Optical Fiber for 1310 nm Single-Mode and 850 nm Few-Mode Transmission

Ming-Jun Li, Xin Chen, Kangmei Li, Jason E. Hurley, and Jefferey Stone
Corning Incorporated, Science and Technology, SP-AR-02-5, Corning NY 14831
lim@corning.com

ABSTRACT

In this paper, we present an optical fiber that is single-mode at 1310 nm window and few-mode at 850 nm window with high bandwidth. The fiber is compatible with standard single-mode fiber at 1310 nm, which can meet long reach requirements for hyper-scale data centers. In addition, the fiber can be used for few-mode transmission at 850 nm using single-mode or few-mode VCSELs, providing low-cost solutions for short links. We discuss fiber design considerations and present fiber properties and 25 Gb/s transmission results at 850 nm.

Keywords: data center, single-mode fiber, multimode fiber, VCSEL

1. INTRODUCTION

The data center industry is experiencing explosive growth globally driven by the demand for cloud computing and internet of things [1]. To meet the rapid traffic growth, data centers are changing both in architectures and connection speeds. Data centers are becoming larger, more modular and more homogenous. Networks are migrating from traditional 3-tier to flattened 2-tier topology. Workloads are now spread across 10s, 100s, sometimes 1000s of virtual machines (VMs) and hosts, and a higher degree of east-west traffic across networks are required. Data center connections are moving from 1 G and 10 G, to 40 G and 100 G, and will be beyond 400 G in the near future.

In data centers, VCSEL-based multimode fiber transmission provides low-cost solutions for short links of less than a few hundred meters [2]. With the emerging hyper-scale data centers, single-mode transmission is deployed to meet the need of longer system reach. Even in hyper-scale data centers, there are still a significant amount of short links where multimode transmission is more cost-effective [3]. While it is feasible to use both multimode and single-mode fibers in data centers, it poses challenges in managing different types of fiber cables and planning for future system upgrades.

Here we report an optical fiber that supports a single mode at 1310 nm window and two mode groups at 850 nm window. The fiber is fully compatible with standard single-mode fiber at 1310 nm, which can meet long reach requirements for hyper-scale data centers. In addition, the fiber is few-mode at 850 nm with high modal bandwidth, and hence can be used for few-mode transmission at 850 nm using single-mode or few-mode VCSELs, providing low-cost solutions for short links. The design considerations of this fiber as well as its properties and transmission characteristics will also be discussed.

2. FIBERS FOR DATA CENTER APPLICATIONS

There are two types of optical fibers used in data centers: multimode fiber (MMF) and single-mode fiber. A MMF has a large core of 50 μm or 62.5 μm in diameter, and high numerical aperture (NA) greater than 0.18. The large core and high NA of MMF make it easy to couple light from a low-cost multimode VCSEL around 850 nm to a MMF using low-cost coupling optical components. However, an MMF guides many modes simultaneously, as shown in Figure 1. These modes may have different propagation constants, which cause a single input pulse to split into multiple pulses with different time delays, resulting in bandwidth limitation. Generally, MMFs are used in short distance data links of a few hundred meters or shorter depending on the data rate. On the other hand, a single-mode fiber has a smaller core of about 9 μm in diameter, and lower NA of 0.12. It guides only one mode, as shown in Figure 1, without the pulse splitting problem in MMF. However, to couple light to a single-mode fiber core, a single-mode laser at 1310 or 1550 nm and

Broadband Access Communication Technologies XIII, edited by Benjamin B. Dingel,
Katsutoshi Tsukamoto, Spiros Mikroulis, Proc. of SPIE Vol. 10945, 1094503
 · doi: 10.1117/12.2516013

more expensive coupling optical components must be used. One advantage of single-mode fiber is that it has much higher bandwidth than MMF and can be used for data links up to ~100 km.

