Record Low Loss 0.144 dB/km 2-Core Optical Fiber for Submarine Transmission

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Abstract *The fabrication of 2-core multi-core fibers having two different core-designs and record attenuation of 0.144dB/km and 0.148dB/km at 1550nm is reported. This was enabled by improvements in core-processing and mitigation of attenuation contributors in the fiber manufacturing, including optimization of the draw conditions.*

Introduction

Trans-Atlantic submarine cables capacity has increased by 5 orders of magnitude in the past 30 years [1], and the largest trans-Atlantic cable capacity announced to date is 500 Tbit/s [2]. The industry is now assessing technology pathways to achieve multi Petabit/s cables. One promising technology is multi-core fiber (MCF), with uncoupled 2-core MCF a potential candidate to deliver Pb/s class subsea cables [3][4].

Ultra-low attenuation and low crosstalk in the MCF are paramount to achieving the transmission performance that is comparable with single-core fiber [3]. The design of the cores, geometry of the MCF, and effective area greatly impact the optical performance properties.

In an uncoupled core MCF design, an increase in the inter-core distance improves the inter-core crosstalk, but also places the cores closer to the outer periphery of the fiber cladding. This results in increased radiation (or, leakage) loss due to the overlap of the mode field with the high refractive-index coating region. Additionally, the choice of propagation configuration, whether co-propagating or counter-propagating, can significantly impact the level of crosstalk between the cores [5].

Over the last decade, several improvements in MCF attenuation have been demonstrated [6-9]. In [6], a coupled 4-core fiber with 0.158 dB/km attenuation at 1550 nm was reported. In [8], a 2-core fiber with 0.155 dB/km and 0.157 dB/km for core #1 and core #2, respectively, were demonstrated, with counter-propagating crosstalk below -50 dB at 100 km.

In this paper, we describe the fabrication and optical performance of 2-core MCFs with two different core designs, and schematic as shown in Fig. 1. The design is based on a common cladding diameter of 125 μm and a target effective area of ~112 μm². We report a record attenuation of 0.144-0.148 dB/km for 2- core MCF design. Crosstalk levels of - 40 to - 45 dB/100km at 1550 nm in a co-propagating configuration and -62 to - 67 dB/100km in a counter-propagating configuration are also reported. The record attenuation in MCF was enabled by a combination of silica-core technology with fluorine-doped common cladding, as well as best practices in fiber processing. The fiber making process relies on core-cladding viscosity matching to reduce residual stresses and reducing the fictive temperature of the resulting fiber utilizing draw condition optimization.

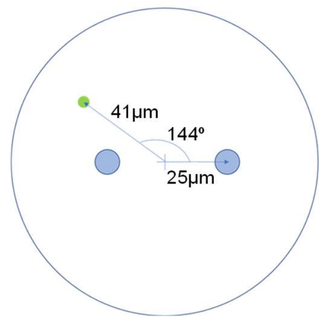

Fig. 1 2-core MCF marker core identification schematic.

2-core MCF design

Core identification techniques, such as symmetric core design with symmetric marker and offset core design with no marker, have been demonstrated in [8]. In this work, we propose symmetric MCF core design with asymmetric marker core identification, as shown in Fig. 1. The core is located at an angle of 144º with respect to one of the cores and at a radius of 41 μm with respect to the center of the fiber. Our choice for this core identification method was driven by three main considerations. First, its capability to uniquely trace both core and fiber direction. Second, it provides a scalable way to identify cores for further iterations of MCF, such as 4-core. Third, both cores experience equivalent radiation loss, as they are equidistant from the cladding, which could provide a better

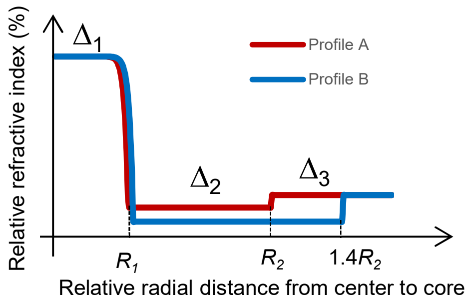

Fig. 2. Fiber core-profiles with different moat volumes

consistency between the loss values in both cores.

Two different moat-assisted 2-core MCF profiles were fabricated and evaluated for their optical properties (Fig. 2). Profile B entailed a core design with moat volume about 4 times larger than to the moat volume in Profile A, where the moat volume is defined as $V = 2\int_{R_2}^{R_1}(\Delta_3 - \Delta_2)rdr$, where Δ_2 is the moat refractive index, Δ_3 is the clad refractive index, R_1 is the core radius and R_2 is the moat radius. For both cases, the core design was tuned to meet the target A_{eff} and other relevant optical attributes, such as mode field diameter (MFD), chromatic dispersion (CD), and dispersion slope (DS). To investigate the optimum inter-core distance that provides a desired balance between crosstalk and attenuation levels, a range of inter-core distances were fabricated for a 2-core MCF: 45, 50 and 55 µm - for Profile A; and 50 and 63.5 µm for Profile B.

