SDM Fibers for Data Center Applications

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Abstract: We will review the recent progresses on SDM fibers for short-reach transmission links. We will describe the design and properties of multicore fibers and discuss the potential applications for short-reach high-density interconnects in future data centers.

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1. Introduction

The exponential growth of traffic in data centers caused by the increasing demands for cloud services and IOT requires a scalable and cost-effective fiber cable infrastructure for data center network. Simply increasing the number of optical fiber links may be too costly and unmanageable. Space-division multiplexing (SDM) is considered as a prospective candidate to support cost-efficient network capacity scaling. Multi-core fiber (MCF) may be a feasible and efficient way to realize such SDM networks, and its deployment inside data centers may be acceptable as the issue of inter-core crosstalk is not severe over short link spans compared to that in long-haul transmission. MCF is also well-suited for optical interconnects in data centers and in short-reach systems where there is no need to address the challenge of multicore amplification. In addition, MCF systems can provide direct connectivity to silicon photonic (SiP) and InP chips for high-degree integration and high-density interconnects. Few-mode fiber might also provide connectivity in data centers since MIMO is not necessary if the distance is short enough. Hence, SDM may possibly find its first application in data centers to meet the exponential growth of data traffic.

In this talk, we will review the recent progresses on SDM fibers for short-reach transmission links. We will describe the design and properties of MCF fibers, examine the practical aspects such as connectivity and cabling of MCF, and discuss the challenges and future potential opportunities of SDM fibers for short-reach high-density interconnect.

2. Recent progresses on SDM fibers for short-reach links

An early demonstration of MCF for short-reach link is to use multimode MCF fibers in parallel data transmissions with vertical-cavity surface-emitting lasers (VCSELs) for high performance computer (HPC) applications [1-3]. The MCF used in this demonstration is a high bandwidth graded-index multimode seven-core fiber that is arranged in a hexagonal structure with 26µm core diameter and 39µm core-to-core pitch [1]. The cladding diameter is 125µm and the acrylate dual coating diameter is 250µm, which are compatible with conventional fibers (see Fig.1-a). Core crosstalk is one of most important aspects for MCF designs and the crosstalk depends on core refractive index profile design, core-to-core pitch, operation wavelength, and bending or twist of the fiber. The measured crosstalk between two neighboring cores in this multimode seven-core MCF is less than -40dB at 850nm wavelength for 550m long fibers. Each core carried 10Gb/s NRZ signals parallel transmission over a 550m multimode seven-core fiber has been demonstrated using fan-in/out device and 850nm VCSELs [2]. End-to-end multimode MCF transmission link operating up to 120Gb/s (6x20Gb/s) without fan-in/out has also been demonstrated using 2-D VCSELs and photodiode (PD) arrays [3]. However, it was soon realized that multimode MCF whose every core complies a tight-tolerance high-grade specification, such as OM4 or OM5 for suppressing modal dispersion, would result in a low yield and high cost of the fiber; the high thermal and electrical crosstalk in the 2-D VCSEL array would make extremely difficult to develop small pitch VCSELs array that needs to match the multimode MCF's

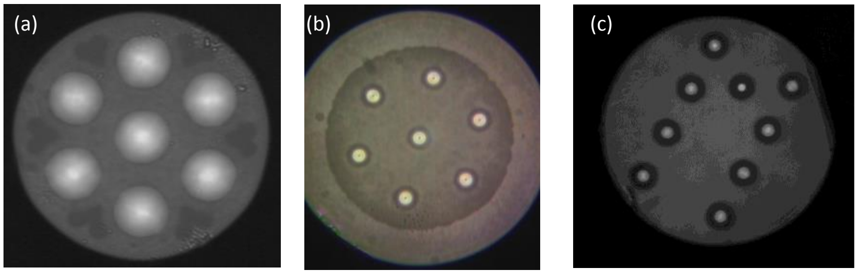

Fig. 1. Photos of MCFs (a) multimode 7-core MCF, (b) single-mode 7-core MCF, (c) 2x4 linear array MCF

pitch; the tight tolerance of alignments between 2-D VCSEL array and MCF would further challenge the practical realization of such end-to-end MCF links.

