Optical Fiber Technology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte

Invited Papers

Multimode and single-mode transmission over universal fiber for data center applications

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A B S T R A C T

Universal fiber is a multimode fiber that has an LP_{01} mode field diameter approximately matched to that of standard single-mode fiber. It can transmit both multimode and single-mode signals using transceivers designed for either multimode fiber or single-mode fiber. By using universal fibers, one can bridge the needs for both single-mode and multimode transmission through a uniform and simplified cable infrastructure to accommodate the full distance range needed, while having upgradability from 10G to 40G to 100G and to even higher data rates. We build on our previous work that analyzed the dependence of LP_{01} mode-field diameter on fiber parameters, and the coupling loss for both single-mode and multi-mode transmission, with a further study of mode coupling and multiple path interference associated with single-mode operation. We demonstrate system performance in both single-mode and VCSEL-based multimode transmissions for a number of 100G transceiver types using a QSFP form factor – the preferred choice in data centers.

1. Introduction

1.1. Use of multimode fibers and single-mode fibers in the data center

In data centers (DC), both multimode fibers (MMF) and single-mode fibers are used with VCSEL-based multimode transceivers and single-mode transceivers, respectively. With the emerging hyper-scale DC, single-mode transmission is deployed more frequently to meet the need of longer system reach.

Enterprise data centers primarily use OM3/OM4 multimode fiber for data transmission as most channel lengths are less than 100 m, and the trend looks to continue since multimode (MM) transmission remains a cost-effective solution covering the majority of transmission distances [1]. Even in large scale DC, a portion of the optical transmission has short distances, less than tens of meters, where MM transmission is more cost-effective than single-mode (SM) transmission. At the same time, continued efforts are underway to develop novel approaches for using long wavelength MMF over longer system reaches [2–3].

On the other hand, single-mode connectivity is used in data centers both at short distances, similar to MMF, and at longer distances, above 100 m. Because SM transmission enjoys high system bandwidth and is capable of longer system reaches, mega- and hyper- data centers tend to predominantly adopt SM transmission. Even in such large scale data centers, there is still a large percentage of SM transmission for distances less than 100 m, as reported in Ref. [4]. For very short distances in enterprise data centers, single-mode fiber is used for the carrier interface to provide linkage to the router and FICON (i.e. Fibre Connection) mainframe for storage applications [5]. For distances up to several hundred meters, both MM and SM transmission co-exist, depending on the data rate and the type of data centers.

1.2. Fundamental mode transmission in multimode fiber

It is desirable to do single-mode transmission over conventional MMF, which has a 50 µm core diameter. Although it is possible to launch the light into only the fundamental mode of MMF using various complicated mode expansion techniques to bridge the difference of fundamental modes between 50 µm core MMF and standard single mode fibers [6–9], the solutions are too expensive for cost-sensitive data center applications as they involve complex experimental setups. An alternative and more promising solution is to alter the MMF design to allow the mode field of fundamental mode to match that of standard single mode closer [10–12]. In Ref. [10], we presented a design of MMF we referred to as universal fiber (UF) with a core having a relative refractive index delta of 1% and a core diameter of about 23 µm. This study also demonstrated 850 nm VCSEL based multimode transmission at 10 Gb/s and 25 Gb/s over 100 m and 50 m, and 1310 nm single-mode

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https://doi.org/10.1016/j.yofte.2017.11.003
Received 28 April 2017; Received in revised form 27 September 2017; Accepted 6 November 2017
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25 Gb/s NRZ and 44 Gb/s PAM4 transmission over 2 km. The main limitation of that particular fiber design is high insertion loss of about 5 dB when it is coupled to either a VCSEL transmitter or a 50 μm core MMF. An improved UF design was subsequently reported in Ref. [11] with core delta at 1.2% and core diameter around 30 μm, the typical insertion loss to VCSEL was reduced to below 3 dB and improved system performance in a number of applications was demonstrated. These include 110 m MM transmission with 100G SR4, 150 m MM transmission using 40G SWDM4 and 2.7 km SM transmission using a 100G CWDM4 transceiver. We also note here that a gradient-index multimode fiber that is designed for both 850 nm VCSEL transmission and single-mode transmission was previously proposed for home network applications [12]. The core of this fiber has very high relative refractive index delta of 2.5–2.9% between the core and the cladding and a core diameter of 40 μm. The transmission experiments demonstrated single-mode transmission using single-mode laser at 10 Gb/s over 100 m and similar distance for 1.25 Gb/s MM transmission. The high delta of the core, which results in very high numerical aperture, facilitates the coupling of the light from transmitter into the fiber and reduces the macrobend loss, as needed for a home network, but makes it difficult to achieve high modal bandwidth. The UFs proposed in [11] have much lower delta and are close to that of existing high bandwidth MMFs. They can be used in DC, LAN and central office environments, which can go as long as 2 km. Although the core diameter of 30 μm is smaller than the 50 μm MMF, the coupling losses from typical VCSELs and between UFs are good enough for short reach transmissions. With improved coupling optical designs inside VCSELs and connector technology, the coupling losses can be reduced further for future high speed applications. Table 1 compares the attributes for different standard-based MMFs and single-mode fibers.

