First Demonstration of Uncoupled 4-Core Multicore Fiber in a Submarine Cable Prototype with Integrated Multicore EDFA

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Abstract: We demonstrate the first 15.2 km prototype of submarine cable with 4-core MCF. Cabled MCF changes are negligible. We confirmed MC-EDFA integration to the cable improves Q-value by 0.6 dB through real-time 5,350 km transmission.

1. Introduction

Demand for higher capacity communication systems has been increasing due to always more frequent usage of wireless devices including cutting-edge 5G technology, and due to the continuous shift to online services, which has recently been accelerated by the COVID-19 pandemic. As conventional single mode fiber (SMF) based systems are approaching their capacity limitation, Space Division Multiplexing (SDM) appears as a promising technology to meet this increasing demand [1]. For submarine cable systems, the capacity demand increase leads to a Compound Annual Growth Rate of 32% [2]. In such energy and space limited systems, SDM leads to a linear system design, spreading the signal energy among spatial channels and reducing degradation due to the fiber non-linear effect [3]. Thus, increasing the number of Fiber Pairs (FP) in submarine cable is an efficient way to improve their capacity, notably by doubling FP from 8 to 16 (i.e. 16 to 32 cores) with standard 125 μm cladding diameter SMF[4]. Nonetheless, further increase of FP is limited by the submarine cable size; therefore, other scalable solutions are required to keep the pace of the CAGR for the next decade. A next step into SDM using Multicore fiber (MCF) is an efficient solution to further increase the number of spatial channels [5-7]. Uncoupled Core (UC-MCF) [8] and Coupled Core (CC-MCF) are two potential candidates. While CC-MCF is promising in term of core density, low nonlinearities [9-11], ease of splicing and manufacturability [9], it will require novel Multiple Input Multiple Output (MIMO) [10-12] technology ASIC. As UC-MCF is compatible with current generation transponders, this approach is a potential next step in SDM systems.

Early trials of UC-MCF transmission over a terrestrial cables have been reported [13, 14] to validate cabled fiber performance; however, UC-MCF remains to be tested for space and energy limited submarine cable systems. In this paper, we report experimental results using what is to our best knowledge the world first submarine cable featuring MCF, notably 60.8 km spans made of the serial connection of 4 FP of the 15.2 km cabled 4-core UC-MCF shown in Fig.1. As inline amplification is an important feature in submarine systems [15], we also use core pumped 4-core EDFA and we clarify the benefit of integrating the amplifiers [16], i.e. splicing the amplifier and fiber, removing the connecting Fan-In Fan-Out (FIFO) devices.

2. Manufacturing of submarine cable prototype featuring 4-core uncoupled multicore fiber

To accommodate the 4-core UC-MCF and realize our prototype, we selected SC520 type submarine cable, which design is robust and can withstand 8,000 m depth water pressure [4]. Notably, the 3-Divided Steel Segments design contributes to overcome attenuation induced by the cabling process. Furthermore, Light Weight (LW) SC520 design with 17 mm outer cable diameter reduces the cable weight by 20 % compared to conventional 20 mm cables for almost

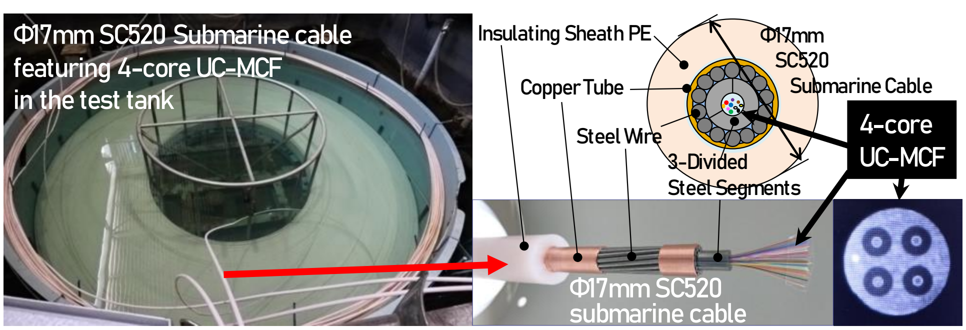

Fig. 1. Fabricated submarine cable prototype featuring 4-core UC-MCF

constant fiber mounting density; this increases the amount of shipped cable and finally reduces system installation costs. The LW SC520 cable can accommodate 32 fiber, i.e. 16 FPs. Our prototype was manufactured with 4 FP of 4-core UC-MCF and 12 FP of SMF, for the purpose of detailed investigations, having a total of 56 cores. It could therefore potentially accommodate up to 128 cores per cable. The main properties of the SDM submarine cable prototype are shown in Tab. 1.

