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OAM-enhanced transmission for multimode short-range links

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ABSTRACT

We propose, experimentally demonstrate, and evaluate the performance of a multimode (MM) transmission fiber data link which is based on orbital angular momentum (OAM) modes. The proposed scheme uses OAM modes to increase capacity or reach without recurring to mode division multiplexing (MDM) or special fibers: we first excite an OAM mode and couple it to a 50 m, 100 m, 200 m and 400 m MM fibers. We compare three OAM modes and a conventional optical multimode under the same launch and received optical power conditions. The proposed OAM based solution is a promising candidate for the data centers interconnects and short range links that employ the existing multimode fiber infrastructure.

Keywords: Optical Communication, Data Center Interconnects, OAM

1. INTRODUCTION

Vertical cavity surface emitting lasers (VCSELs) are the dominant optical sources in the data center's interconnects due to their low power consumption and a small footprint. In particular, 850 nm VCSELs together with OM3 multi mode fiber (MMF) or OM4 MMF are the base of the short-range links, widely employed in the existing data center infrastructures. The main restraint in this type of links is the intermodal dispersion, which limits the transmission distance to a few hundred meters for bitrates of 10 Gbps. IEEE 802.3ae 10G Ethernet standard specifies 300 m as the multimode span length for 10 Gbps transmission and IEEE 802.3ba 40G/100G Ethernet gives 75 m as the maximum transmission length required at 40 Gbps. Due to the increasing lengths of connections between buildings in data centers there is a need for longer reach multimode interconnects supporting high bit-rates.[1] Several ways of achieving further distances with 850 nm VCSELs have been presented in the literature. First approach involves mode filtering of a multi-mode VCSEL. This results in a VCSEL that emits single or quasi-single fundamental transverse mode with a high side-mode suppression ratio of e.g. 16 dB,[2] 22 dB,[3] or 30 dB.[4] The mode-filtering is performed within the VCSEL structure. Error-free transmission with the single mode 850 nm VCSEL is achieved over 1 km OM4 MMF at 25 Gbps,[5] over 1.1 km OM4 MMF at 20 Gbps,[6] over 600 m OM3+ MMF at 25 Gbps[7] and over 50 m OM3+ MMF at 40 Gbps. A second approach is to couple the light from a multimode VCSEL to a standard single mode fiber (SSMF). Adding a mode filter to remove LP_{11} mode allows transmission distance of 1 km SSMF at 10 Gbps.[8] The third approach involves using special 850 nm optimized singlemode fiber, e.g. photonic crystal fiber (PCF). The core region of PCF is surrounded by multiple air holes, thus assuring single mode operation. Transmission over 3 km PCF has been presented at 10 Gbps.[9] For the multimode VCSELs over multimode fiber, error free transmission over 200 m has been achieved at 25 Gbps.[10] All these approaches require substantial modifications of the existing data center infrastructure: replacement of the multimode sources in the first approach, or the fibers in the second and third approaches. Therefore, an alternative solution that employs the existing fibers and VCSELs is of interest.

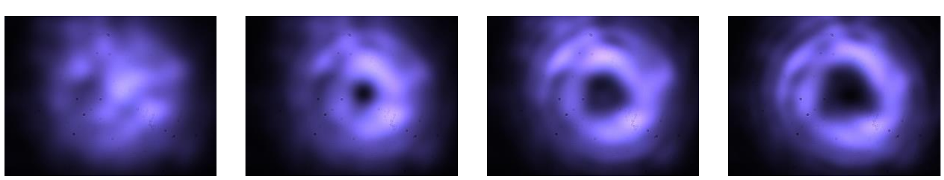

Figure 1. Orbital angular momentum (OAM) modes captured with the camera after spatial light modulator (SLM): M0 (left), M1, M2 and M3 (right); M0 is a standard optical mode.