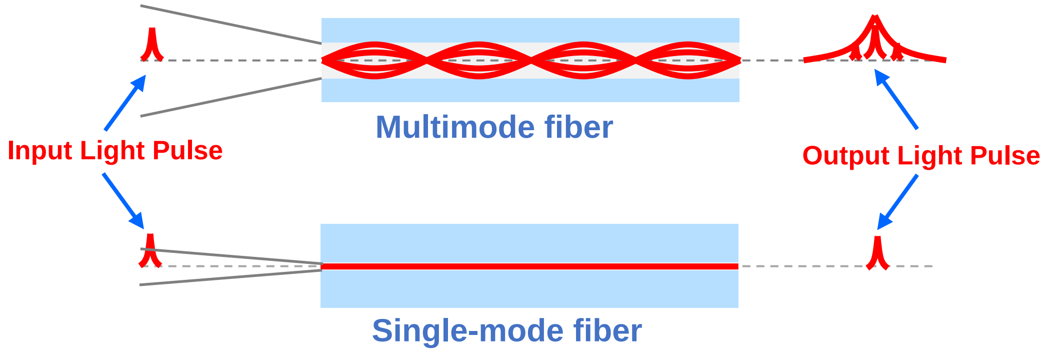

Figure 1. Comparison between multimode and single-mode fibers.

MMFs have been deployed in conventional enterprise data centers with link distances shorter than 300 m due to lower system costs and lower power consumption associated with VCSEL transceivers. MMFs have evolved from OM1 to OM5 to meet system capacity and reach demands. Table 1 summarizes different type of MMFs and comparison with standard single-mode fiber. With the emerging of hyper-scale data centers, the link distance can be longer than a few hundred meters, therefore single-mode fiber must be used for these long links. Although single-mode fiber offers a future proof solution, the overall cost of a single-mode system is much higher than an MMF system. Higher single-mode transceiver prices are due to increased costs related to single-mode laser manufacturing and device packaging. In addition, single-mode systems consume more power, adding to operational costs, which is a very important factor to consider in data center operations. Even in a hyper-scale data center, the majority of link distances are shorter than 300 hundred meters. For hyper-scale data centers, according to the system length distribution for the single-mode cable products manufactured by Corning between 2013 and 2015, the average link length was 152 m with only 2% of lengths greater than 350 m [3]. These data indicate that MMF can support most distances required for hyper-scale data center networks. However, for a small percentage of link lengths that cannot be supported by MMF, single-mode fiber has to be deployed. For data center operations, installing both multimode and single-mode fiber will increase network complexity and make cable management more challenging. A single fiber type that can accommodate both multimode and single-mode transmissions is therefore highly desirable for new data center deployment and offers flexibility for future system upgrades. Recently, a new type of fiber with a core diameter about 30 μm to accommodate both multimode transmissions at 850 nm and single-mode transmissions at 1310 nm was proposed [4-9]. The fiber is a smaller core MMF that has a mode field diameter for the fundamental mode compatible with that of standard single-mode fiber. Its single-mode and multimode transmission capabilities were demonstrated using different types of transceivers. However, because it is a non-standard fiber type, the industry is not able to readily accept it.

Table 1. Comparison of different multimode and single-mode fibers for short reach applications

Fiber	Core Δ (%)	Core diameter (μm)	OFL Bandwidth (MHz.km)	EMB Bandwidth (MHz.km)	Link distance at 850 nm (m)			Relative transceiver cost			Relative power consumption		
			850 nm	850 nm	10G	40G	100G	10G	40G	100G	10G	40G	100G
OM1	2	62.5	200	N/A	33	N/A	N/A	1	6	13	1	2	4
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						
OM5	1	50	3500	4700	400	150	100						
SMF	0.34	9	NA	N/A	N/A	2 km at 1310 nm		2	15-21	13-37	1.5	5	5.5

In this paper, we propose using a single-mode fiber with a graded refractive index profile for both 1310 nm single-mode and 850 nm few-mode transmissions. Because the fiber is fully compliant with the G.652 single-mode fiber standard, it is compatible with any single-mode transmission system for data centers. On the other hand, the graded refractive index profile design makes it possible to have high bandwidth for 850 nm transmission using single-mode VCSEL transceivers.

