Advanced Low-Loss Fibers for High-Capacity Transmission: from Data Center to Undersea

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Abstract: We review recent progresses of advanced ultra-low-loss (ULL) fibers, introducing an 85μm^2 effective-area fiber with record-low-attenuation of 0.1474 dB/km at 1550 nm. We also highlight system demonstrations using ULL fibers and their relevance to DCI/metro and undersea network.

1. Introduction

Sustained and ongoing exponential network bandwidth growth drives the need for high-capacity transmission system and lower network cost. New advanced fibers play a pivotal role in enabling the operators to increase the capacity and reduce network cost by optimizing fiber cabling infrastructures. Ultra-low-loss (ULL) large effective-area (A_{eff}) fibers G.654.D/E have already been deployed in undersea cable systems, and some terrestrial networks. In recent years, submarine system design has evolved towards space division multiplexing (SDM) systems [1-2], optimizing the transmission systems to operate in a lower-power linear regime. Consequently, the need for large A_{eff} in fiber design has been diminished for transoceanic submarine systems, and significant interests have been generated in reduced A_{eff} [3] or ~80 μm^2 A_{eff} fibers [4]. Moreover, the demand for high capacity reaching 1~5 Petabits per second in submarine cable system drives the new development of smaller diameter fibers [5] and multicore fibers (MCF) [6-8]. Nonetheless, ultra-low attenuation characteristic in all these new advanced fibers is still critical to maximize capacity and minimize system cost/bit. In addition, these ULL reduced A_{eff} or ~80 um^2 A_{eff} fibers have much more potential for cost reduction and capacity scaling in data center interconnect (DCI) and metro network.

This paper reviews the recent progresses in advanced ULL fibers and introduces an 85 μm^2 A_{eff} fiber with record-low-attenuation of 0.1474 dB/km at 1550nm. We also describe a two-core fiber with the average 1550 nm loss of 0.1478 dB/km and co-propagating inter-core crosstalk < -62dB/100km for submarine SDM systems. We then highlight experimental demonstrations of real-time high-capacity DWDM transmissions using these advanced ULL fibers for DCI/metro applications and briefly discuss the system impact and benefit of total cable capacity of transoceanic undersea systems in the context of fixed and limited power supplies.

2. Advanced ultra-low-loss optical fibers

Over the past two decades, there has been a continual improvement in the attenuation levels of Ge-free silica core fibers, as illustrated in Fig. 1 (a). Notable progress has been made in large effective area (A_{eff} >147 μm²) fibers, with recorded 1550 nm losses of 0.1467 dB/km [9] and 0.1424 dB/km [10] for R&D fibers in 2015 and 2017, respectively. These advancements have extended to commercial products [3,11], reflecting a consistent trend in enhancing fiber performance. It should be noted that the 1550 nm losses are referenced for the comparisons in this paper. As the design of submarine system has been shifted to SDM, fiber manufactory companies have been focusing on developing the fibers with reduced A_{eff} [3] or ~80 μm^2 A_{eff}. For Ge-free silica core fibers, however, reducing the A_{eff} makes it challenging to maintain the loss levels, as the loss due to Rayleigh scattering has been shown to increase with decreasing A_{eff} [12]. Despite this significant technical challenges, remarkable reductions in loss levels have been realized in TeraWave® SCUBA 125 and SCUBA 110 fibers, both featuring a moderate effective area of 125 μm² and

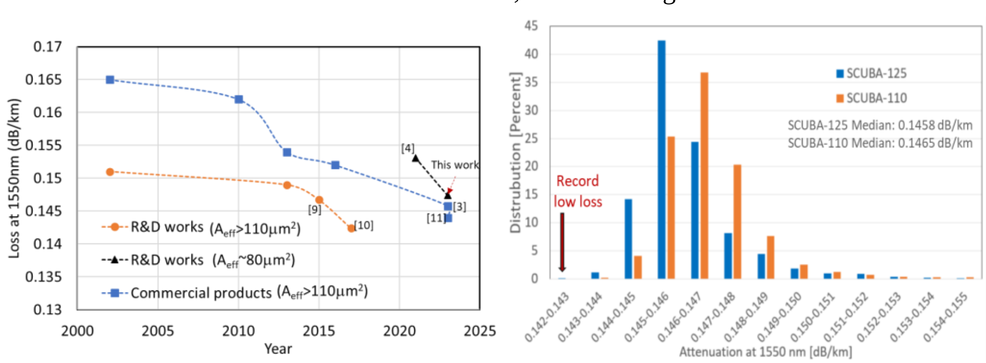

Fig. 1 (a) Improvement in losses of Ge-free silica core fiber, (b) Loss distribution at 1550 nm for SCUBA-125 and SCUBA110

