ULTRA-LOW LOSS FIBERS FOR POWER EFFICIENT TRANSMISSION

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Abstract: Ultra-low loss has been the key performance of optical fiber for submarine transmission, especially since digital coherent transmission entered the mainstream because it improves OSNR and hence spectral efficiency, as well as low nonlinearity does. As the transmission capacity and distance grow further, and power supply to undersea repeaters become a limitation on the capacity and distance, ultra-low loss fiber will gain more importance than ever, because it reduces the number of repeaters and thereby increases available power per repeater. In order to advance ultra-low loss fiber, we applied measurement of fictive temperature of silica glass core to improvement of fiber production so as to reduce the fictive temperature. As a result, we achieved a new ultra-low loss of 0.14 dB/km for the first time in the history of optical fiber. Compared to the state-of-the-art fiber product with a loss of 0.15 dB/km, this new ultra-low loss fiber reduces attenuation by 7%, but can reduce approximately 12% of repeaters in a power-limited system. In the conference, we will present recent progresses of this ultra-low loss fiber and discuss the increasing benefit as the system becomes limited by power supply.

1. INTRODUCTION

The growth of cloud network infrastructure in global scale have been enabled by increasing capacity and distance of subsea optical transmission systems. In order for such increase in capacity and distance, optical fibers have been continuously improved for lower attenuations and larger core areas, resulting in longer repeater spans and higher optical signal to noise ratio. After those continuous improvement, advanced optical fibers having attenuations as low as 0.150 –0.155 dB/km at 1550 nm wavelength, and effective core areas as large as 150–153 μm^2 are currently commercially available.

However, further increase in capacity or distance would face the limitation in power supply to undersea optical repeaters [1-2], so that improvement in power efficiency (capacity per power) is necessary. For this purpose, spatial division multiplexing (SDM) that reduces signal power per spatial channel and increases the number of spatial channels instead is gaining importance because it can improve power efficiency [3-5]. Since the limitation in power supply is considered to be fundamental, subsea optical transmission would shift from the conventional nonlinear optimized regime, where the signal to noise ratio (SNR) is limited by fiber nonlinearity, to the power optimized regime, where it is limited by available power.

In this paper, we show further improvement in fiber attenuation will be available by improving its fictive temperature, and such fibers can contribute to reducing the expensive repeaters in a greater magnitude in power optimized regime than in the conventional nonlinear optimized regime.

2. ULTRA-LOW LOSS FIBER

Low-loss fibers for subsea transmission have been based on Ge-free silica core that is free from additional Rayleigh scattering loss due to GeO_2 concentration fluctuation. More recently, Rayleigh scattering loss of Ge-free silica core fibers have been further reduced by reducing glass network disorders (or lowering the fictive temperature of glass), which has been realized by improving the fiber production toward lower fictive temperatures, with the help of the technique to measure the fictive temperature of the fiber core. As a result of these improvements, a record-low attenuation of 0.1424 dB/km at 1550 nm wavelength was achieved using slightly fluorine-doped core with low fictive temperature [6], and repeatable fabrication in a range of 0.142–0.144 dB/km was also demonstrated [7], as shown in Fig. 1. Not only such ultra-low attenuations, those fibers can be made with effective areas as large as 150 μm^2 and optical characteristics compliant with ITU-T G.654.D recommendations, and can be fusion spliced to G.652 single mode fibers with as low as 0.26 dB/splice using a commercial splicer without special techniques such as bridge fiber or tapering. Promising impact of those ultra-low loss fibers on power optimized systems is discussed in the following section.

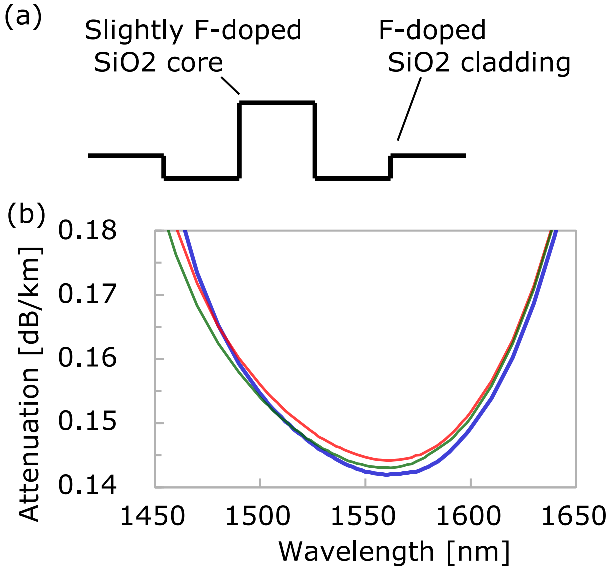

Figure 1: Schematic structure of ultra-low loss Ge-free silica core fiber (a) and attenuation spectra of its samples with 12–50 km spools (b).

