The First 0.14-dB/km Loss Optical Fiber and its Impact on Submarine Transmission

Yoshiaki Tamura, Hirotaka Sakuma, Keisei Morita, Masato Suzuki, Yoshinori Yamamoto, Kensaku Shimada, Yuya Honma, Kazuyuki Sohma, Takashi Fujii, and Takemi Hasegawa, *Member, IEEE, Member, OSA*

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***Abstract*—We achieved the lowest-ever transmission losses of 0.1419 dB/km at 1560 nm wavelength and 0.1424 dB/km at 1550 nm in a Ge-free silica-core optical fiber. It was an improvement by 4 mdB/km from the previous record realized in 2015. The Ge-free silica core included fluorine co-doping, which helps to reduce disorder in the microscopic glass network structure that causes Rayleigh scattering loss without a significant increase in waveguide imperfection loss. A two-layered polymer coating with an inner layer having lower elastic modulus than before also contributed to the ultralow loss without influence of microbending loss increase even with an enlarged effective area of 147 μm^2. The present fiber with ultralow loss and a large effective area benefits an ultralong haul optical transmission system including transoceanic submarine cable systems. We estimate system performance based on the fiber figure of merit theory that the present fiber enables a 0.10 bit/s/Hz increase in spectral efficiency or 7% reduction in the number of repeaters, compared to the previous record-loss fiber.**

***Index Terms*—Ge-free silica-core fibers, optical fiber communication, optical fibers, submarine transmission.**

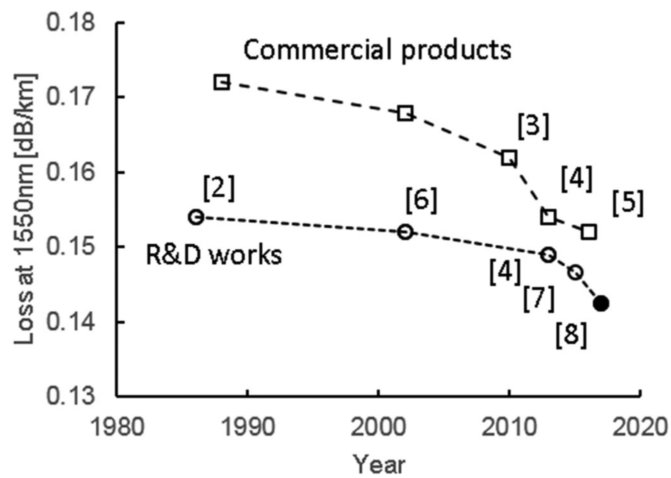

Fig. 1. History of improvement in losses of Ge-free silica core optical fibers measured at 1550 nm wavelength.

I. Introduction

Since Kao predicted low loss silica glass fiber as a communication medium in 1966 [1], remarkable achievements have realized optical fibers with lower losses that support today's communication infrastructure. Among them, the advent of Ge-free silica core fiber in 1986 [2] made an epoch by enabling a 0.154 dB/km loss at 1550 nm wavelength and commercialized in 1988 at a loss of 0.170 dB/km, much lower than 0.20 dB/km of typical Ge-doped silica core fibers at that time. Since then, losses of Ge-free silica core fibers have been improved continuously as shown in Fig. 1. Regarding commercial products, whereas the losses were improved slowly before 2010, the improvement after that has been more rapid, such as 0.162 dB/km in 2010 [3], 0.154 dB/km in 2013 [4], and 0.152 dB/km in 2016–17 [5]. This rapid improvement after 2010 have been definitely driven by adoption of digital coherent techniques in long distance submarine transmission systems, in which the lower loss becomes essential since it enhances optical signal-to-noise ratio (OSNR), as described in Section III. Such increased importance of lower loss also influenced the R&D fibers with a slight delay from the commercial fibers. As also seen in Fig. 1, whereas the improvement in the R&D fibers was slow until 2013, such as 0.150 dB/km in 2002 [6], and 0.149 dB/km in 2013 [4], the improvement after 2013 has been rapid, such as 0.1467 dB/km in 2015 [7], and most recently 0.1424 dB/km in 2017 [8]. The rate of improvement after 2013 is −1.7 mdB/km/year, being almost seven times as fast as −0.25 mdB/km/year before 2013.

