The First 0.14-dB/km Ultra-low Loss Optical Fiber

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We have been producing pure-silica core fibers that enable low-loss transmission since as early as 1980s, contributing to the development of submarine optical cable networks through continuous reduction in transmission loss and nonlinearity of fiber. We have succeeded in further reducing the density fluctuation of a pure-silica core and developed an optical fiber with a transmission loss of 0.14 dB/km.

Keywords: optical fiber, pure-silica-core fiber, submarine optical fiber

1. Introduction

Optical-fiber-based communication networks are growing on a global scale. Presently, the quantity of optical fiber produced throughout the world amounts to 400 million km a year. The essential function of optical fiber is to transmit light over a long distance. For this purpose, it is important that both the transmission loss, which indicates the attenuation of light per unit length, and the nonlinearity, which limits maximum optical power to be transmitted, must be low. In addition, losses caused by micro-bends in cables and macro-bends or splices with different fibers in repeaters also need to be reduced.

Sumitomo Electric Industries, Ltd., ahead of its competitors, commercialized an ultimate low-loss optical fiber, the Z Fiber, and continuously improved the low-loss and low-nonlinearity properties of the Z Fiber to achieve the Z-PLUS Fiber 150 with the industry's highest performance and develop an extremely low-loss optical fiber with the world's lowest loss of 0.14 dB/km. This report reviews the performance of these fibers.

2. History of Pure-Silica Core Fibers

2-1 Z Fiber

In 1966, Kao proposed that it would be possible to make a low-loss optical fiber using impurity-free silica glass (SiO_2).[1] After subsequent technological developments, a low loss of 17 dB/km was demonstrated by Keck et al. in 1970[2],[3] and 0.20 dB/km by Miya et al. in 1979.[4] These developments paved the way to optical fiber-based communication networks. These early optical fibers were made of a core doped with TiO_2 or GeO_2 to guide light with an increased refractive index and a cladding made of silica glass[3],[4] (Fig. 1). However, from the perspective of transmitting light, which is the essential function of optical fiber, Sumitomo Electric considered that transmission loss should be further reduced by a pure-silica-core fiber (PSCF), which has a core made of pure silica glass and a cladding made of silica glass doped with fluorine (F) to have a reduced refractive index.

Based on this idea, Shiraishi et al. of Sumitomo Electric applied for a patent on a PSCF structure, which was registered in Japan in 1980 and in the United States in 1978.[5],[6] It is noteworthy that they began to work on an essentially low-loss structure in the early years of optical fiber, when transmission losses were improved by means of removing metal and other impurities.

In 1986, Kanamori et al. of Sumitomo Electric reported a PSCF having a transmission loss of 0.154 dB/km, which was significantly lower than that of the standard optical fibers, as well as substantially low additional losses when exposed to hydrogen and radiation.[7]-[9] These advantages implied that PSCF would be optimal for submarine optical cables because submarine optical cables are installed over long distances, used for a long period of time, and, if failure occurs, subject to the generation of hydrogen gas due to the reaction between metal in the cable and water. Sumitomo Electric, ahead of its competitors, commercialized PSCF with a low loss of 0.17 dB/km in 1988 under the trade name "Z Fiber," as an optical fiber with ultimately low transmission loss.

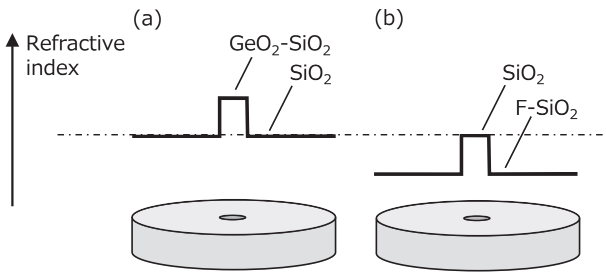

Fig. 1. Schematic diagrams of standard optical fiber (a) and pure-silica-core fiber (b)

2-2 Z-PLUS Fiber

For submarine optical fibers, low nonlinearity is required in addition to low transmission loss for launching high-power signals so as to transmit them over a long distance. Low nonlinearity can be achieved by using a material of low nonlinearity and enlarging the core area for reduced power density. These are equivalent to a low nonlinear refractive index*1 n_2 of the core and to a large effective core area*2 A_{eff}, respectively. Since doping GeO_2

increases n_2, PSCF that has a GeO_2-free core is superior in n_2 to standard optical fibers. Although A_{eff} can be enlarged by physically enlarging the core area while keeping the low bending loss, it causes higher order modes to propagate, potentially causing noise. As a solution to this problem, in 1999, Kato et al. of Sumitomo Electric proposed changing the cladding structure from matched to depressed (Fig. 2), which would cut off the higher order modes and allow A_{eff} to be enlarged from the previous 80 μm^2 to 110 μm^2.[10] Sumitomo Electric commercialized PSCF with A_{eff} enlarged to 110 μm^2 as Z-PLUS Fiber (Z+). In 2002, Nagayama et al. of Sumitomo Electric proved that this structure would ultimately achieve a low loss of 0.1484 dB/km.[11]

