Advancements in Key Technological Building Blocks for Enabling MCF Implementation

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Abstract: Multi-core fiber (MCF) technology has made significant progress since the capacity limitations of single-mode fiber had been posed. This presentation will review the advancements and readiness of MCF and its key components, showcasing the technical feasibility of MCF technology in real-world applications. © 2024 The Author(s)

1. Introduction

Concerns about the transmission capacity limitations of single-mode fiber [1,2] have spurred R&D efforts dedicated to multicore fiber (MCF) technology and significant progress has been made in related technologies, since the late 2000s [3-5]. And as a major milestone, the first mass-producible MCF is announced to be adopted on the Taiwan-Philippines-U.S. submarine transmission system [6]. This achievement can be attributed not only to the enhancements in transmission capacity, but also to the realization of several crucial practical advantages offered by MCF, such as higher density (cores/mm^2), lower shipping and transportation costs ($/core), and reduced environmental impact resulting due to lower manufacturing energy consumption and material usage (J/core, g/core). It is also beginning to be pointed out that the use of massively parallel spatial channels in short-distance to long-haul networks is inevitable to ensure sustainable system capacity scalability [7,8], and MCF is gaining recognition as a promising solution to address these challenges. However, for MCF to achieve broad practical application and actual deployment, it is crucial to fully develop its peripheral technology ecosystem. This presentation aims to outline the progress of MCF, MCF cables, and MCF connection technologies as key building blocks of MCF networks.

2. Classification of the MCFs and their areas of application

As shown in Table I, MCFs can be categorized into two types: Uncoupled MCFs (UC-MCFs) and Strongly-Coupled MCFs. UC-MCFs are designed to sufficiently minimize crosstalk (XT) between cores, allowing each core to function as an independent spatial channel [9,10], thus existing transceivers can be used. In long-haul transmission applications, low crosstalk and low loss UC-MCFs are commonly used. Very recently, UC-MCFs with significantly low attenuation below 0.16 dB/km and low counter-propagating crosstalk applicable for a transoceanic submarine transmission have been realized [11,12]. In short-haul applications, UC-MCFs with moderate crosstalk and increased core density are typically selected to achieve high-density cables and/or interconnects [13]. On the other hand, strongly Coupled MCFs are the MCFs where XT/coupling between the cores cannot be ignored, and it is further divided into randomly-coupled MCFs (RC-MCFs) and systematically-coupled MCF [10]. Among them, RC-MCFs are the most major type of strongly-coupled MCFs, in which the modes are strongly and randomly coupled over propagation, and neither supermodes nor local core modes stably propagate without modal coupling [10]. Although compensation for random coupling is required using MIMO DSP, the resulting properties, such as square-root/sublinear accumulations of modal dispersion (MD) and mode-dependent loss (MDL), are advantageous in reducing computational complexity of MIMO DSP [10]. Because RC-MCFs can place cores closer together than UC-MCFs, they can further increase spatial channel density and are strong candidates for further transmission capacity scaling.

Tab. 1: MCF classification (modified from the tables in **[9,10]**).

FIBER TYPE	**UNCOUPLED MCF**		**STRONGLY-COUPLED MCF**
			(Randomly-coupled MCF)
Core pitch Λ (Typical)	**Large** (35~50 μm)	**Medium** (25~40 μm)	**Small** (around 20 μm)
Mode coupling	**Very weak**	**Weak**	**Strong & random**
MIMO DSP	**Not required**		**Required** (Random coupling mitigates complexity of MIMO DSP calc.)
Expected application area (MCF status in 2023)	**Subsea/Long-haul/ Metro (In market) [12]**	**Metro/Short reach (Trial)**	**Subsea/Long-haul/Metro (Under R&D)**

3. MCF cables

3.1. MCF Cables for subsea application

A recent milestone in the use of UC-MCFs was the successful demonstration of the first submarine cable installation test using a commercially available submarine cable design [14,15]. Fibers were accommodated in divided steel segments filled with jelly, covered with steel wires, a water-blocking compound, copper tubing, and a polyethylene insulating sheath. Although the loose-tube cable itself can be very straight, optical fibers in loose-tube cables are stranded with slight excess fiber length (for isolating the fibers from external tension to the cables), and stranding and excess fiber length can sufficiently introduce bends to MCFs to control their coupling characteristics [16]. A 15.2 km submarine cable, capable of accommodating up to 16 fiber pairs, was fabricated using a 4-core UC-MCF with a standard cladding diameter of 125 µm. Comparisons made before and after cable installation, as well as before and after cable installation, showed no degradation in optical characteristics, including XT, and showed negligible changes in Q-factor [15]. Also, long-haul transmission over a 15 km loose-tube type submarine cable using an RC-MCFs was also demonstrated [17]. The propagation loss after cable installation was almost unchanged (0.16 dB/km), the spatial mode dispersion coefficient was kept low (5.1 ps/√km), and successful error-free transmission was achieved over distances of up to 6,600 km.