In addition to lower loss, the larger effective area (A_{eff}) also enhances OSNR by allowing the signal with higher power to be launched into the fiber without nonlinear impairments. In the history of submarine fiber, the first generation fiber in the 1980s had a compatible mode-field diameter with standard single-mode fibers (SSMF) [2], which means A_{eff} of 80 μm^2. The second generation fiber released around year 2000 had an A_{eff} of 110 μm^2 [3], designed for composing the positive dispersion segments of dispersion managed transmission links. The most recent third generation fibers have A_{eff} as large as 130–153 μm^2

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The authors are with the Optical Communications Laboratory, Sumitomo Electric Industries, Ltd., Yokohama 2448588, Japan (e-mail: tamura-yoshiaki@sei.co.jp; sakuma-hirotaka@sei.co.jp; morita-keisei@sei.co.jp; suzuki-masato@sei.co.jp; yamamoto-yoshinori@sei.co.jp; shimada-kensaku@sei.co.jp; honma-yuuya@sei.co.jp; somakazu@sei.co.jp; fujii-takashi@sei.co.jp; hase@sei.co.jp).

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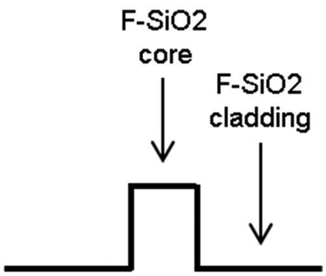

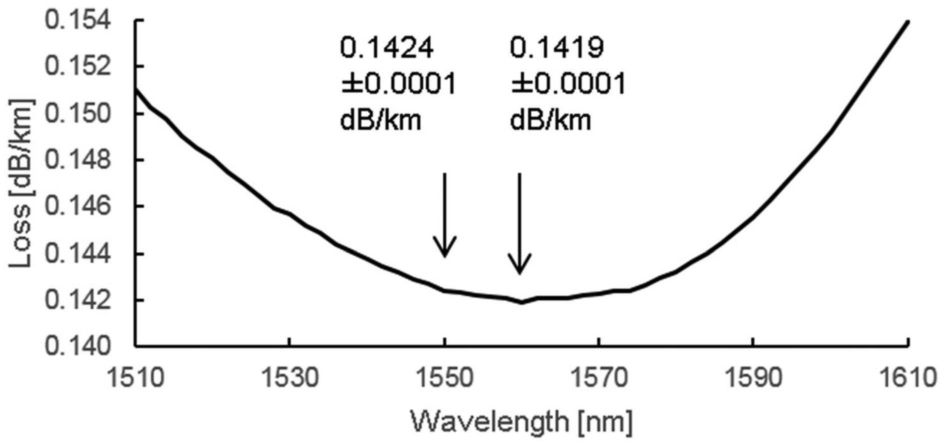

Fig. 2. (a) Schematic index profile of the fabricated fiber. (b) Its transmission loss spectrum by the cutback method. The inset values show the mean and standard error of 10-time cutback measurements.

[4], [7]–[9], especially designed for digital coherent transmission. Although an enlarged A_{eff} makes the fiber more vulnerable to macro- and micro-bending losses, an accurate glass index profile and/or advanced polymer coatings suppress those bending losses.

Those low losses and the large A_{eff} of the transmission fiber are especially valuable in trans-oceanic submarine transmission, because the construction of such trans-oceanic systems often costs as much as several hundred million dollars [10], so that expanding transmission capacity with improved fibers is often more economical than constructing more systems for additional capacity. Moreover, the electrical power supply to the undersea repeaters to compensate fiber transmission losses is becoming a constraint for the maximum capacity of the submarine transmission system [11], [12]. So that reduced fiber loss has increasing importance for expanding capacity under the constraint of the electric power supply.

