Modal Bandwidth and Single-Mode VCSEL Transmission Capability Over Multimode Fibers

Xin Chen, Kangmei Li, Jason E. Hurley, Jeffery S. Stone, and Ming-Jun Li, *Fellow, IEEE*

***Abstract*— Single-mode VCSELs have been demonstrated with great transmission capability over multimode fibers in the literature through restricted launch, which is beyond what is allowed by the effective modal bandwidth (EMB) defined for multimode transmission with the encircled flux launch condition. However, the impact of fiber index profile errors and their interactions with launch conditions have not been thoroughly studied. We conduct a detailed experimental study to gain insight on the impacts of the fiber index profiles and launch conditions on the system performance of single-mode VCSELs transmitting over multimode fibers. Experimentally, our results show that a launch spot roughly matching the fiber LP_{01} mode field leads to very high bandwidth and robust performance, largely independent of the imperfection of the index profiles and therefore can perform well in very high data rates. For a restricted launch without mode matching, the performance highly depends on the quality of the fiber, in line with EMB. We found that the center offset tolerance is around 2 μm for a mode matched launch. We also conducted single-mode VCSEL transmission experiments over 600-m and 1000-m multimode fibers, which agree well with the modal bandwidth results.**

***Index Terms*— Optical fiber communications, single-mode VCSEL, multimode fiber, optical fiber testing, fiber bandwidth, data center.**

I. Introduction

FOR short reach communications, especially in data centers, multimode fibers (MMFs) together with VCSEL-based transceivers provide low-cost solutions. Over the past decades the modal bandwidth of MMF has been pushed higher, with the highest grade MMF, OM4, reaching an effective modal bandwidth (EMB) of 4700 MHz · km at 850 nm. At this bandwidth level, the chromatic dispersion (CD) becomes a limiting factor due to large laser linewidths (~0.6 nm) of multimode (MM) VCSELs. The system reach for standard defined VCSEL transceivers is 100 m at 25 Gbauds. One promising solution for reducing the CD effects is to replace the MM VCSELs with single-mode (SM) VCSELs with much narrower linewidths of around 0.1 nm. Significant progress has been made in developing SM VCSELs for transmission over MMFs modulated at 25 Gb/s, 100 Gb/s and beyond [1]–[5].

The EMB of MMF is defined by using a set of 10 weights obtained from MM VCSELs [6]. When the light from an SM VCSEL is launched into an MMF meeting the encircled flux requirements by using proper optics, the modal bandwidth follows the conventionally defined EMB for different grades of MMF with transmission reaches that can be modelled [2]. However, due to the small spot size of an SM VCSEL, light can be launched into an MMF with limited number of modes, which is outside the encircled flux launch. It has been reported that SM VCSEL transmission over MMF can reach 2.2 km at 54 Gb/s OOK [3] and 2 km at 40 Gb/s NRZ [4], beyond what is allowed by the EMB defined by the respective grade of MMF. In such cases, restricted launches (RL) are expected to be adopted. With RL, a small number of modes are excited. In a well-controlled case such as in [4], special effort has been made to launch light only into the LP_{01} mode of the 1060 nm optimized MMF, which carries essentially infinite modal bandwidth. However, for RL in general, imperfections of fiber profile such as centerline defects (CLD) [7], which occurs in a portion of MMFs leading to split pulses, can degrade the system performance significantly. Offset single-mode launch through a modal conditioning patch cord has been used with LRM transceiver for 1310 nm transmission over MMF to avoid the penalty due to CLD [8]. The question that can be raised here is if RL can deliver enhanced performance for all MMFs or just for selected high-quality MMFs. A systematic study is lacking to understand how the launch conditions and fiber index profile features such as CLD can affect the performance of an SM VCSEL over MMF transmission system although mode matching concept has been explored through modeling [2]. In this letter, we present a detailed experimental and modelling study to understand the factors affecting the modal bandwidth and therefore the transmission capability under RL.

