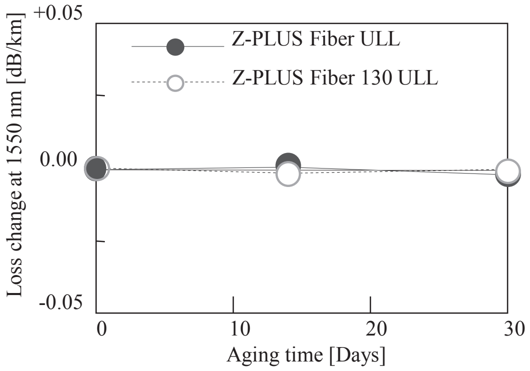


Fig. 9. Damp heat test at 85°C, 85%RH

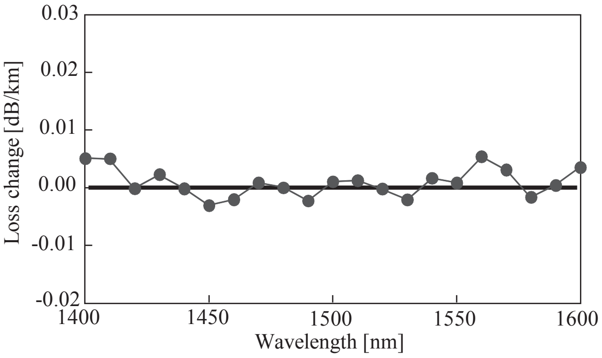


Fig. 10. Hydrogen aging test result

5. Conclusion

We successfully realized a record low loss of 0.149 dB/km at 1550 nm with a ring core PSCF having enlarged Aeff of 135 μm^2. By virtue of ultra-low loss and optimal value of Aeff, the newly fabricated PSCFs have the highest fiber FOM ever reported among transmission fibers. Furthermore, we verified the ultra low-loss of 0.154 dB/km over accumulated length of 25,000 km based on mass-production processes, and high mechanical reliability and environmental durability were also confirmed. These results will bring fiber loss of 0.15 dB/km into reality. The ultra-low loss PSCFs, Z-PLUS ULL and Z-PLUS 130 ULL will contribute to a dramatic acceleration of capacity growth in submarine systems in the near future.

- Z Fiber and Z-PLUS Fiber are trademarks or registered trademarks of Sumitomo Electric Industries, Ltd.

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