3.2. High-Density MCF Cables for terrestrial and short-reach application

High-fiber-count, high-density fiber cables enabled by the pliability of partially-bonded fiber ribbons, ranging from a few hundred to thousands of single mode fibers [18], are widely deployed in metro networks and hyperscale DCs. MCFs have emerged as a promising candidate to increase the spatial channel capacity of these high-density ribbon cables or reduce their size and weight. Notably, fiber ribbons are stranded together in cables, and the bend radius of MCFs can be kept tighter than cable bending. This feature makes it possible to suppress/control XT in UC and RC-MCFs [19]. Application trials conducted by telecommunication carriers using MCF ribbon cables, including UC-MCFs from multiple vendors, have demonstrated successful interconnectivity, low XT, and reliable signal transmission after deployment [20,21]. Furthermore, a recent proposal of pre-terminated cables with connectors at both ends has gained attention due to its potential for significantly reducing installation costs by eliminating the need for fusion splicing during deployment [22]. Pre-terminated cables incorporating MCFs (and MCF connectors described in the subsequent sections) are expected to be a promising solution for further reduction in cable diameter or increase in the number of cores/cable.

4. MCF connectivity

4.1 MCF connectors

The realization of MCF connectors requires both accurate rotational alignment of the MCF angle and floating structure for mechanically reliable mating. Various MCF connection technologies are being developed to achieve MCF links [23,24]. Among them, a simple structure single-fiber MCF connector has been demonstrated [25]. The ferrule angle is fixed in the plug itself and floats when connected, making it suitable for mass production without requiring high-precision parts. It achieved an average loss of 0.07 dB in random connection tests and passed the mechanical and environmental reliability tests of Telcordia GR-326-CORE. As for the multi-fiber MCF connector, it allows for denser connections and further reduces the number of connecting operations. A method has been reported for implementing MCF arrays using a versatile V-groove substrate and MT ferrules [26]. This method is compatible with the conventional production method and does not require special MT ferrules. An implemented 256-channel multi-core MCF connector, consisting of an 8-core MCF and 32 MT ferrules, achieved an average connection loss of 0.26 dB and a maximum loss of 0.93 dB. Further development on multi-fiber MCF connector aiming at achieving a standard connector loss level of less than 0.5 dB is on-going [27].

4.2 MCF Fan-in/Fan-out

Interoperability with existing SMF systems is important, and fan-in/fan-out (FIFO) devices are essential for the practical application of MCFs. Various types of FIFOs have been proposed, including fiber bundle type [28,29], vanishing core (VC) type [30], free-space optical type [31,32], and waveguide type [33,34]. Each of these FIFOs has its own advantages, and it is believed that the appropriate type will be selected for each particular application. Among these, the VC type combined with fusion splicing techniques is considered to be used in subsea applications, where cost constraints are relatively low. This technology can connect SMFs to pure silica-core subsea grade MCFs by fusion bonding, eliminating the need for resin bonding, which can be a reliability issue for subsea applications, and achieving low insertion loss of less than 0.15 dB in the C-band [30].

4.3 MCF splicer

Fusion splicer is essential for low-loss, highly-reliable fiber splicing, especially in submarine cable deployment. In response to this, practical automatic MCF fusion splicers that meet the stringent requirements of submarine applications and withstand operation on board the laying vessel are currently under development [35]. The fusion splicing of subsea-grade, low-loss two-core MCF has demonstrated typical splicing losses lower than 0.1 dB, thereby establishing a pathway for the feasible implementation of MCF technology [36].

5. Conclusion

In the last decade, MCF technology has witnessed remarkable advancements and has entered the commercialization phase, particularly in subsea applications. While this paper mainly takes an overview of MCF fiber, cables, and connection technology, it should be pointed out that the industrial ecosystem through demonstration efforts of various communication systems using these technologies and development of peripheral technologies is an essential element for the practical application of MCF. Currently, communication systems ranging from short-haul communications such as data centers and HPC to ultra-long-haul optical submarine cables face scalability challenges due to Shannon limit, bit-rate saturation per lane, energy constraints, and spatial constraints. SDM technology, represented by MCFs, is expected to be strong candidate for those solutions.

6. References

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