Record Low Loss, Record High FOM Optical Fiber with Manufacturable Process

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Abstract: Record-low loss of 0.149dB/km at 1550nm is realized by pure-silica-core fiber having optimally enlarged Aeff, which indicates record-high figure-of-merit for digital coherent system. Mass-productivity is verified with 7,000km long fabrication whose averaged loss of 0.154dB/km.
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1. Introduction

In a high capacity long haul transmission system based on digital coherent technologies, a major challenge is to improve the system OSNR. This is because Q-factor came to be proportional to the OSNR as a result of equalization of linear impairments induced by chromatic dispersion and PMD by digital signal processors. Therefore, various non-dispersion managed fibers with low loss and low nonlinearity have been proposed [1-3]. In order to quantitatively calculate contribution of fiber parameters to the OSNR improvement, fiber figure-of-merit (FOM) that can predict the degree of improvement on system performance should be known. Very recently, an analytical fiber FOM [4] and Q-factors as a function of launched signal power [5] were developed using the Gaussian noise model treating nonlinear interaction (NLI) [6], which are well consistent with transmission experiments [4,5,7]. With these formulations, available transmission distance, Q-factor and optimal signal power can be precisely predicted for systems using different fibers. In addition, in the case where EDFA output is limited, for example a submarine transmission link, it was found that fibers with possible low loss are most preferable and there is an optimal value of Aeff depending on the transmission distance [5].

In this paper, we modify the fiber FOM to easily predict a system performance as functions of fiber parameters and launched signal power. According to the FOM calculation, we find that the optimal value of Aeff is ranging from 110 to 140 μm^2. We actually fabricate a pure-silica-core fiber (PSCF) with a ring-core profile [1], and successfully realize the record-low loss of 0.149 dB/km at 1550 nm and an enlarged Aeff of 135 μm^2. This is the first fiber having the loss less than 0.150 dB/km at 1550 nm, 11 years after we reported the loss of 0.150 dB/km [8]. What is even better is that the PSCF fabrication is applied with manufacturable processes. We verify the ultimately low loss of 0.154 dB/km over accumulated length of 7,000 km, and confirm its high reliability and durability.

2. Fiber Figure of Merit

As is schematically shown in Fig. 1, we assumed a multi-span link composed of a non-dispersion-managed fiber, an EDFA and coupling losses between them [4,5]. The EDFA gain at each span was assumed to completely compensate for the span loss of α_{span}. Q-factor has its maximum of Q_{max} at the optimal launched signal power of P_{opt}, and the Q_{max} and P_{opt} were developed in [5] as

$$P_{opt}\,[\mathrm{dB}] = -10/3\cdot log\left\{\gamma^2 L_{eff}\,|D|^{-1}\right\} + 1/3\alpha L + 4/3\alpha_{sp} + C_1\,, \qquad (1)$$

$$Q_{max}[\mathrm{dB}] = -10/3\cdot log\left\{\gamma^2 L_{eff}\,|D|^{-1}\right\} - 2/3\alpha L - 2/3\alpha_{sp} - 10\,log\{Ns\} + C_2\,, \qquad (2)$$

where γ, L_{eff}, D, α, L, α_{sp}, N_S are nonlinear coefficient ($\propto n_2$/Aeff), effective length, chromatic dispersion, fiber loss, span length, coupling loss to EDFA, and number of spans, respectively. C_1 and C_2 are coefficients determined by a transmission system including Back-to-Back penalty, EDFA noise-figure, baud rate, spectral efficiency, and number of channels. Using transmission distance (D_T), N_S is in equal to $\{D_T/L\}$, and therefore we add the 10log[L] to the fiber FOM in [4] and modified as

$$FOM\,[dB] = -10/3\cdot log\left\{\gamma^2 L_{eff}\,|D|^{-1}\right\} - 2/3\alpha L + 10\,log[L] - 2/3\alpha_{sp}\,. \qquad (3)$$

Using this FOM, equations (1) and (2) can be expressed as below respectively,

$$P_{opt} = FOM - \{\alpha_{span}\} - 10\,log[L] + C_1\,, \qquad (4)$$

$$Q_{MAX} = FOM - 10\,log[D_T] + C_2\,. \qquad (5)$$

When a system configuration is the same, difference between FOMs of applied fibers will present a difference of the system performance, that is, Q-factor and transmission distance.

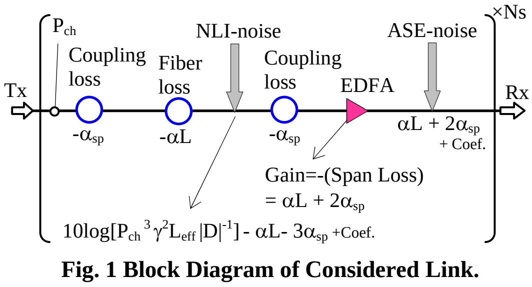

Fig. 1 Block Diagram of Considered Link.

