

INVITED PAPER

Transmission Loss of Optical Fibers; Achievements in Half a Century

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SUMMARY This paper reviews the evolutionary process that reduced the transmission loss of silica optical fibers from the report of 20 dB/km by Corning in 1970 to the current record-low loss. At an early stage, the main effort was to remove impurities especially hydroxy groups for fibers with GeO₂-SiO₂ core, resulting in the loss of 0.20 dB/km in 1980. In order to suppress Rayleigh scattering due to composition fluctuation, pure-silica-core fibers were developed, and the loss of 0.154 dB/km was achieved in 1986. As the residual main factor of the loss, Rayleigh scattering due to density fluctuation was actively investigated by utilizing IR and Raman spectroscopy in the 1990s and early 2000s. Now, ultra-low-loss fibers with the loss of 0.150 dB/km are commercially available in trans-oceanic submarine cable systems.

key words: optical fiber, transmission loss, Rayleigh scattering, fictive temperature, ultra-low-loss

1. Introduction

In 1970, Kapron et al. of Corning Glass Works (present Corning) in the US reported on their prototype silica glass optical fiber with a transmission loss of 20 dB/km [1]. The value of 20 dB/km was a symbolic performance for optical fibers to be comparable to coaxial cables in terms of the repeater distance. Since this achievement, the development of optical fiber quickly gained momentum in the US, the UK, and Japan. Along with the “semiconductor laser that continuously oscillates at room temperature [2],” which was also realized in 1970, “20 dB/km optical fiber” became a milestone in the practical application of optical fiber communication. At half a century from 1970, this paper looks back chronologically over the progress on the transmission loss, which is an attribute that most directly shows the performance of an optical fiber.

2. Early Days of Optical Fiber

In advance of 1970, Kao of Standard Telecommunication Laboratories in the UK foretold that the loss of transition metal-free high-purity glass fiber could be below 20 dB/km in 1966 [3]. For this achievement, the 2009 Nobel Prize in physics was awarded to him. Meanwhile, in 1964, Nishizawa and Sasaki applied a patent for a graded index (GI) fiber concept. Although this patent application was not successful, researchers said that their prescience regarding

the potential of optical fiber communication is comparable to Kao’s achievements. In 1969, GI fiber made of multi-component glass was successfully manufactured by Uchida et al. by the ion exchange method [4]. This fiber was named SELFOC®. SELFOC® was not widespread as a transmission line for optical communication because the intrinsic loss of multi-component glass fibers did not reach that of silica fibers which became popular later. The technology of SELFOC®, however, has been widely used as collimating lenses for optical devices as well as copy machines.

3. Initiatives of Silica Optical Fiber

The optical fiber reported by Kapron et al. in 1970 was a single-mode (SM) fiber with a core diameter of 3–4 μm and a core/cladding diameter ratio of 1:60, and a loss of 20 dB/km was confirmed at a wavelength of 0.6328 μm. According to a later publication [5], the fiber that achieved 20 dB/km was drawn from a silica glass tube, in which silica glass was deposited as a core by using a flame hydrolysis reaction on the inner surface of the tube. The deposited silica glass was doped with TiO₂ to increase the refractive index. Immediately after drawing, the fiber showed a large absorption loss due to Ti³⁺, the reduced state of Ti ion. By heating the drawn fiber in an oxygen atmosphere to oxidize Ti³⁺ to the Ti⁴⁺ state, the loss of 20 dB/km was obtained. Since heating drawn fiber at a high temperature made it brittle, it could not be put to practical use. As a countermeasure, GeO₂ has come to be used [6] as a core dopant instead of TiO₂. GeO₂ doped fiber does not require heat treatment after drawing because tetravalent state of Ge ion is present stably in silica glass.

Following “20 dB/km,” Keck et al. of Corning reported that the loss of 7 dB/km at 1.06 μm in 1972 [7], and 4 dB/km at 0.8–0.85 μm and 1.05 μm in 1973 [8] with multi-mode (MM) fibers. Although the materials and manufacturing methods were not disclosed in the papers at that time, the outside vapor deposition (OVD) method, shown in Fig. 1(a), was developed by Corning [9], [10] around that time. In the OVD method, glass particles called “soot” are generated by a flame hydrolysis reaction of gaseous raw material of glass such as SiCl₄ fed to a burner. The soot deposits on the starting mandrel to form a porous preform. Next, the mandrel is removed from the porous preform, and the porous preform is heated at a high temperature to make it transparent, which is called “sintering” process.

In 1974, MacChesney et al. of Bell Laboratories in

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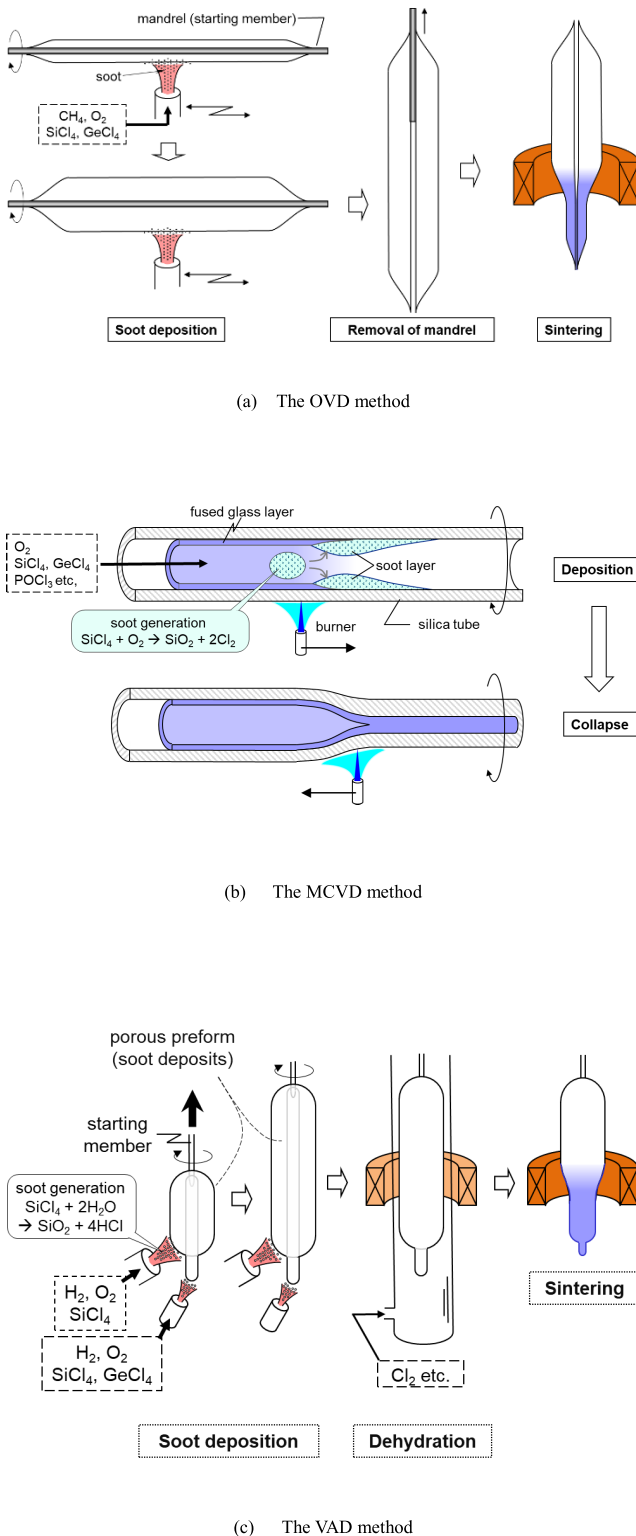