3. MERIT OF LOW ATTENUATION FOR POWER LIMITED SYSTEMS

Since digital coherent technique is advancing to approach the theoretical Shannon limit, we can assume it continues to be the mainstream even if subsea transmission shift from the nonlinear optimum regime to the power optimum regime. On such assumption, generalized OSNR can be formulated analytically [8-10],

$$\frac{1}{\mathrm{OSNR}} = \frac{P_{\mathrm{ASE}}+P_{\mathrm{NLI}}}{P_{\mathrm{ch}}}, \qquad (1)$$

where definitions of symbols are summarized in Table 1.

Symbol	Definition
P_{ch}	Signal power per wavelength channel at the repeater output
P_{ASE}	ASE noise power per wavelength channel
P_{NLI}	Nonlinear impairment power per wavelength channel
P_{opt}	Nonlinear optimum signal power
h	Planck constant
ν	Optical signal frequency
B_{ch}	Band width of wavelength channel
F	Noise figure
C	Coefficient in nonlinear impairment
γ	Fiber nonlinear coefficient
l_{eff}	Effective span length
α_{sp}	Splice loss in dB scale
α	Fiber attenuation coefficient in dB scale
L	Transmission distance
N_{rep}	Number of repeaters
P_{tot}	Total optical output power of amplifiers
P_{amp}	Output power of an amplifer
N_{dim}	Number of spatial channels

Table 1: Definition of symbols in formulation of system performance. The parameters are in linear scale unless noted otherwise.

In the conventional nonlinear optimum regime without power limitation, signal power per channel P_{ch} can be optimized so as to maximize the OSNR in eq. (1):

$$P_{\mathrm{opt}} = \left\{\frac{27h\nu B_{\mathrm{ch}}F}{8\pi C(\gamma l_{\mathrm{eff}})^2}\right\}^{\frac{1}{3}} \cdot 10^{\frac{0.1}{3}\left(4\alpha_{\mathrm{sp}}+\frac{\alpha L}{N_{\mathrm{rep}}+1}\right)} \qquad (2)$$

$$\mathrm{OSNR}_{\max}^{-3/2} =$$

$$\sqrt{\pi C}\gamma L h\nu B_{\text{ch}} F \cdot N_{\text{rep}}^{1/2} \cdot 10^{0.4\alpha_{\text{sp}} + \frac{0.1\alpha L}{N_{\text{rep}}+1}} \quad (3)$$

The degree of how close the system operates to nonlinear optimum can be expressed by a nonlinearity ratio R:

$$R = P_{\text{ch}}/P_{\text{opt}} \quad (4)$$

$$\text{OSNR} = \text{OSNR}_{\max} - 10\log_{10}\left\{\frac{R^3+2}{3R}\right\} \quad (5)$$

In the above derivation, amplifier gain G is assumed to be equal to the span loss caused by transmission fiber and two splices at the beginning and the end of the span:

$$G = 10^{0.2\alpha_{\text{sp}} + \frac{0.1\alpha L}{N_{\text{rep}}+1}} \quad (6)$$

Assuming the system should operate at a given $\text{OSNR}_{\max}$ given by eq. (5), a relationship holds between the number of repeaters N_{rep} and fiber attenuation coefficient α:

$$\frac{1}{2}\ln N_{\text{rep}} + \frac{\ln 10}{10}\frac{\alpha L}{N_{\text{rep}}+1} = \text{const.} \quad (7)$$

Eq. (7) expresses how lower attenuation contributes to reducing the number of repeaters, in a nonlinear optimum system.

On the other hand, in power optimum regime, a limitation is imposed on the total optical power (TOP) of amplifiers:

$$P_{\text{tot}} = N_{\text{dim}} N_{\text{rep}} \cdot P_{\text{amp}} \quad (8)$$

$$P_{\text{amp}} = N_{\text{ch}}(P_{\text{ch}} + P_{\text{ASE}}) \quad (9)$$

Assuming a power optimum system with high degree of spatial division multiplexing (SDM) where the nonlinearity ratio R much lower than 1 and thus nonlinear impairment noise P_{NLI} can be negligible compared to ASE noise P_{ASE},

$$\text{OSNR} \approx \frac{P_{\text{ch}}}{P_{\text{ASE}}} = \frac{P_{\text{amp}}}{N_{\text{ch}} P_{\text{ASE}}} - 1$$

$$\frac{1}{\text{OSNR}+1} \approx \frac{N_{\text{ch}} P_{\text{ASE}}}{P_{\text{amp}}} = \frac{N_{\text{dim}} N_{\text{rep}} N_{\text{ch}} P_{\text{ASE}}}{P_{\text{tot}}} =$$

$$\frac{N_{\text{dim}} N_{\text{ch}} h\nu B_{\text{ch}} F}{P_{\text{tot}}} N_{\text{rep}}^2 10^{0.2\alpha_{\text{sp}} + \frac{0.1\alpha L}{N_{\text{rep}}+1}} \quad (10)$$

