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# Experimental demonstration of variable rate SWDM VCSEL-MMF systems for 400Gb links

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**Abstract**— In a transmission experiment, we show the potential of the variable rate approach applied to SWDM VCSEL-MMF systems. Rate adaption allows to reach 400G up to 125 m using OM4 fibers and MLSE processing.

**Keywords**—VCSEL, SWDM, Variable Rate, 400G

## I. INTRODUCTION

The demand for high-speed IntraDataCentre (IDC) links is growing rapidly. Fast connections require increased bandwidths and reduced latency forcing the transition from electrical to optical solutions. As a result, multi-mode (MM) 100G optical systems are the preferred solution in IDC communications[1]. A key factor in these advances has been the use of vertical cavity surface emitting lasers (VCSELs), proving to be the most promising technology for cost reduction.

Various strategies are under study to meet the challenge of achieving high data rates with VCSEL technology: the implementation of bandwidth-efficient modulations such as Pulse Amplitude Modulation (PAM4/PAM6/PAM8) or Discrete Multi-Tone (DMT)[2]; the improvement of VCSEL manufacturing processes to increase bandwidth and reduce distortion[1]; and the use of Short Wavelength Division Multiplexing (SWDM)[3], which uses multiple wavelengths on a single fibre to transport information. At the same time, efforts are underway to mitigate range degradation by investigating SM VCSELs with minimal spectral width and increasing the appropriate modal bandwidth of fibres (OM4 and OM5 rated) to reduce chromatic and modal dispersion[1].

This work focuses on SWDM and aims to experimentally prove the variable rate approach, which compensate the limited performance of longer wavelength channels rate with an increased rate in the shorter wavelength channels rate, as detailed in [4].

## II. EXPERIMENTAL SETUP

The SWDM approach was implemented by measuring four VCSELs, each emitting at different wavelengths: 850 nm, 880 nm, 910 nm and 940 nm. The experimental setup, shown in Fig.1, consisted of a fast Digital to Analog Converter (DAC) (AWG Keysight 96 GS/s) connected to the VCSEL via a bias tee and a 40 GHz RF probe. The VCSEL was directly modulated by the PAM4 signal generated by the DAC, and no current drivers were used. A lens-mirror-lens system focused

the modulated light onto a 100 m or 125 m OM4 MM fibre. Due to the lack of a multiport probing station, we were forced to measure one VCSEL a time. To mimic the presence of a SWDM MUX/DMX system we inserted a lumped loss of about 3 dB. The receiver section consisted of an optical isolator, a 30 GHz photodiode (Thorlabs DX30BF) followed by a low noise, high bandwidth amplifier (SHF 807C 22dB 50 GHz). The received signals were sampled using a fast real-time oscilloscope (RTO) (Tektronix, 70 GHz -200 GS/s) and post-processed using Feed Forward Equaliser (FFE) and Maximum Likelihood Sequence Estimator (MLSE) to extract the bit error rate (BER).

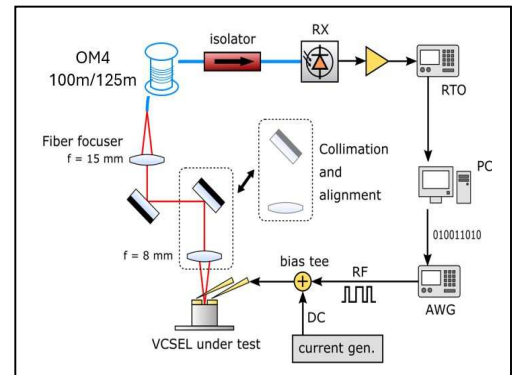


Fig 1: Experimental Setup

The T/2-spaced FFE was a 20-tap filter with a  $10^4$  symbols training sequence followed by a decision-directed adaptive tuning of the taps. To mitigate the complexity of the MLSE, a channel shortening technique was employed. This involved pre-filtering the received signal using a 2 SpS 50-tap equaliser, effectively reducing the channel memory length and the number of Viterbi trellis states. The outputs of this filter were then processed through a 3-tap Desired Impulse Response (DIR) filter, followed by a sequence MLSE equaliser. Both the 20-tap pre-equaliser and the DIR filter taps were determined by minimising the Mean Squared Error (MSE) between the DIR outputs and a training sequence, subject to the Unit Energy Constraint (UEC) [5]. A strong enhanced FEC (E-FEC) with 10.35% overhead and a BER Threshold ( $BER_T$ ) =  $4 \cdot 10^{-3}$  was assumed. To measure the bandwidth of the VCSEL, we used the same setup but with two modifications: we removed the fibre and the receiving

amplifier and we substituted the DAC and the RTO with a vector network analyser (VNA).

### III. RESULTS

Fig.2 shows the -3dB bandwidth of the tested VCSEL as a function of different bias currents. The bandwidth measurements identified an initial set of bias currents, but the final decision was based on BER performance; for each VCSEL and each fibre length, it was decided to operate at the bias currents and modulation voltages that gave the best BER performance. A pre-characterisation of the spectral profile of the VCSELs verified their multimode nature, showing a  $\Delta\lambda_{rms}$  linewidth of approximately 0.4 nm at the bias currents used in the operating conditions.

