

Fifty Year History of Optical Fibers

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Optical fiber communication started to become practical use in 1970, when an optical fiber with a transmission loss of 20 dB/km and a laser diode continuously emitting at room temperature appeared. Sumitomo Electric Industries, Ltd. has enterprisingly dedicated the development and commercialization of optical fibers since the early days. Utilizing the vapor-phase axial deposition method, which has spread worldwide as a preform manufacturing process, we have kept launching high-quality optical fibers and cables such as ultra-low-loss silica core fibers and ultra-high-density optical cables. This way, we have continued to support the expansion of optical fiber networks as one of the indispensable social infrastructure. This paper looks at the evolution of optical fiber technology and our efforts in developing optical fibers and cables that would meet the need of the time.

Keywords: optical fiber, VAD, ultra-low-loss optical fiber, ultra-high-density optical cable

1. Introduction

In the history of optical fiber communication, optical fiber with transmission loss of 20 dB/km and continuous oscillation of semiconductor laser at room temperature emerged in 1970, and the year 2020 marks 50 years since then. This paper looks back chronologically over the evolutionary process of development of optical fiber and business approaches at Sumitomo Electric Industries, Ltd.

2. Early Days: 1964-1974

In 1966, Kao of Standard Telecommunication Laboratories in the UK foretold that the loss of transition-metal-free high-purity glass fiber can be below 20 dB/km.⁽¹⁾ For this achievement, the 2009 Nobel Prize in physics was awarded to him. Meanwhile, in 1964, Nishizawa and Sasaki applied for a patent in terms of a graded index (GI) fiber*¹ 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 1970, Corning Glass Works (present Corning) in the US reported on their prototype silica glass optical fiber with transmission loss of 20 dB/km.⁽²⁾ The value of 20 dB/km was an index of performance for optical fiber to be comparable to coaxial cables in repeater distance. Since the achievement of this index, the development of optical fiber quickly gained momentum in the US, UK, and Japan. Also, Sumitomo Electric began researching optical fiber. In the first half of the 1970s, the Company proposed important optical fiber technologies, including the concept of preform manufacturing method leading to the vapor-phase axial deposition (VAD) method described later,⁽³⁾ tandem primary coating⁽⁴⁾ used to coat the fiber immediately after drawing from the preform, and pure-silica core fiber.⁽⁵⁾ In 1974, Bell Laboratories in the US achieved transmission loss of 2 dB/km using a novel preform manufacturing method known as the modified chemical vapor deposition (MCVD) method.⁽⁶⁾ In the MCVD method, raw glass materials in the gas phase and oxygen are flown into a silica tube and heated from outside with an oxyhydrogen burner to form

glass layers of the desired composition on the tube's inner surfaces, and the tube is then contracted radially and solidified by further heating. Owing to disclosure of the details, the MCVD method spread to many countries as an early preform manufacturing technique.

3. Development Period: 1975-1984

3-1 Joint research in Japan

In Japan, to catch up with the US and Europe in optical fiber development, Nippon Telegraph and Telephone Public Corporation (NTT-PC, present NTT) led an organization formed to conduct joint research on optical fiber with Sumitomo Electric, the Furukawa Electric, and Fujikura Cable Works (present Fujikura). This joint research continued for three periods.

In the first period (1975-1978), the MCVD method was used to develop GI fiber, and the first field trial of a 0.85 μm optical fiber transmissions system was successfully conducted in 1978 over a distance of 20 km between Karagasaki and Kuramae, Tokyo, using a GI 48-fiber optical cable.⁽⁷⁾ At the time, the optical fiber was 150 μm in glass diameter, 60 μm in core diameter, and with a two-layer coating consisting of a silicone resin and a thermoplastic resin.

In parallel with this field trial, the joint research invented the VAD method⁽⁸⁾ as a Japanese original preform manufacturing technique rivaling the MCVD method. In the VAD method, a porous preform is grown in the axial direction, by feeding raw glass materials in the gas phase into oxyhydrogen burners, allowing produced fine glass particles (soot) to deposit on the tip of the rotating starting member, and lifting the starting member (Fig. 1). Then the porous preform is heated in a dehydrating gaseous atmosphere for high-level purification, and exposed to higher temperatures for sintering to make it transparent. The VAD method was claimed to enable large preform sizes and to be highly suitable for volume production. However, in its early days, the VAD method suffered many problems such as deformation or cracks in the porous preform during deposition, difficulty in forming a refractive index profile

suitable as GI fiber, and bubbles formed during the sintering process. The team of the joint research tackled these challenges, working day and night. Eventually, they prepared GI fibers by the VAD method, which was installed in a part of the first field trial (between Hamacho, Tokyo and Kuramae). This was an important initial step for completion of the VAD method.