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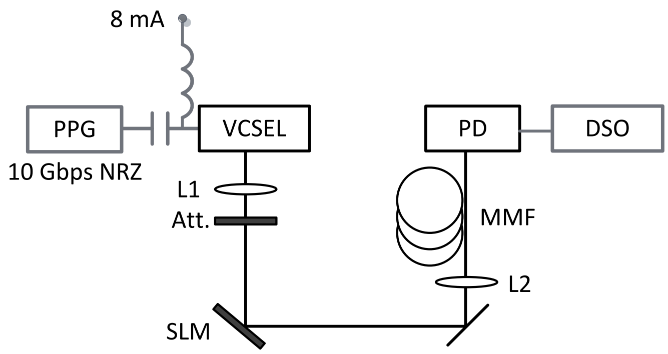


Figure 2. Experimental setup for the transmission of the orbital angular momentum (OAM) modes over multi mode fiber (MMF); Signal from pulse pattern generator (PPG) directly modulates vertical cavity surface-emitting laser (VCSEL) biased at 8 mA; the VCSEL beam is collimated at lens L1 and in free-space passes through the attenuator to the spatial light modulator (SLM), where the beam is shaped to the OAM mode; the shaped beam is coupled to the 3 m OM3 MMF patchcord; Lens L2 is used for the coupling; The signal is then transmitted through the multi mode fiber (MMF): 3 m back to back (B2B), 50 m OM3, 50 m OM4, 100 m OM3, 200 m OM3, 400 m OM3, 400 m OM4 and 400 m customized OM4 by Draka; the signal is then received with photodiode (PD) with the inbuilt transimpedance amplifier (TIA) and the data is stored at digital storage oscilloscope (DSO).

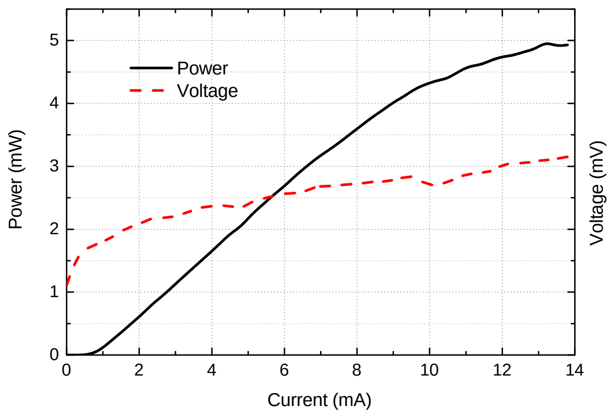
In this paper we propose an approach to increase the obtainable transmission distance for the multi-mode sources over multi-mode fibers. Shaping a multimode VCSEL beam as an orbital angular momentum (OAM) mode (Fig. 1) enabled achieving performance below forward error correction (FEC) threshold during transmissions at 10 Gbps over 400 m MMF. We provide a comparison between transmission of OAM modes M1, M2, and M3 and standard optical mode M0. The modes are transmitted over: 50 m OM3, 50 m OM4, 100 m OM3, 200 m OM3, 400 m OM3, 400 m OM3, and 400 m Draka OM4. The last mentioned fiber is a Max-CAP-OM4 fiber designed by Prysmian Group Draka. It will be further referred to as Draka OM4 fiber.

2. SETUP

The experimental setup is shown in Fig. 2. The 850 nm multimode commercially available VCSEL is biased at 8 mA and directly modulated with 10 Gbps or 11 Gbps pseudo-random bit sequence (PRBS). The sequence length is $2^{15} - 1$ and the amplitude is 800 Vpp. The LIV curves and optical spectrum of the VCSEL used are presented in Fig. 3 and Fig. 4, respectively. The modulated optical beam from the pigtailed VCSEL is collimated and passed through the variable attenuator to the spatial light modulator (SLM) in the free-space part of the setup. The optical power level is controlled by the variable attenuator. The SLM is used to shape the multimode beam to the OAM mode. We verify the transmission performance with OAM modes M1 to M3 and a conventional multimode M0. For M0, SLM behaves as a mirror. The 4 modes under investigation are captured with the camera after SLM and presented in Fig. 1. The full length of the free-space link is 1.5 m. At the end of the free-space link the beam is coupled into the 1 m long MMF OM3 patchcord. The coupling after free-space is aligned to obtain maximum output power and is readjusted for each OAM mode.

The OM3 patchcord used for coupling is connected to the multimode fiber spool via the fiber connector. Several MMFs are tested: 50 m OM3, 50 m OM4, 100 m OM3, 200 m OM3, 400 m OM3, 400 m OM4 and 400 m OM4 special fiber by Draka. The loss in 50 m, 100 m and 200 m is below 0.5 dB. For 400 m spools the measured loss is: 0.98 dB for OM3, 0.95 for OM4, and 0.97 dB for Draka OM4. After transmission the signal is received by the 850 nm commercially available photodiode (PD) with 25 GHz bandwidth. The signal is then stored at digital storage oscilloscope (DSO) with 14 GHz bandwidth. For each BER point 10^7 symbols are saved and errors are counted. No additional equalization is used.