Fig. 1 Preform manufacturing methods.

the US achieved a transmission loss of 2 dB/km at 1.06 μm utilizing the modified chemical vapor deposition (MCVD) method [11]. The core was doped with GeO_2 . In the MCVD method, as shown in Fig. 1(b), gaseous glass raw materials

and oxygen are fed into a silica glass tube. The tube is externally heated by an oxyhydrogen burner to form a glass layer of a desired composition on the inner surface of the tube, and then the tube is shrunk in the radial direction to be solidified by additional heating, which is called the “collapse” process. Tasker et al. of Bell Laboratories fabricated a GI fiber using B_2O_3 to form parabolic refractive index distribution with a loss of 1.7 dB/km at 1.05 μm , and a step index fiber with a SiO_2 core and B_2O_3 added SiO_2 cladding with a loss of 1.1 dB/km at 1.02 μm [12].

During the early stage of optical fiber development, which started from 20 dB/km optical fiber, the main target for loss reduction was the reduction of absorption loss due to impurities. Hydroxy (OH-) groups and transition metals were the most important impurities particularly in the visible to near infrared (IR) region [8], [13]. As for the OH-groups, the fundamental vibration of OH occurs at a wavelength of 2.7 μm , and its first overtone appears at 1.38 μm . The absorption loss at 1.24 μm is due to the combination of the OH first overtone and the fundamental vibration of SiO_4 tetrahedron. While these absorption losses due to the OH group had been a barrier to lowering the loss of the optical fiber, Horiguchi of NTT and Osanai of Fujikura achieved the loss of 0.47 dB/km at 1.2 μm by reducing the OH absorption loss with an optical fiber manufactured by the MCVD method in 1976 [14]. This fiber was a step-index type MM fiber with a P_2O_5 - SiO_2 core and a B_2O_3 - SiO_2 cladding. They paid attention to the purity of raw materials and gases, and the contamination from the raw material container. At the longer wavelength side, the loss was high due to the effect of the tail of IR absorption of B-O and P-O [15]. In 1979, Miya et al. of NTT achieved the loss of 0.20 dB/km at 1.55 μm with an SM fiber manufactured by the MCVD method [16], where GeO_2 - SiO_2 was used for the core and SiO_2 for the cladding to remove the effects of IR molecular vibrations of B-O and P-O. Additionally, in the manufacturing process of the preform, the starting silica glass tube was heated to remove surface scratches, the glass deposition temperature was increased to sufficiently fuse the glass deposition layer so as to improve the structural uniformity of the optical fiber.

In 1977, the vapor phase axial deposition (VAD) method was invented as a preform manufacturing method by Izawa et al. of NTT [17]. The process of the VAD method is schematically illustrated in Fig. 1(c). Gaseous glass raw materials are fed to oxyhydrogen burners to generate soot by a flame hydrolysis reaction, and the soot deposits on the tip of the rotating starting member. The starting member is pulled upwards to axially form a porous preform, that is the deposited body of soot. The porous preform synthesized by a flame hydrolysis reaction contains a large amount of OH-group. Elmer et al. disclosed that OH-groups in porous glass could be removed by heating in a gas atmosphere containing chlorine (Cl_2), where the OH-groups are replaced with chlorine ions [18]. Accordingly, in order to achieve high purity, the porous preform manufactured by the VAD method is heated in an atmosphere containing Cl_2 , and further heated at a higher temperature to form a transparent glass preform.

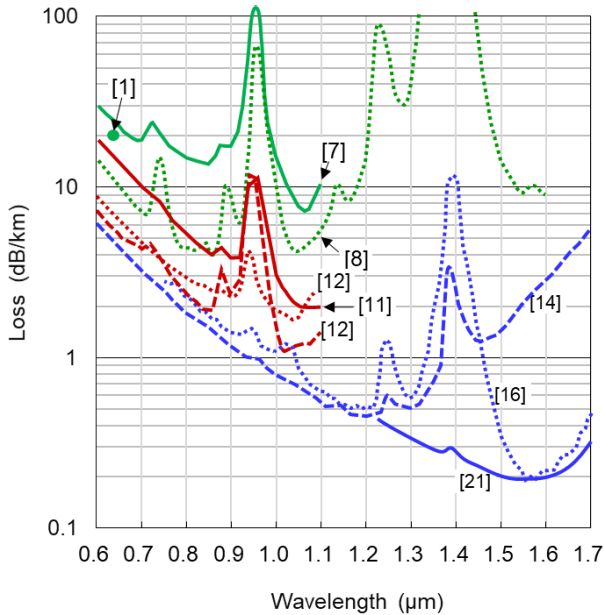
Table 1 Loss achieved from 1970 to 1981.

Year	Loss (dB/km)	Wavelength (μm)	Method	Core Composition	Fiber Type ^{*3}	Ref.
1970	20	0.6328	IVD ^{[5]*1}	TiO ₂ -SiO ₂ ^[5]	SM	[1]
1972	7	1.06	---	---	MM	[7]
1973	4	0.8-0.85, 1.05	---	---	MM	[8]
1974	2.0	1.06	MCVD	GeO ₂ -SiO ₂ ^{*2}	MM	[11]
1974	1.7	1.04	MCVD	B ₂ O ₃ -SiO ₂ ^{*2}	MM	[12]
1974	1.1	1.02	MCVD	SiO ₂ ^{*2}	MM	[12]
1976	0.47	1.21	MCVD	P ₂ O ₅ -SiO ₂ ^{*2}	MM	[14]
1979	0.20	1.55	MCVD	GeO ₂ -SiO ₂	SM	[16]
1981	0.20	1.55	VAD	GeO ₂ -SiO ₂	SM	[21]

*1 IVD : Inside Vapor Deposition

*2 Cladding : B₂O₃-SiO₂

*3 SM : Single-mode, MM : Multi-mode

**Fig. 2** Loss spectra from 1970 to 1981.

Moriyama et al. of Fujikura and Hanawa et al. of NTT reported “OH-free” fibers manufactured by the VAD method [19], [20], in which the losses due to residual OH-groups were less than the detectable level. The loss of the VAD fiber was also improved as that of the MCVD fiber, and an SM fiber with the loss of 0.20 dB/km at 1.55 μm was successfully fabricated by Tomaru et al. of NTT in 1981 [21].