In this paper, we expand our recent work on the Ge-free silica core fiber having the lowest transmission loss of 0.1419 dB/km at 1560 nm, and a loss at 1550 nm of 0.1424 dB/km [8]. Both are record-low losses 4 mdB/km lower than the previous record reported in 2015 [7], and it was the first fiber having a loss rounded to be 0.14 dB/km. We show that the core glass of the ultra-low loss fiber has a microscopic glass network with less disorder than that of the conventional fiber, based on a Raman micro-spectroscopy. Then, we discuss the benefit of the ultra-low loss fiber based on the fiber figure-of-merit (FOM) theory. It will be shown that the ultra-low loss fiber has benefits over the previous record-low loss fiber in the viewpoint that it can increase the theoretical limit of the spectral efficiency by 0.10 bit/s/Hz, or that it can reduce the number of repeaters by 7%.

II. Characteristics of UltraLow Loss Fiber

We fabricated an optical fiber composed of a Ge-free silica core surrounded by a matched cladding also doped with fluorine, as shown in Fig. 2(a), wherein the core composition included (but was not necessarily limited to) slight fluorine doping. The fluorine in the core does not have significant effect on the refractive index but reduces the viscosity and the activation energy for relaxation of the microscopic glass network [13], which can contribute to reduction in loss, as discussed below.

A 12.85-km-long spool of the fiber was wound on a standard shipment reel and its transmission loss spectrum was measured by the standard cutback method. The measurement was iterated 10 times and an average and standard error were evaluated at each wavelength. Fig. 2(b) shows the measured loss spectrum, where the loss was lowest at 1560 nm wavelength with a value of 0.1419 $\pm$ 0.0001 dB/km (average $\pm$ standard error), and the loss at 1550 nm wavelength was 0.1424 $\pm$ 0.0001 dB/km. Both the values were the new record of lowest losses being 4 mdB/km lower than the previous record of lowest loss [7], and 7 mdB/km lower than our last work in 2013 [4].

In order to understand the cause of this significant loss reduction, we evaluated the fictive temperature rather than conventional loss spectrum analysis that is susceptible to higher order modes in the wavelength shorter than the cut-off wavelength. Fictive temperature is defined as the temperature of equilibrium SiO_2 liquid having the same degree of disorders, which causes Rayleigh scattering, as the non-equilibrium SiO_2 glass under test [14]. Such a disorder originates from the melted state in the fiber-drawing process, and is reduced by the glass relaxation process while the drawn fiber is cooled down [15], but such relaxation is limited because of the increased viscosity of cooled glass. Due to that, the fictive temperature of the fiber is determined by the relationship between viscosity and temperature and by the temperature history of the glass relaxation process, so that glass composition and drawing conditions affect the fictive temperature. Regarding glass composition, inclusion of fluorine [13], chlorine [16], and alkali metals [17], [18] are known to enable promoting reduction in fictive temperature. Regarding drawing conditions, reducing the drawing temperature, reducing the drawing speed and passing the annealing furnaces after exiting the drawing furnace [19], [20] are also known to be effective for reducing the fictive temperature. Those measures would be

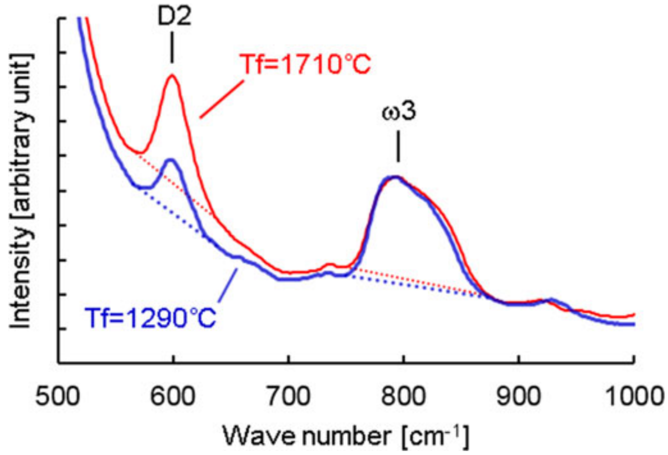

Fig. 3. Raman spectra of two optical fibers with different fictive temperatures. The dotted lines show assumed base lines to define peak areas.