The optical system frequency response is characterized with the vector network analyzer (VNA) before the transmission is performed. For the S_{21} measurement the output of pulse pattern generator (PPG) is replaced



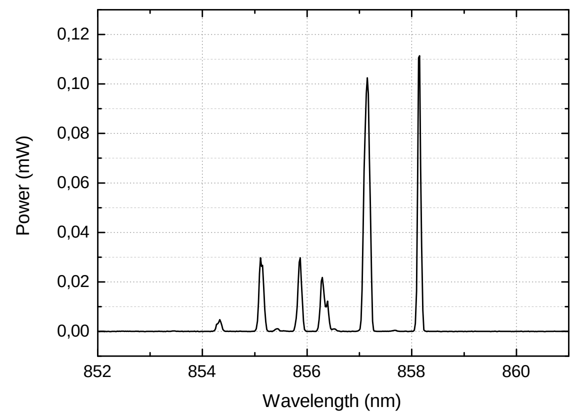


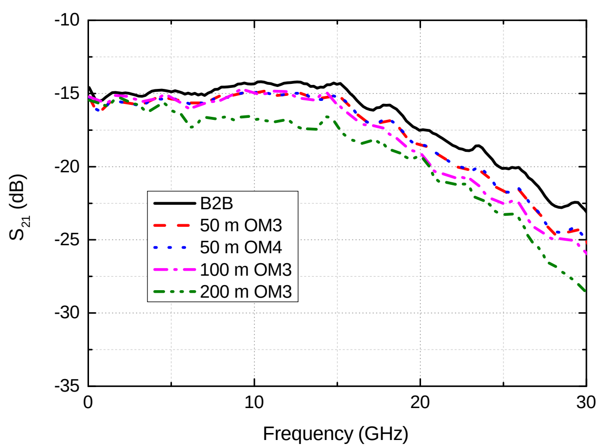
Figure 3. Static characteristics of the VCSEL: Power versus current and voltage versus current (LIV curves).

Figure 4. Optical spectrum of the VCSEL captured after 400 m of MMF; two major modes are around 858 nm.

with the VNA output and input to DSO is instead received by the VNA input. The optical path, from VCSEL to PD included, is kept the same.

3. RESULTS

We compare a transmission performance for different OAM modes (M1, M2, M3) and for a conventional multi-mode M0. Firstly, the modes M0 – M2 are transmitted at 11 Gbps over 100 m OM3 and 200 m OM3. Secondly, the modes M0 – M2 are transmitted over two 50 m long MMFs, OM3 and OM4, at 11 Gbps. Finally, modes M0 – M3 are transmitted over 3 types of 400 m MMF. The performance is compared in terms of the bit-error-ratio (BER) relative to the received average power measured before PD. Transmission over 1 m of OM3 MMF is referred to as back to back (B2B) transmission. Additionally, the S_{21} is measured for each optical system.



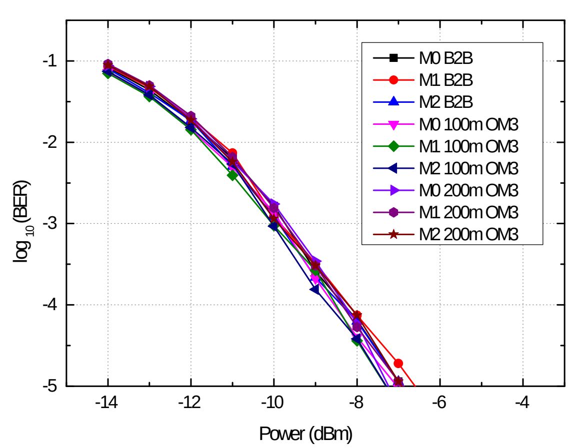


Figure 5. S_{21} measured for the optical system with back to back (B2B) and four different multi mode fiber (MMF): 50 m OM3, 50 m OM4, 100 m OM3 and 200 m OM3; All curves are measured with a conventional multimode M0.

