Linearly polarized modes enabled PAM-4 data transmission over few-mode fiber for data center interconnect

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This letter proposes a high data rate optical transmission system for data center interconnects (DCIs), where we employ vertical cavity surface emitting lasers (VCSEL) and graded index few-mode fibre (GI-FMF) having modal bandwidth of around 24.3 GHz.km to enhance the link capacity and range. Additionally, we consider PAM-4 modulated data transmission at the rate of 2×100 Gbps using a pair of VCSELs and employing mode group division multiplexing (MGDM) of two linearly polarized (LP) modes LP_{01} and LP_{11} of the GI-FMF. Digital signal processing (DSP) techniques are applied at the receiver to process the received PAM-4 signals for equalization in order to mitigate the channel impairments. Furthermore, standard OM3 and OM4 fibers are considered as a benchmark to compare the transmission performance of the designed GI-FMF. We observe that the designed GI-FMF supports longer transmission distance for both LP_{01} and LP_{11} modes upto 900 m and 450 m at 50 Gbps and 100 Gbps data rates, respectively, while achieving lower receiver sensitivities for forward error correction (FEC) limit of 3.8×10^{-3}. The proposed optical transmission system can be a potential applicant in future data center networks supporting transmission rates in 800 Gbps to 1.6 Tbps range.

Introduction: Contemporary technologies, such as artificial intelligence (AI), cloud computing and internet of things (IoTs) are dominating in next generation communication networks [1]. These technologies require high bandwidth as the demand for higher data rate applications is increasing exponentially. High-speed data transmission can be ensured for inter and intra data centers by allocating more bandwidth resources. To cope with the higher data rate demand, an optical transmission system for data center interconnect (DCI) application is required to support 400 Gbps or even higher data rate as standardized by IEEE P802.3cm task force [2]. Studies have shown that 90% of communication in data centers is intra-rack whereas only 10% is inter-rack or inter-data centers. Furthermore, optical transmission systems can be efficient in terms of power consumption, footprint and cost. Among optical inter-connects, the vertical cavity surface emitting lasers (VCSEL) and multi-mode fibers (MMF) based DCIs are preferred due to their low cost and low power consumption [3]. Moreover, by adopting advanced modulation formats along with intensity modulation-direct detection (IM-DD), the VCSELs and MMFs based DCIs can further simplify the system while achieving Tera-bits per second (Tbps) data rates at a reduced cost [4]. The transmission of high data rate signals over SMF based optical links using VCSELs has been extensively researched. Various studies based on SMF have been reported for optical transmission employing single mode VCSELs operating in 1065-1550 nm [5, 6], where despite having the higher modal bandwidth to support high data rates in data centers, the corresponding transceivers are not power efficient leading to higher deployment cost specially for short reach DCIs. Hence, VCSEL and MMF based IM-DD transmission systems operating around 850 nm could be an attractive solution in order to achieve cost efficiency and low power consumption [7].

High data rate and high capacity VCSELs and OM2 MMF based short range optical links using PAM-4, wavelength division multiplexing (WDM) and mode division multiplexing (MDM) were proposed in [8, 9]. Additionally, MDM and WDM along with IM-DD schemes have been exploited using discrete multi-tone (DMT) and PAM in [10–13], which are advanced modulation formats. Furthermore, DMT transmission at 90.6 Gbps per spatial mode has been achieved successfully over 2.2 km OM2 MMF in [10]. In [11], 38 Gbps and 50 Gbps transmission rates per channel have been realized for PAM-4 and DMT over few mode fiber (FMF). On the other hand, transmission rate of 104 Gbps per channel using DMT modulation for an integrated MDM-WDM IM-DD system based on silicon micro-ring modulator has been demonstrated in [12]. Moreover, 167.5 Gbps data rate per channel has been achieved over 20m OM2 MMF using PAM-6 modulation scheme [13]. The above-mentioned studies employ external modulation resulting in increased cost in a data center scenario. Moreover, as compared to DMT and PAM-6, PAM-4 modulation is widely used as recommended by IEEE P802.3bs 400 GbE for DCI due to lower power consumption, lower complexity and implementation cost. Therefore, implementation of DCIs based on VCSELs operating at 850 nm using PAM-4 with MGDM is a viable solution to achieve higher bit rate per channel along with the added benefits of cost and energy efficiency.