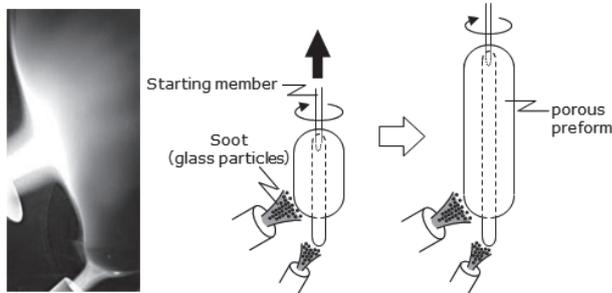


Fig. 1. The VAD method

In the second period (1978-1980), the dehydration technique of the VAD method improved, which led to rapid development of low-loss optical fiber. Based on a breakage theory of brittle materials, a technique for assuring the strength of optical fiber was built. Moreover, a screening test method was established to exclude low-strength portions in-line by applying a suitable level of tension to the overall length of drawn fiber.

Based on these achievements, in 1980, the second field trial of optical fiber transmission system was conducted in the Kawasaki district, Kanagawa.⁽⁹⁾ In the trial, a 20 km optical cable including aerial sections was installed, and the world's first 100 Mbps transmission at 1.3 μm was successfully demonstrated. In this trial, the glass diameter and core diameter were reduced to 125 μm and 50 μm , respectively. Moreover, a six-nylon-coated-fiber unit structure was completed as optical cable, and this had been a standard structure at NTT until the introduction of a ribbon-slot structure in 1986. The GI fiber-based optical fiber transmission system was adopted in 1982 for actual use after commercial test in 1980.

In the second period, development of single mode (SM) fiber*² also began using the MCVD method. A field trial of this fiber was conducted in October 1980 as an F-400M transmission system, connecting Musashino Laboratories and Atsugi Laboratories of NTT.⁽¹⁰⁾ In this test, a wavelength of 1.3 μm was used, a transmission rate was 400 Mbps, and a repeater distance was 20 km. In addition, a field trial of a non-repeater submarine cable transmission system (1980) and a field trial of a subscriber system (1980) were conducted. Thus, optical fiber was steadily coming closer to its full commercialization.

In the third period (1981-1983), the joint research team worked on the development of SM fiber using the VAD method. SM fiber needs a sufficient cladding thickness for reduced loss. However, depositing soot thickly in the cladding portion was subject to limitations. Therefore,

making the core relatively thin was necessary. Accordingly, many ideas were implemented for the thin core to grow stably, including a soot depositing burner structure. As a result, as an SM fiber manufacturing method, VAD surpassed MCVD both in terms of properties and productivity. Finally, in 1983, as a grand sum of the joint research achievements, construction of a trans-Japan trunk line using the F-400M transmission system began, connecting Asahikawa and Kagoshima.

However, immediately before this construction, a serious problem emerged in 1982, which was the loss induced by hydrogen. The optical cable installed for the second field trial exhibited increases in transmission loss over time. The joint research team worked on cause investigations as an urgent issue. The investigation results revealed that a trace amount of hydrogen generated from the materials, such as optical fiber coating resin, penetrated the glass fiber and combined with the defective structure of the Ge component in the glass to form photo-absorbing hydroxyl groups, and the hydroxyl groups noticeably increased with the presence of phosphorus (P) doped. This was a serious problem with the MCVD method, which used P in the manufacturing process. In this respect, the VAD method, which used no P, demonstrated its advantages.

3-2 Activities besides the joint research

In a period overlapping the joint research with NTT-PC and cable manufacturers, Sumitomo Electric conducted a joint development project with power companies as well. Power companies supplied their own communication lines to operate their power transmission/distribution systems. Being non-inductive, optical fiber was advantageous because it could be installed next to a power cable.

Meanwhile, the Ministry of International Trade and Industry (present Ministry of Economy, Trade and Industry) considered replacing the existing transmission wire with optical fiber in a field trial of a regional information system, which covered video data delivery, started by the Ministry. In 1976, the ministry selected Sumitomo Electric's optical fiber. It was the Higashi-ikoma Optical Visual Information System (Hi-OVIS). The optical fiber used in this trial was plastic clad fiber (PCF) prepared by drawing a high-purity silica rod and coating with a silicone resin as cladding.