3. GRADED REFRACTIVE INDEX PROFILE SINGLE-MODE FIBER

The refractive index profile of a graded index optical fiber can be described by an α-profile:

$$\Delta = \Delta_0 \left[1 - \left(\frac{r}{r_0}\right)^{\alpha}\right]$$

where r_0 is the core radius, and Δ_0 is maximum relative refractive index change in the core:

$$\Delta_0 = \frac{n_0^2 - n_1^2}{n_0^2}$$

where n_0 is the refractive index in the center of the core, and n_1 is the refractive index of the cladding. Figure 2 plots α-profiles with different α values. For α=1, the profile is a triangular profile, for α=2, the profile is a parabolic profile, and for, α >10, the profile is a step index profile.

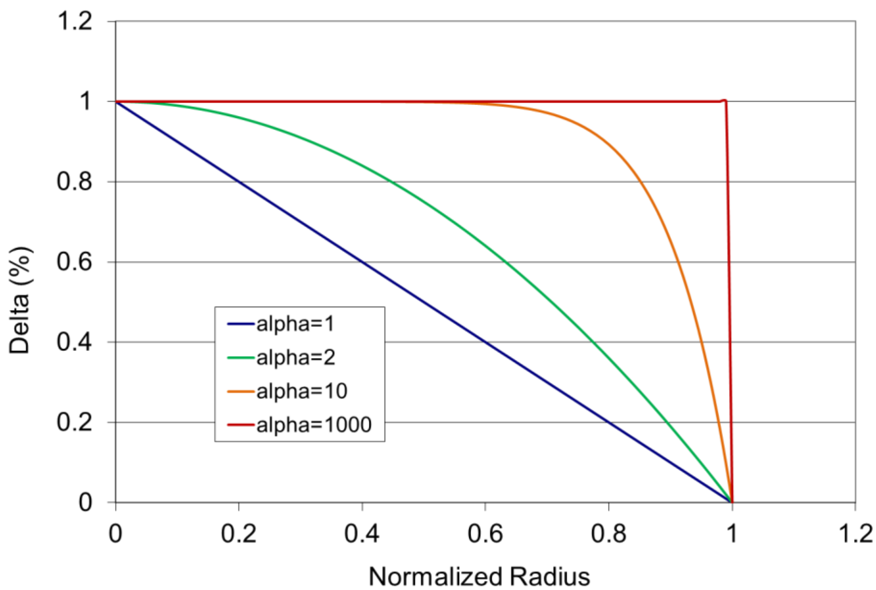

Figure 2. Alpha profiles with different alpha values

A standard single-mode fiber is designed to have a cable cutoff wavelength below 1260 nm, so that the fiber supports one mode at 1310 nm and few-modes at 850 nm. Many commercially-available single-mode fibers have a step index profile. The step index profile is simple, but the modal bandwidth at 850 nm is low due to the large differences between the propagation constants of the LP_{01} and LP_{11} modes. Therefore, a standard single-mode fiber with a step index is not suitable for multimode transmission at 850 nm.

A standard single-mode fiber can also be designed with a graded index profile. When the α value is around 2, the bandwidth can be optimized for multimode transmission at shorter wavelengths in the 850 to 1100 nm range. Figure 3 plots the differential mode delay (DMD) at 850 nm as a function of profile parameter alpha for a graded index single-mode fiber. In this example, the core delta is 0.41%, and the core diameter is 11.9 μm. At 850 nm, the fiber supports two mode groups, LP_{01} and LP_{11}. As it can be seen in Figure 3, the DMD depends on alpha. When the alpha value is below 2.5, the DMD between the LP_{01} and LP_{11} modes is negative, and when the alpha value is above 2.5, the DMD is positive. When alpha is about 2.5, the DMD is nearly zero, which means that the fiber can have very high bandwidth. Another advantage of graded index profile design is that it has gradual transition from the core to the cladding, which minimizes loss contributions due to core-clad interface imperfections.