Tab. 1. Properties of the submarine cable prototype

Cable type		LW SC520
Length		15.2 km
# of FPs	4-core UC-MCF	4
	SMF	12
# of Cores	(4 x 4 + 12) x 2	56
Outer diameter		17 mm

Tab. 2. Properties of the 4-core UC-MCF

Outer diameter	250 μm
Effective core area	77 μm^2
Core pitch	45 μm
Cladding diameter	125 μm
Loss (1550 nm)	0.177 dB/km
Chromatic dispersion (1550 nm)	21.7 ps/nm/km
Polarization mode dispersion	0.058 ps/√km
Inter-core cross talk	-62.7 dB/km

Tab. 3. Variation of properties before and after cabling

Loss	0.0001 dB/km
Chromatic dispersion (1550 nm)	-0.009 ps/nm/km
Dispersion slope (1550 nm)	-0.0085 ps/nm^2/km
IC-XT	-1.45 dB

In order to validate our MCF based submarine cable prototype, we first evaluated the optical characteristics of the fiber. We compared loss, Inter-Core cross Talk (IC-XT), chromatic dispersion and its slope before, during and after the cable manufacturing. The variation of fiber characteristics between the factory incoming test (i.e. un-cabled 4-core UC-MCF) and the LW cable completion (i.e. cabled 4-core UC-MCF) is summarized in Tab. 3. The measurement methods are compliant with the ITU-T G.650.1 and G.650.2 standards [17, 18], except for IC-XT, which remains to be standardized. For this item, we used a FIFO device pair, which we calibrated for IC-XT. SC520 cabling process was already validated for SMF as changes in fiber properties were negligible [4]. These results are also valid for 4-core UC-MCF, at the exception of IC-XT. The fluctuation of the measured IC-XT after the acceptance test are attributed to misalignments during splicing of the reference FIFO and the measured UC-MCF. Nonetheless, low IC-XT characteristics are validated in the following transmission experiment. Rather than pointing at problems of IC-XT of the fiber, this result shows the necessity of a standard measurement method, possibly without FIFO or with more accurate and stable MCF connecting technology.

3. Long haul transmission experiment using the cable prototype and MC-EDF

To validate our submarine cable prototype, we then proceeded to the evaluation of its transmission characteristics. Fig. 2 shows the loop experimental set-up using 4-core UC-MCF and core pumped MC-EDFA with built-in FIFO. We used 120 wavelengths on the C-band (1528.773 nm to 1564.679 nm). Loading channels were shaped from ASE. Five channels were modulated with 34.7 GBd PM-QPSK signal and measurement were realized in real-time with an ASIC synchronized to the loop switch, to analyze properties and stability, including possible IC-XT transients. We have selected PM-QPSK according to the test modem recommendation from Subsea Open Cables [19].

The 60.8 km span was realized by splicing four 15.2 km-length cabled MCF as shown in Fig. 2. Serial connection of the cores of evaluated MCF ensures that they are all loaded and that IC-XT is realistic [15], here -44.4 dB per span, and enabling 4 spans per lap. The cable was laid in 15℃ water. For the experiment with FIFO between MCF and MC-EDF, the span loss was 13.5 dB, including 7 splices, with MCF splice losses around 0.3 dB, which should be improved in the future. The insertion loss and IC-XT of FIFO was 1.0 dB and -54 dB respectively per device pair. The output power of the MC-EDFA was set to its maximum of 16.4 dBm/core to compensate the span loss. The optical gain and noise figure per core were 13.5 dB and 6.3 dB respectively. The minimum NF of our 4-core MC-EDFA is 6.3 dB. The operating condition of the 4-core MC-EDFA in this experiment was same as that of the minimum NF condition. The

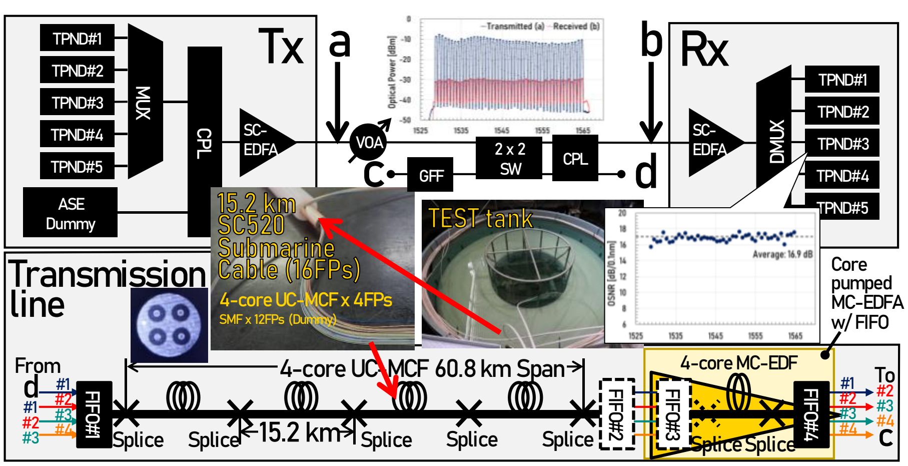

Fig. 2. Experimental-setup using 4-core MCF submarine cable prototype and 4-core MC-EDFA with and without FIFO

