High-Capacity Optical Wireless VCSEL Array Transmitter with Uniform Coverage

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ABSTRACT

Optical wireless communication (OWC) promises high-speed data transmission of multiple Gb/s per user and aggregate capacities beyond Tb/s. To achieve such data rates in an eye-safe environment, we envisage an array of arrays of optical emitters, with each emitter addressing a small atto-cell. To realise this vision, each array emitter must provide uniform illumination of the desired atto-cell while minimising interference to adjacent cells. Vertical Cavity Surface Emitting Laser (VCSEL) is an attractive optical emitter for such a design due to their high modulation bandwidth (BW), circular beam waist, low cost and commercial availability of low cost arrays in the near-infrared spectrum. However, available arrays are typically multi-mode devices developed for data communications, often exhibiting a doughnut-shaped beam profile. If used with a simple lens arrangement, the resulting illumination shows non-uniform SNR over the intended atto-cell area and interference into adjacent cells. In this work, a 5×5 VCSEL-array-based OWC multi-beam transmitter using microlens arrays is designed to homogenise each VCSEL output beam intensity at the receiver plane. The performance of the proposed transmitter is verified in simulation and experiments, demonstrating a beam intensity uniformity of up to 90% over a 1 m^2 square area and 25.5 mW/m^2 uniform irradience distribution for each atto-cell area. We demonstrate the data transmission capability of a single array element achieving an 8 Gb/s data rate for a single channel using OOK modulation and Decision Feedback Equalization (DFE) with a Silicon Photomultiplier (SiPM) over a 3-metre free space link.

Keywords: Optical wireless communication, vertical-cavity surface-emitting laser, beam homogeniser

1. INTRODUCTION

With multimedia services and applications continuously evolving, an exponential increase in mobile data traffic is anticipated to impose great demands on the capacity of wireless communication links (5016 EB/month in 2030) [1]. However, the radiofrequency (RF) spectrum is limited, heavily congested and highly regulated, leading to the consideration of the use of other frequency bands to overcome the foreseen bandwidth crunch in wireless communications [2].

Optical wireless communications (OWC) is a promising solution to RF congestion issues because it can provide high-speed data access of multi-Gb/s while supporting multiple users. The available spectrum of OWC, which includes the visible (380 - 750 nm) and infrared (IR) spectrum (750 nm-1 mm), offers more than 20,000 times bandwidth capacity than the RF spectrum and is license-free[3]. In OWC links, near-infrared VCSEL sources are considered for use in indoor environments to achieve a Tb/s optical wireless communication system because such devices are low-cost, exhibit high power efficiency and offer higher bandwidth (> 5 GHz). They can also be readily formed into 2D arrays [4]. A few such VCSEL-based OWC systems have been proposed. For example, an OWC system using a VCSEL array was studied by Sakai et al. in [5]. The system was equipped with a diffuser and a reflective surface to shape the output beams from multiple VCSELS into a single pill-box light intensity distribution beam profile. In [6], T. Nakamura et al. studied an OWC system based on a high-power 940 nm VCSEL. Dong et al. proposed a two-user QAM–OFDMA OWC system using a 940 nm VCSEL array. With a working distance of over 2 m, the system demonstrated an aggregate data rate of 2.7 Gb/s [7]. A 3-meter 850 nm VCSEL OWC system with 1 GHz modulation bandwidth was proposed by Z. Wei et al. in [8]. These reported VCSEL-based OWC systems have been focused on single-channel communication with point-to-point wireless links offering high data rates over relatively long communication distances but do not address the issue of indoor atto-cell coverage and user mobility. Moreover, available VCSEL arrays developed for data communications are multi-mode devices, which provide a doughnut-shaped beam profile. This means that if they are used with a simple lens arrangement, the illumination shows a no-signal zone at the centre of the atto-cell area and interference between adjacent cells.