II. Launch Conditions and Fiber Bandwidths

The refractive index profile of an ideal MMF is described by an α-profile for the relative index change: $\Delta(\mathrm{r}) = \Delta_0 \cdot [1-(\mathrm{r}/\mathrm{r}_0)^{\alpha}]$, where r_0 is the core radius, and Δ_0 is maximum relative refractive index change in the core defined as $\Delta_0 = (\mathrm{n}_0^2 - \mathrm{n}_1^2)/(2\mathrm{n}_0^2)$, where n_0 is the refractive index in the center of the core, and n_1 is the refractive index of the cladding. The α-value describes the shape of the profile. For a typical 50-μm core MMF, Δ_0 is 1%, and α is around 2.1 for optimal bandwidth at 850 nm. Fiber profile imperfections such as CLD are common in various manufacturing processes affecting the modal bandwidth and hence system performance. To quantify the effects of fiber profiles and launch conditions, we measured the EMB of two representative commercial fibers [6], labelled as MMF1 and MMF2 in Table I.

Manuscript received December 9, 2020; revised December 30, 2020; accepted December 30, 2020. Date of publication January 4, 2021; date of current version January 15, 2021. *(Corresponding author: Xin Chen.)*

The authors are with Corning Incorporated, Corning, NY 14831 USA (e-mail: chenx2@corning.com; lik11@corning.com; hurleyje@corning.com; stonejs@corning.com; lim@corning.com).

Color versions of one or more figures in this letter are available at https://doi.org/10.1109/LPT.2020.3049067.

Digital Object Identifier 10.1109/LPT.2020.3049067

TABLE I
PROPERTIES OF FIBERS USED IN THE EXPERIMENTS

Launch fibers	MFD (μm)	MMFs	EMB (GHz.km)
LF1	5.3	MMF1	2.08
LF2	10.4	MMF2	6.74

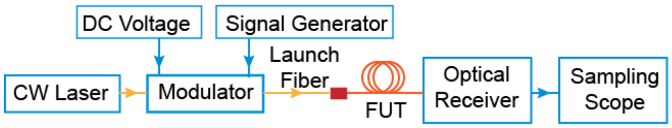

Fig. 1. Experimental setup for the bandwidth measurement.

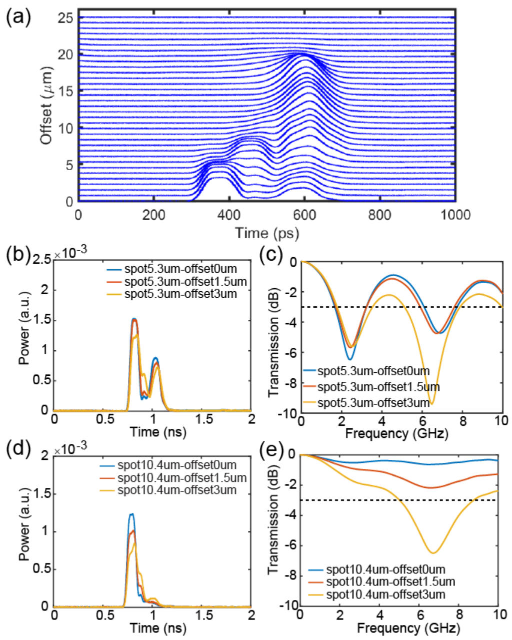

Fig. 2. Bandwidth measurement results for MMF1. (a) DMD; (b) output pulse using LF1; (c) transfer function using LF1; (d) output pulse using LF2; (e) transfer function using LF2.

The modal bandwidth measurement setup is shown in Fig. 1. A continuous-wave laser at 850 nm is intensity modulated to generate pulses in the time domain. The modulated light is launched into the fiber under test (FUT) with a short piece of fiber that is single mode at 850 nm to control the launch spot size. This launch fiber is then butt coupled to the FUT. We used two different launch fibers as listed in Table I, LF1 has a LP_{01} MFD of 5.3 μm and LF2 has a LP_{01} MFD of 10.4 μm that roughly matches the LP_{01} MFD of the MMFs, which is 11.6 μm at 850 nm. Although in the experiments we use fibers to control the launch spot sizes, other techniques like using lenses can generally be utilized to achieve the same purpose. The pulse is measured before the FUT as reference and after the FUT as output. The frequency domain transfer function is obtained by taking the ratio of the Fourier transform of the output pulse and reference pulse. The modal bandwidth is then obtained by extracting the frequency value at which the transfer function drops 3 dB from its maximum.