The losses achieved from 1970 to 1981 mentioned above are summarized in Table 1 and the loss spectra are overwritten in Fig. 2. It can be seen that the minimum loss window had shifted from 0.63 μm to 1.55 μm with the progress of the technology to remove OH-groups.

4. Formulation of Optical Fiber Loss Factors

The transmission loss of an optical fiber α can be expressed as a function of wavelength λ by

$$\alpha(\lambda) = A/\lambda^4 + B + C(\lambda) + D(\lambda) + E_1 \exp(E_2/\lambda) + F_1 \exp(-F_2/\lambda) \quad (1)$$

A/λ^4 is a term that represents the intrinsic scattering loss of the material itself constituting the optical fiber. The

scattering loss includes Rayleigh scattering loss due to fluctuations smaller than the order of the light wavelength in density and composition, Mie scattering due to fluctuations equal to or greater than the light wavelength, Brillouin scattering due to interaction with acoustic phonons, and Raman scattering due to interaction with molecular vibrations. Among them, Rayleigh scattering is dominant. Rayleigh scattering is inversely proportional to the fourth power of the wavelength λ , and A is called Rayleigh scattering coefficient. Rayleigh scattering is separated into a term due to density fluctuation of glass, A_d/λ^4 , and a term due to composition fluctuation, A_c/λ^4 as Eq. (2) [22].

$$A/\lambda^4 = A_d/\lambda^4 + A_c/\lambda^4 \quad (2)$$

The term due to density fluctuation can be expressed by [23]

$$A_d/\lambda^4 = \frac{8\pi^3}{3\lambda^4} n^8 p^2 k T_f \beta_{T_f} \quad (3)$$

where n is the refractive index, p is the photo-elastic constant, k is Boltzmann’s constant, T_f is the fictive temperature, and β_{T_f} is the isothermal compressibility. T_f is defined as the temperature at which the glass would be in equilibrium if suddenly brought to that temperature from its given state [24], [25]. In other words, T_f is the temperature at which liquid glass in equilibrium has the same degree of disorder as that for the glass tested.

B is a term representing a structural imperfection loss, that is scattering loss caused by foreign materials and/or bubbles in the optical fiber, irregularity of the interface between the core and the cladding, and so on. Generally, B does not depend on the wavelength.

$C(\lambda)$ is a term that represents the effect of absorption loss due to impurities.

$D(\lambda)$ is a term that represents the effect of absorption loss due to glass defects.

$E_1 \exp(E_2/\lambda)$ is the influence of the ultraviolet (UV) absorption tail of glass. The empirical rule that the effect of electronic transition absorption on the edge is proportional to the exponential of photon energy is known as Urbach’s rule [26]. In the case of SiO₂ glass, it is negligible in the wavelength range used for optical communication systems.

$F_1 \exp(-F_2/\lambda)$ is the influence of the infrared (IR) absorption of glass, that is, the tail of the absorption due to molecular vibration. Generally, the frequency peak of molecular vibration is inversely proportional to the square root of the reduced mass of the cation-oxygen pair. Therefore, as the glass component contains a lighter element, the influence of IR absorption to the near IR region used for optical communication systems becomes greater. Osanai et al. showed that IR absorption of B₂O₃-doped silica optical fiber is higher than that of GeO₂-SiO₂ core optical fiber [27]. In the case of SiO₂ glass [28], the effect of IR absorption at a wavelength of 1.55 μm is about 0.01 dB/km.

Since Rayleigh scattering is inversely proportional to the fourth power of the wavelength λ , Inada proposed plotting a loss spectrum of an optical fiber with the horizontal axis of $1/\lambda^4$ as a convenient method to analyze the loss

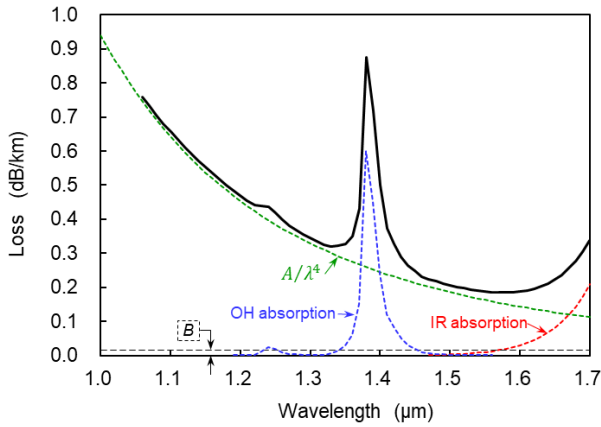


Fig. 3 Example of loss spectrum of typical SM fiber.

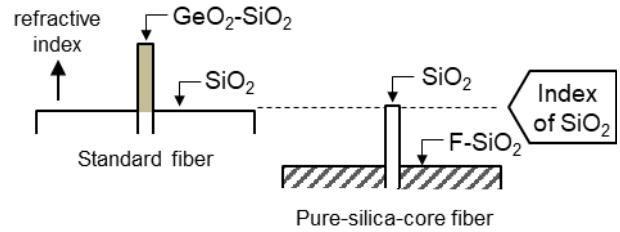


Fig. 5 Structure of pure-silica-core SM fiber.

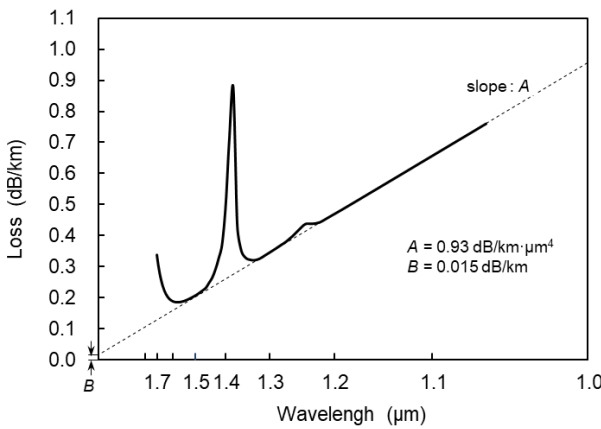


Fig. 4 $1/\lambda^4$ plotting of loss spectrum of typical SM fiber.

