Experimental Demonstration of 38 Gbps over 2.5 m OWC Systems with Eye-safe 850 nm SM-VCSELs

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Experimental Demonstration of 38 Gbps over 2.5 m OWC Systems with Eye-safe 850 nm SM-VCSELs

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***Abstract*—With a directly modulated 850 nm single-mode vertical cavity surface emitting laser (SM-VCSEL), we experimentally achieve a gross data rate of ∼38 Gbps over a 2.5 m optical wireless communication (OWC) link at the 7% Reed-Solomon forward error correction (RS-FEC) limit. The OWC link is demonstrated using an eye-safe transmitted optical power of -1.47 dBm and discrete multi-tone (DMT) modulation with adaptive bit-and-power loading. The SM-VCSEL has a relative intensity noise (RIN) of ∼-137 dB/Hz, which is lower than that of a typical commercial 850 nm multimode VCSEL (∼-129 dB/Hz). Therefore, under almost identical OWC link operating conditions, the SM-VCSEL provides a gross data-rate increase of ∼19 Gbps and an optical signal-to-noise-ratio (SNR) gain of ∼5 dB compared to its multimode counterpart having a similar modulation bandwidth. Furthermore, we demonstrate an error-free net data rate of ∼17 Gbps at a received optical power of -7 dBm, which suggests the feasibility of utilising the SM-VCSEL to realise indoor gigabit OWC applications.**

***Index Terms*—optical wireless communication (OWC), single-mode vertical cavity surface emitting laser (SM-VCSEL), eye safety, discrete multi-tone (DMT)**

I. Introduction

Optical wireless communication (OWC) provides access and cross-haul links with significant opportunities for satisfying the requirements associated with 5G and beyond, and it has been employed for applications including device-to-device (D2D) communications and internet-of-things (IoT) [1]. Visible light communications (VLC) and infrared OWC (IOWC) are being considered for short-range OWC links with experimentally demonstrated data rates of <25 Gbps [2]. While VLC has been reported to achieve data rates of up to 35 Gbps with wavelength division multiplexing (WDM) [3], IOWC offers better flexibility where illumination is unnecessary for scenarios such as VLC uplink, datacentres, etc. IOWCs are increasingly becoming prominent because they can be integrated with high-speed fibre communication systems to provide terabits-per-seconds (Tbps) indoor wireless access (interfacing with the fibre-to-the-home access network) [4]. Despite many advantages, high-speed IOWC systems have limited mobility due to their use of narrow divergence transmitters and narrow field-of-view (FOV) receivers. To overcome the mobility issue, robust user tracking and localisation mechanisms with optical beam steering are imperative for the practical deployment of IOWC [3], [4].

Vertical cavity surface emitting lasers (VCSELs) are widely recognised as an important integrated light source for intensity modulated/direct detection (IM/DD)-based OWC systems due to their unique characteristics compared to other optical sources, i.e., VCSELs are cheaper to fabricate and require lower electrical power consumption than edge-emitting lasers [5]. In addition, they offer higher modulation bandwidths and better emission coherence than light-emitting diodes (LEDs). Due to their vertical emission and ease of fabrication, VCSELs can be monolithically integrated into two-dimensional (2D) arrays for spatial diversity and multiple-input multiple-output (MIMO) OWC systems. Experimental works on gigabit OWC were implemented with individual VCSEL sources at wavelengths of 650 nm [6], 850 nm [7], and 1310 nm [8] - with data rates of up to 25 Gbps.

VCSELs were first fabricated in the 850 – 980 nm band [5], and they still dominate the market today because these wavelengths coincide with the high responsivity of low-cost silicon photo-detectors (PDs). Furthermore, communications at these wavelengths in multimode silica and plastic fibres offer lower attenuation than visible light, making it suitable for realising fibre-OWC-fibre systems. However, it is important to ensure that the 850 nm system operates within the eye-safety limit to protect the retina. To satisfy the class-1 laser safety requirement, the accessible emission limit (AEL) specified by the International Electrotechnical Commission (IEC 60825-1) for a point source operating at 850 nm is about -1.10 dBm [9]. This AEL is the product of a maximum permissible exposure (MPE) set at 20 W/m^2 and a pupil area of $\sim$39 mm^2.