In this work, a 5×5 VCSEL array-based OWC multi-beam transmitter is designed. Microlens arrays are used to homogenise each VCSEL output power at the receiver plane. The performance of the proposed transmitter is verified in simulation using off-the-shelf lenses. The design provides a beam intensity uniformity of up to 90% over a 1 m^2 area. The transmitter also ensures class-1 eye safety standards because each VCSEL optical output power satisfies the Maximum Permissible Exposure (MPE) at the most hazardous position [9]. In addition, we experimentally demonstrate the data transmission capability of a single array element achieving an 8 Gb/s data rate for a single channel using OOK modulation and Decision Feedback Equalization (DFE) with a Silicon Photomultiplier (SiPM) over a 3-metre free space link and 5mW/m^2 uniform power distribution for each atto-cell area.

2. DOWNLOAD TRANSMITTER DESIGN

An Arrays of Arrays of VCSELs to provide wide coverage and aggregated data rate of Tb/s has been proposed and it is illustrated in Figure. 1.[4] An access point is formed of multiple transmitters, each one oriented in a different direction to cover the entire space. Each transmitter includes a 5 × 5 VCSEL array to cover a 1 × 1 m area, with each individual VCSEL illuminating a 20 ×20 cm area. Assuming no multiplexing techniques are employed, each VCSEL in the array can serve one user within its illumination area. As a result, the proposed VCSEL-based transmitter can serve 25 users in a 1 m^2 area, if no two users occupy the same VCSEL cell.

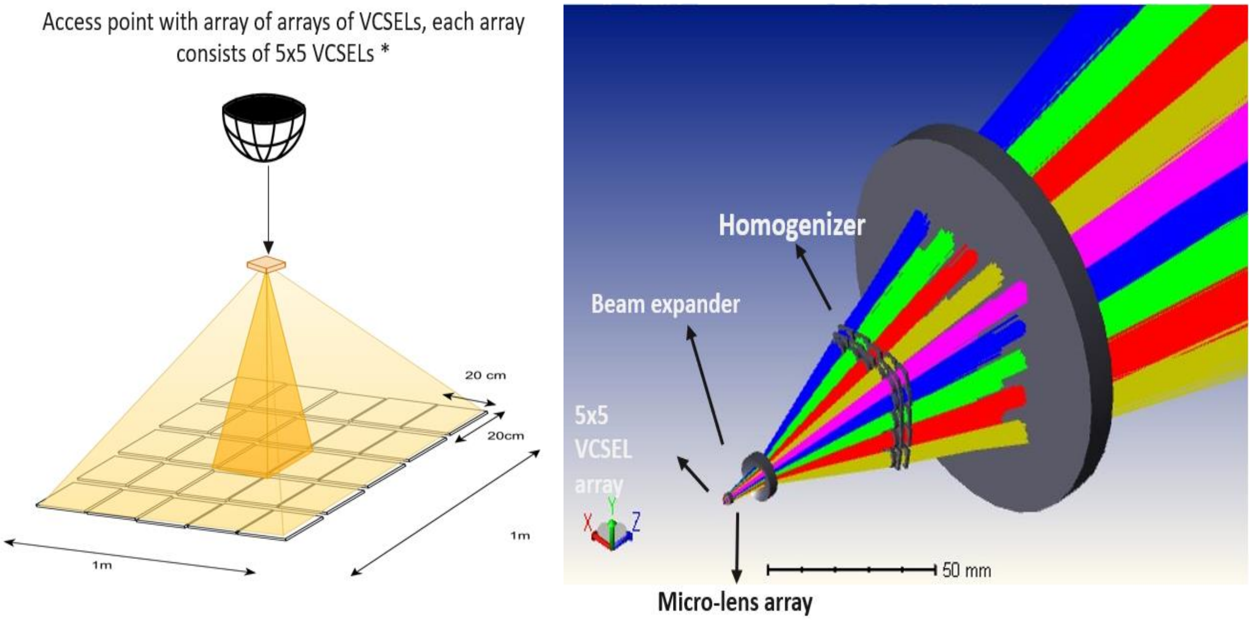

Figure 1.(a) the concept of Arrays of Arrays of VCSELs system (b) the schematics of each VCSEL array transmitter