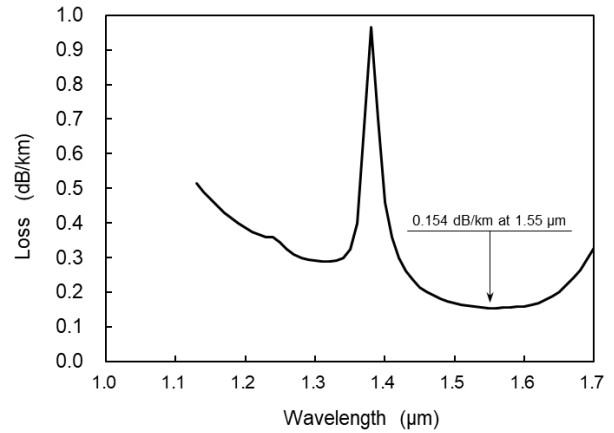


Fig. 6 Loss spectrum of pure-silica-core SM fiber.

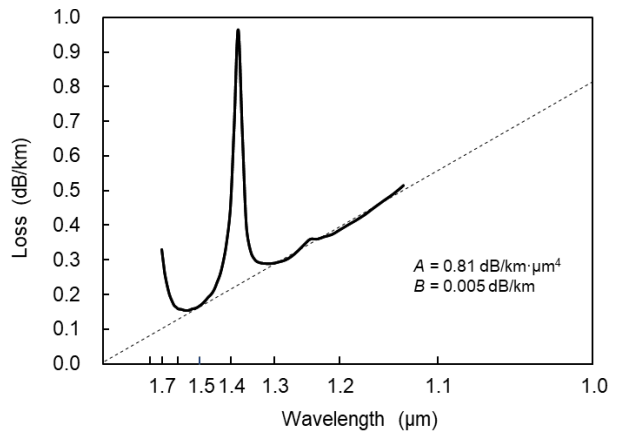


Fig. 7 $1/\lambda^4$ plotting of loss spectrum of pure-silica-core SM fiber.

spectrum [29]. With this $1/\lambda^4$ plotting, Rayleigh scattering coefficient A can be obtained from the slope of the straight-line portion, and the y axis intercept of the straight line can be recognized as B . Figure 3 shows an example of typical loss spectrum of a standard SM fiber, and Fig. 4 is a $1/\lambda^4$ plotting for the loss spectrum. In this example, $A = 0.93 \text{ dB/km}\cdot\mu\text{m}^4$, and $B = 0.015 \text{ dB/km}$ are obtained by this method.

5. Pure-Silica-Core Fiber

5.1 Development of Pure-Silica-Core SM Fibers

For $\text{GeO}_2\text{-SiO}_2$ core optical fibers, Rayleigh scattering due to composition fluctuation increases with increase of GeO_2 content [30]. It was said that the value of 0.20 dB/km achieved with the conventional $\text{GeO}_2\text{-SiO}_2$ core optical fiber should be almost the theoretical limit.

In order to overcome the limit for the conventional fibers, Kanamori et al. developed a pure-silica-core SM fiber [31]. In this fiber, Rayleigh scattering due to composition fluctuations of GeO_2 is suppressed by using pure silica glass as the core. As shown in Fig. 5, instead of using GeO_2 which raises the refractive index of the core, fluorine (F) is added to

the cladding, which has the effect of lowering the refractive index.

With a pure-silica-core SM fiber, Yokota et al. demonstrated a record-low loss of 0.154 dB/km achieved at a wavelength of 1.55 μm [32]. Figure 6 shows the loss spectrum of the fiber, and Fig. 7 is $1/\lambda^4$ plotting of the loss spectrum.

In addition to the low loss, the pure-silica-core SM fiber has special features that irreversible loss increase due to generation of OH-groups induced by hydrogen penetration does not occur, and that loss increase due to γ -ray irradiation is suppressed as well [31]. Owing to these advantages, pure-silica-core SM fibers started to be employed for submarine cable applications that require high reliability as

well as low loss.

5.2 Residual Stress in Pure-Silica-Core SM Fiber

For pure-silica-core SM fibers, the core has much higher viscosity than the F-doped cladding. Consequently, the drawing tension is concentrated to the core, which may cause high residual stress in the axial direction on the core. Accordingly, when the drawing condition is not appropriate, that means the drawing tension is too high, photo-elastic effect due to the residual tensile stress causes decrease of the refractive index of the core [33]. Hibino et al. reported the dependence of the relative refractive index difference on the drawing tension for pure-silica-core SM fibers [34], and clarified, by the Brillouin gain shift measurement, that it can be attributed to the residual stress [35]. Hibino et al. and Ohashi et al. observed not only the refractive index decrease of the core but increase of the loss with increasing high drawing tension [35], [36]. The mechanism of the loss increase induced by high drawing tension for pure-silica-core SM fiber was not clear, but slight fluctuation in drawing process might result in a structural imperfection loss.

The residual stress in the axial direction is expressed as sum of the mechanically induced stress and the thermal stress. The mechanically induced residual stress σ_j can be expressed by [37]

$$\sigma_j = F \left(\frac{\eta_j}{\sum_{i=1}^n A_i \eta_i} - \frac{E_j}{\sum_{i=1}^n A_i E_i} \right) \quad (4)$$

In Eq. (4), F is the drawing tension. The lower index j ($1 \leq j \leq n$) indicates the portion in the fiber. A_j , η_j and E_j are the cross-sectional area, the viscosity and Young's modulus of the portion j , respectively, at the temperature where the fiber starts to behave elastically. If the fiber consists of just a core and a cladding, Eq. (4) becomes

$$\sigma_1 = F \left(\frac{\eta_1}{A_1 \eta_1 + A_2 \eta_2} - \frac{E_1}{A_1 E_1 + A_2 E_2} \right) \quad (4a)$$

$$\sigma_2 = F \left(\frac{\eta_2}{A_1 \eta_1 + A_2 \eta_2} - \frac{E_2}{A_1 E_1 + A_2 E_2} \right) \quad (4b)$$

where, $j = 1$ means core, and $j = 2$ means cladding.