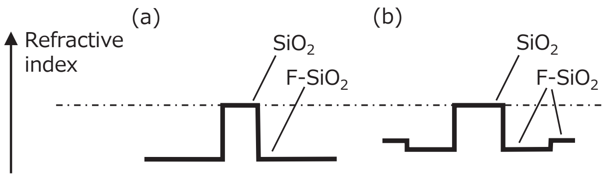

Fig. 2. Schematic diagrams of matched (a) and depressed (b) cladding structures

2-3 Z-PLUS Fiber 130

For a further enlarged effective core area A_{eff}, it was necessary to reduce losses caused by microbends, which occur when an optical fiber was integrated into a cable and installed. In 2010, Yamamoto et al. of Sumitomo Electric demonstrated that by improving the flexibility of the polymer layer used to coat optical fiber glass for reduced microbends generated in the glass, A_{eff} could be enlarged to 130 μm^2.[12],[13] However, this substantially enlarged A_{eff} in comparison with the 80 μm^2 of the standard single-mode fiber (SSMF) is subject to the problem of an increased fusion splicing loss between PSCF and SSMF. As a solution to this problem, in 2012, Hirano et al. of Sumitomo Electric proved that the splicing loss could be reduced by employing a core having a ring-shaped index profile (Fig. 3).[14] Splicing losses are caused by discontinuity in the mode-field diameter*3 (MFD), which indicates how broadly optical power is distributed. The ring core enables a large A_{eff} with a small MFD, thereby reducing discontinuity in MFD for splicing between PSCF and SSMF. In 2013, Hirano et al. of Sumitomo Electric achieved a low loss of 0.148 dB/km with ring-core PSCF.[15],[16] This type of PSCF was commercialized as the Z-PLUS Fiber 130 (Z+130) featuring a low loss of 0.154 dB/km. The above-described series of development results greatly contributed to the growth of submarine optical cable networks. Consequently, Sumitomo Electric received the Kenjiro Sakurai Memorial Prize from the Optoelectronics Industry and Technology Development Association for recognition of the contribution.

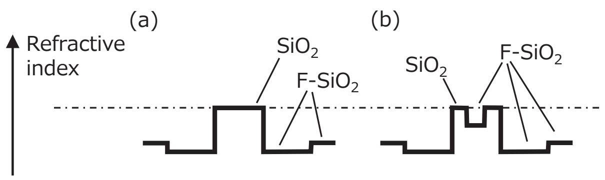

Fig. 3. Schematic diagrams of step core (a) and ring core (b)

2-4 Z-PLUS Fiber 150

The higher power output of submarine optical repeaters implies the need for larger A_{eff}. To meet this need, Sumitomo Electric made the coating further softer to reduce losses caused by microbends and enlarged A_{eff} to 150 μm^2. The product was commercialized in 2017 as the Z-PLUS Fiber 150 (Z+150).[17] The Z+150 features a low loss of 0.152 dB/km in addition to a large A_{eff}. Sumitomo Electric has produced more than 50,000 km accumulated length of Z+150 and proven that the standard deviation of transmission loss is as narrow as 0.003 dB/km (Fig. 4).

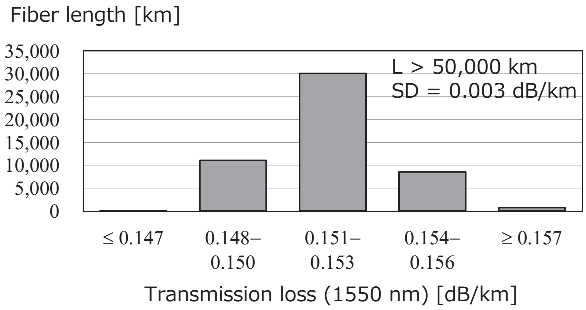

Fig. 4. Transmission loss distribution of Z+150 fiber

Table 1 summarizes the series of products described in this section. The Z+150 and Z+130 exhibit the most outstanding performance at a low loss and a large A_{eff}. These fibers are suited mainly for long-distance trans-oceanic transmission cables. The Z+ and Z with smaller core areas are higher in productivity and lower in cost. Therefore, these fibers are suited for medium-distance and regional submarine transmission cables.