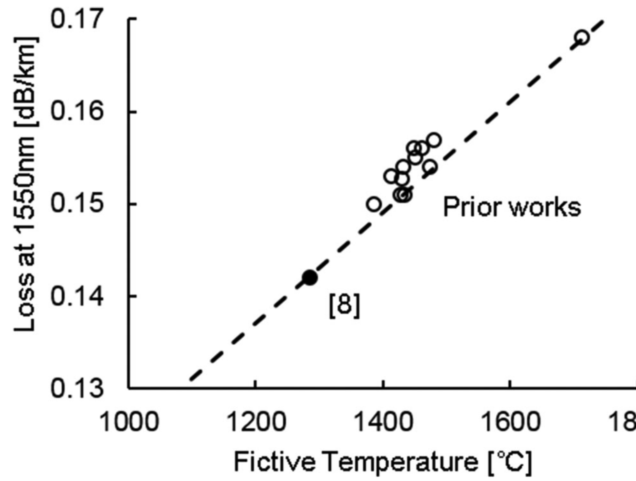

Fig. 4. Correlation between fiber loss and fictive temperature by Raman spectroscopy.

combined to reduce the fictive temperature more effectively. However, depending on the constraints in individual facilities, there can also be adverse effects on transmission loss such as increased Rayleigh scattering due to concentration fluctuation in altered composition [17], [18], [20], or difficulty in coating caused by an additional annealing process [20]. Nevertheless, measuring the fictive temperature of the fiber should always be an essential way to improve the fabrication process. We measured the fictive temperatures of our fabricated fibers by the Raman spectroscopy method [21], where the core region in the end face of the fiber was illuminated by a pump laser lightwave having a wavelength of 532 nm, and resultant Raman scattering spectra were measured, whose example is shown in Fig. 3.

The Raman spectra has a broad peak $\omega 3$ at $800\,\mathrm{cm}^{-1}$ attributed to Si-O-Si network vibration in a homogeneous amorphous state, and another peak D2 at $605\,\mathrm{cm}^{-1}$ attributed to symmetric stretching of three member rings of SiO_2, which is a kind of disorder that can cause density fluctuation and hence Rayleigh scattering. Since the logarithm of the normalized peak area D2/$\omega 3$ is known to be fitted to a linear function of inverse fictive temperature, we calibrated the function by measuring normalized peak areas D2/$\omega 3$ of calibration samples with the known fictive temperature. We prepared the calibration samples by heating a 1 mm-diameter glass rod in a furnace with known temperature for more than 48 hours and then cooling the rod rapidly in water. We assumed the rod had a fictive temperature equal to the furnace temperature.

Next, we measured the fictive temperatures on low loss Ge-free silica core fibers, whose structures differed and transmission losses varied in a range. Fig. 4 shows the correlation between the loss and the average fictive temperature, which was obtained by averaging fictive temperature in the cross section with weight by calculated power distribution of the fundamental guided mode at 1550 nm wavelength. The loss at 1550 nm wavelength was in a good linear correlation to the fictive temperature with a slope of 6.0×10^{-5} dB/km/K. If we assume the loss reduction is due to reduced Rayleigh scattering, the slope of Rayleigh scattering against the fictive temperature corresponds to 3.5×10^{-4} dB/km/μm^{-4}/K, which is in a fair agreement with 4.0×10^{-4} dB/km/μm^{-4}/K in the literature [13]. Since the fictive temperature and loss of the present ultra-low loss fiber are in the same correlation, we assume the loss reduction of the present fiber can be attributed to reduced Rayleigh scattering due to a reduced disorder in SiO_2 microscopic glass network. A significant reduction in fictive temperature as large as 110 K can result in a loss reduction by 6.6 mdB/km compared to our previous record-low loss fiber with a loss of 0.149 dB/km [4].