The experimental results of MMF1 and MMF2 are shown in Fig. 2 and Fig. 3, respectively. Fig. 2(a) and Fig. 3(a) show the measured differential mode delay (DMD) results for the two fibers. Following Ref. [6], we obtained the EMB to be 2.08 GHz · km and 6.74 GHz · km for MMF1 and MMF2, respectively. MMF1 has a significant CLD, resulting in pulse splitting near the fiber center and a low EMB of 2.08 GHz · km. MMF1 is a borderline OM3 limited by the CLD, so that it is a worst-case OM3 for the RL launch study. In contrast, MMF2, which has an EMB of 6.74 GHz · km as high quality OM4, represents how an OM4 can perform over RL launch.

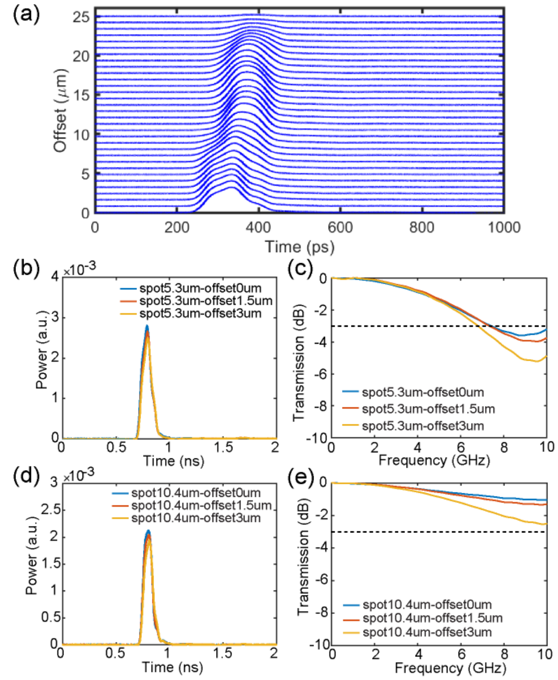

Fig. 3. Bandwidth measurement results for MMF2. (a) DMD; (b) output pulse using LF1; (c) transfer function using LF1; (d) output pulse using LF2; (e) transfer function using LF2.

Fig. 2(b) and (c) show the measured pulses and transfer functions after 1000-m MMF1 launched via LF1 with three offset positions from the center of MMF1. As illustrated, for MMF1 that has significant CLD and overall lower bandwidth, the input pulse splits into two pulses, and the bandwidth extracted from the transfer function is 1.67 GHz · km. Such low bandwidth is due to the excitation of multiple fiber modes and the big modal delay between these excited modes resulting from the CLD. To the contrary, in Fig. 2(d), using LF2 as the launch fiber, the pulse has a single peak, and the small tail is part of the reference pulse feature from the modulator. As a result, we do not see a 3 dB drop in the transfer function with an offset up to 1.5 μm (Fig. 2(e)), indicating that the modal bandwidth is higher than at least 10 GHz · km. This can be explained by the fact that LF2 has a spot size roughly matching the LP_{01} mode field of the MMF so that the LP_{01} mode is predominantly excited in the MMF [9]. Using LF2, the observed modal bandwidth remains high with offset up to 3 μm.

We conducted the same measurements using 1000-m MMF2, as shown in Fig. 3. Launched with LF1, the pulses have a single peak but show slight distortions, as depicted in Fig. 3(b). Based on the transfer functions in Fig. 3(c) we extract the modal bandwidth to be around 7.0 GHz · km. On the other hand, using LF2 as launch fiber, the pulses are clean and the transfer functions do not exhibit a 3 dB drop up to 10 GHz, even with an offset of 3 μm, indicating a modal bandwidth higher than 10 GHz · km.

Learning from the four test cases, we conclude that using a launch spot roughly matching the LP_{01} mode field of MMF leads to high modal bandwidth regardless of fiber profile imperfections, so that this launching method works robustly for any conventional 50-μm MMFs. The launch spot size does not have to be exactly the same as the MFD of the MMF LP_{01} mode, the benefit stays with a tolerance of around 2 μm [2]. The offset also has a tolerance around 2 μm without affecting the bandwidth. For case with launching spot significantly different from the MFD of the MMF LP_{01} mode, the bandwidth depends on the quality of refractive index profile of MMF. High bandwidth and good system performance cannot be guaranteed for MMFs in general.