In laboratory experiments, launched signal power will be set at P_{opt} that is often more than practical limit of launched power, P_{ch_max}. Therefore, system performance considering P_{ch_max} should be discussed. At arbitrary P_{ch} (= $r \cdot P_{opt}$), Q-factor (Q_R) becomes [5],

$$Q_R = Q_{MAX} + 10\log\left\{ 3r \big/ (r^3+2) \right\}$$
$$= FOM - 10\log[D_T] + 10\log\left\{ 3r \big/ (r^3+2) \right\} + C_2 \,. \qquad (6)$$

Comparing (6) to (5), FOM_R at $P_{ch}=r \cdot P_{opt}$ can be written as

$$FOM_R = FOM + 10\log\left\{ 3r \big/ (r^3+2) \right\} . \qquad (7)$$

In a submarine wet-repeater having output of +18 dBm over 100 channels, P_{ch_max} becomes -2 dBm/ch. For this case, iso-FOM_R lines calculated with (7) as functions of loss and Aeff are shown in Figs. 2 at L of (a) 80 km and (b) 100 km as solid lines, along with FOM *not* considering the P_{ch_max} as dashed lines. In this calculation, P_{ch} was set at P_{ch_max} of -2 dBm/ch when P_{opt} is calculated to be more than -2 dBm/ch using (3), and otherwise, $P_{ch}=P_{opt}$ (or r=1). We set C_1 as -6.6 dBm/ch [5] fitted from 100G-QPSK-DWDM transmission experiment in [9]. D=+21 ps/(nm·km) and n_2= 2.2×10^{-20} m^2/W were assumed, and the coupling loss between a fiber and EDFA was calculated as dissimilar splice loss using MFD-mismatching between the applied fiber and a SSMF [1, 10].

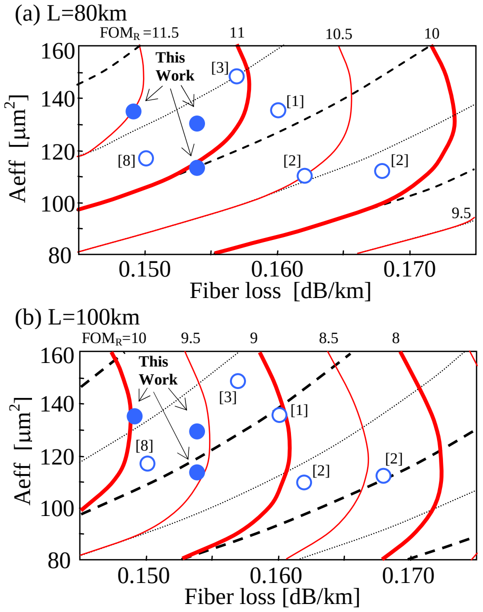

Fig. 2 Iso-FOM_R as Functions of Loss and Aeff at Span Length of (a) 80km and (b) 110km.

It is clearly found from Figs. 2 that the FOM_R improvement is mainly depending on the lowering of fiber-loss. As for the Aeff, there exists an optimal value in which the FOM_R becomes saturated at around 120 to 140 μm^2 for L of 80 km and 110 to 130 μm^2 for L of 100 km.

3. Fabrication of Ultra-low Loss PSCF

According to the FOM calculation, we actually fabricated PSCF with Aeff around 130 μm^2 in order to realize high FOM_R in a wide range of span lengths. We employed a ring-core profile as shown in Fig. 3 composed of a slightly fluorine-doped center-core surrounded by a pure-silica ring-core and fluorine-doped W-cladding. We showed that the ring-core profile gives better dissimilar-splice loss to an optical repeater than that of a step-core one at same Aeff [1]. In order to relax micro-bending loss that is a major issue of Aeff-enlarged fibers to be deployed to submarine cables, we applied a soft primary coating. By comparison to actually deployed PSCF having Aeff around 110 μm^2 applied with a conventional coating, we confirmed that PSCF having Aeff around 130 μm^2 applied with the soft primary one will be practical for cabling [11]. Characteristics of fabricated PSCF at 1550 nm are summarized in Table 1. Figure 4 shows the fiber loss spectra of fabricated PSCF along with a standard single mode fiber (SSMF), and the PSCF has realized record-low loss of 0.149 dB/km at 1550 nm, which is the first optical fiber having the loss less than 0.150 dB/km to the best of our knowledge. The minimum loss is 0.148 dB/km at 1570 nm, which is equivalent to the previous report [8]. In this measurement, 20 km-long PSCF was spooled on a bobbin with 170mm-diameter barrel, and there is no obvious degradation due to macro and micro bending losses in longer wavelength range.

Table 1 Characteristics of Fabricated PSCF at 1550 nm.

	Aeff [μm^2]	Fiber Loss [dB/km]	Dispersion [ps/nm/km]	Disp. Slope [$ps/nm^2/km$]
PSCF	135	0.149	21.0	0.061

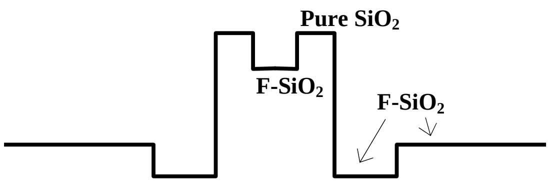

Fig.3 Schematic Refractive Index Profile.

