ULTRA-LOW LOSS PURE-SILICA CORE FIBER FOR CAPACITY EXPANSION

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Abstract: Optical fiber for high capacity submarine transmission will be discussed. In a viewpoint of bandwidth expansion, utilizing of the L-band in addition to the C-band is promising. Bending loss characteristics and fiber figure-of merit of ultra-low loss pure-silica-core fiber with the Aeff of 130micron2 at 1550nm are evaluated, and we confirm that the PSCF has the excellent performance for the L-band transmission.
We will also discuss about the required performance for future enhancement of transmission capacity, and we conclude the possible lowest loss will be the most important.

1. INTRODUCTION

Digital coherent transmission technology has ramped up capacity and distance of submarine transmission systems. Since coherent technology can compensate linear impairments due to chromatic and polarization mode dispersions, low loss and low nonlinearity of transmission fiber have become even more important. There have been successive achievements in developing low loss and low nonlinearity fibers [1-5]. Among them, pure silica core fiber having 0.149 dB/km ultra-low loss and 130 μm^2 large effective area (PSCF-130) has been confirmed to have excellent transmission performance [2,4-5], and it is also available in mass production at an ultra-low loss of 0.154 dB/km [6], and even 0.152 dB/km very recently [7].

In this paper, we show the PSCF-130 have high figure of merit and low bending and splice losses in both C and L bands, and therefore would be the fiber of choice for systems with enhanced transmission capacity.

2. CHARACTERISTICS OF PSCF-130

PSCF-130 has a characteristic index profile comprising a pure silica ring core with fluorine doped center core, surrounded by fluorine doped depressed cladding, as shown in Figure 1. Because of the pure silica core, PSCF-130 exhibits ultra-low losses in a wide wavelength range covering C and L bands, as shown in Figure 2 in comparison to standard single mode fiber (SSMF). The losses are as low as 0.149 dB/km at 1550 nm and 0.151 dB/km at 1590 nm.

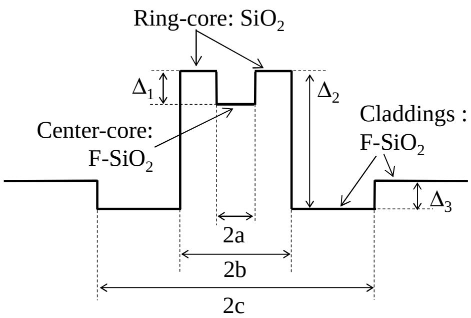

Figure 1: Structure of PSCF-130. Typically Δ_1=0.1%、Δ_2=0.34%、Δ_3=0.1%、b/a=2.5、2b=12μm、c/b=3.5

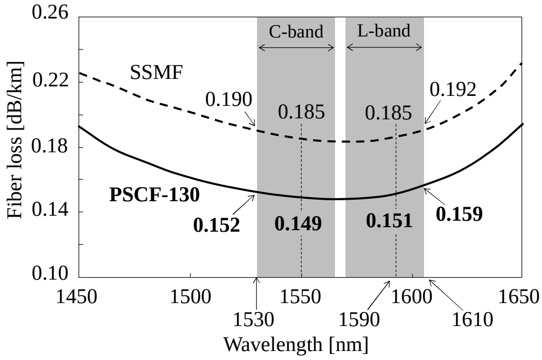

Figure 2: Loss spectrum of PSCF-130

Because of the W-shaped depressed cladding, PSCF-130 has excellent characteristics such as large effective area (A_{eff}), low macro-bending loss, and high dispersion both in C (1550 nm) and L (1590 nm) bands, as shown in Table 1. The wavelength and radius dependences of macro-bending loss are almost compatible with those of SSMF in C&L bands and negligible at 25 mm radius, as shown in Figure 3. Since typical bending radius of excess length fiber in submarine repeaters are above 30 mm, PSCF-130 can be efficiently enclosed within repeaters.