III. Modeling Results

To gain more insight, we modeled two MMFs with numerically generate index profiles exhibiting similar CLD features shown in Fig. 4(a) and the zoom-in of the centerline region in Fig. 4(b) to explore their modal bandwidth changes under different launch conditions. The modal properties of the MMFs are calculated by solving scaling wave equation using finite element method [10].

As shown in Fig. 4, two example MMFs (MMF3 and MMF4) with modal bandwidths and profile imperfections similar to that of MMF1 and MMF2 were modeled. MMF3 in Fig. 4(c) has an EMB of 2.10 GHz · km mainly due to the limitation of CLD and MMF4 in Fig. 4(d) has a high EMB of 7.42 GHz · km due to slight CLD and random non-alpha errors in other regions of the core. As the SM VCSEL has only one mode, we assume a Gaussian spot is launched into the MMF. The spot size launched into the MMF can be controlled by the coupling optics. We show the excited power as broken down by the mode group number [9] in Fig. 4(e) and (f) using MMF3 as an example, and the results should be similar in general MMFs. As shown in Fig. 4(e), using a small launch spot (LF1), several modes are excited in the MMF with any offset position. On the contrary, when the launch spot size matches roughly the LP_{01} mode of the MMF using LF2, only mode group 1 with LP_{01} is predominantly excited, while slight excitation in high order modes can occur with a large offset, as illustrated in Fig. 4(f). When several mode groups are excited, the modal bandwidth highly depends on the quality of the fiber, with a high-quality fiber showing high modal bandwidth. This is because high-quality fiber has smaller modal delays between different mode groups. Theoretically, if only one mode is excited the modal bandwidth is infinity, which is why in some cases SM VCSEL can show extremely long transmission reach with high data rate [3], [4]. The modeling results agree well with the experimental results shown in Section II. We also show the modal bandwidth for the two launch spot sizes as a function of the offset from 0 to 5 μm for MMF3 and MMF4 in Fig. 4(g) and (h). For both fibers with a roughly mode matched launch, the modal bandwidth stays above 30 GHz · km and only drops to be comparable to the EMB (black dashed line) when the launch offset is increased to around 2.5 μm as some high-order modes are excited in the MMF. For the smaller launch spot, the modal

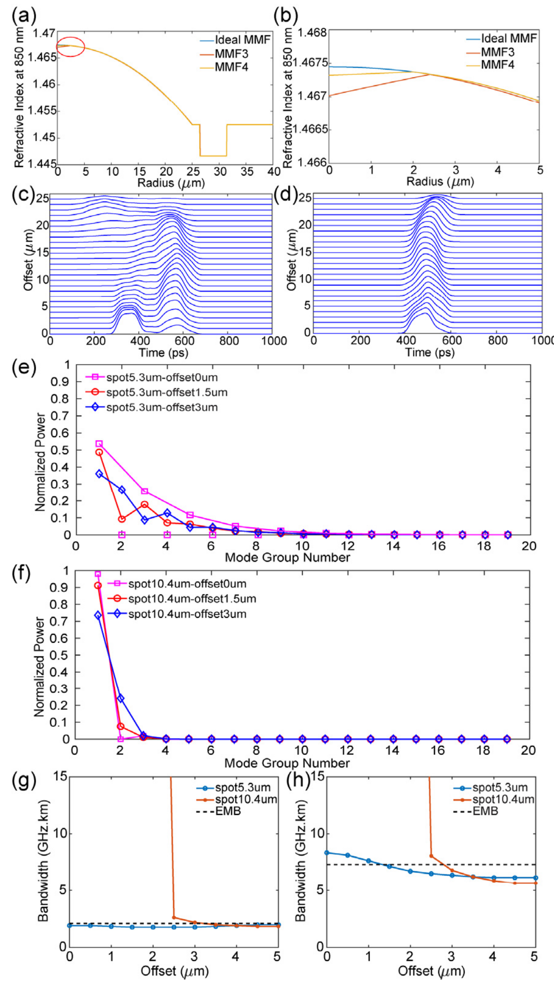

Fig. 4. (a) and (b) show the index profiles and the zoom-in of the centerline region of the two simulated MMFs, MMF3, MMF4 and an ideal MMF; (c) and (d) are DMD charts, MMF3 and MMF4, respectively; (e) and (f) are excited power for the MMF with LF1 and LF2 launch conditions under three offset positions; (g) and (h) are the bandwidth vs. offset for MMF3 and MMF4 under LF1 and LF2 launch fibers, respectively.