It should also be noted that the fluorine in the core reduces the viscosity [13], which could contribute to lower waveguide imperfection loss that is supposed to be caused by the viscosity mismatch between the core and the cladding [22]. As was reported by Ogai *et al.* [23], Ge-free silica core fiber slightly doped with fluorine had a lower wavelength-independent loss, which was assumed to be caused by waveguide imperfection, than pure silica-core fiber, resulting in a minimum loss of 0.156 dB/km at 1550 nm wavelength. Whereas Ogai did not mention fictive temperature, reducing fictive temperature in the slightly fluorine-doped core structure should be an effective way to realize the present ultra-low loss.

In addition, it is also significant that the present fiber had a microbending loss as low as 0.1 dB/km in spite of 147 μm^2 large A_{eff}, standard 125 μm glass diameter and also standard 245 μm uncolored coating diameter. The microbending losses were measured by winding 0.5-km-long fibers under test on a 405-mm-diameter wire mesh drum with a tension of 80 gf [24]. As shown in Fig. 5, the present fiber had nearly one order of magnitude lower microbending loss than the previously reported fibers [25], because the present fiber employed a new soft primary (inner) coating with a reduced elastic modulus compared to that of the previously reported one. The improved coating also passed reliability tests for submarine cables and is applicable to field use. Reduction in microbending loss can contribute to ultra-low loss not only by preventing extrinsic losses but also by enabling enlargement of A_{eff} and to reduce the power fraction in the fluorine-doped cladding.

The measured results of optical and mechanical characteristics of the present fiber are summarized in Table I, which were

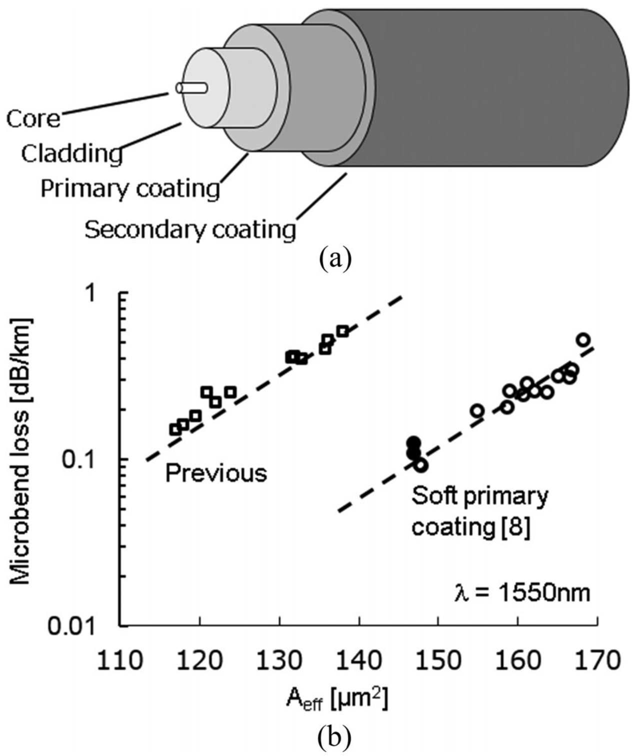

Fig. 5. (a) Schematic diagram of polymer coatings surrounding glass of optical fiber. (b) Correlations between microbending loss measured on wire mesh drum test and effective area, for different coatings.