A theoretical study in [10] demonstrated the feasibility of 1 Tbps OWC using an 850 nm 3×3 VCSEL array (assuming a bandwidth of 20 GHz and an optical power of 0 dBm). Experimental studies using 850 nm VCSELs for OWC transmissions have presented data rates below 25 Gbps for launched optical powers over 0 dBm. For instance, the study in [7] practically demonstrated a data rate of 8.23 Gbps over a 1 m OWC channel with an optical power of ∼5 dBm. A higher data rate of 25 Gbps was achieved using a 7×7 VCSEL array with an optical power of ∼22 dBm [11].

To the best of the authors' knowledge, this paper reports

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TABLE I: OWC System Parameters

Device/System	Setup/Parameters
AWG	MD – Keysight M8195A, BW = 25 GHz, SR = 60 GSa/s, 8-bit Res. DAC
Photodetector	MD – Newport 818-BB-45A, BW = 9 GHz, ⌀60 μm, ∼550V/W Gain at 850 nm
Optics Lens	MD – Thorlabs ACL2520U, ⌀25 mm, Focal length = 20 mm
Oscilloscope	MD – Tektronix DPO71254C, BW = 12.5 GHz, SR = 50 GSa/s, 8-bit Res. ADC
DMT	FFT/IFFT Size = 4096, Cyclic Prefix Length = 120, No. of data sub-carriers = 595

MD – Module Description, BW – Bandwidth, SR – Sampling Rate, Res. – Resolution

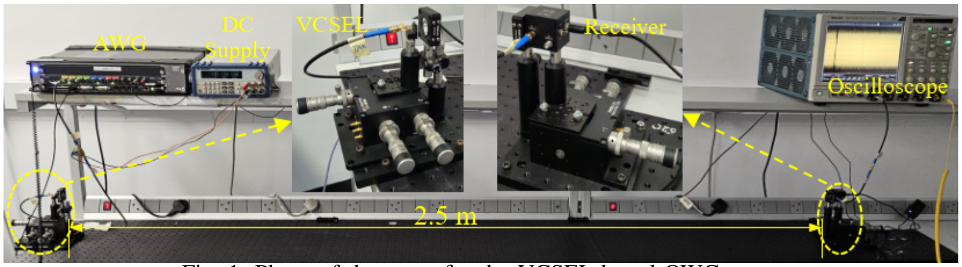

Fig. 1: Photo of the setup for the VCSEL-based OWC system

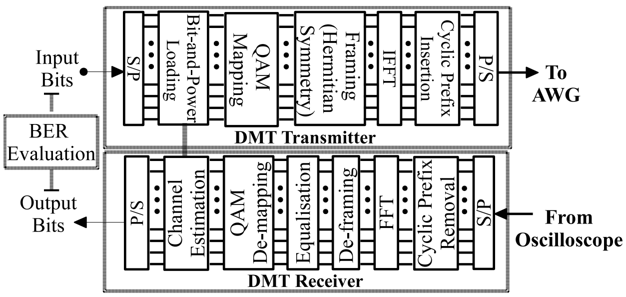

Fig. 2: Schematic of DMT modulation with bit-and-power loading

the first experimental evaluations of directly modulated eye-safe single-mode VCSELs (SM-VCSELs) at 850 nm for high-speed OWC and demonstrates a record-high gross data rate of 38 Gbps over a 2.5 m OWC link. The SM-VCSEL is launched at a transmitted optical power of -1.47 dBm, which is below the AEL (-1.10 dBm) of a class-1 laser, and is therefore eye-safe. Compared to its multimode counterpart, the SM-VCSEL is particularly suitable for fixed point-to-point OWC links due to its lower beam divergence and smaller spot size, thus resulting in an improved optical coupling efficiency. Furthermore, as SM-VCSELs have narrower spectral widths than multimode VCSELs (MM-VCSELs) [5], then for fibre-OWC-fibre, the SM-VCSELs have the advantage of long-distance high-speed fibre communication as they suffer less modal dispersion and chromatic dispersion penalties. In this work, we use SM-VCSELs designed by Integrated Compound Semiconductor (ICS) and grown on high capacity/uniformity metal-organic chemical vapour deposition (MOCVD) reactors by Compound Semiconductor Centre (CSC) [12]. The SM-VCSELs were fabricated and tested on wafers by ICS prior to full characterisation in an OWC system. The VCSELs also have lower relative intensity noise (RIN) than a commercial 850 nm VCSEL used in [7] and a customised VCSEL used in [11]. We adopt discrete multi-tone (DMT) modulation with adaptive bit-and-power-loading to maximise the achievable data rate of the OWC link. We have obtained 38 Gbps at a link distance of 2.5 m, which is about a 50% increase in the data rate compared to the work in [8] and [11]. Based on the analysis in [10], when spatial division multiplexing is considered, a 5×5 array based on such VCSELs can potentially achieve Tbps communications.