bandwidth is driven largely by the EMB of the respective MMF. In cases for low grade of MMFs with severe CLD, the modal bandwidth can be much lower than the EMB due to the overemphasis of the centerline region with defects, which is why people have adopted offset launch [8].

The key finding of this letter as supported by both the experiments and the modeling is that with a LP_{01} mode matched launch, the bandwidth can be very high, theoretically being infinite. The slight impairment in practical implementation is caused by the launch offset. To achieve higher modal bandwidth the offset needs to be controlled less than 2.5 μm. If the launch spot size is mismatched significantly, high bandwidth using RL can be realized only for fibers with high quality refractive index profiles, but cannot be obtained for fibers with large CLD.

IV. System Transmission Performance

We also conducted system transmission experiments using an 850 nm SM VCSEL from V-I-Systems to further validate the above findings. The setup is shown in Fig. 5 similar to that in [11]. A Keysight BERT system, which includes a pattern generator (N4951B) with 5-tap de-emphasis and

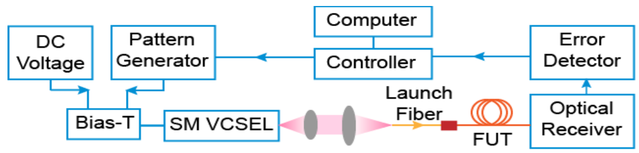

Fig. 5. Experimental setup for the system transmission test.

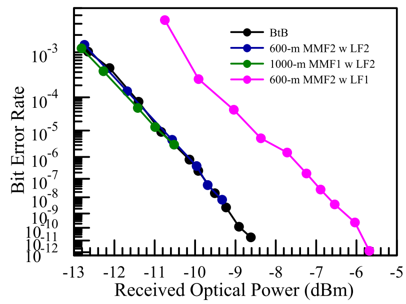

Fig. 6. Measured BER curves from several configurations.

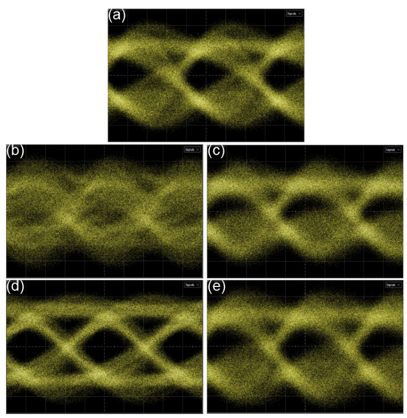

Fig. 7. Eye diagrams. (a) back-to-back; 1000-m MMF1with LF1 (b) and LF2 (c); 600-m MMF2 with LF1 (d) and LF2 (e).

an error detector (N4952A-E32), is used for the bit error rate (BER) measurement. De-emphasis is used to boost the baseline VCSEL performance. The pattern generator produces a 25 Gb/s 2^7-1 PRBS non-return-to-zero (NRZ) signal with 1.4 Vpp to drive the VCSEL together with a DC voltage of 2.7 V using a bias-T (SHF 122C). The SM VCSEL output is first coupled into the launch fiber using two lenses and then butt coupled to the MMF. A Discovery Semiconductor's 850 nm Lab Buddy optical receiver (R409) with a 15 GHz bandwidth is used with the error detector to measure the BER.