3-3 Inauguration of business division

At Sumitomo Electric, the R&D department in the Communications Division was first in charge of the development of optical fiber. The organization was transferred to the R&D Unit in 1976. In 1981, when commercialization of optical fiber and cables came into view, halves of the researchers in fiber optics and optical communication systems assembled to set up the Fiber Optics Development Division, which was renamed the Fiber Optics Division in 1984.

4. Prevailing Period: 1984-1990

While the joint research agreement signed with NTT-PC expired in 1983, individual optical fiber development projects were pursued with NTT-PC. However, as

NTT-PC was privatized to establish NTT in 1985, manufacturers were thrown into intense competition for optical fiber development.

4-1 UV-cured resin coating and ribbon-slot cable

With a lateral pressure applied, optical fiber deforms slightly and optical loss occurs. For this reason, the coating is required not only to protect the glass surface of the optical fiber, but also to absorb the lateral pressure so as not to cause any optical loss. In Japan, for these purposes, optical fiber was coated with a soft thermosetting silicone resin up to an outer diameter of 400 μm when being drawn, and hard nylon was applied on it to an outer diameter of 900 μm . Meanwhile, in the US, optical fiber was coated with a UV-cured acrylate resin, developed primarily by Bell Laboratories, to an outer diameter of 250 μm . If optical fiber 250 μm in outer diameter had been used in the Japanese cable structure in which optical fibers were tightly stranded, optical loss would significantly increase. In contrast, overseas countries used loose-tube cables in which optical fibers were placed in tubes, thereby loss was suppressed. Nevertheless, even with this technical backdrop, the joint research team decided that optical fiber should be coated with a UV-cured resin, considering the need for high-density cables with smaller diameter for future deployment of optical fiber to subscriber systems. The issue of increasing loss in optical fiber due to hydrogen also facilitated switching from silicone resin prone to hydrogen production to UV-cured resin. The challenge was to develop a cable structure suitable for optical fiber with UV-cured resin coating surpassing the loose tube cables, and the team devised a ribbon-slot cable,⁽¹¹⁾ illustrated in Fig. 2. In this structure, multiple ribbons are placed in slots. Fibers with UV-cured resin coating are formed a ribbon with UV-cured resin in units of four to eight fibers. Since UV curing reaction completes in a shorter time than thermosetting reaction, UV-cured resin is advantageous in terms of drawing and ribbon-making productivity. Today, Japanese original UV-cured resin ribbons have been adopted widely in the world.

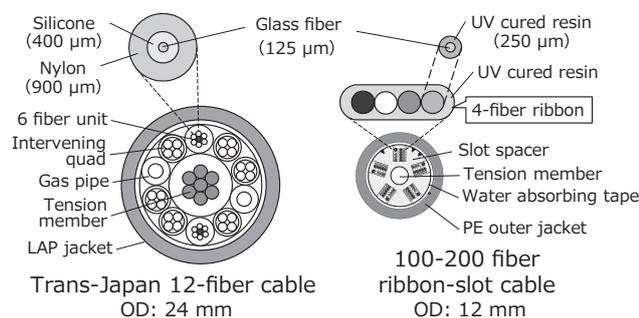


Fig. 2. Transition of fiber coating and cable structure

4-2 Wholly synthesized VAD

In the VAD method, the core and the part of cladding are simultaneously synthesized. In the early days for the VAD method, this core/cladding preform was placed in a

commercially available silica tube, which corresponded to the outer portion of the glass fiber, and heated for solidification, followed by drawing. However, the use of commercial silica tubes resulted in low fiber strength due to the effect of impurities. The low fiber strength posed a limit to the length of fiber yielded after screening. Impurities in the silica tube caused loss increase as well, although slightly. Furthermore, variation in the silica tube wall thickness and circumferential unevenness during solidification were causes of degradation in terms of core eccentricity. Moreover, the price of silica tubes was becoming a bottleneck in making optical fiber economical. As a solution to these challenges, Sumitomo Electric worked on the wholly-synthesized VAD method, in which a glass layer around a core/cladding preform was synthesized by another cycle of VAD, instead of using silica tube. In the mid-1980s, the Company successfully delivered low-loss and high-strength optical fiber through the wholly-synthesized VAD method, with reduced hydrogen-induced loss. This fiber was employed in the trans-Pacific submarine optical cable (TPC-3), which came into service in 1989.