TABLE I
THE OPTICAL AND MECHANICAL CHARACTERISTICS OF THE FABRICATED FIBER, MEASURED AT 1550 NM WAVELENGTH UNLESS SPECIFIED OTHERWISE

Characteristics	Unit	Value
Loss at 1550nm	dB/km	0.1424
Minimum loss	dB/km	0.1419
Wavelength at minimum loss	nm	1560
A_{eff}	μm^2	147.4
MFD	μm	13.5
Cable cut-off wavelength	nm	1507
Chromatic dispersion	ps/nm/km	20.5
Dispersion slope	$ps/nm^2/km$	0.060
30mm-radius macrobending loss at 1625nm	dB/100turn	0.04
PMD on drum	$ps/km^{1/2}$	0.05
Cladding diameter	μm	125
Coating diameter	μm	245

compliant to the ITU-T G.654.D recommendations on cut-off shifted single-mode optical fiber [26], so that this ultra-low loss fiber would be applicable to ultra-long haul transmission applications.

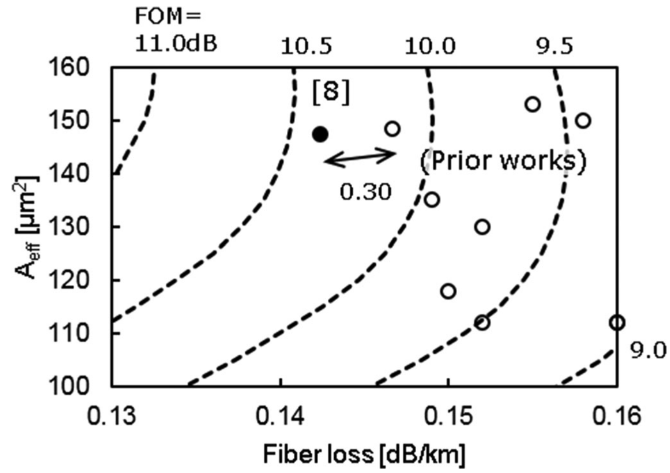

Fig. 6. FOM contour map for an 80 km span system. The solid and open plots show the present and previously reported works, respectively. The dashed lines show contours of FOM value represented as Q-factor assuming QPSK-100G transmission.

In addition, since splice loss to the SSMF in the repeater is also important for higher OSNR of the submarine cable system, we also measured the splice losses to an SSMF having $82.8\,\mu m^2$ $A_{\rm eff}$ and 10.5 μm MFD at 1550 nm using a commercial splicer. The average splice loss and standard error were 0.258 ± 0.011 dB/splice at 1550 nm by measuring 5 splices, which is comparable to the splice loss of 0.296 dB for the previously reported record-low loss fiber [7], [27].

III. IMPACT ON SYSTEM PERFORMANCE

Lower loss can always benefit trans-oceanic long distance submarine transmission, because the fiber transmission losses need to be compensated for by around or more than one hundred amplifiers that can increase the noise, cost, and power consumption of the system. We discuss the benefits of reduced loss by the theory of fiber figure-of-merit (FOM) [28]–[30] that formulates FOM as a relative OSNR in reference to known fibers in a repeated DWDM system composed of positive dispersion fiber, where the nonlinear impairment can be treated as an additive white Gaussian noise [31].

We calculated the FOM as a function of fiber loss and $A_{\rm eff}$ and showed the results as the contour lines in Fig. 6. The FOM were expressed as an expected Q-factor in a 10,000 km-reach 50 GHz-grid QPSK-100G transmission based on the reference experiment in [32]. In the calculation shown in Fig. 6, we assumed the span length to be 80 km, the EDFA output limit to be -2 dBm/ch and splice losses at repeaters to be given by the MFD mismatch loss [33] between SMF's 10.5 μm. As seen in Fig. 6, the present ultra-low loss fiber with 0.1424 dB/km at 1550 nm had 0.30 dB or higher FOM than the previously reported low-loss and large $A_{\rm eff}$ fibers. This improvement in FOM, or equivalently OSNR, approximately corresponds to an additional 0.10 bit/s/Hz spectral efficiency in the nonlinear Shannon limit theory, so that it could add 0.44 Tbps/fiber-core capacity in the 4.4 THz C-band frequency window. It should be noted that the improvement might be greater if the system operates in