2-core MCF optical properties

In this section the attenuation and inter-core crosstalk of each of the fabricated designs is evaluated. The attenuation was measured using the spectral cutback technique that is compliant to the IEC 60793-1-40 standard [10]. The inter-core crosstalk is an additional impairment specific to MCF, and there is no standardized technique to perform the crosstalk measurement. The co-propagating (XT_{co}) and counter-propagating ($XT_{counter}$) crosstalk measurement techniques described in this work can provide useful insights for subsequent standardization discussions.

The crosstalk measurement setup is shown in Fig. 3. For this, a selection of 2-core fibers of length between 20 and 25 km on a standard shipping spool were tested. The test equipment

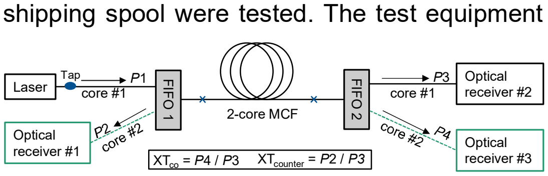

Fig. 3 Experimental setup for measuring XT_{co} and XT_{couter} crosstalk in 2-core MCF.

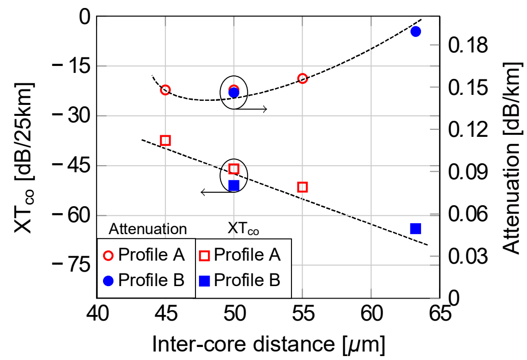

Fig. 4. Co-propagating crosstalk (XT_{co}) and attenuation at 1550 nm vs. inter-core distance for both Profile A and B.

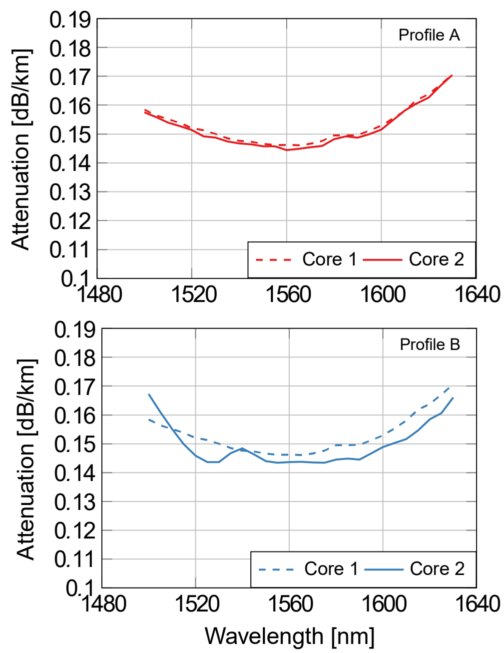

Fig. 5: 2-cores MCF spectral attenuation for (a) Profile B and (b) Profile A.

was comprised of a tunable laser source (TLS) with linewidth of 200 kHz, a tap to monitor the laser output power, and a 1x2 MCF fan-in/fan-out (FIFO 1) spliced to the fiber to inject the source light into one core while directing backward propagating light in the other core. A fan-out (FIFO 2) is spliced at the far end of the fiber, and its outputs are connected to optical receivers to measure forward propagating light out of each core. The optical receivers #1 and #3 have a high sensitivity detector with -109 dBm noise sensitivity and linearity error with <20% deviation over the entire power measured range (+5 to - 75 dBm). All three optical receivers were calibrated and read out the same power at one power level. The MCF used to fabricate FIFOs had the same mode field diameter (MFD) and core-to-core pitch as the transmission MCF.

We have implemented models for estimating co and counter-propagating crosstalk based on methods outlined in [11-12]. The FIFO crosstalk was calculated to be 8.4 dB lower at 1550 nm than the crosstalk from the fiber alone, and its contribution was subtracted out. For the crosstalk measurements, the tunable laser wavelength was varied from 1515 to 1595 nm in 0.004 nm steps, using four polarization states, with an average of 5,000 data points per wavelength measurement.