Table 1. Types and applications of pure-silica-core fibers

	Z	Z+	Z+130	Z+150
Transmission loss [dB/km]	0.171	0.154	0.152	0.152
A_{eff} [μm^2]	78	112	130	150
Application	Short to medium distances		Long distances	

3. World Record-Breaking Extremely Low-Loss Fiber

3-1 Properties of extremely low-loss fiber

The core of PSCF is made of impurity-free silica glass (SiO_2). The principal cause of transmission loss in PSCF is the scattering of light resulting from SiO_2 density fluctuation. In contrast to a quartz crystal (SiO_2), where silicon (Si) and oxygen (O) atoms are arranged in a regular structure, Si and O atoms in silica glass are randomly arranged, as schematically shown in Fig. 5. The basic structure of silica glass is a 6-membered ring consisting of 6 Si atoms. However, with increasing irregularity, the number of 3-membered or 4-membered rings increase, which is the cause of density fluctuation. This irregularity originates from thermal vibrations when optical fibers are drawn at approximately 2000°C. The irregularity generated under the high temperature is partially fixed while the drawn optical fiber is rapidly cooled. During the cooling process, atoms tend to be arranged in a more regular structure, which is known as structural relaxation. By promoting structural relaxation, it is possible to produce an optical fiber with reduced density fluctuation, hence with reduced scattering losses.

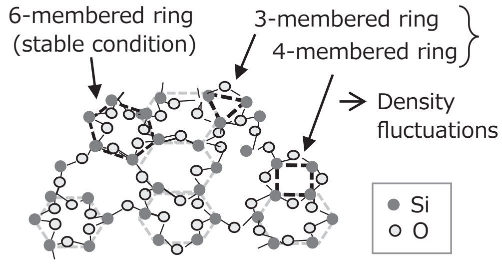

Fig. 5. Schematic diagram of irregularity in glass structure

We reduced density fluctuation by developing an optical fiber with the pure-silica glass core of PSCF containing a trace amount of fluorine (F). As a result, the PSCF had an extremely low loss of 0.1419 dB/km at the lowest-transmission-loss wavelength of 1560 nm and 0.1424 dB/km at a typical communication wavelength of 1550 nm.(18) These values set a world record, being lower than the previous world record(19) by 0.004 dB/km. In addition, this optical fiber is the world's first in that the loss is 0.14 dB/km when rounded to the second decimal place. Moreover, its effective core area A_{eff} is 147 µm^2, exhibiting low nonlinearity at the same level as the previously mentioned Z+150.

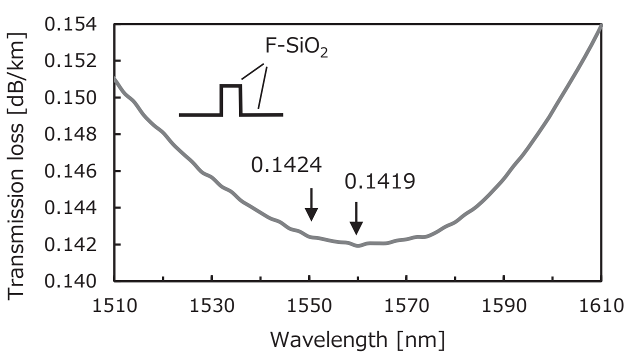

Fig. 6. Loss vs. wavelength characteristics and the structure of an extremely low-loss fiber

Extremely low-loss optical fibers are beneficial in that they operate with a reduced number of repeaters in submarine optical cable systems. The currently state-of-the-art FASTER trans-pacific optical cable enables high-capacity transmission at 150 Gbit/s per wavelength.(20) For transmission over a distance of 10,000 km at this capacity, use of the extremely low-loss optical fiber enables a 7% reduction in the number of repeaters in comparison with the previous world-record optical fiber, according to an estimation based on the figure-of-merit (FOM) theory.(21)-(23) By reducing the number of repeaters, it becomes possible to reduce their cost and power consumption. With high-capacity submarine cables, the maximum capacity can be limited by the maximum power that can be supplied.(24)-(26) In such situations, where the capacity is limited by power supply, the use of an extremely low-loss optical fiber allows for an increase in the capacity by reducing the power per fiber and increasing the number of fibers in the cable.