Table 1: Optical characteristics of PSCF-130

	PSCF-130		SSMF (ref.)	
Wavelength [nm]	1550	1590	1550	1590
Fiber loss [dB/km]	0.149	0.151	0.185	0.185
Aeff [μm²]	135	138	80	83
Dispersion [ps/nm/km]	21.0	23.4	16.5	18.8
Disp. Slope [ps/nm²/km]	0.061	0.058	0.058	0.056
Macro-bend. loss (R=10mm) [dB/m]	3	4	3	6
Cable cutoff wavelength [nm]	1410		1180	

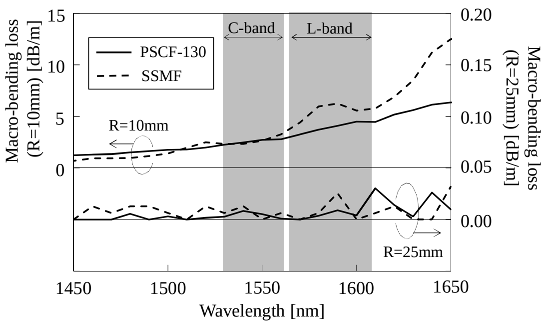

Figure 3: Macro-bending loss of PSCF-130

Although micro-bending loss tends to increase with larger A_{eff}, fiber coating with low Young's modulus in inner primary layer can suppress micro-bending loss, which is measured in wire-mesh bobbin test under 80g force tension [8]. PSCF-130 employs a primary coating whose modulus is 2/3 as low as that of the conventional PSCF-110 [9]. The low modulus primary coating enables to increase A_{eff} by 20 μm^2, as shown in Figure 4. In addition, because of the higher-order mode coupling in W-shaped depressed cladding, wavelength dependence of micro-bending loss is almost flat over C&L bands [5], while that of SSMF increases with wavelength, as shown in Figure 5. Therefore, micro-bending loss of PSCF-130 is less than 0.6 dB/km over C&L bands, which is compatible with conventional PSCF-110.

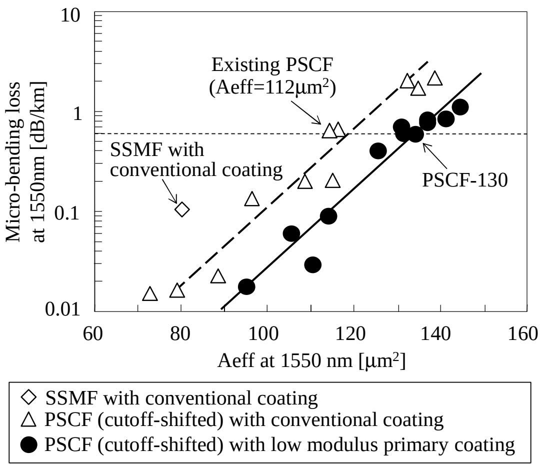

Figure 4: Effect of low modulus primary coating on micro-bending loss.

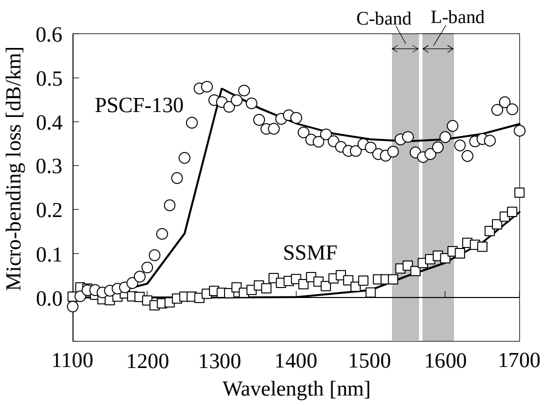

Figure 5: Micro-bending loss of PSCF-130

Dissimilar splice loss to SSMF used in repeaters is another challenge for increasing A_{eff} of PSCF, because mode field diameter (MFD) gets larger than that of SSMF as increasing A_{eff}, and splice loss α'_{sp} is caused by MFD mismatch [10] described by