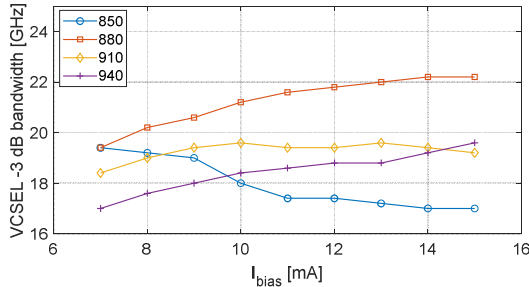


Fig 2: VCSELs -3dB Bandwidths at different Bias current

Fig.3 and Fig.4 show the achieved BER at different rates, for the two equalisation methods and link lengths. A direct comparison between -3dB bandwidth and BER results shows that the frequency response of VCSELs alone is not sufficient to determine their transmission performance. This is because the coupling between the multimode fibre and the VCSEL, the modal dispersion of the fibre and the number of transverse modes of the VCSEL all affect performance [6].

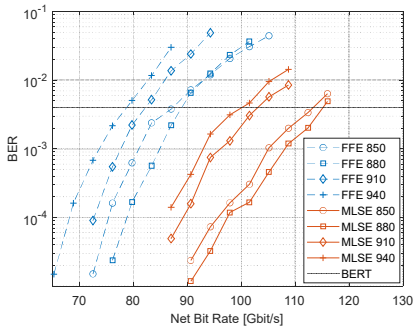


Fig 3: BER vs Net Bit Rate after transmission over the 100 m OM4 fiber. Blue lines/markers refer to FFE, red to MLSE.

Considering  $BER_T$ , we can define the maximum achievable rate for each wavelength and equalizer case and estimate the maximum achievable rate per  $\lambda$  (Tab. I). In a system operating under the constraint of maintaining the same bit rate at all wavelengths, it is clear that the net rate is limited by the underperforming 940 nm VCSEL and the SWDM system cannot guarantee the 400G target. On the other hand, by summing the maximum bit rate on each wavelength the target 400G SWDM throughput becomes feasible up to 125m. In agreement with previous results[4], there is a well-defined

hierarchy with 800 nm VCSELs performing better than 900 nm VCSELs.

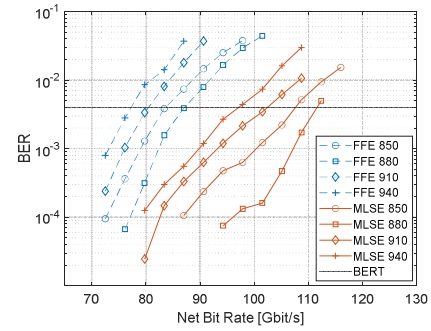


Fig 4: BER vs Net Bit Rate after transmission over the 125 m OM4 fiber. Blue lines/markers refer to FFE, red to MLSE

TABLE I. - NET RATE AT DIFFERENT DISTANCES AND DSP

Wavelength [nm]	OM4 100m		OM4 125m	
	Net Rate [Gbps]	Net Rate [Gbps]	Net Rate [Gbps]	Net Rate [Gbps]
	FFE	MLSE	FFE	MLSE
850	87.30	111.85	87.56	107.61
880	89.00	115.08	87.17	110.51
910	82.28	103.10	80.49	102.32
940	78.74	99.99	77.25	97.03
<b>SWDM</b>	<b>337.32</b>	<b>430.02</b>	<b>332.47</b>	<b>417.48</b>

### IV. CONCLUSION

The variable-rate technique is experimentally validated increasing the maximum range of SWDM systems in VCSEL MMF short-range links. Implementing bit-rate adaptation on a per-wavelength basis has the advantage of overcoming the limitations of a fixed-rate approach, where the maximum achievable rate is imposed by the worst-performing wavelength.

### REFERENCES

- [1] N. Ledentsov, et al., "High Speed VCSEL Technology and Applications," J. Lightwave Technol. 40, 1749-1763 (2022).
- [2] J. Tatum, et al., "VCSEL-Based Interconnects for Current and Future Data Centers," J. Lightwave Technol. 33, 727-732 (2015).
- [3] C. Kocot, et al., "SWDM Strategies to Extend Performance of VCSELs over MMF," in Optical Fiber Communication Conference, OSA Technical Digest (online) (Optica Publishing Group, 2016), paper Tu2G.1
- [4] A. M. R. Brusin, et al., "Maximizing 425G SWDM VCSEL-MMF Systems Reach Through Variable Rate per  $\lambda$ ," in Optical Fiber Communication Conference (OFC) 2023, Technical Digest Series (Optica Publishing Group, 2023), paper Th2A.23.
- [5] N. Al-Dhahir, and J. M. Cioffi, "Efficiently Computed Reduced-Parameter Input-Aided MMSE Equalizers for ML Detection: A Unified Approach," IEEE Transactions on Information Theory, Vol. 42, 3, 1996
- [6] P. Torres-Ferrera et al., "Statistical Analysis of 100 Gbps per Wavelength SWDM VCSEL-MMF Data Center Links on a Large Set of OM3 and OM4 Fibers," JLT, vol. 40, no. 4, pp. 1018-1026, 2022