In this case, the relationship between the number of repeaters N_{rep} and fiber attenuation coefficient α becomes different from that in nonlinear optimum regime given by eq. (7):

$$2\ln N_{\text{rep}} + \frac{\ln 10}{10}\frac{\alpha L}{N_{\text{rep}}+1} = \text{const.} \quad (11)$$

Next we show the increased merit of ultra-low attenuation in power optimum regime, by numerical calculation of eq. (1) under the power constraint of eq. (8). The assumption on the system is summarized in Table 2. The maximum power supply is assumed to be equal to that of a system with a 11,000 km distance, 8fp, 156 amplifiers with +18.3dBm output power at 70.1km span. Transmission technique is assumed to be able to achieve 18Tb/s/fiber capacity in the above system composed of fibers with a 0.152 dB/km attenuation and a 0.59 /W/km nonlinear coefficient (150 μm^2 effective area).

Item	Assumption
Transmission distance L	11,000 km
Noise figure F	2.9 (= 4.6dB)
Nonlinear coefficient g	0.59 /W/km (150μm^2 effective area)
Splice loss α_{sp}	0.21 dB
P_{tot}	86 W (per direction)
Optical frequency ν	194 THz (1550 nm)

Table 2: Assumptions on calculating the merit of low losses on system performance

As an example, theoretical capacity (or achievable information rate) is calculated as a function of the number of repeaters, as shown in Fig. 2 (a). If we impose a target capacity of 12 Tb/s/fiber and 8 fiber pairs, a reduction in attenuation from 0.150 to 0.142 dB/km can result in longer span length (or fewer repeaters) by 7%. On the other hand, in case of 12 Tb/s/fiber and 16 fiber pairs, the same improvement from 0.150 to 0.142 can result in 12% longer span length. This difference derives from the difference in how close to the nonlinear optimum regime the system operates, as shown in Fig. 2 (b). In the 8fp case, the nonlinearity ratio is close to 1, corresponding to operation in nonlinear optimum regime, and that in the case of 16fp is far below 1, corresponding to operation in power optimum regime.

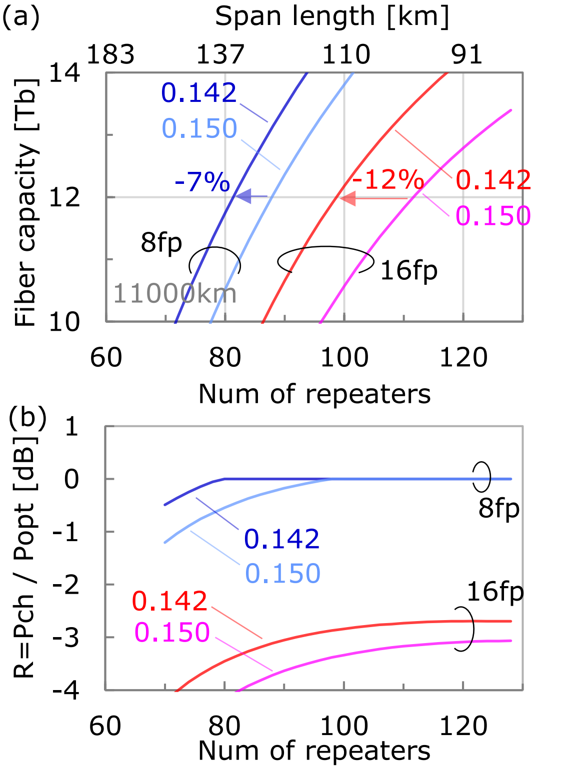

Figure 2: Fiber capacity under power limitation as a function of the number of repeaters (or span length) (a), and difference in nonlinearity ratio (b) that illustrates difference between conventional nonlinear optimum regime (8fp) and power optimum regime with reduced signal power (16fp).

The increasing merit of lower losses in power optimum regime can be illustrated more clearly by plotting the number of repeaters as a function of fiber attenuation, as shown in Fig. 3 (a,b). As fiber pair increases and the nonlinear ratio decreases, the number of repeaters becomes more sensitive to the change in fiber attenuation. In addition, it is also illustrated that the approximate relationship between the number of repeaters N_{rep} and fiber attenuation α derived in eqs. (7) and (11) agree well to numerical calculation of eq. (1), for the cases of nonlinear optimum and power optimum, respectively.