A technique required to improve the soot deposition rate was important for the commercialization of the wholly-synthesized VAD fiber. In the first half of the 1980s, the deposition rate with one burner of the VAD method was about 1 g/min. At this level, the productivity was very low. To meet this challenge, the double-flame VAD method was devised.⁽¹²⁾ A double flame formed by an elaborate burner structure accelerates the reaction of soot generation and improves the deposition efficiency (Fig. 3). In the second half of the 1980s, after refinement of this technique, the deposition rate increased to 20 g/min.⁽¹³⁾ This was a remarkable 20-fold improvement in production rate in five years.

With the wholly-synthesized VAD method, the preform size increased dramatically, contributing to improved productivity, because it could avoid the use of commercially available silica tubes, which was a restrictive factor to the preform size. Moreover, the wholly-synthesized VAD method reduced the eccentricity of the core to substantially below 1 μm , and this made low-loss splicing of fibers possible, simply using the glass periphery as reference for fusion splicing and connector connection. Multi-fiber mass splicing and various optical connectors were essential for the construction of optical fiber networks. It was impossible for these technologies to be implemented without low-eccentricity optical fiber.

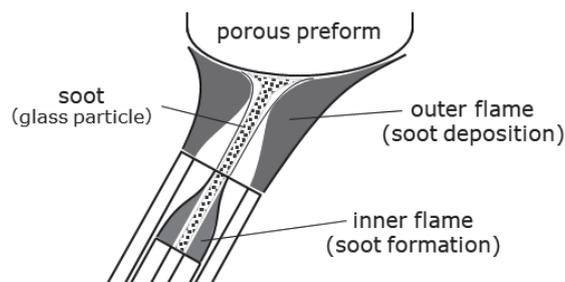


Fig. 3. Double-flame VAD method

4-3 Pure-silica core fiber

The transmission loss of optical fiber in the 1.55 μm band was lowered to 0.20 dB/km in the early 1980s, owing to an improved dehydrating process and other efforts. This was viewed as having reached the low-loss limit almost solely determined by the materials. While GeO_2 had been commonly used as an additive for raising the refractive index of the core, Sumitomo Electric attempted to push the low-loss limit by forming a pure-silica core to avoid scattering loss attributable to GeO_2 . This was achieved by adding fluorine (F) to the cladding, thereby reducing the refractive index of the cladding (Fig. 4), and this principle had been conceived in the early days of optical fiber development in the 1970s, as described earlier.⁽⁵⁾ Some time later in the first half of the 1980s, a fluorine adding technique was invented, which was to heat a porous preform, produced by the VAD method, in a fluorine-containing atmosphere. This technique realized pure-silica core SM fiber with the loss as low as 0.154 dB/km in 1986.⁽¹⁴⁾

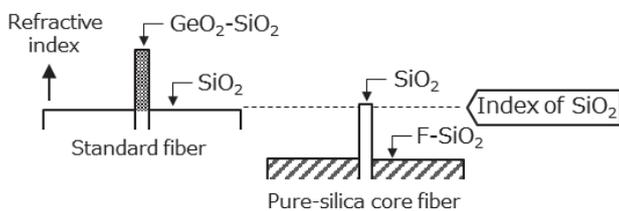


Fig. 4. Refractive index profile of pure-silica core fiber

4-4 Dispersion-shifted fiber

In addition to transmission loss, chromatic dispersion*³ is a factor limiting transmission distance of SM fiber. While the chromatic dispersion of typical SM fiber is zero in the 1.3 μm band, in the 1.55 μm band in which transmission losses decrease to a minimum, the transmission distance is limited by the effect of chromatic dispersion. Accordingly, dispersion-shifted fiber was required to reduce the chromatic dispersion as small as zero in the 1.55 μm band. Additionally, the challenges were not only to make the chromatic dispersion zero but to ensure the mode field diameter*⁴ around 8 μm for easy connection with keeping loss increase low enough when placed in a cable. Through various theoretical study and repeated prototype fabrication, a dual-shape-core structure has been found to be a solution. The structure consists of a central high-refractive index portion and a peripheral low-refractive index portion.⁽¹⁵⁾ This fiber extended repeater intervals to 100 km or more by using the 1.55 μm band, in contrast to previous repeater intervals of about 40 km at 1.3 μm . In 1987, this fiber was employed in NTT's submarine optical cable 120 km in length between Oita and Matsuyama. Moreover, in 1988, this fiber began to be fully used in NTT's terrestrial trunk line.