II. Experiment Setup

Fig. 1 and Fig. 2 show the photograph and schematic diagram of the VCSEL-based DMT-encoded OWC system over a transmission distance of 2.5 m, respectively. Important parameters for the OWC system are listed in Table I.

We used the Levin-Campello bit-and-power loading algorithm [13] with the standard DMT generation and decoding for IM/DD system. A random bit sequence is generated offline with MATLAB and mapped unto quadrature amplitude modulated (QAM) symbols. Then, the serial QAM symbols are re-arranged into parallel data via serial-to-parallel (S/P) conversion, which is transformed into the Hermitian symmetry format with zeros in the middle so that the parallel QAM symbols serve as inputs to the inverse fast Fourier transform (IFFT). The cyclic prefix is added after the IFFT operation, and the resulting outputs are converted to a serial signal after parallel-to-serial (P/S) conversion. Finally, the DMT signal is sent to an arbitrary waveform generator (AWG) to generate an analogue waveform that directly drives the VCSEL via a bias-tee (Tektronix PSPL5542, 50 GHz).

The VCSEL output is collimated via an aspheric lens (Thorlabs ACL2520U). At the receiver side, the optical signal is collected with an aspheric lens and focused on a PIN PD module (818-BB-45A). The VCSEL and PD are mounted on 3D-axis stages (Thorlabs NanoMax 300) to align the OWC link and adjust the optical power at the receiver. An oscilloscope captures the received signal. Standard digital signal processes, including synchronisation, removing the CP, applying the fast Fourier transform (FFT), and equalisation, are performed on the collected signal to recover the transmitted data. Finally, the transformed serial QAM signal is de-mapped into the received bitstream to evaluate the bit-error-rate (BER) performance.

III. VCSEL Characteristics

This study considers two 850 nm VCSELs: the first device (VCSEL1) is a custom-designed SM-VCSEL designed, manufactured and packaged on TO-46 cans by ICS from

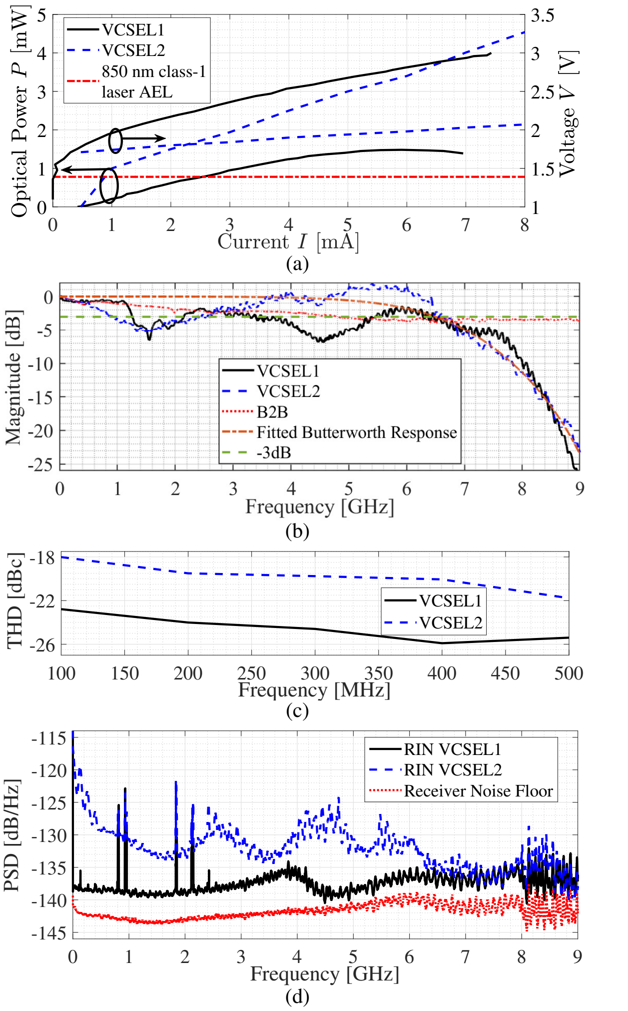

Fig. 3: Measured VCSEL Characteristics: (a) L-I-V Curve (b) Normalised frequency response (c) Total harmonic distortion (THD) and (d) Noise PSD. VCSEL1 denotes the 850 nm SM-VCSEL designed by ICS & CSC; VCSEL2 denotes the commercial 850 nm VCSEL (OPV310).