average pump power among core was 640 mW. A Gain Flattening Filter (GFF) was used to equalize the output of the MC-EDFA every 4 spans, i.e. once per lap. For example, 22 laps of the loop transmission line in Fig. 2 corresponds to 4 spans of 60.8 km, i.e. 5,364 km length. As the MC-EDF was optimized for high gain, its core layout was different from that of the transmission UC-MCF [20]. Thus, the core layout conversions between the MC-EDF and MCF were done inside the pump combiner at MC-EDF input and the isolator at its output. Fig. 3 shows the measured real-time Q-values for cabled UC-MCF and identical un-cabled fiber, denoted as ΔQ_{cable}, both using the set-up of Fig. 2 for a signal wavelength of 1546.52 nm. Q values for cabled MCF were less than 0.2 dB higher than un-cabled MCF. Thus, our cable prototype can accommodate UC-MCF without significant change of transmission characteristics in accordance with the evaluation results shown in Tab. 3. Fig.4 shows Q-value real-time measurement results for 12 hours after 5,350 km transmission on cabled MCF in the conditions of Fig. 3. Post FEC error-free transmission was confirmed at five wavelengths (1529.066 nm, 1537.397 nm, 1546.518 nm, 1555.747 nm, 1564.373 nm). The standard deviation of Q-value was 0.15 dB, identical to the back to back value, showing the stability of the cabled UC-MCF. Comparing this value to ΔQ_{cable} of Fig. 3, for measured distances and taking into account the results of Tab.3, the penalty due to the cable assembly is negligible.

Finally, we investigated the benefit of integrating the MC-EDFA splicing it to the MCF. Since the core layout of MC-EDF and MCF for transmission is different, its conversion is indispensable. Built-in FIFO of MC-EDFA can be used for the core layout conversion from transmission MCF. However, here, we chose the option to solve the layout difference problem by using both pump combiner and stripper inside the MC-EDFA for conversion instead of using FIFO, removing its additional loss. Fig. 5 plots the difference of Q-value and OSNR, ΔQ_{FIFO} and $\Delta OSNR_{FIFO}$, between spliced case and FIFO used between MC-EDF and MCF as shown in dashed lines on Fig.3. Without FIFO#2 / #3 and the additional splice point, the span loss was reduced by 1.3 dB. Measurements show that MC-EDF integration improves Q value, by 0.6 dB (from 5.9 dB to 6.5 dB) at 5,350 km, mainly in virtue of the OSNR improvement obtained with lower span loss. Indeed, ΔQ_{FIFO} is in accordance with the calculated Q-value improvement for the same $\Delta OSNR$ condition. Considering a total IC-XT -25 dB after 88 spans, the transmission was OSNR limited and the crosstalk penalty on the signal was negligible [5, 21].

4. Conclusions

In this paper, we have reported the world first prototype of submarine cable featuring 4-core Uncoupled Multicore Fiber to our best knowledge. Characterization of the 4-core MCF before and after cable manufacturing show that the influence of this process was negligible and Q value changes of 0.2 dB were close to standard deviation of 0.15 dB. We transmitted a 34.7 GBd PM-QPSK signal among 120 channels on 5,350 km of 4-core UC-MCF with 60.8 span length in a 15.2 km submarine cable. Finally, integrating the 4-core MC-EDFA by removing the connecting FIFO with the MCF contributes to improve the received OSNR improving Q by 0.6dB at 5,350 km transmission.

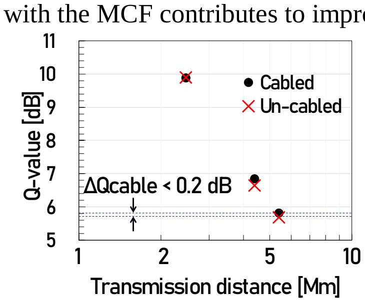

Fig. 3. Measured Q-value of cabled and un-cabled UC-MCF transmitted signal

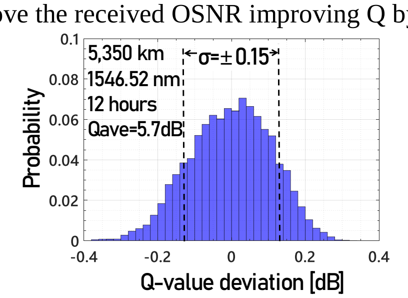

Fig. 4. Histogram of Q-value deviation during 12 hours UC-MCF cable transmission

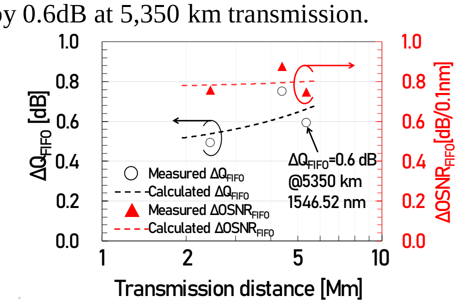

Fig. 5. Q-value and OSNR change by the reduction of the number of FIFO and UC-MCF splice point

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5. References

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