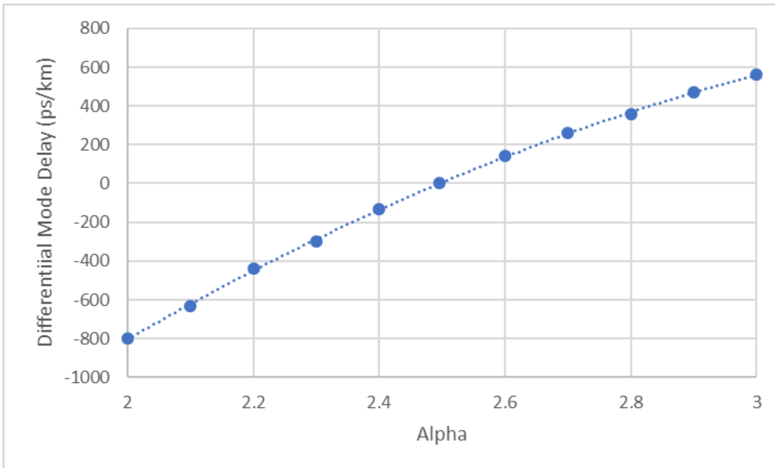

Figure 3. Differential mode delay as a function of alpha

4. SINGLE-MODE VCSELS FOR 850 NM TRANSMISSION

To use a graded index standard single-mode fiber for few-mode transmission at 850 nm, a key component is single-mode or few-mode VCSEL transceiver. Because a single-mode fiber has smaller core than standard MMFs, the coupling loss is too high if a multimode VCSEL is used. A single-mode VCSEL with smaller spot size is essential for short wavelength transmission through single-mode fiber.

Although current MMF systems use multimode VCSELs, significant progress has been made in developing sing-mode VCSELs to overcome encoding bandwidth limitation of multimode VCSELs and to reduce chromatic dispersion effects in MMF links [10]. Single-mode operation in VCSELs can be achieved by reducing oxide aperture to support a smaller number of lasing modes and employing an integrated mode filter to suppress higher order modes. Single-mode VCSELs operated at 25 Gb/s was reported by using a VCSEL with a 5 μm oxide aperture and an integrated mode filter [11] and also a VCSEL with ~3 μm oxide aperture [12]. Small-aperture VCSELs are a simple and effective approach for achieving the required modal properties and to improve energy efficiency. Reducing the aperture is also effective to narrow the VCSEL linewidth [13]. For multimode VCSELs with 11 μm aperture, the linewidth is about 1 nm. Reducing the aperture to 5 μm for few-mode operation results in a linewidth of 0.4 nm. For single-mode operation with the aperture of 3 μm, the linewidth is only 0.03 nm. The narrow linewidth of single-mode VCSELs reduces transmission penalty due to fiber chromatic dispersion, which can increase the system reach.

5. DEMONSTRATION OF 850 NM TRANSMISSION OVER GRADED INDEX SINGLE-MODE FIBER

To demonstrate feasibility of few-mode transmission over a graded index standard single-mode fiber, we made one fiber and characterized its modal bandwidth. The measured modal bandwidth of the fiber is shown in Figure 4. The peak modal bandwidth is at least 9 GHz·km at a wavelength around 820 nm, which shows that very high modal bandwidth is feasible for graded index single-mode fibers. Although the peak of bandwidth for this fiber is not at 850 nm, the modal bandwidth is still 3.6 GHz·km at 850 nm, which is sufficiently high for optical transmission using single-mode or few-mode VCSELs.

The fiber was used in 25 Gb/s transmission experiments with a two-mode VCSEL [14]. The light emitted by the VCSEL was coupled in to the fiber using two aspheric lenses with a coupling loss of 1.5 dB. The transmission experiment was performed by modulating the VCSEL at a bit rate of 25 Gb/s using NRZ modulation format. For a 100 m fiber link, a BER value of 3.1×10^{-7} was achieved at an average optical power value of -5 dBm, which is below the FEC threshold. This experimental result demonstrated the feasibility of few-mode transmission using a two-mode VCSEL at 850 nm over the graded index fiber for short reach application. The system performance can be improved further by using single-mode VCSELs.