A short-reach transmission link using single-mode MCF has first been proposed for passive-optical-network (PON) [4], where there are concerns on congestion problems in some existing conduit line systems when increasing need for high counts fiber cables to meet the growing demand of data traffics. Bi-directional parallel transmissions of 1310nm and 1490nm signals over 11.3-km of seven-core MCF with 64-way splitter has been demonstrated to increase the fiber density and increase the network end users at the subscriber premises of a PON. The seven-core MCF used there is designed for single-mode operation at 1310nm and 1490nm region and the seven cores are arranged in a hexagonal array with 8-μm core diameter and 38-μm core pitch (see Fig 1-b). The cladding diameter and coating diameter are 130 and 250 μm respectively, and the cutoff wavelengths of the seven-core fiber are about 1200nm. The measured crosstalk between two neighboring cores is less than -38dB at 1310nm, and less than -24dB at 1490nm for 11.3km long fibers.

Common MCF designs use hexagonal structures for high core density; however, linear array MCFs may be preferred for SiP to adapt linear transceiver arrays. Fig. 1-c shows an example of 2x4 linear structure MCF having a round cladding as conventional fibers. The core diameter and core-pitch of this 2x4 MCF are 8.6 and 54μm respectively and its cladding diameter is 229μm with 362 μm coating diameter using acrylate dual-coating. This 2x4 MCF is designed to operate at 1550nm (C-band) with the cutoff wavelength less than 1520nm for integration with SiP transceiver, and the crosstalk is less than -40dB over C-band. This eight-core MCF by 2x4 linear structure with round cladding is well-suited to 100 Gb/s bidirectional transmission systems like PSM4 and can potentially be used for 400 Gb/s communications. Though the linear structure with round cladding MCF is compatible with conventional fibers (hence easy to handle and install), the number of cores of a round fiber is limited by the cladding diameter. To ensure long term mechanical reliability requirements, the fiber cladding diameter should be smaller than about 230 μm.

Many MCFs have been reported with large cladding diameter around 200μm, for example in [5-6]; however, the MCF with standard 125-μm cladding diameter is preferable in term of long-term reliability and cabling cost. The larger cladding diameter always degrades the long-term failure probability and the smaller cladding diameter can resist tighter bending radius. This is because the bend-induced stress scales linearly with cladding thickness. The standard 125-μm cladding diameter MCF is especially important for applications in the short-reach optical interconnects, where the bend radius may be difficult to control, and tight bends may be required, while in the long-haul transmission, the larger cladding diameter may be accepted by increasing the minimum bend radius or by carefully controlling the bend radius in the installation. From cabling point view, MCF should have equivalent macro-bending loss properties (i.e. meet ITU-T G.657 A1 standard) for ultra-high-density cable. From above considerations, several 125μm cladding MCFs have been reported such as 5-core [7], 7-core [1] and 8-core MCF designs [8]. The 8-core MCF design [8] is only limited to operate at O-band, while 5-core MCF [7] is designed for either O-band or C/L band. The center core in 5-core MCF is designed to realize smooth upgradability from the conventional signal core system to a 4-core system [7]. Trench type refractive index profile is adopted for the cores for low bending loss and crosstalk. The crosstalk between cores is less than -60dB at 1550nm over 2km fiber and the attenuations at 1310 nm and 1550nm are less than 0.38dB/km and 0.24dB/km respectively. A single fiber and single wavelength 400-Gb/s (56-Gbaud PAM4 signals, 100Gb/s per core) transmission over 2-km is demonstrated using this 125μm cladding MCF unlike 400GbE-PSM4/DR4 using parallel single-mode fibers (SMF). Furthermore, 1.6-Tb/s 4-core/CWDM transmission with 56-Gbaud PAM4 signals (400Gb/s per wavelength) across O- (or C/L-) band is also demonstrated [9]. To make the MCF more realistic and deployable solution for data centers, the core-count of four or eight are preferred. 4-core MCF can realize single fiber and single wavelength 400-Gb/s transmission using 100-Gb/s/λ transceiver (e.g. 56Gbaud PAM4) technology and 8-core MCF can easily realize single fiber single wavelength 400-Gb/s or 800-Gb/s avoid using parallel SMFs such as PSM4 approach [10], thus greatly improving the fiber cable density for data centers.