Table 1: Design parameters for GI-FMF.

Parameter	Value
Core diameter	50 ± 5 (μm)
Over-cladding diameter	490 ± 5 (μm)
Refractive index peak	1.471
Refractive index cladding	1.462
Numerical aperture	0.162 ± 0.015
Refractive index contrast	0.61 %
Dispersion slope	≤ 0.097 (ps/nm^2.km)
Attenuation	2.3 (dB/km)
Zero dispersion wavelength	1295 - 1340 (nm)

In this letter, we propose a high data rate and cost efficient transmission system for DCIs based on VCSELs and GI-FMF, which is designed to optimize the modal bandwidth for extending the link capacity and range. Additionally, we use MGDM in the proposed system to enhance the link capacity by exploiting LP_{01} and LP_{11} modes as independent channels to transport PAM-4 data streams of 200 Gbps per wavelength by employing two VCSELs. The performance of the proposed system is evaluated and comparison has been made with the commercially available OM3 and OM4 MMFs. OptiSystem 17 commercial software is used to simulate this research work. Based on the above discussion, we claim the following novel contributions:

- A new GI-FMF design is proposed and an optical transmission scheme that is capable of achieving 200 Gbps/λ using MGDM is analysed.
- Cost efficiency and low power consumption is achieved via multimode VCSELs and PDs.
- The range of the optical link is extended beyond the commercial OM3/OM4 MMFs by employing the proposed GI-FMF design.

Proposed Design of GI-FMF: OM3 and OM4 MMFs have been standardized by IEEE to support the short reach DCIs due to the limited modal bandwidth. Hence, we propose a solution by designing a FMF with graded index profile to support only LP_{01} and LP_{11} modes. The refractive index profile can be expressed in terms of the α parameter by $n(r) = n_1.\sqrt{1-2\delta(r/a)^{\alpha}}$, where n_1 is the central refractive index of the core, a is the core radius, $\delta = (n_1^2 - n_2^2)/2n_1^2$ is the relative index contrast and n_2 is the refractive index of the cladding. It may be noticed that the refractive index profile $n(r)$ depends upon α and hence by properly adjusting the parameters of the fiber as mentioned in Table 1, the designed fiber supports only two LP modes, LP_{01} and LP_{11}. In addition, by appropriately adjusting the value of α, the modal bandwidth can be enhanced to a higher value, as discussed in [14]. Furthermore, the frequency domain method reported in [15] is used to calculate the modal bandwidth of the proposed design, which is approximately equal to 24.3 GHz.km.

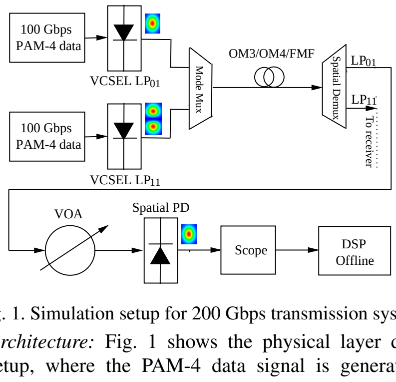


Fig. 1. Simulation setup for 200 Gbps transmission system.