Figure 6. BER versus received optical power (ROP) measured for back to back (B2B), 100 m OM3 and 200 m OM3 for 2 different orbital angular momentum (OAM) modes: M1 and M2 and a conventional multimode M0.

3.1 Transmission over B2B, 100 m OM3, and 200 m OM3

Fig. 5 presents S_{21} measured for the optical system with back to back (B2B), 50 m MMF, 100 m and 200 m. All of the S_{21} are measured for a conventional multimode M0. 3-dB bandwidth of the system ranges from 16 GHz for 200 m to 22 GHz for B2B. The measured analog bandwidths for all presented cases are sufficient for the 11 Gbps transmission. The bit error rate (BER) curves measured at 11 Gbps for B2B and all the fibers are presented in Fig. 6. No penalty is observed, neither for different fiber lengths nor for the different modes. The power measurement error due to the procedure is equal to -/+ 0.25 dB. Receiver sensitivity at BER of 10^{-3} is equal to -10 dBm.

3.2 OM3 vs. OM4

In Fig. 7 the comparison between 11 Gbps transmission over 50 m links, OM3 and OM4 MMF, is presented. As apparent from Fig.5, the bandwidth for both fibers is the same. The measured 3-dB bandwidth is 20 GHz for the length under consideration. The sensitivity at BER 10^{-3} for OM4 fiber is up to 0.2 dB better than for OM3. The same is observed for all of the OAM modes. This difference in the sensitivity is within the power measurement error margin. The difference between OM3 and OM4 is expected to be more significant for longer fiber link.

3.3 400 m

A link of 400 m is used to evaluate the transmission performance with the OAM modes. We use three different 400 m long links in which the intermodal dispersion is dominant. S_{21} curves measured for the optical system with each of the three links are shown in Fig. 8. The S_{21} curves are measured with for M0 OAM mode. The 3-dB bandwidth is only 4.9 GHz for MMF OM4 by Draka, 4.8 GHz for MMF OM3 and 4 GHz for 400 m MMF OM4.

The impact of the OAM modes on the S_{21} of the system is presented in Fig. 9. The frequency response is measured for OM4 Draka fiber with OAM modes from M1 to M3 and with the conventional multimode M0. The measured responses are the same for modes M0 and M1, while responses of modes M2 and M3 have ~2dB less power for frequencies above 15 GHz. For each of the modes the coupling is realigned to reach the highest coupled power. The coupling efficiency is a ratio between the power coupled to the MMF OM3 patchcord and the input power to the lens. Fig. 10 presents the coupling efficiency measured for modes M0 to M3. It shows that there is no difference in coupling efficiency for M0 and M1, however for M2 and M3 the coupling efficiency

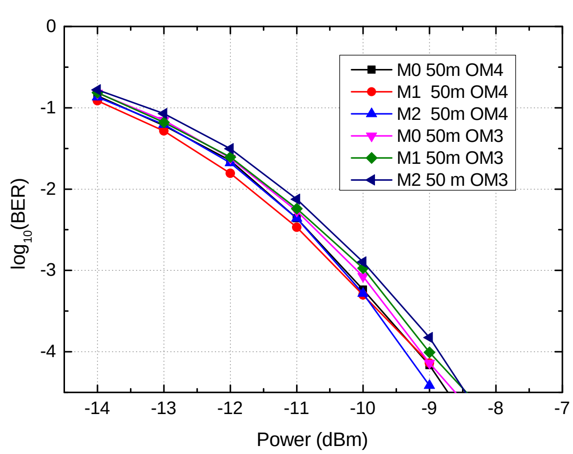


Figure 7. BER versus received optical power (ROP) measured for 2 OAM modes (M1 and M2) and a conventional multimode M0 for two types of 50 m MMF: OM4 and OM3.

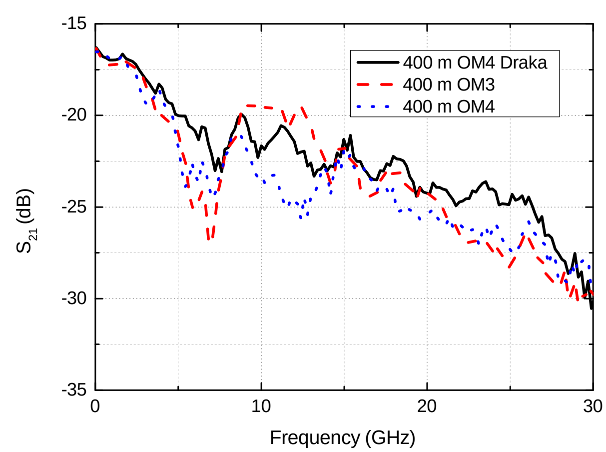


Figure 8. S_{21} measured for the optical system with three 400 m spools: OM3, OM4 and OM4 fiber by Draka; All curves are measured with a conventional M0 mode.