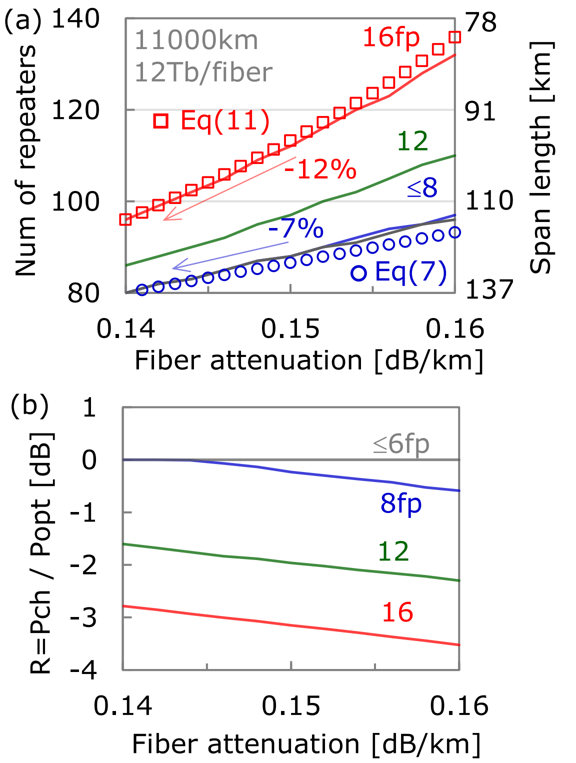

Figure 3: Merit of low attenuation in reducing the number of repeaters (a), and nonlinearity ratio (b). Solid lines show results of numerical calculation, and plots show the approximate formulae for number of repeaters in nonlinear optimum (eq (7)) and power optimum (eq (11)) regimes.

As another example, Fig. 4 also shows the number of repeaters in case of higher capacity of 18 Tb/s/fiber. Again, as the number of fiber pairs increases, the number of repeaters becomes more sensitive to fiber attenuation. An improvement in attenuation from 0.150 dB/km to 0.142 dB/km enables a 10% reduction in repeaters in case of 8 fp system, where the system operates at nonlinear optimum power (R=1) up to 0.152 dB/km attenuation, which corresponds to the assumed power limitation of this calculation. On the other hand, the same improvement in attenuation enables 15% reduction in case of 10 fp where the system operates closer to power optimum. If fiber pairs increase to 12, attenuation needs to be below 0.144 dB/km to achieve the fiber capacity, unless operating margin or transmission technique is changed. Therefore, the merit of lower attenuation increases as the system shifts to power optimum regime from the conventional nonlinear optimum regime.

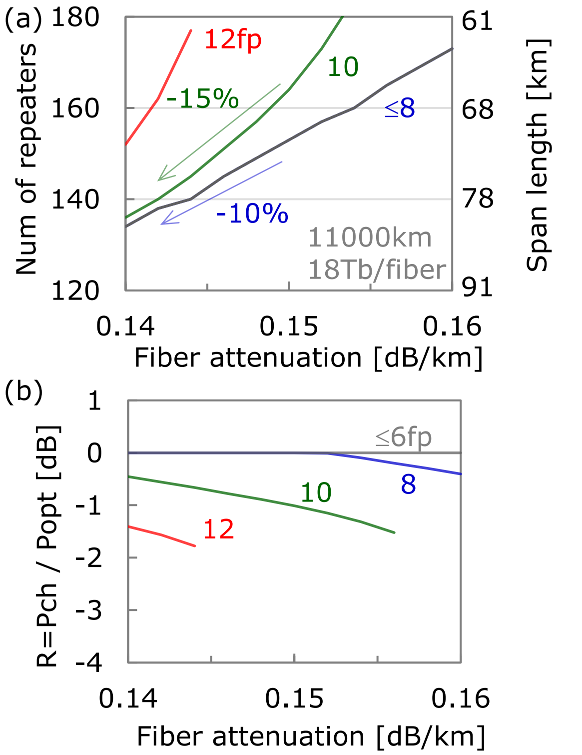

Figure 4: Merit of low attenuation in reducing the number of repeaters (a), and nonlinearity ratio (b). The truncated solid lines mean upper limits of attenuation to achieve the target fiber capacity.

4. CONCLUSIONS

Continuous improvements in fiber attenuation resulted in an ultra-low losses of 0.142–0.144 dB/km. The merit of lower losses increase as the system shifts from the conventional nonlinear optimum regime to power optimum regime. As an example, an improvement from 0.150 dB/km to 0.142 dB/km enables to reduce repeaters by 7% in nonlinear optimum system, and 12% in power optimum system.

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