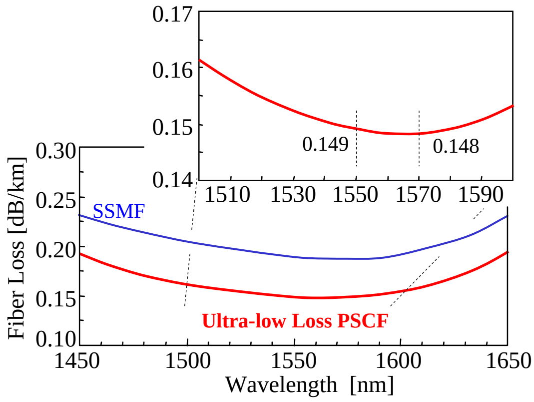

Fig. 4 Loss Spectra of PSCF and SSMF.

The realized Aeff and fiber loss is shown in the iso-FOM map of Figs. 2 as solid plots along with reported values as open plots [1-3,8]. By virtue of the record-low loss and optimal Aeff, the newly fabricated PSCF exhibits the highest FOM_R and also FOM, which achieve higher Q-factor in the transmission system. Alternatively the higher FOM_R achieves a longer span length at a fixed Q-factor; for example, a fiber having 1 dB higher FOM will realize more than 10 km longer span length calculated from (3). This reduces the number of expensive wet-repeaters in a submarine link and therefore the construction cost.

3. Mass-productivity Verification of Ultra-low Loss PSCF

What is even better is that fabrication of the ultra-low loss PSCF was applied with manufacturable processes. In order to verify its mass-productivity, we fabricated PSCFs with accumulated length about 7,000 km. In this verification, two types of PSCFs with respective Aeff of 110 (hereinafter PSCF-110) and 130 μm^2 (PSCF-130) are designed for long and short span lengths as shown in Figs. 2. Typical characteristics of PSCF-110 and PSCF-130 are summarized in Table 2. Figure 5 shows distribution of fiber loss at 1550 nm over 7,000 km long PSCFs, and its averaged loss was confirmed to be ultra-low, 0.154 dB/km. The loss distribution seems to be Gaussian in shape having its standard deviation of less than 0.002 dB/km. These manufacturable PSCFs have very high FOM as shown in Figs. 2. Other properties including Aeff, chromatic dispersion and dispersion slope also showed good stability.

Finally, we validated environmental and mechanical tests on PSCF-110 and PSCF-130 according to IEC60793-2-50 including the damp heat, dry heat, temperature cycling, water immersion, tensile strength, stress corrosion susceptibility, fiber curl and proof tests. The PSCFs exhibited excellent stabilities in all tests, which show high reliability and durability. For example, Fig. 6 shows the fiber loss change during damp heat test in a temperature of 85 °C and a relative humidity of 85 %, in which measurable degradation was not confirmed.

Table 2 Typical Characteristics of PSCFs at 1550 nm.

	PSCF-110	PSCF-130
Fiber Loss [dB/km]	0.154	0.154
Aeff [μm^2]	112	130
Dispersion [ps/nm/km]	20.6	20.7
Disp. Slope [$ps/nm^2/km$]	0.061	0.061

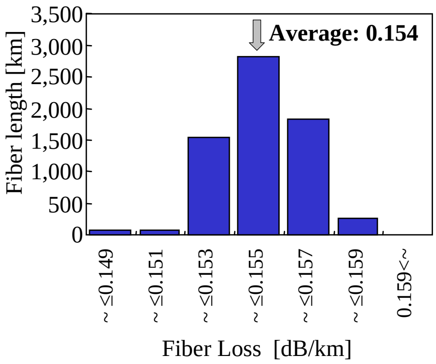

Fig.5 Fiber Loss Distribution over 7,000km PSCFs.

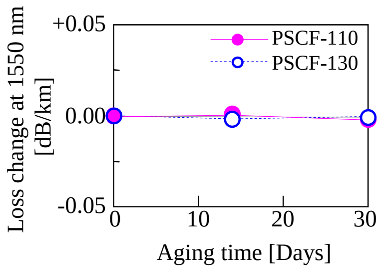

Fig.6 Damp Heat Test at 85 °C, 85 %RH.

5. Conclusion

We successfully realized record low loss of 0.149 dB/km at 1550 nm with a ring core PSCF having enlarged Aeff of $135 \mu m^2$. By virtue of ultra-low loss and optimal value of Aeff, the newly fabricated PSCF has the highest fiber FOM for non-dispersion-managed links applicable to digital coherent transmission systems. Furthermore, the PSCF fabrication was based on mass-production processes. We verified the ultra-low loss of 0.154 dB/km over accumulated length of 7,000 km, and high mechanical reliability and environmental durability were also confirmed. These results will bring fiber loss of 0.15 dB/km into reality, which will be able to contribute to the dramatic capacity growth especially in submarine systems.

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