The thermal stress σ_{th} arising from the non-uniformity of thermal expansion coefficient can be expressed by

$$\sigma_{th}(r, T) = \int_{T_{room}}^{T^*} \frac{E(r, T)}{1 - \nu(r, T)} \{\alpha(r, T) - c(T)\} dT \quad (5a)$$

where

$$c(T) = \int_0^R \alpha(r, T) r dr \quad (5b)$$

In Eq. (5a), T^* is a virtual temperature where stress starts to occur in drawing process. $\alpha(r, T)$ is the thermal expansion coefficient at radial position r and temperature T , $E(r, T)$ and $\nu(r, T)$ are Young's modulus and Poisson's ratio, respectively. In case of pure-silica-core fibers with F-doped

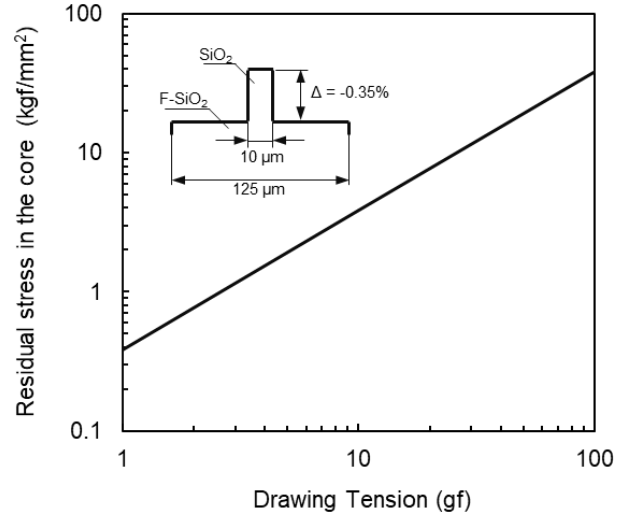


Fig. 8 Relationship between the drawing tension and the residual stress. Residual stress is obtained for the fiber parameters shown in the inset.

cladding, difference of thermal expansion coefficient between pure-silica-core and F-doped cladding is small. Consequently, the thermal stress can be ignored, and the mechanically induced stress dominates the residual stress.

Figure 8 shows the relationship between the drawing tension and the residual stress in the core obtained from Eq. (4a) for the pure-silica-core/F-SiO₂ cladding fiber with a core diameter of 10 μm and the relative refractive index difference of -0.35%, assuming the viscosity ratio η_{clad}/η_{core} as 0.17, which is read off Fig. 9 of the reference [37], and $E_{clad}/E_{core} = 1$.

From the viewpoint that lower residual stress is better, it was considered the drawing tension should be lowered as much as possible. It means elevating the temperature of the drawing furnace, and/or decreasing the drawing speed. But these drawing conditions were not economical. Moreover, only this simple hypothesis could not lead to a clue for further loss reduction.

6. Viscosity Matching

Regarding loss factors of optical fibers, the concept of “viscosity matching” attracted attention at a certain period of early 1990s. At that time, dispersion-shifted fibers (DSFs) whose chromatic dispersion becomes zero at around 1.55 μm wavelength region were being developed. In order to control the chromatic dispersion with keeping low bending loss as well as relatively large mode field diameter for easy splicing, a complex refractive index profile became necessary. In order to reduce the loss with the complex profile, it was considered smaller residual stress would be advantageous, and Tateda et al. proposed a design method that yielded arbitrary refractive index profiles with homogeneous viscosity throughout the cross section by tuning the content of Ge and F in GeO₂-F-SiO₂ glass systems [38]. Ohashi et al. investigated the relationship between the viscosity distribution and the loss, and found that the viscosity matching

at the core/cladding interface is important to reduce the loss [39].

7. IR Transmission Fiber

Aiming at realizing an extremely low loss optical fiber, IR transmission optical fibers made of IR transmissive material were investigated in the 1980s to 1990s. As shown in Fig. 9, IR transmissive materials have the absorption band due to molecular vibration at the longer wavelength region than silica. Since the main factor of the loss of the optical fiber is Rayleigh scattering, which is inversely proportional to the fourth power of the wavelength, the achievable loss of IR transmission fiber was expected to be an order of magnitude lower than that of silica fibers.

The materials used were IR transparent glass such as fluoride glass, halide glass, chalcogenide glass and the like. Optical fibers using these materials had been proposed from the 1970s and were expected to realize ultra-low loss of 0.01 to 0.001 dB/km or less in the wavelength range of 2 to 10 μm . Among them, ZrF_4 based fluoride glass was most actively studied [40]. However, unlike silica glass, these IR transmissive glasses tend to crystallize, and microcrystals are easily formed during the cooling process in the optical fiber manufacturing. As a result, the IR transmission fibers showed large structural imperfection loss. Indeed, the fibers with a loss less than 1 dB/km were developed [41], [42], but the loss lower than silica fibers have not been realized. The lowest loss record was 0.45 dB/km at 2.35 μm reported by Szebesta et al. with ZrF_4 based glass fiber [43], but the fiber length was as short as 60 m. Although it is considered to be difficult to use fluoride glass fibers for long-distance optical communication, it has been employed as a host fiber for a rare-earth-doped optical fiber amplifier. It is because fluoride glasses have low phonon energy and can suppress non-radiative transition due to multi-phonon absorption from the excitation level of the rare-earth elements, leading to high amplification performance [44].

8. Reduction in Rayleigh Scattering of Silica Fibers

8.1 Evaluation of T_f and Rayleigh Scattering

In the 1990s, it was widely recognized that it is necessary to reduce Rayleigh scattering loss, which accounts for 80% or more of the total loss, in order to reduce further the loss of the optical fiber. As mentioned above, Rayleigh scattering loss is expressed as the sum of the term due to density fluctuation of glass, A_d/λ^4 , and a term due to composition fluctuation, A_c/λ^4 .

The way to reduce A_c/λ^4 is simple. The answer is the pure-silica-core fiber. Researchers, therefore, put much effort to reduce A_d/λ^4 .

Glass is a solid frozen from the liquid state. In the liquid state, the density fluctuation increases as the temperature increases. The density fluctuation of glass can be expressed by T_f as a scale, which means the temperature of the frozen

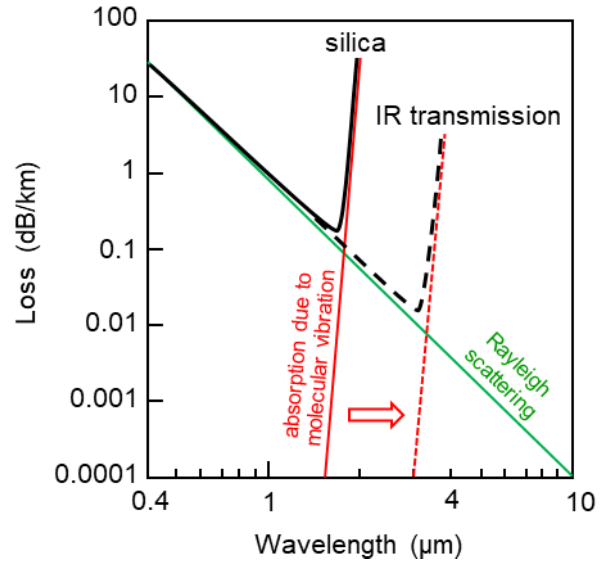


Fig. 9 Concept of loss reduction with IR transmission fibers.