4-5 Overseas business expansion

In the first half of the 1980s when the VAD method began to be recognized in many countries for its excellence, Sumitomo Electric expanded its business into over-

seas ahead of its Japanese competitors. In 1984, the Company concluded a technical licensing agreement with a British cable manufacturer and a Korean cable manufacturer. In 1985, the Company founded a local joint venture with an Australian cable manufacturer. In the US, which held the majority of the world market, Sumitomo Electric founded an optical fiber/cable manufacturing subsidiary in 1983 to conduct its own business.

5. Growth Period: 1990-2000

5-1 EDFA and DWDM

1990s was an era characterized by a significant advance in optical fiber communications technology owing to an erbium-doped fiber amplifier (EDFA) and dense wavelength-division multiplexing (DWDM).

(1) EDFA

An optical fiber amplifier amplifies optical signals as they are, without converting them to electrical signals. Since the report on the phenomenon of optical amplification in an erbium-doped silica fiber in the 1.55 μm band was presented in 1987 at University of Southampton in the UK,⁽¹⁶⁾ optical fiber manufacturers in Japan and abroad worked on development of optical fiber designed for amplification. In synergy with the commercialization of concurrently developed semiconductor pump laser, an erbium-doped fiber amplifier (EDFA) instantly reached a commercial level. Using an existing cable television (CATV) facilities, as early as in 1990, Sumitomo Electric succeeded in amplification and branching for transmitting an optical amplitude modulation/vestigial side-band (AM/VSB) signal and proved that EDFA was suitable for optical CATV.⁽¹⁷⁾ Next, EDFA helped to extend the repeater distance and to improve the transmission rate of backbone transmission networks. Using dispersion-shifted fiber and EDFA, KDD (present KDDI) installed a submarine cable system (TPC-5) designed for transmission across the Pacific without using a repeater. TPC-5 boosted the transmission rate to 5 Gbps at a signal wavelength of 1.558 μm and came into service in 1995.

(2) DWDM

After the mid-1990s, commercialization of DWDM advanced. DWDM is a technology for transmitting multiple signals slightly differing in wavelength simultaneously on a single optical fiber. Combined with EDFA, which was already in wide use, DWDM enabled order-of-magnitude improvements in the transmission capacity of optical fiber.

The submarine cable system that first adopted DWDM came into service in 1999. This system multiplexed eight wavelengths with 1.6 nm wavelength spacings (100 GHz spacings in terms of frequency), achieving a transmission rate per wavelength of 2.5 Gbps (20 Gbps per fiber). In 2001, the transmission rate increased to 16 wavelengths \times 10 Gbps = 160 Gbps. Since then, the number of wavelengths continued to increase. Today, DWDM systems that multiplex about 100 wavelengths were put into commercial use.

5-2 Optical fiber for DWDM

If used in a wavelength band in which chromatic dispersion is close to zero, DWDM allows signals with different wavelengths to propagate at the same velocity.

Under these conditions, signal-to-signal interactions generate noticeable nonlinear optical effects, resulting in degraded transmission quality. To address this problem, a technique came into use, which was to reduce the nonlinear effects by means of non-zero dispersion-shifted fiber (NZ-DSF) designed to purposefully avoid zero chromatic dispersion in the 1.55 μm band and to use dispersion compensating fiber (DCF) exhibiting inverse chromatic dispersion to that of NZ-DSF to cancel the accumulated dispersion.

Owing to the combination of NZ-DSF and DCF, the transmission distance and capacity of optical fiber transmission paths increased continuously until the emergence of a digital coherent technology described later. However, along with increases in the number of wavelengths and transmission rate improvements, NZ-DSF and DCF were required to achieve higher levels of chromatic dispersion properties. Accordingly, it became necessary to accurately form a complex refractive index profile resembling annual growth rings numbering three to four. Since the VAD method was not very suitable for achieving a complex refractive index profile, engineers encountered manufacturing difficulties constantly.