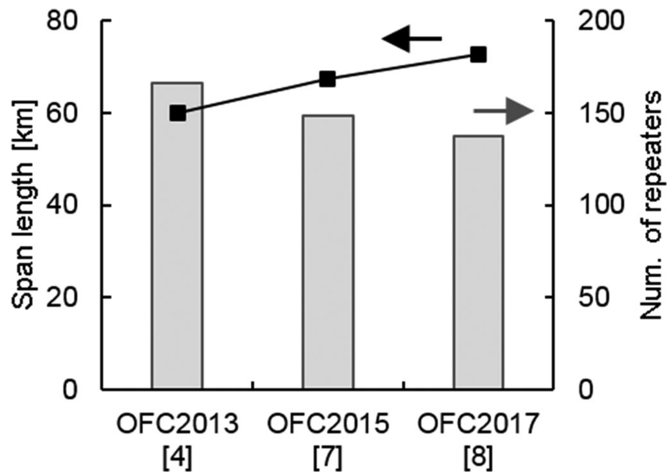

Fig. 7. Expected reduction in repeater numbers in 10,000 km, 8QAM-150G ($Q \geq 7.0$ dB) system.

a more linear regime, with lower signal power or larger A_{eff}, where the ASE noise is dominant over the nonlinear impairment noise. For example, an improvement of 0.15 bit/s/Hz is anticipated from the FOM theory with either an EDFA output limit of -5.2 dBm/ch or an A_{eff} of $161\ \mu\mathrm{m}^2$, although it should also be noted this anticipation assumes that the amplifier's NF is constant even with reduced gain and that the splice loss at the repeater is constant even with enlarged MFD, both of which are technically challenging works.

In another aspect, the ultra-low loss fiber is also beneficial in terms of the reduced number of repeaters necessary for transmission. Such benefits can also be estimated by applying the FOM theory with varied span length and a constant FOM. We calculated the number of repeaters necessary to carry a 50 GHz-grid 8QAM-150G signal over 10,000 km reach with a minimum required Q-factor of 7.0 dB. We assumed an 8QAM signal needs 4.1 dB higher OSNR than a QPSK signal to obtain the same bit error rate, based on [34, eqs. (27) and (28)]. Other assumptions were the same as those in Fig. 6. Fig. 7 shows the calculated results on span lengths and numbers of repeaters. The present ultra-low loss fiber can reduce the number of repeaters by 7% or more compared to the previously reported low-loss fibers [7]. Such reduction in repeater count would make the system more efficient in terms of repeaters' cost and electric power.

In the context of trans-oceanic transmission, it should be noted that the electric power supply from the shore to the submarine repeaters is becoming the constraint for system capacity [11], [12]. Since the power efficiency, the system capacity per unit electric power, is proportional to the inverse of the number of the repeaters [35], the reduction in the number of repeaters can provide an effective option to expand the capacity of the power-limited system.

IV. Limitations

The present experimental results are obtained on a single sample of 12.85 km short length, so that they do not necessarily guarantee that the same performance will be realized in a large volume production for submarine cable. It should be the work for the future to produce the reported fiber in a larger amount, see the statistic distribution and test environmental and mechanical reliabilities, as done in [4].

V. Conclusion

The advances in Ge-free silica core and microbending-resistant polymer coating resulted in the optical fiber with a loss of 0.14 dB/km for the first time. Once this ultra-low loss fiber is employed in submarine transmission systems, it would enable a significant increase in spectral efficiency or reduction in the number of repeaters. As the transmission capacity approaches the limit imposed by the electrical power supply to submarine repeaters, the ultra-low loss fiber will become ever more important.

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Yoshiaki Tamura received the B.E. and M.E. degrees in chemical engineering from the University of Osaka, Suita, Japan, in 2006 and 2008, respectively.