Proposed Architecture: Fig. 1 shows the physical layer design of the proposed setup, where the PAM-4 data signal is generated by using pseudo-random bit sequence (PRBS) generator having length of 2^{16}-1. The LP_{01} and LP_{11} modes of two VCSELs having center wavelength of 850 nm are directly modulated by PAM-4 data signals at 100 Gbps, as shown in Fig. 1. The modulated LP_{01} and LP_{11} modes of VCSELs are combined by using a mode multiplexer and then the multiplexed signal is transmitted over the proposed GI-FMF towards the receiver. At the receiver, a mode demultiplexer is used to separate the LP_{01} and LP_{11} modes of the VCSELs, with each carrying 100 Gbps PAM-4 data signal. Additionally, a variable optical attenuator (VOA) is used to vary the received optical power (ROP). The transmitted optical signal is then

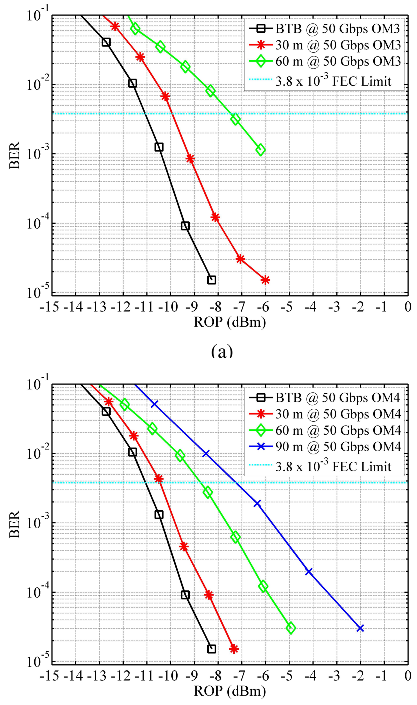


Fig. 2 *BER versus received optical power performance.*
(a) For different length of OM3 fiber at 50 Gbps.
(b) For different length of OM4 fiber at 50 Gbps.

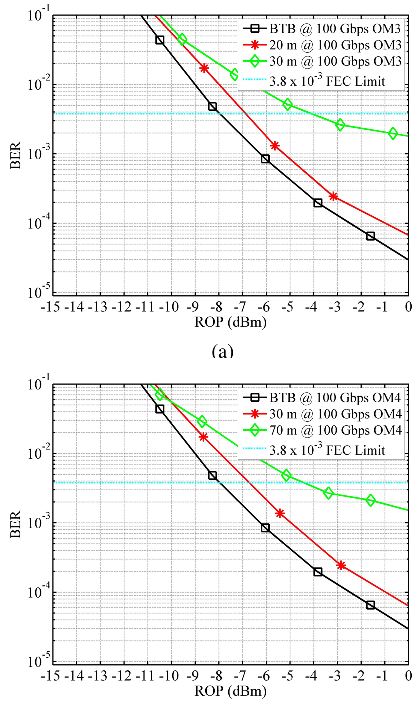


Fig. 3 *BER versus received optical power performance.*
(a) For different length of OM3 fibre at 100 Gbps.
(b) For different length of OM4 fibre at 100 Gbps.

Table 2: Simulation Parameters.

Parameter	Value
Bit rate/LP mode	100 Gbps
VCSEL bias current	5 mA
Modulation peak current	8 mA
VCSEL threshold current	5 mA
VCSEL temperature	25^o C
PD responsivity	0.6 AW^{-1}
PD Thermal Noise	20 pA/Hz$^{0.5}$
PD Dark Current	10 nA