1.3. Benefit of universal fiber for both single-mode and multimode transmission

For the majority of small to large enterprise data centers operating between 1G and 40G, multimode OM3/OM4 fibers working with VCSEL-based transceivers remain the most cost-effective way to cover the moderate distance requirements. This is driven mostly by the large difference in prices between SM and MM transceivers [13–14], with up-to-date information in Table 2. However, as speeds approach 100G and beyond, the difference in price is shrinking. In fact, at or beyond 100G, many data center operators are being advised and are expected to be deploying single-mode optics due to the price and capability requirements. Therefore, operators who would like to build an infrastructure that is capable of supporting the needs for today, yet be flexible enough to also support the future, are faced with a difficult choice between two options. The first option is to deploy MMF today to take advantage of the lower cost of MM transceivers today, but then rip the cable infrastructure and replace with SM version within the first or second upgrades. The second option is to deploy single-mode fiber today and pay more for the SM transceivers with each upgrade until the SM transceiver price becomes comparable to the MM option. Therefore, selecting an appropriate fiber is both a financial and technological decision with consequences for today as well as for the future. Multimode and single-mode fiber each has their own advantages and drawbacks. The universal fiber provides the freedom to choose low cost MM transceivers for the current and future needs, but is ready for upgrade to SM transceivers in the future, when MM technology becomes limited by distance and when SM transceiver prices become more favorable.

Another factor that has attracted increased attention is the power consumption in DC [13]. DC operations are highly sensitive to cost and power consumption – in particular for mega- and hyper data center operators. The rise of SM transmission is driven by the desire to have a simplified and uniform transmission medium and cable infrastructure. However single-mode systems consume more power, as shown in Table 2. Better understanding of link length distribution can shed more light on the power consumption consideration. For enterprise DC, according to the system length distribution for the OM4 MMF cable products manufactured by Corning between 2013 and 2015 [4], the average length was 48 m with about 2% of lengths greater than 250 m. For hyper-scale data centers, based on the system length distribution for the single-mode cable products manufactured in the same period of time, the average length was 152 m with only 2% of lengths greater than 350 m. These data indicate that MMF can support most distances required for enterprise and hyper-scale data center networks. However, for the percentage of link lengths that cannot be supported by MMF, single-mode fiber has to be deployed. For data center operations, installing two types of fibers, both MM and SM, will increase network and logistics complexity, as well as make fiber cable management more challenging. A UF that can accommodate both MM and SM transmission will bridge the gap in fiber cable deployments for new DC and offers flexibility for future system upgrades.

In this paper, we review recent progress on UF and present new system testing results to illustrate the UF transmission properties and performance covering several new 100G QSFP transceiver variants. In Section 2, we present the fiber design, and study the multiple path interference (MPI) associated with the SM transmission. In Section 3 we show new system performance results for several 100G QSFP transmission. Finally, in Section 4, we present a brief conclusion.

Table 1
Comparison of attributes and system performance for different multimode and single-mode fibers. 40G standard based SM transceivers have 2 km, 10 km, and 40 km variants for distance specifications. 100G standard based SM transceivers have 10 km and 40 km variants, while 100G MSA based SM transceivers have 500 m distance for PSM4, and 2 km distance for CWDM4.

	Core Δ (%)	Core diameter (μm)	OFL BW (MHz.km)	EMB BW (MHz.km)	Link distance (@850 nm) (m)		
			850 nm	850 nm	10G	40G	100G
OM1	2	62.5	200	N/A	33	N/A	N/A
OM2	1	50	500	N/A	82	N/A	N/A
OM3	1	50	1500	2000	300	100	70
OM4	1	50	3500	4700	400	150	100
SMF	0.34	9	NA	N/A	N/A	500 m/ 2 km/ 10 km/ 40 km	

Table 2
Comparison of cost and power consumption for multimode and single-mode transceivers. For both the cost and power consumption, the values are shown relative to that of 10G MM transceivers.

Fiber	Relative transceiver cost			Relative power consumption		
	10G	40G	100G	10G	40G	100G
MMF (OM1-OM4)	1	6	17	1	1.5	3.5
SMF	3	15–21	13–37	1.5	5.0	5.5

2. Fiber design, multiple path interference and coupling into standard single mode fiber

UFs are designed for both SM and MM transmissions. Various considerations have been taken into account so that the fiber performs sufficiently well for both types of operations [10–11]. In this section, in addition to the coupling loss for MM operation and SM operation from Ref. [1], we present new results on understanding the effect of MPI related to SM operation, both through numerical modeling and experimental study.

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