LOW-LOSS MULTI-CORE FIBERS FOR SUBMARINE TRANSMISSION

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Abstract: Spatial division multiplexing (SDM) is a key technology to improve the capacities and the power efficiencies of submarine optical fiber transmission systems, and it is considered that multi-core fiber (MCF) is one of optimum transmission fibers to overcome the limited spaces for increasing the spatial channel count in submarine cables and repeaters. However, it has been a challenge for MCF to achieve low attenuation with standard 125 µm cladding diameter. In order to demonstrate solving this problem, we fabricated two types of pure-silica-core MCFs: uncoupled two-core fiber (U-2CF) and coupled four-core fiber (C-4CF). The U-2CF has attenuations of 0.162 dB/km and effective areas of 112 µm^2, which are comparable to the conventional single-core submarine fibers. The excess loss due to the coupling to the neighboring core and the coating is expected to be lower than 0.0003 dB/km at 1550 nm, which should be sufficiently low for counter-propagating configuration where each core carries signal in opposite direction. The C-4CF has attenuations of 0.158 dB/km and effective areas of 112 µm^2, which as well are comparable to the conventional single-core submarine fibers. The spatial mode dispersion was 3.14 ps/√km, which should be low enough for transoceanic transmission using multiple-input multiple-output (MIMO) digital signal processing. At the conference, we will also discuss pros and cons of each type of MCFs and issues to be addressed for serving such MCFs to practical submarine cables.

1. INTRODUCTION

Electrical power supply to undersea optical repeaters limits the available capacity and distance of the state-of-the-art subsea optical transmission systems [1-2]. In order to increase the capacity and distance of transmission, one of the most promising ways is considered to be spatial division multiplexing (SDM) [3-5], where system's spatial channels are increased and optical power is split among those spatial channels. Since Shannon capacity linearly depends on the number of spatial channels but logarithmically on power per channel, SDM enables optimization of power efficiency of the system.

The most straightforward way of SDM is increasing the fiber count within a cable. However, current submarine cables would be able to accommodate around 32 fibers (16 fiber pairs) [6], and significant further increase in fiber count is challenging because of difficulties in fiber identification and in changing the established cable structure. These difficulties in increasing fiber count cause motivation for SDM fibers that have plural spatial channels in a single cladding.

In this paper, we discuss low-loss uncoupled 2 core fiber and low-loss coupled 4 core fiber would be most promising for subsea SDM applications, because fiber attenuation has increasing impact on the capacity in power-limited systems, compared to the conventional systems free from power limitation.

2. SDM FIBERS FOR SUBSEA TRANSMISSION

SDM fibers that have plural cores (multi-core) and/or plural modes per core (few-mode) have been the subject of intensive research for scaling the capacity. As a most outstanding example, a capacity as high as 10.16 Pb/s over 11.3 km distance was demonstrated using an SDM fiber having 114 spatial channels (6 modes × 19 cores) within a 267-μm diameter cladding [7]. However, such a thick cladding compared to the standard 125 μm increases bend-induced stress in proportion to the cladding diameter, so would necessitate further investigation to achieve enough reliability.

Among the SDM fibers having the standard 125-μm cladding, a few-mode fiber having 45 modes [8] and a multi-core fiber having 12 coupled cores [9] were demonstrated. However, those fibers have attenuations as high as 0.22 dB/km for the 45-mode fiber, and 0.23 dB/km for the 12-core fiber, significantly higher than 0.15 dB/km attenuation of the current subsea fibers. Since the impact of fiber attenuation increases by power limitation, as illustrated in Section 4 and also detailed in [10], those attenuations higher than 0.2 dB/km would be prohibitive in high degree SDM systems with limited power.

For above reasons, SDM fibers having 125-μm cladding and low attenuation comparable to or better than those of the current subsea fibers should be required for application to power limited systems.