Fig. 4 shows the measurement of co-propagating crosstalk and attenuation at 1550 nm for different inter-core distances and profiles A and B. For both profiles, it was found that the inter-core distance of 50 µm yields the lowest attenuation of 0.144-0.148 dB/km amongst all inter-core distances studied in this work, while maintaining lower XT_{co} of -46 to - 51 dB/25km for profiles A and B, respectively.

The spectral attenuation for Profiles A and B, both corresponding to the 50 µm inter-core distance, is shown in Fig. 5(a) and (b) respectively. Both profiles achieved a record attenuation of 0.144 to 0.148 dB/km at 1550 nm (see Table 1).

The co and counter-propagating crosstalk wavelength dependency for Profile A with 50 µm inter-core distance is shown in Fig. 6. The XT_{co} and $XT_{counter}$ crosstalk increased with wavelength at a rate of 0.113 dB/km/nm and 0.104 dB/km/nm, respectively. This is due to an increase in MFD with wavelength leading to stronger overlap between the light from the two cores. The measured $XT_{counter}$ was approximately 30 dB below the XT_{co} for all wavelengths. Such a difference in crosstalk levels can be attributed to the relatively short 25 km spool used for the measurement – this is consistent with previously published predictions [5][13]. For a longer 100 km span length, we calculate the $XT_{counter}$ to be approximately 22 dB lower than XT_{co} for fiber with the MCF effective area and Rayleigh scattering characteristics studied here, consistent with the results presented in [5][13].

Tab. 1: 2-core MCF optical properties at 1550 nm

	Profile A		Profile B	
	Core		Core	
	#1	#2	#1	#2
Loss [dB/km]	0.148	0.147	0.148	0.144
A_{eff} [µm^2]	116.8	116.1	122.5	121.7
XT_{co} [dB/25km]	-46		-51	
XT_{co} [dB/100km]	-40		-45	
$XT_{counter}$ [dB/25km]	-76		-82	
$XT_{counter}$[dB/100km]	-62		-67	
MFD [µm]	12.15		12.35	
CD [ps/nm/km]	20.1		20.8	
DS [ps/nm^2/km]	0.06		0.06	

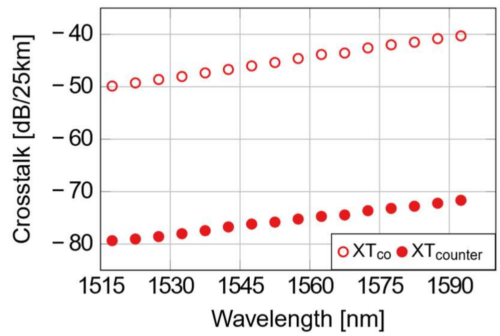

Fig. 6: Wavelength dependence inter-core crosstalk.

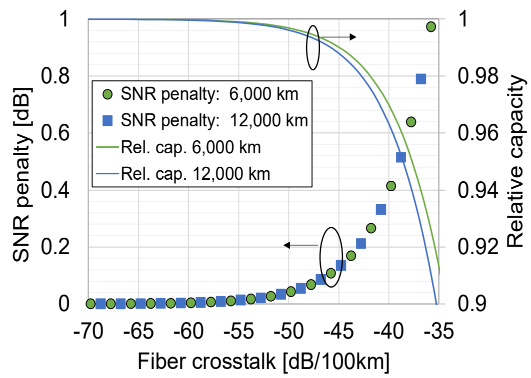

Fig. 7: SNR penalty as a function of inter-core crosstalk.

The measured crosstalk in dB/25km and estimated crosstalk for in dB/100km, along with other relevant optical characteristics is summarized in Table 1 at 1550 nm wavelength.

To understand the impact of fiber crosstalk on the transmission system performance, Fig. 7 illustrates the estimated SNR penalty as a function of the fiber crosstalk. The estimated counter-propagating crosstalk levels of -62 to - 67 dB per 100 km for both Profiles A and B with 50 µm inter-core distance have nearly zero impact on transmission performance in a counter-propagation regime for trans-Atlantic and trans-Pacific distances. The results in Fig. 7 assume SNR values of 12 dB and 9 dB without crosstalk at 6000 km and 12000 km, respectively, and are consistent with the analyses in [14-15].

Conclusions

A two-core MCF is a promising solution to further scale subsea cable capacity to 1 Pb/s and possibly beyond. The proposed moat-assisted silica-core MCF design with 50 µm inter-core distance enabled to achieve a record-low attenuation of 0.144 - 0.148 dB/km and estimated counter-propagating crosstalk < -62 dB/100km. The latter is expected to result in negligible SNR penalty. We also presented ideas and methodologies related to crosstalk measurement and core identification techniques, which could serve as a blueprint for further industry discussions and standardization.

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