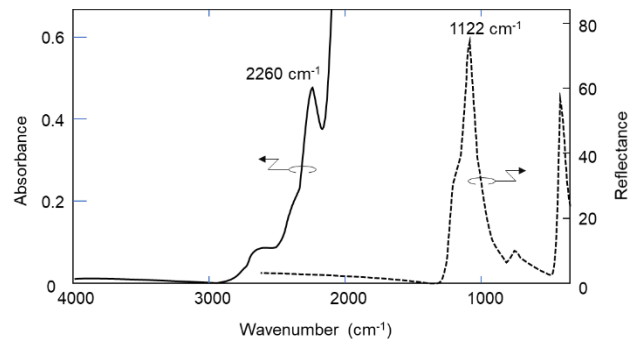


Fig. 10 IR transmission/reflection spectra of silica glass.

liquid state (or equilibrium state). T_f can be measured using an IR transmission/absorption spectrum [25], [45] or a Raman scattering spectrum [45], [46]. The IR absorption spectrum of silica glass is shown in Fig. 10 and the Raman scattering spectrum of silica glass is shown in Fig. 11.

In Fig. 10, the 1122 cm^{-1} band of the reflection spectrum is the stretching vibration band of Si-O-Si bridges, and the 2260 cm^{-1} absorption band of the IR transmission spectrum is the overtone of the vibration [25]. When the sample is heated to a specified temperature corresponding to T_f , held for a sufficiently long time and rapidly cooled, the peak wavenumbers of the bands of 1122 cm^{-1} and 2260 cm^{-1} shift depending on T_f [25], [45]–[49]. Accordingly, from the precise measurement of the peak wavenumber of IR absorption, T_f of silica glass can be estimated.

In the Raman spectrum shown in Fig. 11, broad peaks labeled ω_1 , ω_3 , $\omega_4(\text{TO})$ and $\omega_4(\text{LO})$ are identified as vibrations of glass network [46]. On the other hand, D_1 and D_2 are the so-called defect lines, interpreted as occurring from the symmetric stretch of planar four-fold and three-fold ring, respectively [46], [47], [50] as shown in Fig. 12. Six-fold ring is normal for SiO_2 glass, and three and four-

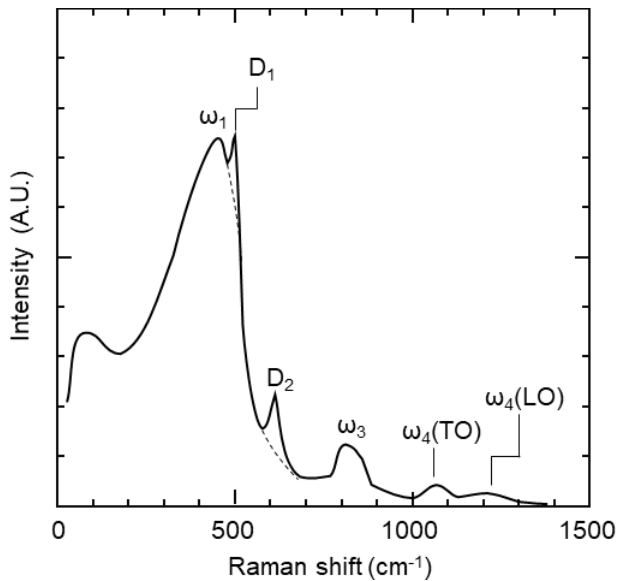


Fig. 11 Raman spectrum of silica glass.

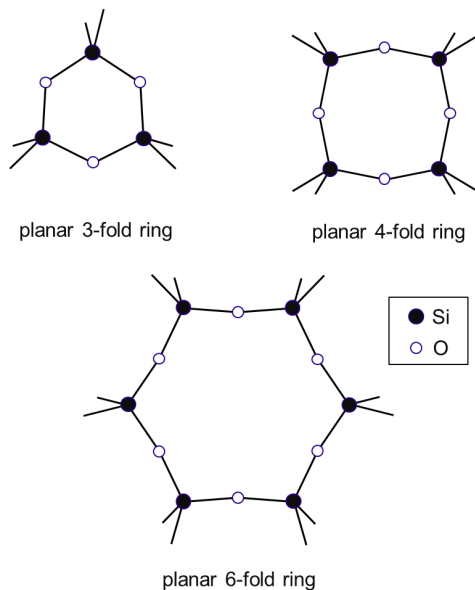


Fig. 12 Planar rings of SiO₂ glass network [48].

fold rings increase with increase of irregularity of SiO₂ network. Hence, from the intensity of D₁ or D₂, degree of disorder of network corresponding to T_f can be estimated.

Rayleigh scattering can be directly measured by irradiating a sample with a laser beam such as Ar ion laser and detecting the intensity of scattered laser beam with a photomultiplier [51]–[53]. If devised, it is possible to measure Rayleigh scattering even in the drawn fiber state [54]. It has been confirmed that the scattering intensity of bulk glass has a nearly linear relationship with T_f [45], [55].

For bulk silica glasses, Rayleigh scattering coefficient A in Eq. (1) is reported to be 0.6 dB/km· μm^4 [52], and T_f is usually 1400°C or below. On the other hand, A of optical fibers are 0.8 to 0.9 dB/km· μm^4 , as shown in Fig. 4 and

Fig. 7. As for T_f of a silica fiber, Sakaguchi et al. reported it is around 1600°C [56]. Therefore, it was considered that if the T_f of the optical fiber could be lowered, the loss of the optical fiber would be reduced.

In the optical fiber drawing process, since glass is generally cooled at a cooling rate of several thousand °C/sec, a state with large density fluctuations is frozen. In order to lower T_f of the optical fiber to reduce the loss, it is important to promote the structural relaxation of the glass. That is, it was considered that if the structural relaxation of the glass could be promoted, the lower temperature state where the density fluctuation becomes smaller could be frozen in the cooling process, resulting in the lower loss of the optical fiber.

8.2 Effect of Dopant

The first method to promote glass relaxation is to add dopants that have the effect of reducing the viscosity of glass. Of course, the addition of an excessive amount of dopant increases the density fluctuation, which has an adverse effect on Rayleigh scattering reduction. With this in mind, various researches to verify the dopant addition effect were conducted as below.

