Record Low Loss Optical Fiber with 0.1397 dB/km

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Abstract: We have achieved low loss record of 0.1397 dB/km at 1566 nm wavelength and 0.1406 dB/km at 1550 nm on a Ge-free silica-core fiber that has been achieved by the further reduction of fictive temperature. © 2024

1. Introduction

There is a strong need to increase the transmission capacity of submarine cables. Recently, transmission capacity has been increased with performance improvement of submarine optical fibers, including reduced transmission loss, and with the increase in the number of optical fibers in a submarine cable. When the power supply to the repeaters is limited in a submarine system, reduction of transmission loss of optical fibers is quite important because the maximum theoretical transmission capacity in a cable increases proportionally with $1/\alpha^2$, where α represents transmission loss of optical fibers [1]. Transmission loss of optical fibers has been improved continuously as shown in Fig. 1. Regarding commercial products, whereas the losses were improved slowly before 2010, the improvement after that has been more rapid, such as 0.162 dB/km in 2010 [2], 0.154 dB/km in 2013 [3], 0.152 dB/km in 2016-17 [4,5], and 0.144 dB/km in 2020 [5]. Improvement of transmission losses at 1550 nm in R&D fibers have also been achieved, such as 0.150 dB/km in 2002 [6], 0.149 dB/km in 2013 [3], 0.1467 dB/km in 2015 [7], and most recently 0.1424 dB/km in 2017 [8].

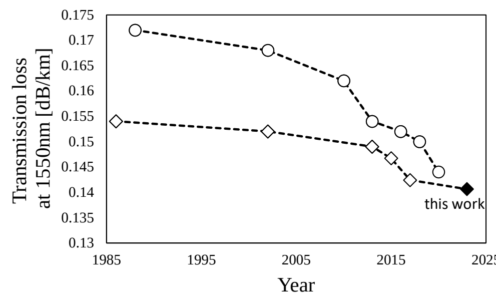


Fig.1 History of improvement in losses of silica core optical fibers measured at 1550 nm wavelength.

In this paper, we present record low fiber transmission loss of 0.1406 dB/km at 1550 nm and 0.1397 dB/km at 1566 nm wavelength. This is the first optical fiber with the transmission loss of less than 0.1400 dB/km. We show that the core glass of the fiber has a microscopic glass network with less disorder than that of the conventional fiber, based on a Raman micro-spectroscopy.

2. Fabricated ultra-low loss fiber

Ge-free silica core fiber consists of slightly F-doped core and F-doped cladding. Dopants in silica-based glass induce the Rayleigh scattering loss depending on the spatial compositional homogeneity called as concentration fluctuation. In the case of single dopant in the silica glass matrix, Rayleigh scattering loss due to the concentration fluctuation α_c dB/km at wavelength of 1550 nm is expressed as,

$$\alpha_c = An_0^2\left(\frac{dn_0}{dc}\right)^2 c(1-c) \tag{1}$$

where A, n_0, and c are the constant, refractive index of the binary glass, dopant concentration, respectively [9]. In the case of low dopant concentration limit, α_c approximately depends on the concentration c linearly. Rayleigh scattering of concentration fluctuation in slightly F-doped silica glass is experimentally expressed as $\alpha_c = 1.3 \times 10^{-2} \times c_F$ by using fluorine concentration c_F mol% [10]. Considering into the fiber, α_c is weighted by the normalized power distribution as,