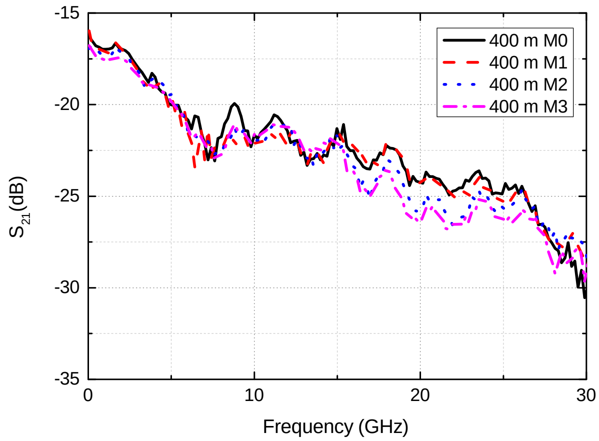


Figure 9. S_{21} measured for the optical system with 400 m OM4 by Draka with 4 OAM modes: M0, M1, M2 and M3.

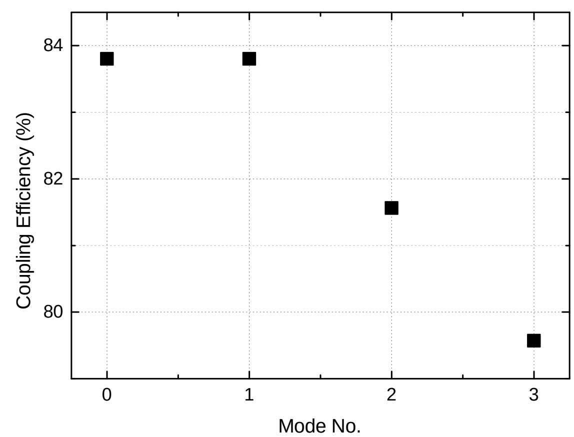


Figure 10. Coupling efficiency measured in the system as $P_{coupled}/P_{IN}$ for 4 modes.

decreases. Higher order modes suffer from larger loss, as the power is distributed outside of the beam center and the coupling is imperfect.

Fig. 11, Fig. 12 and Fig. 13 depict the BER curves measured at 10 Gbps for three 400 m links. For all of the curves the same tendency is observed: the higher the order of OAM mode, the lower amount of errors is counted. During the measurement the coupling from the free-space through the second lens L2 is realigned for each mode to reach the highest coupling efficiency. The BER below FEC threshold is obtained by transmitting the beam shaped in OAM mode. The error floor observed at $log(BER)$ of -1.8 for 400 m OM3 link is moved down to -2.1 with M1 and M2 and down to -2.8 with M3. OM4 fiber has the lowest 3-dB bandwidth out of the three links under consideration, as shown in Fig.8. The error floor for this fiber is measured at $log(BER)$ of -1.3. Using OAM mode M1 allows to move the error floor down to $log(BER)$ of -1.5, M2 to -2.3 and M3 to -3.3. In case of Draka 400 m OM4 fiber, the 3-dB bandwidth is the highest of the three links (Fig.8). Therefore, the error floor

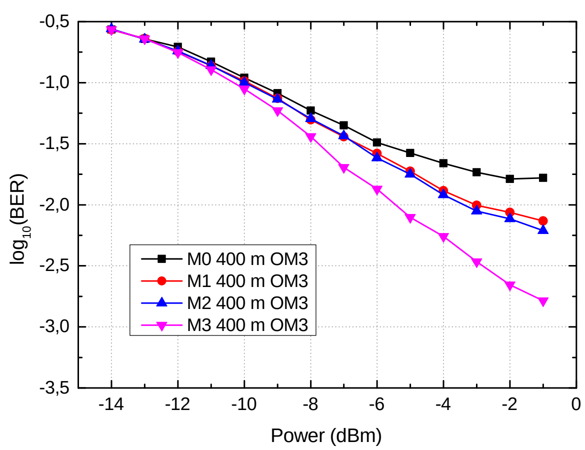


Figure 11. Bit error rate (BER) versus received optical power (ROP) measured at 10 Gbps for 400 m OM3 multi mode fiber (MMF) for 3 OAM modes (M1, M2, and M3) and a conventional multi mode M0.