Tajima et al. confirmed the Rayleigh scattering loss of P₂O₅-F-SiO₂ glass (P₂O₅: 8.5 wt.%, F: 0.3 wt.%) is 0.8 times lower than that of pure SiO₂ glass [57], and Rayleigh scattering coefficient of 0.66 dB/km· μm^4 was obtained for a P₂O₅-SiO₂ core SM fiber [58]. Unfortunately, the fiber showed a structural imperfection loss as high as 0.36 dB/km, which was attributed to viscosity mismatch between the core and the cladding.

Lines reported Rayleigh scattering loss in the bulk state was reduced by up to 20% compared to pure SiO₂ glass by adding alkali or alkaline earth elements [59]. Saito et al. proposed the method to dope SiO₂ with only 10 wt. ppm of Na₂O, by which scattering loss could be reduced by 13% [60].

Fluorine (F) had gathered attention because of the effect to lower viscosity from the viewpoint of imperfection loss induced by viscosity mismatch. Ogai et al. demonstrated very low loss of 0.156 dB/km by an SM fiber with SiO₂ core slightly doped with F [61], and Ohashi et al. reported viscosity matching in the cross section of the fiber from the core to the cladding by utilizing F in order to reduce structural imperfection loss [39]. At that time, they did not mention the effect of F to lower T_f . Afterwards, Lines pointed out the possibility of F to lower T_f [62], and Saito, Kakiuchida, and Shimodaira et al. conducted basic researches of F-SiO₂, regarding effect of F to T_f by analyzing the specific band of Raman spectrum [47] as well as IR spectrum [63], [64]. Saito found chlorine (Cl) was also has the effect to promote relaxation of silica [65].

8.3 Heat Treatment

The second method to promote glass relaxation is heat treatment of drawn optical fibers. Sakaguchi et al. analyzed the end face of drawn optical fibers by Raman spectroscopy [56]. They found that its T_f was 1600°C as drawn state, and that it was reduced to 1400°C by heating the optical fiber piece. Although reheating drawn optical fibers was not practically applicable, this result was an important clue to realize ultra-low-loss fibers.

Tajima et al. have shown that the loss of a standard GeO₂-SiO₂ core SM fiber could be reduced to 0.16 dB/km by lowering the temperature of the drawing furnace to the limit at which drawing was possible [66]. In Tajima's work, drawing speed was 1 m/sec [67] and it was difficult to directly put it into practical use from the viewpoint of productivity.

Saito et al. proposed a method to reduce the loss of an optical fiber by focusing on the cooling process during drawing [68], where an annealing furnace was set beneath a drawing furnace. The annealing furnace lowers the cooling rate of the optical fiber, and it was estimated that the transmission loss of the optical fiber could be reduced below 0.141 dB/km with an annealing temperature of 1567°C and an annealing time of 1 sec.

9. Loss Reduction of Commercial Fibers

9.1 Growing Needs of Low-Loss Fiber

Development of low-loss optical fibers at the mass production level has been activated since 2010 with the practical application of digital coherent technology. The impact of the digital coherent technology on optical fibers was very significant in long haul transmission systems, especially for transoceanic submarine cable systems.

Digital coherent technology allows the linear waveform distortion due to chromatic dispersion and dynamic polarization dispersion fluctuation that occur during propagation in the optical fiber can be corrected by the digital signal processor at the receiving end. In the dense wavelength division multiplexing (DWDM) transmission systems before the advent of the digital coherent technology, the requirement on the chromatic dispersion characteristics of the optical fiber became stringent, and it was required to accurately form the refractive index distribution structure of the optical fiber into a three- to four-fold annual ring shape. It was also required to thoroughly reduce polarization dispersion. However, with the advent of digital coherent technology, the requirements for chromatic dispersion and polarization dispersion of optical fibers were relaxed. Instead, the low loss and suppression of nonlinear waveform distortion became to be strongly required. In parallel, the number of transoceanic optical submarine cable projects have continued to increase since 2013, when cloud services became popular on a global scale and borders began to disappear for

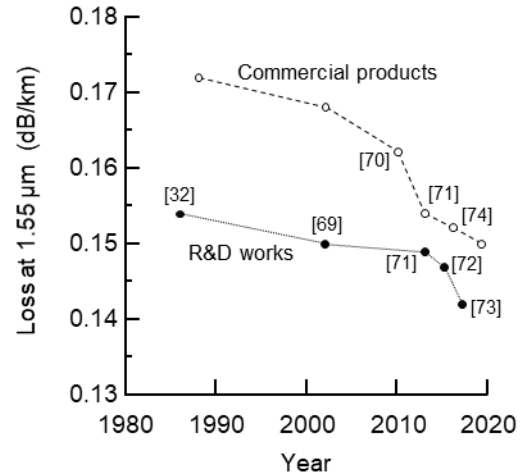


Fig. 13 Loss transition of pure-silica-core fibers.

data exchange. Thus, digital coherent technology has also been applied to submarine systems, and the required ultra-low-loss optical fiber has come into the spotlight.

9.2 Ultra-Low-Loss Fibers of Recent Date

Figure 13 shows the transition of loss reduction of optical fibers under the background as mentioned above. The loss improvement has been accelerated in the 2010s. Eventually, in 2017, Tamura et al. reported the record-low loss of 0.1419 dB/km obtained at 1.56 μm [73].

As shown in Fig. 13, not only the top data achieved in R&D work but also the transmission loss of mass-produced products has been improved, and ultra-low-loss products of 0.150 dB/km at 1.55 μm are now being manufactured and commercialized.

The loss spectrum for the fiber which showed the lowest loss record is shown in Fig. 14. The loss at 1.55 μm was 0.1424 dB/km. The loss was realized with an optical fiber, of which core was doped with small amount of fluorine as the inset in Fig. 14.

Figure 15 shows the relationship between T_f and Rayleigh scattering coefficient in pure-silica-core fibers [75]. The fictive temperature was deduced from the normalized peak area of D_2/ω_3 in Raman spectrum averaged over the fiber cross section of 100 μm, compared with that for the calibration sample with known T_f . In Fig. 15, Rayleigh scattering coefficient shows a good correlation with T_f .