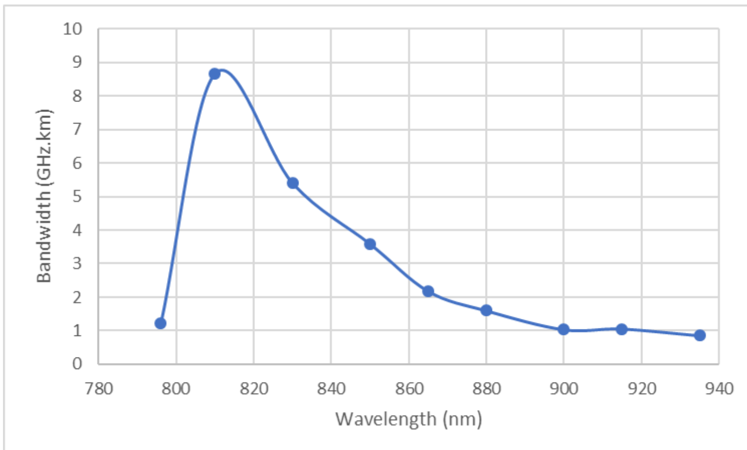

Figure 4. Measured bandwidth of graded index standard single-mode fiber.

To explore the transmission capacity of the graded index single-mode fiber at 850 nm, we did 25 Gb/s transmission experiments using a single-mode VCSEL from V-I-Systems as the laser source. Figure 5 illustrates the experimental setup. The free-space output power of the VCSEL is around 0.76 mW (-1.2 dBm) with a driving voltage of 2.7 V (~ 3.5 mA current). The VCSEL has a numerical aperture (NA) of around 0.25 and emission spot size of approximately 3 µm. We measured the root mean square (RMS) linewidth of the VCSEL to be 0.12 nm centered at 842 nm. The VCSEL is packaged with a V-connector, and then mounted on a plate; two sequential lenses are utilized to couple light from the VCSEL to the fiber, as shown in the dashed rectangle in Figure 5. This system gives a coupling loss of 2.4 dB and the optical power achieved from the output fiber is -3.6 dBm.

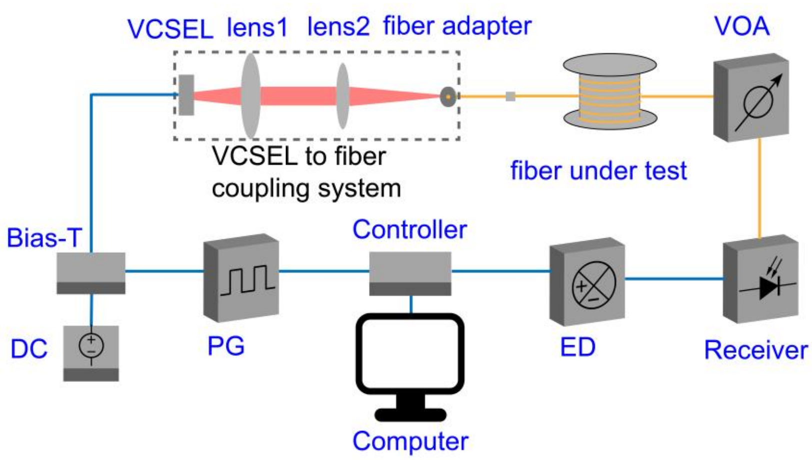

Figure 5. Schematic of the experimental setup for system transmission test. PG: pattern generator; VOA: variable optical attenuator; ED: error detector.