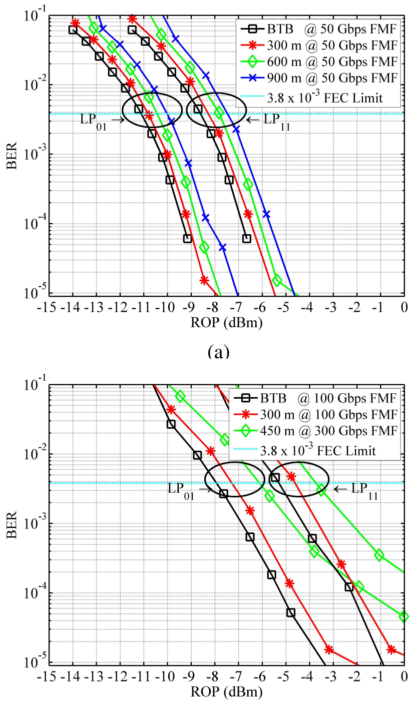
detected by the spatial PDs, where the signal at the output of the PDs is then passed through a 4^{th} order Bessel low pass filter (LPF) having a bandwidth of 0.75 $\times$ symbol rate (GHz). The photo-detected PAM-4 signals are then sent to offline DSP block for further processing, where the received signal is first normalized and then re-sampled to two samples per symbol to perform re-timing operation. A 5 tap $T/2$ least mean square (LMS) based adaptive equalizer is used for channel equalization. The parameters used in the simulation are shown in Table 2.

Results and Discussion: The performance of our proposed system is analysed using the bit error rate (BER) versus the received optical power (ROP). It may be noted that we are considering a hard-decision FEC limit corresponding to a BER of 3.8×10^{-3} and a 7% overhead. The value of optical power incident at the input of spatial PD can be varied using a VOA, where the variation in optical power incident at the spatial PD results in different BER values corresponding to different values of the ROP. More explicitly, the performance of the proposed optical transmission system operating at 850 nm is analysed by employing OM3, OM4 MMFs and the designed GI-FMF having modal bandwidth values equal to 2 GHz.km, 4.7 GHz.km and 24.3 GHz.km, respectively. The BER performance is evaluated at the maximum achievable length of fibers for different data rates.

Fig. 2 and Fig. 3 show the BER versus ROP at different lengths of OM3 and OM4 MMFs for different data rates. It may be observed from Fig. 2(a) that for back to back (BTB) configuration, the value of the receiver sensitivity is around -11 dBm at the FEC limit for OM3 MMF at 50 Gbps. At 30 m length of OM3 MMF, 1 dB power penalty is observed compared to the BTB performance, while the penalty raises to 3.5 dB for 60 m length as shown in Fig. 2(a). On the other hand, when employing OM4 MMF at the same data rate of 50 Gbps, the value of the receiver sensitivity is around -11 dBm at the FEC limit for BTB configuration, as shown in Fig. 2(b), while the power penalties compared to the BTB performance are 0.6 dB, 2.3 dB and 3.7 dB for 30 m, 60 m and 90 m, respectively.

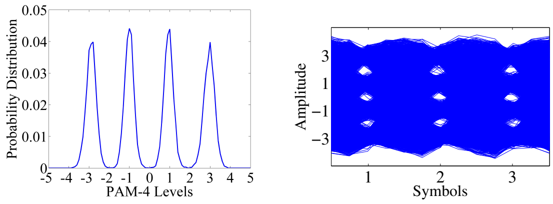
Additionally, the transmission performance of the proposed system is analysed at 100 Gbps data rate for both OM3 and OM4 MMFs, as shown in Fig. 3. Fig. 3(a) shows the BER plots for BTB, 20 m and 30 m while using OM3 MMF and Fig. 3(b) shows the BER plots for BTB, 30 m and 70 m when using OM4 MMF. The value of the receiver sensitivity for BTB configuration is around -8 dBm at 100 Gbps for both OM3 and OM4 MMFs and the values of the power penalties compared to the BTB performance are 1 dB and 3.8 dB for 20 m and 30 m length of OM3 MMF, respectively, while for OM4 MMF the penalties are around 1.3 dB and 3.5 dB for 30 m and 70 m, respectively. It can be deduced from Fig. 2 and Fig. 3 that power penalties are a little bit higher at the maximum length supported by OM3 and OM4 MMFs but the BER is still reaching the FEC limit.