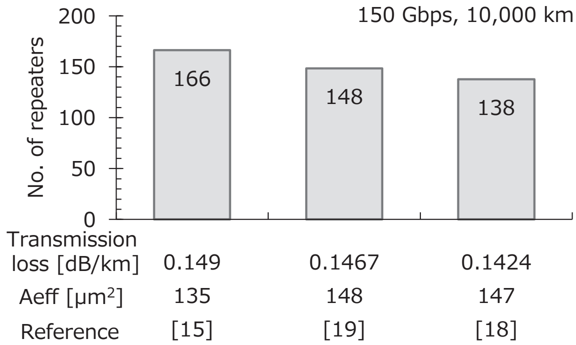

Fig. 7. Benefits of extremely low-loss fiber in reducing the number of repeaters

3-2 Reducing density variations

To verify that the extremely low loss of 0.14 dB/km was enabled due to reduced density fluctuations, we evaluated fictive temperature by Raman spectroscopy. In Raman spectroscopy, 532 nm laser beams are focused at the end face of an optical fiber core and the resultant frequency spectra of Raman scattering light are measured. Raman spectra exhibit a wide ω3 peak at 800 cm^{-1} attributed to the Si-O-Si deformation vibration inherent to silica glass and a narrow D2 peak at 605 cm^{-1} attributed to the stretching vibration of 3-membered rings that cause density fluctuations. Therefore, it is possible to quantify the degree of density fluctuation by calculating the peak area ratio D2/ω3. The degree of density fluctuation can be represented by a fictive temperature defined as a temperature of the equilibrium liquid state of SiO_2 that has a same degree of density fluctuation. Consequently, by providing measurements of the aforementioned D2/ω3 ratio using silica glass samples of known fictive temperatures, it is possible to determine a fictive temperature of an unknown sample by measuring its D2/ω3 ratio.

Fictive temperatures were measured, as described above. The results of the measurement revealed a trend of decreasing transmission losses at a rate of -0.006 dB/km per 100°C decrement in fictive temperature, as illustrated in Fig. 8. Since the extremely low-loss fiber described in this report is on the same trend line, it has been revealed that the extremely low-loss feature was enabled by the reduced density fluctuation represented by fictive temperatures.

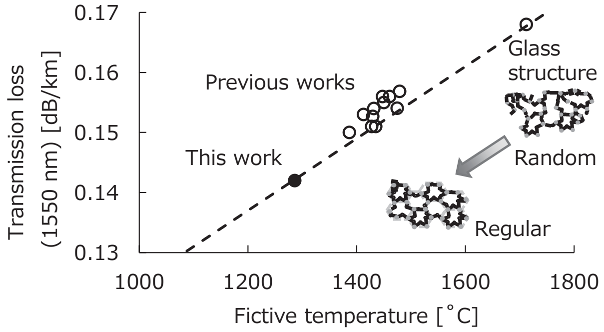

Fig. 8. Transmission loss vs. fictive temperature

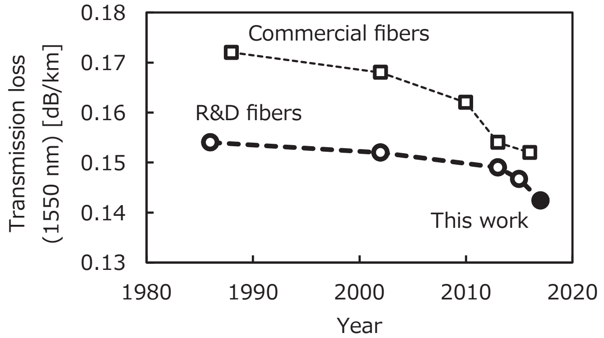

Fig. 9. History of transmission loss reduction

4. Future Developments

Steady efforts have been made for more than 30 years to reduce the transmission loss of pure-silica-core fibers (PSCF). The reduction of 0.004 dB/km achieved in two years by the present extremely low-loss fiber is notably rapid in the history of PSCF. In recent years, PSCF has been in wide use for submarine and long-distance terrestrial cable applications. This has been promoting rapid improvements in transmission loss of commercial PSCF. It is expected that an extremely-low transmission such as those presented here would also become available in commercial PSCFs in the near future.

Meanwhile, one limiting factor to the transmission capacity of a trans-oceanic submarine cable is the electric power for regenerating optical power lost due to the transmission losses of optical fiber. For improved power efficiency, it is effective to reduce optical power per fiber by using more fibers in the cable.[25] Therefore, cables containing higher count of fibers or multi-core fibers will be needed. In either case, low-loss optical fibers will fundamentally improve power efficiency and are expected to become increasingly important. We have been working for low-loss multi-core fibers, achieving the lowest loss of 0.158 dB/km for the multi-core fibers.[27] We intend to continue working on developing the technology to contribute to future high-capacity systems.

5. Conclusion

Sumitomo Electric pioneered the development of pure-silica-core fibers for achieving low transmission losses and has contributed to the growth of submarine cable networks. Moreover, by reducing the density fluctuation of pure silica core, we have realized the world's first optical fiber featuring an extremely low transmission loss of 0.14 dB/km.

Technical Terms

∗1 Nonlinear refractive index: The refractive index of a medium changes slightly depending on optical power density. The nonlinear refractive index is the coefficient between the power density and changes in the refractive index.

∗2 Effective core area: In an optical fiber, optical power density is distributed to be the highest at the center of the core and to decrease towards the periphery. The effective core area is the area of distribution of the same overall power distributed at uniform density so as to exhibit equivalent nonlinearity.

∗3 Mode-field diameter: The distribution range of optical power in an optical fiber.

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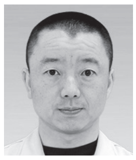

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