In the transmission experiments, we measured the bit error rate (BER) using an Agilent BERT system. As shown in Figure 5, a 2^7-1 PRBS non-return-to-zero (NRZ) signal with 1.4 V_{pp} at 25 Gb/s is generated by the pattern generator

(N4951B) with 5-tap de-emphasis, which is sent to a bias-T (SHF 122C) to modulate the VCSEL together with a DC voltage. After transmission through the single-mode fiber, the optical signal is sent into a variable optical attenuator (VOA) to control the received optical power, and then detected by a Discovery Semiconductor's 850 nm Lab Buddy optical receiver (R409) and an error detector (N4952A-E32). Both the pattern generator and the error detector are connected to a controller and controlled by a computer program. To improve the system performance, the de-emphasis feature of the pattern generator is used to overcome the bandwidth limitation of the SM VCSEL.

The transmission performance of the graded-index single-mode fiber in Figure 4 was characterized, and BERs at 25 Gb/s were measured under four fiber length configurations: back-to-back (1 m); 100 m; 150 m; and 250 m by concatenating the100 m and 150 m fibers. By tuning the attenuation using VOA, we obtained the BER as a function of received optical power for each configuration, as shown in Figure 6. The system reached error-free performance with around -7.8 dBm power under the back-to-back condition. For the 100 m fiber case, the system reached a low BER around 10^{-12} with a slight power penalty compared to the back-to-back case. In the case of 150 m fiber, the system showed around 2 dB power penalty relative to the back-to-back condition, while still achieving error-free performance for seven minutes. For 250 m length, the system could reach a BER of 2.4×10^{-11} without using the VOA, which is still well below the forward error correction (FEC) threshold of 5×10^{-5} used for short reach optical communication. The transmission results indicate that the system reach using SM VCSEL and graded index single-mode fiber can potentially be much longer than the typical 25G link distance using MM VCSEL and traditional 50 μm core MMF specified at 100 m.

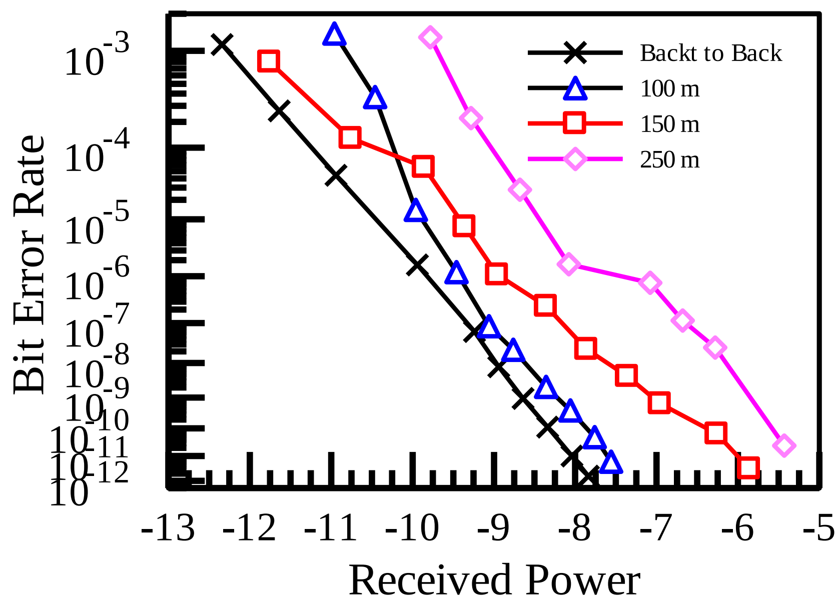

Figure 6. BER vs received optical power for the fiber with graded-index refractive index profile

6. CONCLUSIONS

In this paper we demonstrated that a graded index fiber can support a single mode at wavelength of 1310 nm and few modes at 850 nm with a modal bandwidth of 3.6 GHz·km. The fiber can be used for few-mode transmission at 850 nm using single-mode or few-mode VCSELs, providing low-cost solutions for short links. System transmission experiments at 25 Gb/s using this fiber together with a single-mode VCSEL show that the system reach can be up to 250 m. In addition, the fiber is fully compatible with standard single-mode fiber at 1310 nm, which can meet the long reach requirements for hyper-scale data centers.