Connectivity technologies such as fan-in/out which couples optical signals between MCF and the transceivers through single-core fiber, or the technique directly coupling the optical signals from MCF to integrated transmitters and PDs are crucial for practical use of MCFs. Several types of fan-in/out have been reported [11] including fiber-based bundle or fused taper, PLC based SiP grating coupler and free optics cased devices. Among them, the fiber bundle type fan-in/out is the simplest and has good optical properties (e.g. small coupling loss). Insertion loss less than 0.2dB and crosstalk less than -65dB were reported in a 7-core fiber fan-in/out device based on fiber-based bundle tapering. MU connector type fan-in/out with insertion loss < 0.32dB has also been developed using fiber bundle approach [11]. However, these fan-in/out techniques have focused on how to couple each core of the MCF with individual SMFs and may not be a cost-effective approach for intra data center applications. A fan-in/out device integrated with photonic devices such as laser diode (LDs) arrays and PDs for SDM pluggable transceiver applications may be more useful. For this propose, MCF LC type receptacle with a compact fan-in/out which couples MCF to LDs and PDs with pluggable connections has been reported [12]. A fiber bundle type fan-in/out device was used in this pluggable transceiver receptacle with 125μm cladding diameter 4-core SM-MCF and a 4-channel 1.3μm laser array. On the other hand, a fully integration approach which directly couples the optical signals from MCF to transmitters and receivers without fan-in/out may be more attractive and cost-effective due to its compactness and scalability. Toward this direction, several demonstrations of end-to-end MCF transmission link for optical interconnects have been reported including multimode MCF directly interfaced with 2-D VCSEL and PD array [3] and single-mode MCF transmission link with SiP chips integrated with 2-D grating coupler array [6]. These approaches focused on onboard optics and are not compatible with current conventional pluggable transceiver schemes. Here, the multimode MCF will need to have high bandwidth graded-index core design with high NA to have good directly coupling to 2-D VCSEL arrays, and the MCF should have high temperature and thermal stability properties for low cost non-hermetic optical packaging [13]. In addition, grating coupling in SiP chips still pose challenges in terms of coupling efficiency, polarization/wavelength dependence, and handling of input/output fibers.

Ultra-high-density optical fiber cable with rollable MCF ribbons [14] has also recently been developed for large-scale inter data-center applications. The MCF that used for the optical cable has 5-core with 125 μm cladding and it meets the ITU-T G.657 A1 specifications. An optical cable with 200 fibers (equivalent to 1000 cores) is fabricated, and it has demonstrated the same optical, mechanical and temperature characteristics as the conventional cable with single core SMF. The core density of the cable can reach 10.5 cores/mm^2 which is nearly double of reported cable.

Future large-scale data centers require high bandwidth, high density optical interconnects, and the bandwidth (BW) density at the switch front panels can be improved by replacing pluggable transceivers with on-board optics [15] with ASIC integration. In on-board optics configurations, optical connectors are equipped on switch front panels instead of pluggable transceivers, and the total channel number of the optical connectors is a limiting factor for achievable BW per front panel. The ASIC integrated optics and SiP are expected to support more than 100-channel optical I/O interfaces per switch to meet the future demand of the switching BW. To address the future requirements for the high channel count optical connectivity, MCF may find its application opportunities in the high bandwidth high density optical interconnects for data centers, since it offers a large scalability of the channel count. One of the big challenges will be how to reduce overall cost.

3. Summary

The recent progresses on SDM fibers for short-reach transmission links have been reviewed. The design and optical properties of MCF fibers has been presented, the requirements, technical issues and challenges for practical uses of MCF for short-reach high-density interconnect are briefly discussed.

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