The measured BER curves and eye diagrams are shown in Fig. 6 and Fig. 7, respectively. All eye diagrams are taken at the maximum optical power level in each case. When using LF1 to launch into 1000-m MMF1, the BER is 6.9×10^{-2} with received power of -6.3 dBm, not enough to get a BER curve. The eye diagram is basically closed, as shown in Fig. 7(b). This is consistent with the measured modal bandwidth result in Fig. 2(b) and (c), which indicates a low bandwidth of 1.67 GHz · km. In contrast, when using LF2 and MMF1, the BER curve shows negligible penalty compared to the back-to-back (BtB) case, and the eye diagram shown in Fig. 7(c) is open. Note that the best BER achieved in this case is 3.1×10^{-6} at a maximum optical power level of -10.52 dBm, limited by the amount of light coupled into the fiber. Similarly, using LF2 and 600-m MMF2, the BER curve almost overlaps with the BtB curve, indicating negligible bandwidth penalty, and the eye diagram shown in Fig. 7(e) is open with slight degradation due to the low received power. On the other hand, when using LF1 and MMF2, the BER curve indicates a power penalty of around 2.2 dB compared to the BtB case at 5×10^{-6} BER level. Although an open eye diagram can be obtained at power level of -5.24 dBm (Fig. 7(d)), the curvature of the eye diagram is flattened out compared to the BtB case due to fiber bandwidth limitation. This penalty can be explained by the fact that the fiber has a limited bandwidth of 7.5 GHz · km.

The transmission experimental results further validate that using an MMF LP_{01} mode matched launch spot can lead to high modal bandwidth and good system performance, but for few mode RL launch with mode mismatch, the transmission performance depends on the fiber quality.

V. Conclusion

We experimentally investigate the impacts of fiber index profiles and RL conditions on the system performance using SM VCSELs over MMFs. By conducting fiber bandwidth measurements and modelling, and system transmission experiments, we show that using a launch spot size roughly matching the fiber LP_{01} mode field leads to high bandwidths and robust system performance not obviously limited by data rate, regardless of fiber profile imperfections. For launch conditions without the mode match, the performance can be affected by local index profile defects with significant performance degradation. Mode matched launch can also sustain reasonable offset tolerance of up to 2.5 μm, which is achievable with today's technology. Our results provide a thorough insight on how to achieve optimal and robust system performance using SM VCSELs over MMFs.

References

[1] N. N. Ledentsov *et al.*, "Optical interconnects using single-mode and multi-mode VCSEL and multi-mode fiber," in *Proc. Opt. Fiber Commun. Conf. (OFC)*, Mar. 2020, pp. 1–3, paper M3D.1.

[2] M.-J. Li *et al.*, "Single-mode VCSEL transmission for short reach communications," *J. Lightw. Technol.*, early access, Oct. 13, 2020, doi: 10.1109/JLT.2020.3028972.

[3] G. Stepniak *et al.*, "54 Gbit/s OOK transmission using single-mode VCSEL up to 2.2 km MMF," *Electron. Lett.*, vol. 52, no. 8, pp. 633–635, 20106.

[4] E. Simpanen *et al.*, "1060 nm single-mode VCSEL and single-mode fiber links for long-reach optical interconnects," *J. Lightw. Technol.*, vol. 37, no. 13, pp. 2963–2969, Jul. 1, 2019.

[5] E. Haglund *et al.*, "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.

[6] *Differential Mode Delay Measurement of Multimode Fiber in the Time Domain*, Standard TIA-455-220 FOTP-220, 2003.

[7] A. V. Bourdine, D. E. Praporshchikov, and K. A. Yablochkin, "Investigation of defects of refractive index profile of silica graded-index multimode fibers," *Proc. SPIE*, vol. 7992, Apr. 2011, Art. no. 799206.

[8] *Mode Conditioning Patch Cable Tutorial*. [Online]. Available: https://www.fiber-mart.com/news/mode-conditioning-patch-cable-tutorial-a-851.html

[9] X. Chen *et al.*, "Multimode and single-mode transmission over universal fiber for data center applications," *Opt. Fiber Technol.*, vol. 44, pp. 53–60, Aug. 2018.

[10] T. A. Lenahan, "Calculation of modes in an optical fiber using the finite element method and EISPACK," *Bell Syst. Tech. J.*, vol. 62, no. 9, pp. 2663–2694, Nov. 1983.

[11] K. Li, X. Chen, J. E. Hurley, J. S. Stone, and M.-J. Li, "High data rate few-mode transmission over graded-index single-mode fiber using 850 nm single-mode VCSEL," *Opt. Exp.*, vol. 27, no. 15, pp. 21395–21404, 2019.