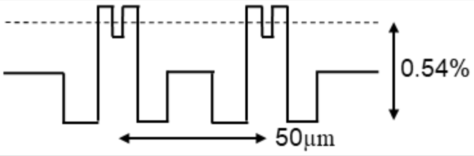
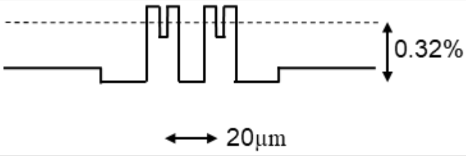
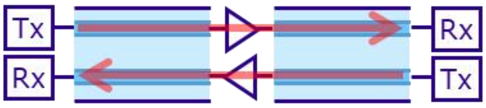
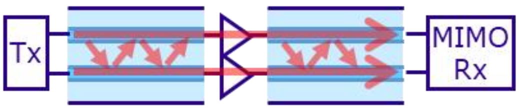
	Uncoupled 2-core fiber (U-2CF) [11]	Coupled 4-core fiber (C-4CF) [12]
Core and cladding structure	 125 μm cladding	 125 μm cladding
Refractive index profile		
Attenuation	0.162 dB/km	0.158 dB/km
Aeff	112 μm2	112 μm2
Transmission scheme	Suited for counter-directional transmission (Crosstalk ≤ -25dB at 10,000km)	Suited for MIMO-aided transmission (Spatial mode dispersion ~ 310ps at 10,000km)
		

Table 1: Comparison between uncoupled 2-core fiber (U-2CF) and coupled 4-core fiber (C-4CF).

3. LOW-LOSS MULTI-CORE FIBERS FOR SUBSEA APPLICATIONS

We have proposed and demonstrated two types of low-loss SDM fibers with 125-μm cladding: an uncoupled 2-core fiber [11] and a coupled 4-core fiber [12]. Their characteristics and transmission scheme are summarized in Table 1.

The uncoupled 2-core fiber (U-2CF) [11] is composed of two Ge-free silica cores surrounded by an F-doped 125-μm silica cladding. Since the cores are basically compatible with that of the current subsea fibers, the U-2CF has attenuations as low as 0.162 and 0.163 dB/km at the two cores, which are fairly comparable to those of the current subsea fibers. The effective areas (A_{eff}) are 112 and 113 μm^2, which are again fairly comparable to the current fibers.

The inter-core crosstalk (XT), defined as the ratio of power leaked from one core to another, was around −36 dB per 10,000 km in co-propagating configuration, and around −59 dB in counter-propagating for 60 km-spans. Whereas these low XTs are partially because of a long cable cut-off wavelength λ_{cc} of 1570 nm, theoretical calculation implies that even if λ_{cc} is adjusted below the standard 1530 nm, the counter-propagating XT will be below −25 dB per 10,000 km with 60 km-spans, and leakage loss to the counter-propagating core and the coating will be below 0.0003 dB/km and thus negligible. The noise due to XT can be treated as an excess noise additive to ASE and nonlinear impairment noises [13] as:

$$\mathrm{SNR}_{\mathrm{MC}}^{-1} = \mathrm{SNR}_{\mathrm{SC}}^{-1} + \mathrm{XT}, \qquad (1)$$

where $\mathrm{SNR}_{\mathrm{SC}}$ and $\mathrm{SNR}_{\mathrm{MC}}$ are the SNRs for single core and multi core fibers respectively.

From Eq. (1), SNR penalty due to XT is derived as:

$$\Delta\mathrm{SNR} = \frac{\mathrm{SNR}_{\mathrm{SC}}}{\mathrm{SNR}_{\mathrm{MC}}} = 1 + \mathrm{SNR}_{\mathrm{SC}} \cdot \mathrm{XT}, \qquad (2)$$

so that assuming an $\mathrm{SNR}_{\mathrm{SC}}$ of 13 dB and a XT below −25 dB, SNR penalty is suppressed below 0.3 dB.