a GaAs/AlGaAs-based epitaxial structure supplied by CSC. The second VCSEL (VCSEL2) is a commercial MM-VCSEL (OPTEK OPV310) with a similar package. Fig. 3a depicts the measured light-current-voltage (L-I-V) curves of both VCSELs. It can be seen that while both VCSELs offer relatively low threshold currents of ~0.5 mA, VCSEL1 has a higher dynamic resistance and emits lower optical power than VCSEL2, largely due to the much smaller oxide aperture used to ensure single-mode emission. Based on Fig. 3a, we adopt a bias-current of ~2.2 mA to drive the VCSEL1, which corresponds to an optical power of ~0.7 mW (-1.47 dBm), ensuring that the SM-VCSEL operates within the eye-safe condition. VCSEL2 is driven at a bias current of ~5.0 mA to emit an optical power of ~3 mW (4.7 dBm). These conditions also ensure that both VCSELs have similar bandwidth to give meaningful comparisons between the two devices (later, we showed that the VCSEL2 offer inferior performance despite higher transmitted power). The PIN PD module operates in its linear region for ≤1 mW optical powers at 850 nm wavelengths. Therefore, unless stated otherwise, the received optical power (ROP) is always set at ~0.67 mW (-1.75 dBm) or below. The same ROP is used to fairly compare the communication performance of the two VCSELs.

The modulation bandwidths of the VCSELs are measured using a programmable network analyser (Keysight N5245B). The measured normalised frequency responses of the VCSELs are presented in Fig. 3b. The input electrical signal amplitudes for both VCSELs are 0.5 V_{pp}, corresponding to about 70% modulation index. The -3 dB bandwidth for back-to-back (B2B) response from the cables and bias-tee is ~7 GHz. Accounting for the frequency response of the B2B system, the measured -3 dB bandwidths of VCSEL1 and VCSEL2 are ~6.2 GHz and ~6.4 GHz, respectively. Furthermore, the VCSEL1 frequency response follows a fitted second-order Butterworth lowpass filter of 6.5 GHz more closely than the VCSEL2 response, which has magnitudes above the filter for frequencies between 4.8 and 6.4 GHz. This anomaly with VCSEL2 is attributed to the higher non-linearity from VCSEL2 compared to VCSEL1, presumably due to the multimode nature of the former device. Fig. 3c shows the non-linearity of both VCSELs via their total harmonic distortion (THD), where VCSEL2 has ~3.5 dB more THD than VCSEL1.

Fig. 3d depicts the measured noise power spectral density (PSD) of the OWC link at an ROP of ~0.67 mW using an electrical spectrum analyser (Rohde & Schwarz FSW). The noise PSD recorded by the receiver without any optical input shows a noise floor of ~-142 dB/Hz. With VCSEL1 and VCSEL2, the noise PSD averages to ~-137 and ~-129 dB/Hz, respectively. Moreover, VCSEL2 has ≳10 dB higher RIN than VCSEL1 at frequencies below 1 GHz. At frequencies between 1 GHz and 6 GHz, it has ≳3 dB higher RIN than VCSEL1. Consequently, this indicates that VCSEL2 has ~8 dB more average RIN than VCSEL1.

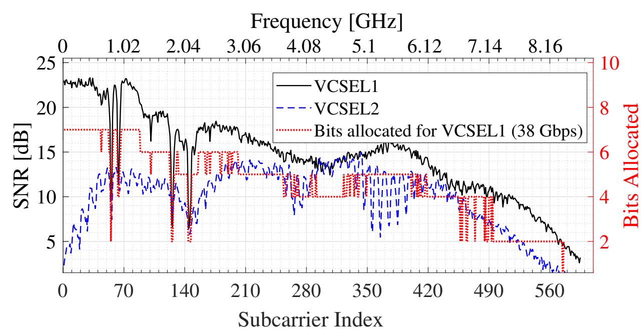

Fig. 4: SNR per sub-carrier from channel estimation. The low-frequency sub-carriers of VCSEL2 have poor SNR performance due to high RIN

IV. Communication Performance

Fig. 4 depicts the signal-to-noise-ratio (SNR) profile for both VCSELs. The channel estimation is performed with a pilot sequence that consists of random quadrature phase-shift keying (QPSK) symbols. The SNR values are obtained by estimating each sub-carrier's error vector magnitude (EVM) of the QPSK constellations. The input signal amplitudes to both VCSELs are set to 1 V_{pp} to avoid significant clipping noise due to the signals' high peak-to-average power ratios

(PAPR). Due to the RINs described in Fig. 3d, VCSEL1 offers higher SNR values compared to VCSEL2 for the same ROP of -1.75 dBm. For instance, the SNR at 1 GHz is ∼23 dB for VCSEL1 and ∼13 dB for VCSEL2, translating to a 10 dB gain at that frequency.