5-3 Building up technologies for FTTH

In the 1980s, the easy-to-connect GI fiber with its high degree of technological perfection was the most viable candidate envisioned for subscriber lines to connect optical fiber to the home. Indeed, the 1984 optical subscriber model experiment conducted in the Mitaka district by NTT-PC used GI fiber. However, NTT-PC was also considering to employ SM fiber with its inherent broadband property for subscriber lines. At the time, the wholly-synthesized VAD method advanced, opening the way to technological insight that SM fiber would excel GI fiber in economy and achieve low eccentricity required for fusion splicing and connector-based multi-fiber mass splicing. Finally, in 1988, NTT decided to use SM fiber for subscriber lines.

In the 1990s, NTT laboratories worked on the development of cables and wiring technologies required for subscriber lines. At first, assuming a single star (SS) system connecting transmission equipment in a telephone office and each home by a single optical fiber, a 4,000-fiber cable was developed as a feeder cable for use between the telephone office and a feeder point.*5 Around 1995, placing importance on economy, they changed it to a passive double-star (PDS) system with a splitter inserted between the telephone office and home, and the number of fibers of the feeder cable decreased to 1,000. Meanwhile, the central terminal/remote terminal (CT/RT) system connecting a feeder point and each home by metal and the π (pi) system connecting a pole erected near each home and each home by metal were commercialized to some partial extent. Nonetheless, these were no more than transient measures.

Sumitomo Electric strived for developing various cables and wiring technologies, competing fiercely with its competitors and taking opportunities of procurement competitions provided by NTT. Sumitomo Electric's technologies thus achieved borne fruit as Fiber To The Home (FTTH) networks constructed in the 2000s in Japan ahead of other countries.

5-4 Mass production optical fiber plant

In the second half of the 1980s, optical fiber began to come into use extensively in Japan and abroad, primarily on backbone communication networks. Since the inauguration of the aforementioned business division, Sumitomo Electric enhanced its optical fiber manufacturing equipment in succession. However, to outperform its competition, the Company needed an integrated production line with all processes incorporating state-of-the-art technologies, from preform fabrication to drawing and to coloring. Hence, Sumitomo Electric pursued plant construction projects for mass production of optical fiber. In 1994, a mass-production plant was completed in Yokohama Works and came into service, which was followed in 1999 by a plant located in the Kiyohara Industrial Park in Tochigi Prefecture.

6. Cataclysmic Changes: 2001-2011

6-1 IT bubble burst, appreciation of the yen, and earthquake

In the late 1990s when the Internet began to be popular, dramatically growing communications demand and expectations for DWDM and other technological innovations led to overheated investments into communications-related firms on a global scale, which peaked in 2000. It was an IT bubble. However, the bubble lacked actual demand, and in 2001, it abruptly collapsed in the US. The same year in Japan, in the initial days of FTTH network construction, demand from carriers in a competition to win customers lagged the collapse. However, in and for several years after 2002, demand for optical fiber fell to its lowest level in Japan as well. Sumitomo Electric lowered the capacity utilization of the new plant in Kiyohara placed into service in 1999, as no other choice was available. The business climate surrounding optical fiber became extremely tough.

Nonetheless, communications demand grew steadily due to the full proliferation of the Internet and emergence of novel services such as exchange of images between mobile phones. The demand for optical fiber hit the lowest point in 2004, subsequently in 2006 with annual global demand recovering to about 100 million km, a level comparable to that observed in the era of IT bubble. After this, demand for optical fiber grew steadily upwards. Since then, although unfavorable factors existed, such as the collapse of Lehman Brothers, sharp appreciation of the yen, and the Great East Japan Earthquake, Sumitomo Electric overcame these difficulties, implementing thorough cost-reduction measures.

6-2 Chinese market

In the 2000s, China strengthened its optical communications infrastructure on a large scale and the principal optical fiber market shifted from the US and Europe to China. In 2000, the US and Europe accounted for 70% of the annual global optical fiber demand of 90 million km. In 2006, the global demand was 100 million km, of which China accounted for 30 million km. Five years later, in 2011, China accounted for 100 million km of the global demand of 200 million km. Optical fiber manufacturers

including Sumitomo Electric began to manufacture optical fiber in China by way of capital alliance and other styles with Chinese manufacturers.

6-3 Widespread of FTTH

Turning our eyes back to Japan, in the late 1990s, the asymmetric digital subscriber line (ADSL) became popular as a low-cost broadband service. In addition, power company-affiliated carriers began to offer FTTH optical services. Under these circumstances, in 2001, NTT commercialized an FTTH system under the brand of B-FLET'S, of which technologies NTT brought nearer to perfection in the 1990s. FTTH subscribers reached 10 million in 2008. Subsequently, along with the proliferation of smartphones, the number of subscribers plateaued, reaching 20 million in 2017.