110 µm², respectively [3]. These fibers are commercially available now, being produced in volumes. Both fibers are fully compliant with the ITU G.654.B and G.654.D for cutoff-shifted fiber. Fig. 1 (b) shows the 1550 nm loss distribution for effective areas of 125 µm² and 110 µm² fibers, displaying remarkably tight distributions, with medians of 0.1458 dB/km and 0.1465 dB/km, along with standard deviations of 0.0017 dB/km and 0.0015 dB/km for SCUBA 125 and SCUBA 110 products, respectively. Notably, SCUBA 125 achieves a minimum loss of 0.142 dB/km, matching the lowest reported loss level [10], however, in this case the ultra-low loss is achieved in moderate A_{eff} fibers. This exceptional loss performance is attributed to the innovative trench-assisted waveguide fiber design [3]. Furthermore, this optimized design allows for negligible micro-bend induced added loss, even when the coating dimensions are reduced to 200 µm, enabling a superior performance across the entire C+L band. Additionally, these two reduced A_{eff} fibers feature low water-peak loss, which has many benefits for distributed Raman amplification.

Advancements in fibers with A_{eff} of ~ 80 µm² have also been achieved, and an 83 µm² A_{eff} with 1550 nm losses of 0.1531 dB/km was reported [4]. We here present an optical fiber with 85 µm² A_{eff} and average attenuation of 0.1485 dB/km at 1550 nm. This attenuation value is an average measured over 184 km using OTDR measurement, the lowest loss in one spool among the 184 km spools is 0.1474 dB/km at 1550 nm. Fig.2 shows the measured loss spectrum for the typical loss. To the best of our knowledge, this is a record low-loss value for ~80 µm² A_{eff} type fibers. The low attenuation is achieved through optimization of the waveguide design and doping level compatible to the OFS SCUBA 80 fibers [13]. Also, consistent improvements in manufacturing practices had been implemented, and a loss less than 0.3 dB/km at 1385nm due to OH (Hydroxyl) is obtained. The average chromatic dispersion and dispersion slope are 20.50 ps/nm/km and 0.058 ps/nm2/km respectively. The polarization mode dispersion (PMD) value measured on the spools is 0.02 ps/√km.

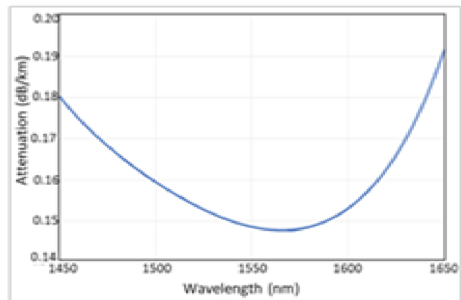

Fig.2 Measured loss spectrum of the 85µm² A_{eff} fiber.

In pursuit of realizing multi-petabit/s transoceanic undersea cables, uncoupled 2-core and 4-core MCF with standard clad-diameter are considered as the potential candidates to deliver Pb/s level cable performance. Ensuring ULL and low crosstalk in MCF is important to attain transmission capabilities that are comparable with single-core fiber. Recently uncoupled 4-core MCF with losses in range of 0.155 dB/km to 0.157 dB/km has been demonstrated along with co-propagating inter-core crosstalk measuring from -61 dB/100km to –63 dB/100km [6]. Uncoupled 2-core MCF with low loss and co-propagating crosstalk with -32 dB/100km [7] and -44 dB/100km [8] have also been reported. We have reported a 2-core MCF with a 125µm standard clad-diameter and an asymmetric marker for core identification [14]. The loss spectra of this 2-core are shown in Fig.3 (inset showing its photo). The key fiber parameters of the 2-core MCF are shown in Table 1, the 1550nm attenuation as low as 0.1479 dB/km and 0.1476 dB/km are achieved and co-propagating crosstalk <-62 dB/100km are achieved. To the best of our knowledge, this is the lowest co-propagating crosstalk with loss <0.148 dB/km in 2-core MCF with standard clad-diameter. SCUBA-4X fiber, which is an uncoupled 4-core MCF, has also been commercialized [15].

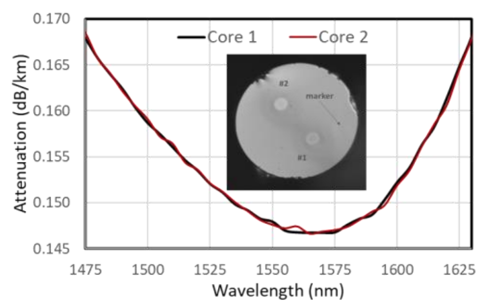

Fig.3 Measured loss spectrum of 2-core MCF.