Therefore, the U-2CF can be a candidate medium for a transoceanic transmission over 10,000 km. Whereas fan-in fan-out (FIFO) devices are needed at the beginning and the end of each span to break out the counter-propagating cores for amplification, a low loss FIFO technique that can be made with a 0.21 dB insertion loss [14] could be useful.

Next, the coupled 4-core fiber (C-4CF) [12] is composed of four Ge-free silica cores, which are again basically compatible to those of the current subsea fibers and are surrounded by an F-doped 125-μm silica cladding. Since the cores are located closer to each other and the core-cladding index contrast is made lower than that of U-2CF, the optical modes in C-4CF are coupled to each other with significant XT. Such coupling has to be compensated by multi-input-multi-output (MIMO) signal processing at receiver and/or transmitter ends. With the help of offline MIMO processing, transmission performance over 9,900 km at a spectral efficiency as high as 11.6 bit/s/Hz/4-core was proved [15]. Real-time MIMO processing was already demonstrated using a field-programmable gate array (FPGA) over a 60-km coupled 3-core fiber [16]. C-4CF's low spatial mode dispersion equivalent to 310 ps at 10,000 km would make the implementation of such real-time MIMO processing practical enough.

Since C-4CF does not need to isolate each cores, it can be made with lower core-cladding index contrast, which makes fabrication with low attenuation more practical. As a result, a core-averaged attenuation of 0.158 dB/km was achieved, which is comparable to those of the current subsea fibers and is the lowest record as an SDM fiber's attenuation.

In addition to low attenuation, the distance of the C-4CF cores from the fiber center as close as ~14 μm, compared to 25 μm for the U-2CF cores, makes the splice loss more robust against rotational misalignment. As demonstrated in [17], the 4CF-4CF splice losses are below 0.06 dB up to rotational misalignment of 2 degree, which should be manageable with commercial splicers.

For amplification, a coupled core amplifier has been demonstrated that can be directly spliced to transmission MCF because of a compatible core-core pitch and have a 15-dB gain and below 5-dB noise figure that are fairly comparable to those of the conventional EDFAs [18].

The proved transmission performance, low attenuation and developments in splice and amplifier will make the C-4CF a most promising candidate medium for applications to transoceanic transmission over 10,000 km.

4. MERIT OF LOW-LOSS SDM FIBERS IN POWER LIMITED SYSTEMS

Merit of the low-loss SDM fibers in the previous section can be estimated in terms of theoretical maximum capacity *C*:

$$C = 2N_{\mathrm{dim}}B \cdot \log_2\left(1 + \frac{\mathrm{SNR}}{M}\right), \quad (3)$$

where N_{dim}, *B*, and *M* stands for the number of spatial channels, system bandwidth and SNR margin, respectively. SNR is calculated from ASE and nonlinear impairment noises [19–21] as:

$$\mathrm{SNR}^{-1} = (P_{\mathrm{ASE}} + P_{\mathrm{NLI}})/P_{\mathrm{sig}}, \quad (4)$$

where P_{sig}, P_{ASE} and P_{NLI} are the powers of signal, ASE, and nonlinear impairment, respectively.

In order to account for power supply limitation, we imposed an upper limit on the total optical power (TOP) P_{tot} that is the sum of the output powers of the amplifiers within a system.

$$P_{\mathrm{tot}} = N_{\mathrm{dim}}N_{\mathrm{rep}}(P_{\mathrm{sig}} + P_{\mathrm{ASE}}), \quad (5)$$

where N_{rep} is the number of repeaters.

In calculating the merit of the low-loss multi-core fibers, we assumed a TOP of +51.9 dBm per direction, which corresponds to a 1-dB improvement from the TOP of a reference system having 12 fiber pairs and 145 repeaters with +18.5-dBm amplifiers. We also assumed the reference system transmits a capacity of 18 Tb/s/fiber and operates at the nonlinear optimum with 75.3-km spans (11,000 km in total) composed of fibers having an attenuation of 0.152 dB/km, a nonlinear coefficient of 0.59 /W/km, and splice losses of 0.1 dB. We also assumed that noise due to XT of U-2CF is negligible and that mode coupling in C-4CF is compensated perfectly by MIMO processing.