6-4 Digital coherent technology

The revolutionary transmission technology that followed DWDM was digital coherent technology. In fact, from the 1980s, engineers were studying coherent transmission systems for optical fiber communications. The aim was to expand transmission capacity by means of multi-valued arrangements combining amplitude and phase modulation. This is a technique used for microwave transmission. Signal detection was achieved using interference between signal light and locally emitted light provided at the receiving end. In the 1990s, interest in coherent transmission was diminishing due to advances in DWDM in addition to substantial technological difficulties regarding synchronization of the phase and the frequencies of the signal light and locally emitted light. However, after the turn of the century, DWDM made little progress, and expectations for innovative technology were high. In a timely fashion, LSI technology advanced, enabling digital computation of phase-modulated signals at the receiving end of coherent transmission. Moreover, relevant device technologies also matured, such as a semiconductor laser with narrow line width. As a result, challenges associated with the coherent system were overcome, enabling a single optical fiber to carry 10 Tbps (= 100 wavelengths × 100 Gbps). In 2006, digital coherent systems began to emerge on a commercial basis.

In the digital coherent system, computations performed at the receiving end enables correction of linear waveform distortions caused by chromatic dispersion produced during propagation through optical fiber and as well as by dynamic variation of polarization mode dispersion. As a result, regarding chromatic dispersion and polarization mode dispersion, requirements posed on optical fiber became less strict, eliminating the need for DWDM fiber with a complex refractive index profile. Optical fiber requirements shifted towards low loss and reduced nonlinear waveform distortions. To reduce nonlinear waveform distortions, enlarging the core diameter to reduce light power density is effective. This was a significant impact on optical fiber, and favorable for the VAD method suitable for relatively simple structures.

7. Towards a New Society: 2012-

7-1 Growing demand for optical fiber, proliferation of VAD, and emergence of OTT

In the 2010s, the proliferation of smartphones and 4G mobile and cloud services, as well as the growing use of high-definition video and other factors, additionally accelerated communications demand. Specifically, in China, optical fiber demand grew tremendously. In 2018, the world's annual optical fiber demand reached 500 million km, of which China accounted for 300 million km. In line with this demand growth, optical fiber manufacturers in many countries made capital investments. Nearly 60% of them adopted the VAD method to manufacture core/cladding preforms. This proved the superiority of the VAD method developed in Japan. Coming into widespread use in the world, in 2015, the VAD method was recognized as an internationally prestigious IEEE Milestone.⁽¹⁸⁾

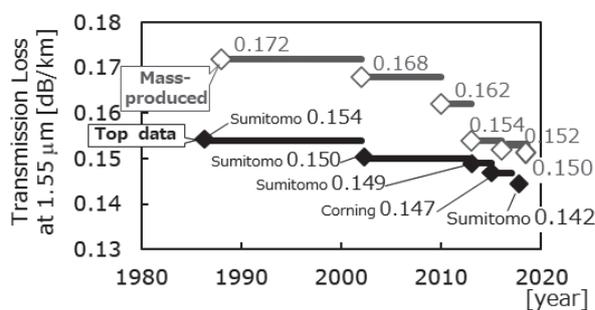


Fig. 5. Loss reduction of pure-silica core fiber

Meanwhile, customers of optical fiber substantially changed. Big enterprises that offered IT services known as Over The Top (OTT) built data centers to store huge amounts of data and even constructed their own submarine cable systems and other communications infrastructure. Currently, enormous OTT businesses appear to be playing a leading role in place of carriers.

7-2 Ultra-low-loss pure-silica core fiber

A major construction boom in submarine cables came during the IT bubble in 2000. Thereafter, the boom diminished for a while. However, since around 2013, when cloud services came into wide use on a global scale and cross-border data exchanges emerged, transoceanic submarine optical cable projects continued to grow until today. As submarine systems have made use of the digital coherent technology, Sumitomo Electric's pure-silica core fiber stepped into the limelight as ultra-low-loss fiber required for the technology.