$$\alpha'_{\text{sp}} = \tfrac{1}{4}\left(x + x^{-1}\right)^2,$$

where x is the ratio of MFD of PSCF to that of SSMF. Therefore it is desirable to reduce MFD of PSCF without reducing A_{eff}, which is equivalent to increasing the k-parameter [1] defined by

$$k = A_{\text{eff}} \Big/ \left(\tfrac{\pi}{4}\,\text{MFD}^2\right).$$

The k-parameter can be maximized by the ring core structure with optimum radius ratio b/a of 2.5, between ring core and center core. The PSCF-130 with optimized ring core has 6% larger k-parameter than step core in both C&L bands as shown in Figure 6, corresponding to 0.03 dB lower splice loss to SSMF with typical MFD of 10.3 μm at 1550 nm [1].

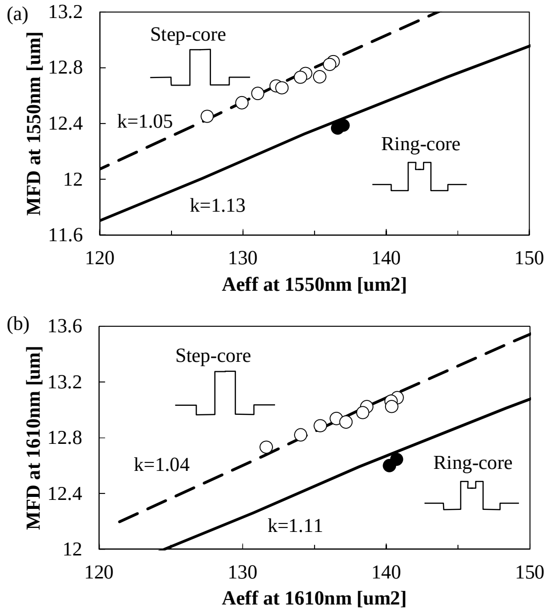

Figure 6: Reduction in MFD by ring core for low splice loss to SSMF in (a) C-band and (b) L-band.

3. ESTIMATED TRANSMISSION PERFORMANCE OF PSCF-130

Impact by choice of fiber on transmission performance or reach in a given system configuration is represented by figure of merit (FOM) parameter [2, 11-12], which is based on the Gaussian noise (GN) model that describes nonlinear propagation in uncompensated coherent system. FOM is given by

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

where γ, L_{eff}, D, α, L and α_{sp} are nonlinear coefficient ($\propto n_2 / A_{\text{eff}}$, n_2 being nonlinear refractive index), effective length, chromatic dispersion, fiber loss in dB scale, span length (repeater spacing) and splice loss in dB scale, respectively.

The optimum launched signal power P_{opt} that maximizes OSNR is expressed using FOM, as

$$P_{\text{opt}}\,[\text{dBm}] = \text{FOM} + \alpha_{\text{span}} - 10\log L + C_1,$$

and the Q-factor at maximized OSNR is

$$Q_{\max}\,[\text{dB}] = \text{FOM} - 10\log D_{\text{T}} + C_2,$$

where α_{span} and D_{T} are span loss and total transmission reach, respectively. C_1 and C_2 are fiber-independent coefficients determined by system characteristics such as back-to-back penalty, EDFA noise figure, baud rate, spectral efficiency and number of channels.

In practical submarine systems, launched signal power P_{ch} is not always equal to the optimum power P_{opt}, because of limitations in power supply to wet repeaters via undersea cables, and wavelength dependence in P_{opt}. The figure of merit FOM_{R} in case of non-optimum launched power is given by [2, 12]

$$\text{FOM}_{\text{R}} = \text{FOM} + 10\log\left[3r\big/\left(r^3 + 2\right)\right],$$

where $r = P_{\text{ch}} / P_{\text{opt}}$. It should be noted that FOM_{R} depends on system configuration through P_{opt}.