In 2008, he joined Sumitomo Electric Industries (SEI), Ltd., Yokohama, Japan. He was engaged in research and development of optical fibers with the Optical Communications Laboratory, SEI.

Mr. Tamura is a Member of the Institute of Electronics, Information, and Communication Engineers of Japan. He received the 31st Kenjiro Sakurai Memorial Prize (2016) from the Optoelectronics Industry and Technology Development Association, Japan.

Hirotaka Sakuma received the B.E., M.E., and Ph.D. degrees in engineering from Hokkaido University, Sapporo, Japan, in 2008, 2010, and 2013, respectively.

In 2013, he joined Sumitomo Electric Industries (SEI), Ltd., Yokohama, Japan. He was engaged in research and development of optical fibers with the Optical Communications Laboratory, SEI.

Keisei Morita received the B.E. degree in engineering from Kyoto University, Kyoto, Japan, in 1998.

In 1998, he joined Sumitomo Electric Industries (SEI), Ltd., Yokohama, Japan. He was engaged in research and development of optical fibers.

Masato Suzuki received the B.E., M.E., and Ph.D. degrees in engineering from Hokkaido University, Sapporo, Japan, in 2011, 2013, and 2016, respectively.

In 2016, he joined Sumitomo Electric Industries (SEI), Ltd., Yokohama, Japan. He was engaged in research and development of optical fibers with the Optical Communications Laboratory, SEI.

Yoshinori Yamamoto received the B.E. and M.E. degrees in electronics, information, and energy engineering from Osaka University, Osaka, Japan, in 2000 and 2002, respectively.

In 2002, he joined Sumitomo Electric Industries (SEI), Ltd., Yokohama, Japan. He was engaged in research and development of optical fibers with the Optical Communications Laboratory of SEI.

Mr. Yamamoto is a Member of the Institute of Electronics, Information, and Communication Engineers of Japan. He received the 31st Kenjiro Sakurai Memorial Prize (2016) from the Optoelectronics Industry and Technology Development Association, Japan.

Kensaku Shimada received the B.E. and M.E. degrees in electronic engineering from the University of Tohoku, Sendai, Japan, in 2009 and 2011, respectively.

In 2011, he joined Sumitomo Electric Industries (SEI), Ltd., Yokohama, Japan. He was engaged in research and development of optical fibers and cable harness with the Optical Communications Laboratory, SEI.

Yuya Honma received the B.E. and M.E. degrees in chemistry from Keio University, Yokohama, Japan, in 2004 and 2006, respectively.

In 2011, he joined Sumitomo Electric Industries (SEI), Ltd., Yokohama, Japan. He was engaged in research and development of optical fiber coating technologies.

Kazuyuki Sohma received the M. S. degree in chemistry from Kyoto University, Kyoto, Japan, in 2001 and the M. B. A. from Hosei University, Tokyo, Japan, in 2010.

In 2001, he joined Sumitomo Electric Industries (SEI), Ltd., Yokohama, Japan. He was engaged in research and development of optical fibers.

Takashi Fujii received the M. S. degree in chemistry from Osaka University, Suita, Japan, in 1995.

In 1995, he joined Sumitomo Electric Industries (SEI), Ltd., Yokohama, Japan. He was engaged in research and development of optical fibers and cables. He is the Group Manager engaged in research and development of optical fiber coating technologies.

Takemi Hasegawa (M'14) received the B.E. and M.E. degrees in electronic engineering from the University of Tokyo, Tokyo, Japan, in 1997 and 1999, respectively.

In 1999, he joined Sumitomo Electric Industries (SEI), Ltd., Yokohama, Japan. He was engaged in research and development on optical fibers and photonic sensors. He is the Group Manager engaged in research and development of new optical fibers.

Mr. Hasegawa is a member of The Optical Society. He received 2002 Hasunuma Prize from the Society of Instrument and Control Engineers.