Then, the OM3 and OM4 MMFs are now replaced with the proposed GI-FMF design in the proposed system. The proposed GI-FMF design supports only two LP modes having modal bandwidth equals to 24.3 GHz.km, which is sufficiently greater than the modal bandwidths of OM3 and OM4 MMFs, which would promise longer transmission distances. The performance is evaluated with BER versus ROP plots for both LP_{01} and LP_{11} modes at 50 Gbps and 100 Gbps data rates, as shown in Fig. 4(a) and 4(b), respectively. The value of the receiver sensitivity for BTB configuration is around -11 dBm at 50 Gbps data rate, as shown in Fig. 4(a), while the power penalty for maximum achievable fiber length of 900 m is around 1.1 dB. Additionally, the value of the receiver sensitivity for BTB configuration is around -8 dBm for 100 Gbps data rate, as shown in Fig. 4(b) and the corresponding power penalties are around 0.7 dB and 1.9 dB for 300 m and 450 m lengths of the proposed GI-FMF design, respectively, as shown in Fig. 4(b). Hence, it can be inferred that the power penalty margin is smaller, i.e below 2 dB, for the proposed design of GI-FMF as compared to around 4 dB for OM3 and OM4 MMFs. Likewise, the ROP for GI-FMF is lower than the ROP of OM3 and OM4 MMFs at the FEC limit. By comparing the results for OM3, OM4 and GI-FMF, it can be observed that as the modal bandwidth increases from 2 GHz.km (OM3)



(b)

Fig. 4 *BER versus received optical power performance.*
(a) For different length of GI-FMF at 50 Gbps.
(b) For different length of GI- FMF at 100 Gbps.



(a) (b)

Fig. 5 *The received PAM-4 signal at FEC limit for LP_{01} at 450 m.*
(a) Probability distribution function.
(b) Eye diagram.

to 4.7 GHz.km (OM4) and to 24.3 GHz.km (GI-FMF), the transmission length reaches to maximum around 60 m, 90 m and 900 m at 50 Gbps, respectively, while it can reach up to maximum around 30 m, 70 m and 450 m at 100 Gbps, respectively, within 2.7 dB margin. It may be further noted that LP_{11} mode experiences an additional power penalty of 2.4 dB as compared to LP_{01} mode at 50 Gbps data rate, which is uniform for all lengths of GI-FMF. Similarly, a power penalty of 2.7 dB is also observed for LP_{11} mode as compared to LP_{01} mode at 100 Gbps data rate. BER plots of Fig. 4(a) and 4(b) show that there is a slight degradation in the performance of LP_{11} mode as compared to LP_{01} mode, which may be attributed to mode coupling in the GI-FMF and mode mismatching between the LP_{11} mode and spatial PD detection area [16, 17]. However, the effect of mode coupling can be ignored for short distance employing FMFs [16, 17]. Finally, the eye diagram and the corresponding probability distribution function of the received PAM-4 signal for LP_{01} mode at FEC limit is shown in Fig. 5 at 450 m length of GI-FMF, where it can be seen that there is an eye opening at the FEC limit.

Conclusion: An optical transmission system supporting 200 Gbps data rate over GI-FMF is proposed for DCI by employing VCSEL. GI-FMF fiber is designed to allow the transmission of only two LP modes having modal bandwidth around 24.3 GHz.km to enhance the link capacity and range. MGDM is used to exploit LP_{01} and LP_{11} modes of GI-FMF as independent channels to transmit 100 Gbps/mode. The performance of the proposed setup is analysed by comparing the OM3, OM4 and the proposed GI-FMF design. It is concluded that the designed GI-FMF supports longer transmission distances for both LP_{01} and LP_{11} modes upto 900 m and 450 m at 50 Gbps and 100 Gbps data rates, respectively, while achieving lower power penalties as compared to OM3 and OM4 MMFs. The proposed optical transmission system could be a potential candidate to support higher aggregated data rates of 800 Gbps to 1.6 Tbps for data center networks.

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