Table 1 Key parameters for 2-core MCF

Core	Cutoff (µm)	OTDR Loss (dB/km)		A_{eff} (µm²)	Xtalk, co-propagating (dB/100km)	
		1550nm	1625nm		1	2
1	1.5	0.1479	0.1653	106	-	-62
2		0.1476	0.1651	106	-64	-

3. Large capacity transmission demonstrations and system impact of advanced ULL fibers

Advanced ULL fibers with reduced A_{eff} or ~80 µm² A_{eff} offer numerous advantages for DCI/metro network, including ease of managing macro- and micro-bending performance during deployment, potential for cost reduction, and the ability to scale-up capacity. We here highlight the experimental demonstration of real-time DWDM transmissions of 39.6 Tb/s (33x1.2 Tb/s) over a 172 km of record-low-loss 85 µm² A_{eff} fiber by using single-carrier 1.2T pluggable [16]. As illustrated in the schematic of the experimental set-up (Fig.4(a)), the transmitters consist of one loading and one measurement path. In the measurement path, one 1.2 Tb/s channel and two adjacent 400 Gb/s channels separated by 125 GHz spacing are combined. The loading path consists of an ASE source that is notch-filtered by a 50 GHz-channelized wavelength selective switch (WSS) filter. The combined DWDM channels are amplified by an EDFA with a 23 dBm output power and 39.6 nm bandwidth and transmit over the fiber span with equal launch power. The transmission link comprises a total of 172 km fiber with an A_{eff} of 85 μm^2 and an average attenuation of 0.1485 dB/km at 1550 nm. The span loss of the link, including splicing and connectors, is 26 dB. A second EDFA is used to amplify the DWDM signals before they are sent to a demultiplexer (DeMux). The selected channel from the DeMux is then fed back to the 1.2T receiver. Fig. 4(b) presents the results of the 1.2 Tb/s capacity experiment with equal channel launch power. The group consisting of the 1.2 Tb/s channel and two adjacent 400 Gb/s channels is translated in a 150 GHz step across the C-band. The average OSNR across the 33 channels is 35.0 dB/0.1nm with a variation of 3.3 dB. The large variation in OSNR is primarily caused by relative strong stimulated Raman scattering. The average Q^2-margin ranges from 0.24 dB to 0.56 dB across the entire C-band. The poorer performance in Q^2-margin observed in the short wavelength channels is due to both relatively low OSNR and high nonlinear impact. These results highlight the excellent performance of SCUBA 80 fiber and its potential for high-capacity DCI transmissions.

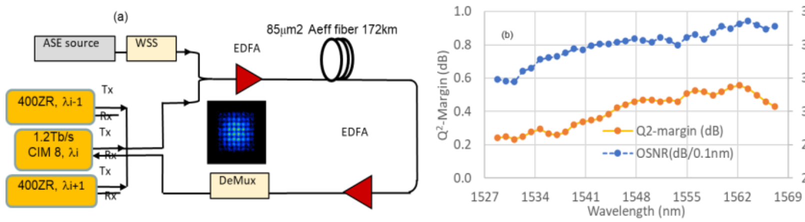

Table 1 High-capacity DCI transmission demonstration

Capacity (Tb/s)	Reach (km)	Fiber type	Avg Q^2-Margin (dB)	Pluggable /ref
39.6	172	85μm^2 A_{eff}	0.41	1.2T CIM
26	200	SCUBA 110	1.6	400ZR /[18]
26	151	Allwave ULL	1.7	400ZR /[19]

Fig. 4 (a) Experimental set-up for 1.2Tb/s DWDM transmission over 172km span, (b) 33x1.2Tb/s capacity results

Moreover, real-time 400 Gb/s DWDM transmissions over much longer distance than that required by 400ZR standard interoperability agreement (IA) [17] have also been reported. This includes achievements such as 200 km using SCUBA110 fiber [18] and 151 km utilizing AllWave® ULL fiber [19], both achieved using 400ZR pluggable modules. These are single spans of fully loaded C-band DWDM transmissions, both yielding a total capacity of 26 Tb/s. Table 1 provides a summary of the performance of these high-capacity DCI transmission demonstrations using advanced ULL fibers. Furthermore, transmissions with a capacity of 23.2 Tb/s have been successfully accomplished over a substantial distance of 1507 km SCUBA110 fiber by using 400ZR+ pluggable modules [18]. These accomplishments represent the significant advantages of employing advanced ULL fibers to enhance transmission capacities and extend reach in DCI/metro applications.

Lower loss can always benefit to increase cable capacity and reduce the number of repeaters for transocnnic submarine system. The theoretical modeling results of total cable capacity for transoceanic undersea systems in the context of fixed and limited electrical power supply will be presented and dicussed in the conference.

4. Summary

We have reviewed the recent progress in advanced ULL fibers and reported an 85 μm^2 A_{eff} fiber with record-low-attenuation of 1474 dB/km at 1550 nm. We have also described the 2-core MCF with the average 1550nm loss of 0.1478 dB/km and co-propagating crosstalk <-62 dB/100km for submarine SDM systems. We summarized experimental demonstrations of real-time high-capacity DWDM transmission systems using these advanced fibers and 400ZR and 1.2 Tb/s single-carrier pluggable modules for DCI/ metro networks.

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