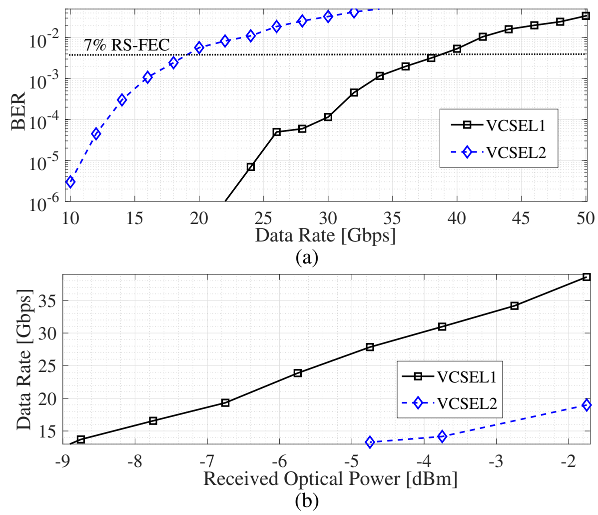

Fig. 5: Plots of: (a) BER versus data rates and (b) Achievable data rates at 7% RS-FEC limit versus received optical power

Fig. 5a presents the BER performance for various data rates for both VCSELs. At a BER of 10^{-5}, VCSEL2 achieves a data rate of ∼11 Gbps, whereas VCSEL1 achieves ∼24.5 Gbps. At the 7% Reed-Solomon forward error correction (RS-FEC) limit (i.e., BER of ∼0.0037) [14], VCSEL1 and VCSEL2 achieve data rates of ∼38 Gbps and ∼19 Gbps, respectively, i.e., VCSEL1 can achieve twice the maximum data rate than VCSEL2 under almost identical conditions. Consequently, the SM-VCSEL demonstrates superior data rate performance than the MM-VCSEL under eye-safe conditions.

Misalignments and extensions of the OWC link reduce the ROP, thereby reducing the SNR and data rate. Hence, Fig. 5b depicts the data rate at the 7% RS-FEC limit for various ROPs from -9 dBm to -1.75 dBm. At a data rate of 15 Gbps, VCSEL1 and VCSEL2 require ROPs of ∼-8.3 dBm and ∼-3.4 dBm, respectively. Moreover, VCSEL1 and VCSEL2 need ROPs of ∼-6.8 dBm and ∼-1.8 dBm, respectively, to achieve a data rate of 19 Gbps. This indicates that for both VCSELs, the data rate increases by ∼2.7 Gbps for every 1 dB increment in ROP. Furthermore, VCSEL1 offers about 5 dB optical SNR gain over VCSEL2 for similar data rates. With VCSEL1, gross data rates of ∼33.5 Gbps and ∼18.5 Gbps can be attained at ROPs of -3 dBm and -7 dBm, respectively. For error-free transmission with FEC, these data rates translate to ∼31 Gbps and ∼17 Gbps. This clearly indicates that the custom-made SM-VCSELs offer significantly higher data rates than the commercial VCSELs, and they are suitable for high-speed OWC systems.

V. Conclusion

We have experimentally demonstrated the OWC system performance based on a custom-made SM-VCSEL from ICS & CSC and a commercial MM-VCSEL (OPTEK OPV310) for a 2.5 m link using bit-and-power-loaded DMT. While the MM-VCSEL offers a similar modulation bandwidth and higher transmitted optical power than the SM-VCSEL, the SM-VCSEL provides the advantage of a lower RIN, enabling communication with higher speeds at lower optical powers than the MM-VCSEL. Hence, a record-high data rate of 38 Gbps is achieved at the 7% RS-FEC limit with the custom-designed SM-VCSEL with an eye-safe transmitted optical power of ∼-1.47 dBm, while the MM-VCSEL offers just 19 Gbps under similar ROP conditions. Therefore, the SM-VCSEL exhibits promising potential for high-speed OWC links while adhering to the eye-safety requirement.

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