Sumitomo Electric developed the pure-silica core fiber in the 1980s, as described above. Since then, the Company broke the loss record successively, as shown in Fig. 5.⁽¹⁹⁾ The current best performance in transmission loss is 0.142 dB/km at 1.55 μm. Not only the best performance, but also the reduction of transmission losses of mass-produced products has achieved. Ultra-low-loss products with a loss as low as 0.150 dB/km are commercially available.

A major factor involved in loss was density fluctua-

tion of glass. To make optical fiber low-loss, an improvement was made, which was to figure out the density fluctuation quantitatively from Raman spectra and to reduce it. Moreover, digital coherent communication required low nonlinearity. Larger cores intended for achieving low nonlinearity resulted in increases in loss, responding sensitively to micro-deformation in glass produced by lateral pressures during cabling. To eliminate this harmful effect, Sumitomo Electric also made successive improvements in optical fiber coating resin. As a result, large-core-diameter ultra-low-loss silica core fiber products (including Z-PLUS Fiber 130 ULL) with an effective cross-sectional core area of 130 μm^2 or 150 μm^2 were commercialized and employed in submarine cables.

7-3 Ultra-high-density optical cables

Large data centers exhibit a strong need for a great many optical fibers installed in outdoor ducts. To meet this need, using a technique designed for packing a high density of optical fibers in a limited space was necessary. Therefore, Sumitomo Electric developed and commercialized ahead of its competitors in the world an ultra-high-density optical cable (Fig. 6) containing 3,456 fibers or more, using 12-fiber Freeform Ribbons that came with both flexibility and ease of mass splicing.⁽²⁰⁾ Freeform Ribbon is a ribbon-like row of optical fibers, with adjacent pairs of fibers being bonded intermittently with each other. While ensuring ease of mass splicing comparable to that of standard fiber ribbons, Freeform Ribbon with improved flexibility can be placed densely within the space of a cable, making an ultra-high density possible. Moreover, efforts are under way to further reduce the diameter and weight of cables by using thinly coated optical fiber 200 μm in outer diameter.⁽²¹⁾

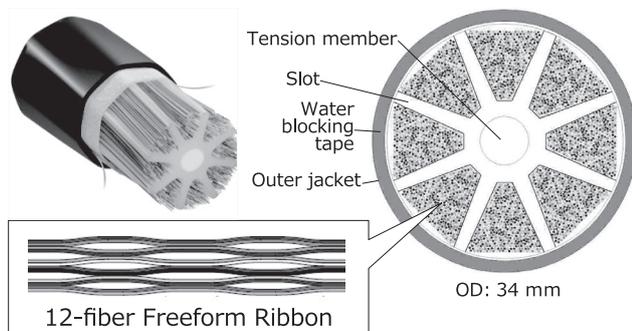


Fig. 6. Ultra-high-density (3456-fiber) optical cable

7-4 Multi-core fiber

The transmission capacity of optical fiber sharply expanded, nearly according to Moore's law (100-fold in 10 years). The transmission rate per fiber has come close to the theoretical limit of 100 Tbps. As a means of pushing this limit, multicore fiber (MCF) was proposed. Sumitomo Electric is also working on the development of MCF.⁽²²⁾ The Company conducts research and development from a practical perspective. It elucidated the phenomenon of crosstalk between cores, which is a challenge associated

specifically with MCF, and proposed MCF with measures to prevent crosstalk.

8. Conclusion

Optical fiber communication networks currently serve as essential lifelines for human society. Sumitomo Electric substantially contributed to the construction of the lifeline. The contribution owes much to efforts of those who strived for optical fiber development and business. This paper narrated no more than a fraction of their efforts. However, it is the author's pleasure if the history it described will serve as a drive for activities for the future.

- Z-PLUS Fiber is a trademark or registered trademark of Sumitomo Electric Industries, Ltd.
- B-FLET'S is a trademark or registered trademark of NTT East and NTT West.
- Freeform Ribbon is a trademark or registered trademark of Sumitomo Electric Industries, Ltd.

Technical Terms

- *1 GI fiber: Optical fiber with reduced differences in propagation time between propagation modes, achieved by a parabolic refractive index profile.
- *2 SM fiber: Optical fiber approximately 10 μm in core diameter, with relative core/cladding refractive index difference between 0.3% and 0.4%, and carrying only a single propagation mode.
- *3 Chromatic dispersion: Wavelength dependency of propagation time of optical signals.
- *4 Mode field diameter: A characteristic that indicates the widening of optical power distribution in optical fiber.
- *5 Feeder point: A branch point of a cable installed from a telephone office to each user.

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