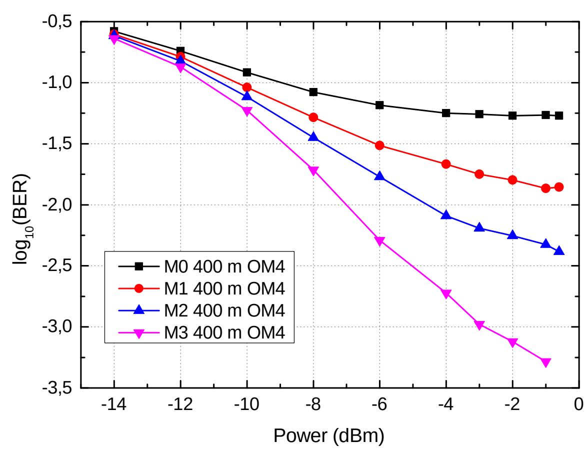


Figure 12. Bit error rate (BER) versus received optical power (ROP) measured at 10 Gbps for 400 m OM4 multi mode fiber (MMF) for 3 OAM modes (M1, M2, and M3) and a conventional multi mode M0.

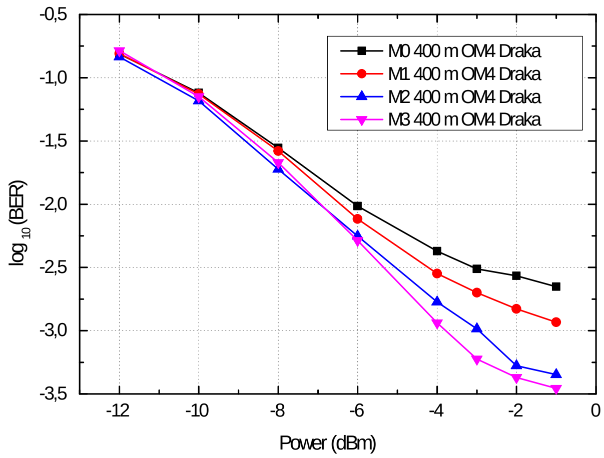


Figure 13. Bit error rate (BER) versus received optical power (ROP) measured at 10 Gbps for 400 m OM4 multi mode fiber (MMF) by Draka for 3 OAM modes (M1, M2, and M3) and a conventional multi mode M0.

for M0 is the lowest, at $log(BER)$ of -2.6. Usage of M3 allows reaching -3.45.

4. DISCUSSION

As shown in Fig. 6, using the OAM modes M1 and M2 over 100 m OM3 and 200 m OM3 results in the same performance in terms of BER as using a conventional multimode M0. The same transmission performance within the tested BER range indicates a potential for simultaneous use of several OAM modes in the future spatial division multiplexing (SDM) systems.

For 400 m transmission, 3-dB system bandwidth becomes a limiting factor, as presented in Fig. 8. The 'dip' in the frequency response occurs due to the interaction between several modes in the fiber. It is the most pronounced for the OM3 fiber and the least for the Draka's OM4 fiber. The 3-dB bandwidth of 4 GHz measured for 400 m OM4 fiber results in the error floor measured at $log(BER)$ of -1.3 for 10 Gbps transmission. Using OAM modes introduces the most significant performance improvement for 400 m OM4 fiber. Using OAM mode M3 allows to reach error floor below FEC threshold, at $log(BER)$ of -3.3. For Draka OM4 fiber, the measured 3-dB bandwidth was 4.9 GHz. It allows for the error floor below $log(BER)$ of -2.6. Using OAM mode M3 enables $log(BER)$ of -3.45. An improvement in the transmission performance while using higher order OAM modes is measured for all 400 m fiber types with the best performance of OAM mode M3 transmitted over Draka OM4 MMF.