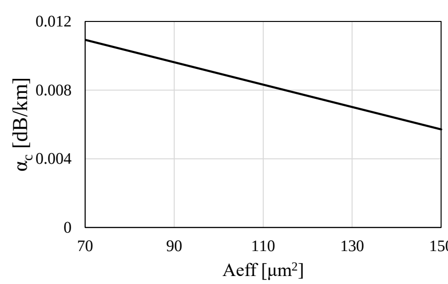
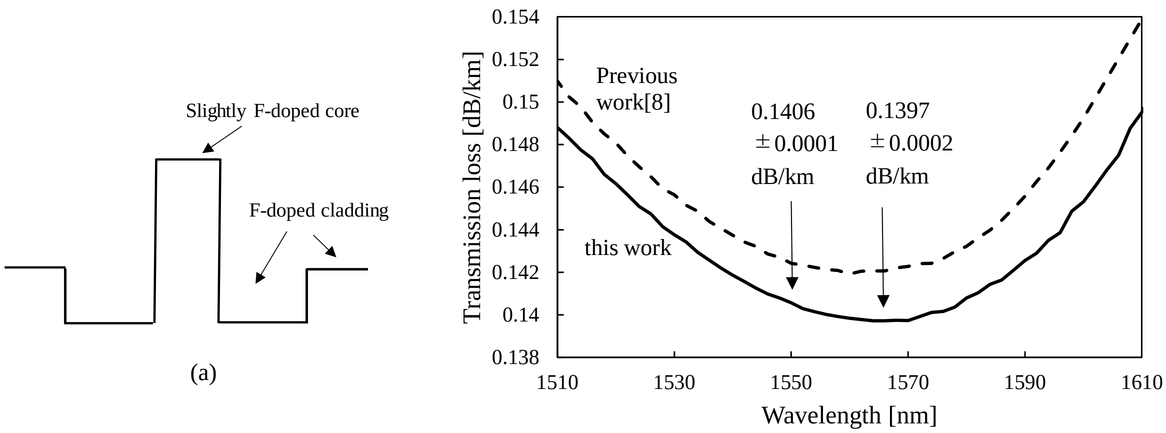


Fig.2 Aeff dependence of Rayleigh scattering loss due to concentration fluctuation.

$$\alpha_c = \int_0^R 1.3 \times 10^{-2} c_F(r)P(r)2\pi r dr \tag{2}$$

where $c_F(r)$, $P(r)$, R represent fluorine concentration, normalized power distribution for the radius r from the core center and cladding radius, respectively. Figure 2 shows the calculated Aeff dependence of Rayleigh scattering loss due to concentration fluctuation. To be simply, we assumed step-index profile composed of pure silica core, as the low concentration limit of F-doped core, and F-doped silica cladding. Refractive index of the cladding was set to normalized frequency v be 2.3 for each structure. As can be seen in Figure 2, Rayleigh scattering loss is expected to be reduced by enlarging Aeff.

In terms of the reduction of Rayleigh scattering loss, larger Aeff is preferable as described above. On the other hand, an enlarged Aeff makes the fiber more vulnerable to macro- and micro-bending losses. In order to suppress macro-bending loss, we applied W-type double-clad structure as shown in Fig. 3(a). Furthermore, we designed Aeff as 150 μm^2 and applied a soft primary coating with reduced elastic modulus [8] to avoid micro-bending losses. F-dopant in the core does not significantly changes the refractive index, however, reduces the viscosity and the activation energy for structural relaxation of microscopic glass network, resulting in the reduction of Rayleigh scattering loss. We measured transmission loss on a 19.11 km-length spool wound on a standard shipment reel. Figure 3(b) shows a measured transmission loss spectrum by cutback method. The transmission loss was measured by a 10-time iteration. The mean value and standard error (SE) was 0.1406 ± 0.0001 dB/km at 1550 nm wavelength, and lowest at 1566 nm wavelength with a value of 0.1397 ± 0.0002 dB/km, as shown in Fig. 3(b). Both the values were the new record of



(b)

Fig.3 (a) Schematic profile of refractive index, (b) Measured transmission loss spectrum of an ultra-low loss fiber.

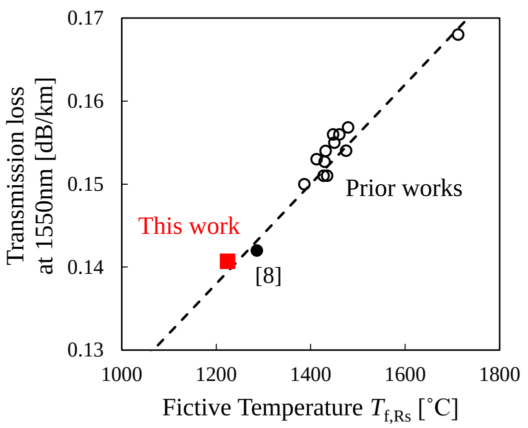


Fig. 4 Correlation between fiber loss and fictive temperature by Raman spectroscopy. Dotted line is the slope of 6.0 × 10^{-5} dB/km/°C.