On those assumption, theoretical capacity of a 11,000-km-distance 16-fiber-pair system was calculated as a function of fiber attenuation for the cases of 1-core, 2-core and 4-core fibers with 112-μm^2 A_{eff}'s. Span lengths were optimized for each attenuation and the number of cores. The results of calculation are shown in Fig. 1. As shown in Fig. 1(a), the capacity would be scaled by increasing the number of cores per fiber if the power supply is unlimited. However, if the power supply is limited, capacity scaling is limited but can get closer to power-unlimited capacity as fiber attenuation gets lower. As a result, capacity gets more sensitive to fiber attenuation as the power gets scarce.

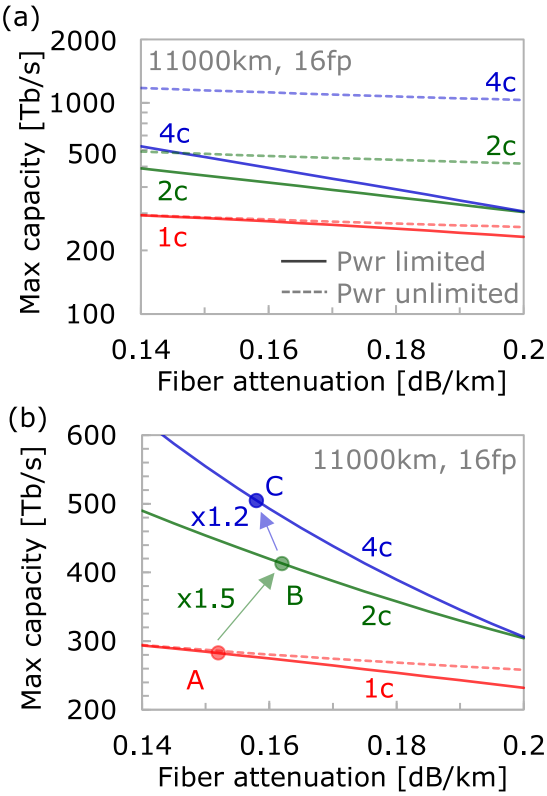


Figure 1: Theoretical maximum capacity as a function of fiber attenuation and the number of cores (a), and its magnified view (b). Plots A, B, and C shows the current fiber, U-2CF, and C-4CF, respectively.

As shown in Fig. 1(b), the uncoupled 2-core fiber (U-2CF) with 0.162 dB/km attenuation can scale the capacity by 1.5 times compared to the current subsea fiber with 0.152 dB/km attenuation. Moreover, the coupled 4-core fiber (C-4CF) with 0.158 dB/km attenuation can scale the capacity by 1.2 times compared to U-2CF (1.8 times to the current fiber).

Whereas the scaling from U-2CF to C-4CF gets smaller than that from the current fiber to U-2CF because of decreased SNR (signal droop) due to the assumption of limited power, the scaling by C-4CF would increase once available power increases by, for example, amplifier efficiency improvement by optimized bandwidth [3].

5. CONCLUSIONS

SDM fiber having low attenuation and 125 µm cladding can enable capacity and distance scaling beyond the limitation of fiber count within a cable. As such SDM fibers, we propose uncoupled 2-core fiber (U-2CF) with 0.162 dB/km, having negligible crosstalk in counter-propagating configuration, and coupled 4-core fiber (C-4CF) with 0.158 dB/km, having negligible spatial mode dispersion that allows MIMO processing. The U-2CF and C-4CF can scale the capacity by 1.5 and 1.8 times respectively in a 11,000-km 16-fiber-pair system.

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