5. FUTURE WORK

The presented results provide an interesting solution for improving performance in terms of BER in the multimode transmission scenarios. A further study is required to define the optimal launching and transmission conditions. The next step is to create an all fiber coupled OAM-enhanced transmission, with no free-space link. Secondly, higher order modes M4 – M6 are expected to result in further performance improvement, hence need to be tested. Additionally, checking the behavior of the OAM enhanced transmission with a single mode source should be verified and compared with the presented results.

6. CONCLUSION

In this work we present a novel OAM-enhanced transmission over multi mode fiber (MMF) which can be applied in the short-range optical interconnects. OAM modes M1 and M2 perform the same as conventional multi mode

M0 within the tested BER range for transmission over 50 m OM3, 50 m OM4, 100 m OM3, 200 m OM3. For a further distance of 400 m, the higher order modes perform better than the conventional M0 mode, enabling BER below FEC threshold at 10 Gbps in the system with 3-dB bandwidth of 4 GHz.

REFERENCES

1. C. Lam, H. Liu, B. Koley, X. Zhao, V. Kamalov, and V. Gill, "Fiber optic communication technologies: What's needed for datacenter network operations," *Communications Magazine, IEEE* **48**, pp. 32–39, July 2010.
2. P. Moser, J. Lott, P. Wolf, G. Larisch, H. Li, N. Ledentsov, and D. Bimberg, "56 fJ dissipated energy per bit of oxide-confined 850 nm VCSELs operating at 25 Gbit/s," *Electronics Letters* **48**, pp. 1292–1294, September 2012.
3. P. Wolf, P. Moser, G. Larisch, H. Li, J. Lott, and D. Bimberg, "119 fJ of Dissipated energy per bit for error-free 40 Gbit/s transmission across 50 m of multimode optical fiber using energy efficient 850 nm VCSELs," in *Lasers and Electro-Optics (CLEO), 2013 Conference on*, pp. 1–2, June 2013.
4. F. Mederer, C. Jung, R. Jager, M. Kicherer, R. Michalzik, P. Schnitzer, D. Wiedenmann, and K. Ebeling, "12.5 Gbit/s data rate fiber transmission using single-mode selectively oxidized GaAs VCSELs at λ=850 nm," in *LEOS '99. IEEE Lasers and Electro-Optics Society 1999 12th Annual Meeting*, **2**, pp. 697–698 vol.2, 1999.
5. M. P. Tan, S. Fryslie, J. Lott, N. Ledentsov, D. Bimberg, and K. Choquette, "Error-Free Transmission Over 1-km OM4 Multimode Fiber at 25 Gb/s Using a Single Mode Photonic Crystal Vertical-Cavity Surface-Emitting Laser," *Photonics Technology Letters, IEEE* **25**, pp. 1823–1825, Sept 2013.
6. R. Safaisini, K. Szczerba, E. Haglund, P. Westbergh, J. Gustavsson, A. Larsson, and P. Andrekson, "20 Gbit/s error-free operation of 850 nm oxide-confined VCSELs beyond 1 km of multimode fibre," *Electronics Letters* **48**, pp. 1225–1227, September 2012.
7. P. Moser, J. Lott, P. Wolf, G. Larisch, A. Payusov, N. Ledentsov, and D. Bimberg, "Energy-Efficient Oxide-Confined 850-nm VCSELs for Long-Distance Multimode Fiber Optical Interconnects," *Selected Topics in Quantum Electronics, IEEE Journal of* **19**, pp. 7900406–7900406, March 2013.
8. Z. Tian, C. Chen, and D. Plant, "850-nm VCSEL Transmission Over Standard Single-Mode Fiber Using Fiber Mode Filter," *Photonics Technology Letters, IEEE* **24**, pp. 368–370, March 2012.
9. H. Hasegawa, Y. Oikawa, T. Hirooka, M. Yoshida, and M. Nakazawa, "10 Gb/s transmission over 3 km at 850 nm using single-mode photonic crystal fiber, single-mode VCSEL, and Si-APD," in *Optical Fiber Communication Conference, 2006 and the 2006 National Fiber Optic Engineers Conference. OFC 2006*, pp. 3 pp.–, March 2006.
10. J. Kropp, J. Lott, N. Ledentsov, P. Otruba, C. Knochenhauer, and F. Ellinger, "25 Gb/s transmission at 850 nm on multimode fiber with low cost optical component assemblies," in *Semiconductor Conference Dresden (SCD), 2011*, pp. 1–4, Sept 2011.