Table 1. The optical characteristics of the fabricated fiber, measured at 1550 nm wavelength unless specified otherwise.

Characteristics	Unit	Value
Loss at 1550 nm	dB/km	0.1406
Minimum loss	dB/km	0.1397
Wavelength at minimum loss	nm	1566
MFD	µm	13.3
Aeff	μm^2	147
Cable cut-off wavelength	nm	1413
Chromatic dispersion	ps/nm/km	21.4
Dispersion slope	ps/nm^2/km	0.061
30mm-radius macro-bending loss at 1625 nm	dB/100 turn	0.0
PMD on spool	ps/$km^{1/2}$	0.01

lowest losses being 2 mdB/km lower than the previous record of lowest loss [8]. Moreover, this is the first optical fiber that achieves 0.14 dB/km (max:0.144dB/km, min:0.140dB/km) in the whole C-band (1530-1565 nm). The measured optical characteristics of the present fiber were summarized in Table 1, which were compliant to the ITU-T G.654.D recommendations on cut-off shifted single-mode optical fiber, so that this ultra-low loss fiber would be applicable to ultra-long haul transmission applications.

In order to understand the cause of the loss reduction, we evaluated the disorder of the SiO_2 microscopic glass network that can cause Rayleigh scattering. Fictive temperature represents randomness of glass molecular network. We estimated the fictive temperature of the fiber using Raman spectroscopy [11]. Raman spectra was obtained by illuminating the optical fiber around the core with wavelength of 532 nm. Fictive temperature was estimated by the peak area ratio between D2(605cm^{-1}) and ω3(800cm^{-1}) [8], which is originating from the symmetric stretching vibration of 3-member ring and Si-O-Si vibration of 6-member ring, respectively. Fictive temperature contributing to Rayleigh scattering loss ($T_{\mathrm{f,Rs}}$) was also weighted by the normalized power distribution as,

$$T_{f,Rs} = \int_0^R T_f(r)P(r)2\pi r dr \quad (3)$$

where, T_{f} (r) represents fictive temperature for the radius r from the core center. As shown in Fig. 4, the fictive temperature by Raman spectroscopy is lowered in the present fiber by approximately 62 K compared to the previous one, which implies significantly reduced randomness in glass molecular network and consequently reduced Rayleigh scattering. The maturity in fiber manufacture that can stably realize the fictive temperature of the previous record [8] should have contributed to this new lowest fictive temperature.

3. Impact on system performance

The system impact by 0.002 dB/km loss reduction can be estimated by the FOM (figure of merit) theory, which formulates improvement in generalized OSNR in reference to a standard system [12]. We assume a 10,000 km reach system that should transmit 8QAM-150G signals with minimum required Q-factor of 7.0 dB, where EDFA output limit is assumed to be -2 dBm/ch and splice losses at repeaters are assumed to be equal to MFD mismatch loss between standard single mode fiber's 10.5 µm. The present fiber can reduce the number of repeaters by 9%, 2% compared to the previous record-low loss fibers [6,7], as shown in Fig. 5. Reduction in the number of repeaters would make the system more cost-efficient and power-efficient, resulting in making more room for spatial and/or wavelength division multiplexing.

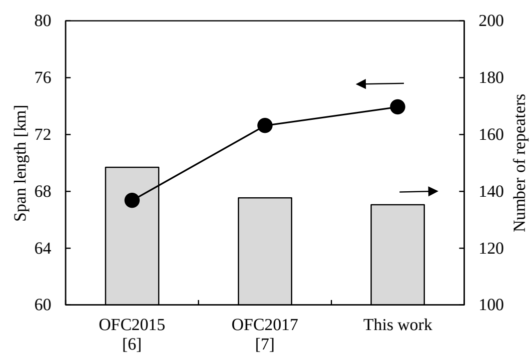


Fig.5 Reduction in the number of repeaters in 10,000 km, 8QAM-150G (Q ≥ 7.0dB) system.

4. Conclusions

We have achieved a new record of lowest loss of silica glass fiber. The lowest loss is 0.1397 dB/km at 1566 nm wavelength, and the loss at 1550 nm is 0.1406 dB/km. This achievement demonstrates the potential for further improvement on the performance of ultra-low loss silica-core fiber.

5. References

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