FOM_R of PSCF-130 is calculated as a function of wavelength based on wavelength characteristics of fiber parameters. Splice losses are calculated from MFD mismatch, and n_2 is assumed to be 2.2×10^{-20} m/W, which is typical for PSCF. The upper limitation in launched signal power is set to be -2 dBm/ch with ±1 dB deviations, assuming typical output power of submarine repeater to be +18 dBm and typical channel number in each C or L band to be 100, with possible variations between systems. C_1 parameter that affects P_{opt} is set to be -6.6dBm/ch based on a 100G-QPSK-DWDM transmission experiment [12]. When launched signal power P_{ch} exceeds the optimum power P_{opt}, it is assumed that actual launched power is attenuated down to P_{opt}.

Calculated FOM_R characteristics are shown in Fig. 7 (a) and (b) for 80 km and 100 km span cases, respectively. In both cases PSCF-130 improves FOM_R by more than 2.5 dB compared to SSMF over C and L bands. It should be noted that FOM_R of SSMF does not increase much with increase in signal power limit, because high loss and small A_{eff} reduces P_{opt} below signal power limit. In contrast, FOM_R of PSCF-130 can increase with signal power limit, because P_{opt} is higher than signal power limit due to low loss and large A_{eff}. The increase in FOM_R means possible capacity enhancement by system optimization.

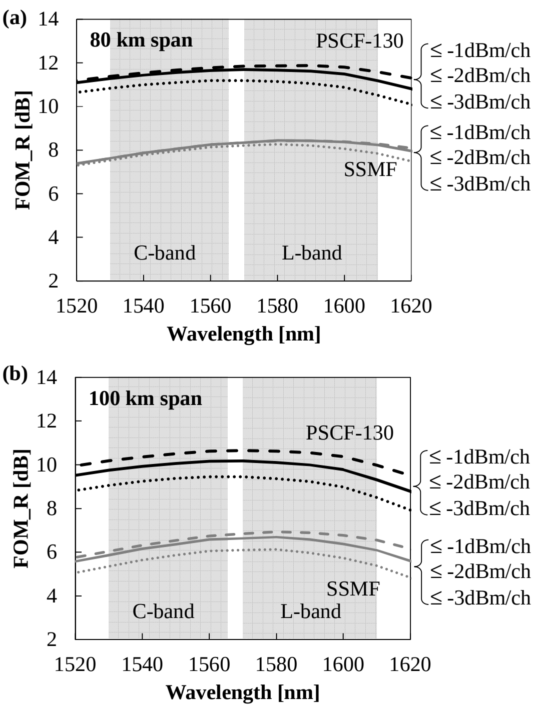

Figure 7: Figure of merit FOM_R under limitation of launched signal power.

4. POTENTIAL FOR CAPACITY ENHANCEMENT

The recent record transmission experiments exceeding capacity distance product (CDP) over 300 Pb/s*km employs C plus L band transmission [13,14]. C plus L band transmission is realized by either C+L EDFA or hybrid Raman EDFA. In either case, it is crucial for transmission fiber to have as high FOM and as low macro- and micro- bending losses in L band as those in C band, which is the case for PSCF-130 as shown in the previous section. In addition, it has been shown that OSNR in systems with hybrid Raman EDFA is improved mainly by low fiber loss, while effect of enlarging A_{eff} saturates above 110 μm^2 [15].

Coded modulation with variable spectral efficiency [13] can maximize total capacity even in system whose OSNR varies with wavelength. Therefore higher OSNR can contribute to larger capacity. While higher OSNR can be realized by lower fiber loss or higher signal power enabled by large A_{eff}, the latter would cause difficulty in power supply to repeaters, especially in future high capacity system employing C plus L band and high fiber-count cable. Therefore ultimate low loss would remain to be the most important characteristics for submarine transmission fiber.

5. CONCLUSIONS

Over C and L bands, PSCF-130 has ultra-low loss of 0.15 dB/km and large A_{eff} of 130 μm^2 resulting in high FOM, in addition to low macro- / micro- bending and splice losses. Because of these excellent characteristics, PSCF-130 is believed to be the fiber of choice for systems with enhanced transmission capacity using C plus L band and coded modulation with variable spectral efficiency. Moreover, ultimate low loss would be most important for further expansion of transmission capacity.

6. REFERENCES

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