REFERENCES

[1] Cisco Global Cloud Index: Forecast and Methodology, 2016–2021, White Paper, https://www.cisco.com/c/en/us/solutions/collateral/service-provider/global-cloud-index-gci/white-paper-c11-738085.html.

[2] M. Li, "MMF for High Data Rate and Short Length Applications," in Optical Fiber Communication Conference, OSA Technical Digest (online) (Optical Society of America, 2014), paper M3F.1, (2014)

[3] D. Coleman, "Ethernet fiber optic cabling trends: Data center channel lengths 2013-2015", OFC 2016, March 23, 2016, http://www.ethernetalliance.org/wp-content/uploads/2016/01/Ethernet-Fiber-Optic-Cabling-Trends-OFC-2016-R3.pdf.

[4] X. Chen, J. E. Hurley, J. Stone, J. D. Downie, I. Roudas, D. Coleman, and M.-J. Li, "Universal fiber for both short-reach VCSEL transmission at 850 nm and single-mode transmission at 1310 nm," Paper Th4E.4, OFC Technical Digest (2016).

[5] X. Chen, J. E. Hurley, J. S. Stone, A. R. Zakharian, D. Coleman, and M.-J. Li, "Design of universal fiber with demonstration of full system reaches over 100G SR4, 40G sWDM, and 100G CWDM4 transceivers," Opt. Express 24, 18492-18500 (2016).

[6] X. Chen, J. Hurley, J. Stone, J. Coleman and M.-J. Li, "Demonstration of Full System Reaches of 100G SR4, 40G sWDM, and 100G CWDM4 Transmissions over Universal Fiber", IEEE Photonics Conference 2016, paper WF2.2, Waikoloa, Hawaii, (October 2-6, 2016).

[7] Ming-Jun Li, Xin Chen, Jason E. Hurley, Jeffery S. Stone, Aramais R. Zakharian, Doug Coleman, "Universal fibers for data center applications," Proc. SPIE 10131, Next-Generation Optical Networks for Data Centers and Short-Reach Links IV, 1013106 (28 January 2017).

[8] Xin Chen, Jason E. Hurley, Aramais R. Zakharian, Jeffery S. Stone, William A. Wood, Bruce Chow, Doug Coleman, Ming-Jun Li, "Multimode and single-mode transmission over universal fiber for data center applications," Optical Fiber Technology, Volume 44, Pages 53-60 (2018).

[9] Chen, J. Hurley, J. Stone, A. R. Zakharian, B. Chow, D. Coleman, and M. Li, "Universal fibers for both single-mode and multimode transmissions in data centers," in Optical Fiber Communication Conference, OSA Technical Digest (Optical Society of America, 2018), paper W3C.2 (2018).

[10] Cheng C H, Shen C C, Kao H Y, Hsieh D H, Wang H Y et al., "850/940-nm VCSEL for optical communication and 3D sensing," Opto-Electronic Advances 1, 180005 (2018).

[11] E. Haglund, Å. Haglund, P. Westbergh, J. S. Gustavsson, B. Kögel, and A. Larsson, "25 Gbit⁄s transmission over 500 m multimode fibre using 850 nm VCSEL with integrated mode filter," Electron. Lett., vol. 48, no. 9, pp. 517–518 (2012).

[12] J. A. Lott, A. S. Payusov, S. A. Blokhin, P. Moser, and D. Bimberg, "Arrays of 850 nm photodiodes and vertical cavity surface emitting lasers for 25–40 Gbit⁄s optical interconnects," Phys. Status Solidi C, vol. 9, no 2, pp. 290–293 (2012)

[13] H. Kao et al., "Modal Linewidth Dependent Transmission Performance of 850-nm VCSELs With Encoding PAM-4 Over 100-m MMF," in IEEE Journal of Quantum Electronics, vol. 53, no. 5, pp. 1-8 (2017).

[14] A. Juarez, X. Chen, J. Hurley, M. Thiermann, J. Stone, and M.J. Li, "Graded-index Standard Single-Mode Fiber for VCSEL Transmission around 850 nm," Accepted for presentation at OFC2019, paper M3C.2 (2019).