In addition, the fiber with the record-low-loss has a large effective core area A_{eff} of 147 μm² in order to realize the low nonlinearity required for digital coherent communication systems. In general, the larger A_{eff} , the higher microbending loss, which corresponds to the sensitivity to the small deformation of the glass induced by the lateral pressure when accommodated in a cable. In order to keep the microbending loss low enough, a new soft primary coating with a reduced elastic modulus, which sufficiently absorbs lateral force and protects the glass fiber, has been developed. Figure 16 shows the dependence of microbending loss on

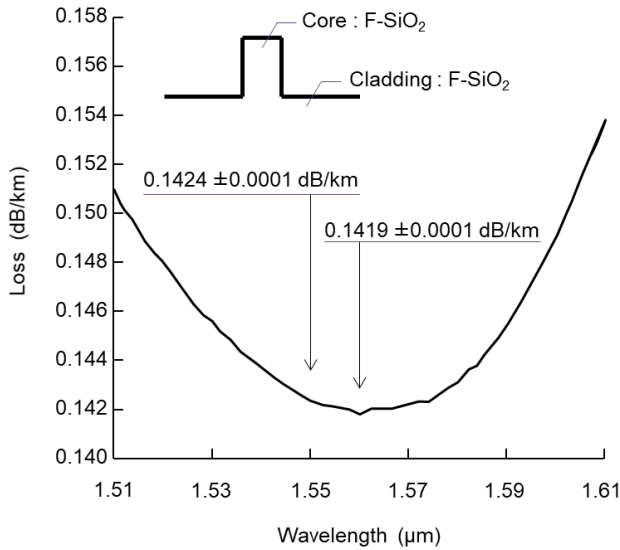


Fig. 14 Loss spectrum of the fiber with the record-low loss.

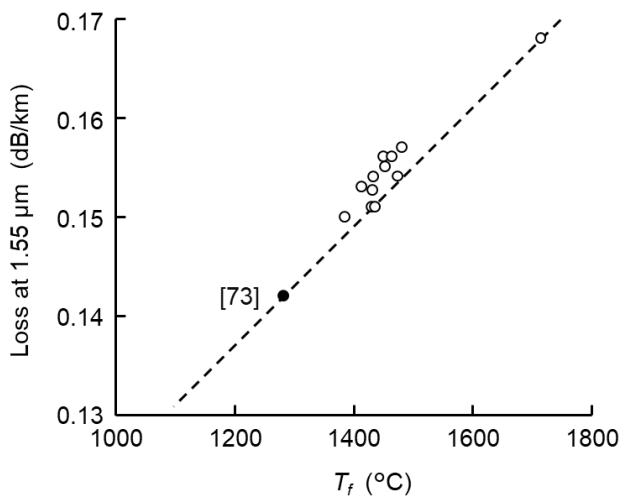
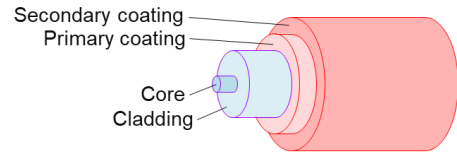


Fig. 15 Relationship between loss of pure-silica-core fibers and T_f .

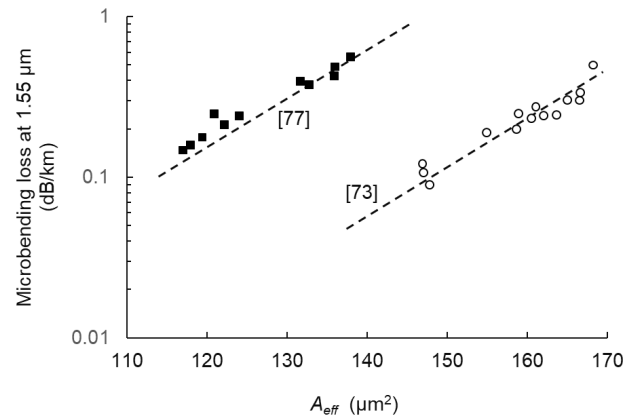
A_{eff} for fibers with the new coating compared with the conventional coating [77]. The microbending loss was measured by the wire mesh drum method [76]. It was confirmed that the microbending loss has been improved to as low as 0.1 dB/km, which is considered to be low enough for usual submarine cables, even with a large A_{eff} of around $150 \mu\text{m}^2$ owing to the new primary coating.

9.3 Impact of Ultra-Low-Loss Fiber on System Performance

Lower loss of optical fibers is surely beneficial for transoceanic systems, because the fiber loss needs to be compensated by large number of amplifiers that increase the noise, cost, and power consumption of the system. Hirano et al. discussed the benefits of reduced loss by the theory of fiber figure of merit (FOM) [71], [73]. In this theory, Q-factor can be estimated from the fiber loss, A_{eff} ,



(a) Polymer coating surrounding glass of optical fiber



(b) Relationship between microbending loss and A_{eff}

Fig. 16 Microbending loss improvement.

Table 2 Example of reduction in repeater numbers of 10,000 km transoceanic systems by loss reduction.

ref	Loss at 1.55 μm	A_{eff}	Span length	Number of repeaters
[71]	0.149 dB/km	$135 \mu\text{m}^2$	60 km	166
[72]	0.1467 dB/km	$148 \mu\text{m}^2$	67 km	148
[73]	0.1424 dB/km	$147 \mu\text{m}^2$	72 km	138

Assuming 10,000 km, 8QAM-150Gbps ($Q \geq 7.0$ dB) system

and the span length. Table 2 shows an example of effect of loss reduction for reduction in repeater numbers in a 10,000 km transoceanic system that transmits 8QAM-150G signals with minimum required Q-factor of 7.0 dB. The ultra-low loss fiber [73] can support a span of 72 km, that is 6% longer than that for previous record fiber [72].

9.4 Multi-Core Fiber (MCF)

In order to meet increasing demand for the transmission capacity of a transoceanic submarine system, increase of fiber count in a submarine cables is one important challenge. For this purpose, a multi-core fiber (MCF), which has plural cores in one fiber, is now attracting rising attentions, and loss reduction is an important issue for MCFs as well. Hayashi et al. has reported the lowest loss of 0.158 dB/km at $1.55 \mu\text{m}$ for MCF with a coupled four core structure [79], and Tamura et al. has reported the loss of 0.162 dB/km at $1.55 \mu\text{m}$ with an uncoupled two core structure [80].

10. Conclusion

The history of loss reduction for silica optical fibers from the first report of 20 dB/km by Corning in 1970 to the current record-low loss of 0.1419 dB/km was reviewed. In 1970–1981, removal of impurities, especially OH-groups, was the main barrier to loss reduction, and eventually 0.20 dB/km was achieved for GeO₂-SiO₂ core SM fibers. Subsequently, in 1986, the loss of 0.154 dB/km was achieved with a pure-silica-core SM fiber by suppressing Rayleigh scattering due to composition fluctuation. In the 1990s and early 2000s, studies on reducing Rayleigh scattering due to density fluctuation were actively conducted by utilizing IR and Raman spectroscopy. Now, ultra-low-loss fibers with the loss of 0.150 dB/km are commercially available in trans-oceanic submarine cable systems.

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