Figure 2 shows the design of the full transmitter system with the main components annotated. The beam emitted from each VCSEL on the VCSEL array is first collimated using a microlens array (MLA1) with the same pitch as the VCSEL array. A pair of Plano-concave lenses (PCV1 & PCV2) is used to generate the required separation between the output beams and allow the insertion of a beam homogeniser system (PCX, MLA2 and MLA3) on each individual beam path. Each VCSEL beam is collimated by a plano-convex lens and shaped into a flat top profile by the respective beam homogeniser. The last plano-convex lens (PCX2) acts as a Fourier lens to form the desired image at the image plane. The total length of the designed transmitter optical system is 11 cm.

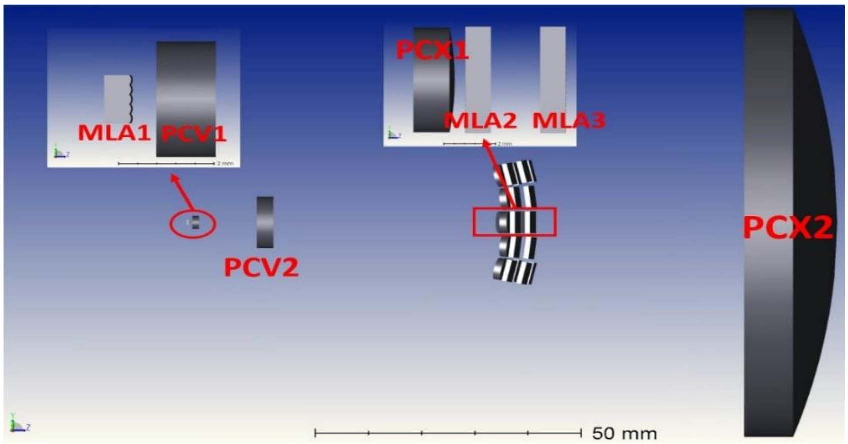

Figure 2. the downlink transmitter optical system design

The structure of the homogeniser is shown in figure 3. It consists of a pair of microlens arrays (MLA2 & MLA3) and a Fourier lens (FL). The incident beam is divided into multiple beamlets by MLA2, while MLA3 acts as an objective lens array, superimposing the image of each sub-beamlet in the MLA2 [10]. These two MLAs have the same size, material, and radius of curvature for lens alignment convenience. The diameter of the flat-top beam profile D_{FT} generated by the optical system can be expressed by:

$$D_{FT} = P_{LA} \frac{f_{FL} \cdot (f_{LA2} + f_{LA3} - a_{23})}{f_{LA2} \cdot f_{LA3}} \qquad (1)$$

where P_{LA} is the pitch of MLA2 and MLA3, f_{LA1} and f_{LA2} are the focal lengths of MLA2 and MLA3, respectively, a_{12} is the spacing between MLA2 and MLA3 and f_{FL} is the focal length of the Fourier lens. The separation a_{12} between two microlens arrays is chosen to equal the focal length of MLA2 in order to fulfil the imaging conditions [11]. As a result, eq. (1) can be simplified as:

$$D_{FT} = P_{LA} \frac{f_{FL}}{f_{LA}} \qquad (2)$$

Eq. (2) indicates that the diameter of the homogenised beam profile D_{FT} depends on the pitch of the microlens array P_{LA}, and the focal length of the microlens array f_{LA}. We assume that the working distance f_{FL} has been determined by the geometry of our OWC system (i.e. The distance of the last plano-convex lens to the imaging plane). The shape of the output beam depends on the shape of the microlens; therefore, different types of microlens arrays can be used in the setup, such as square, cylindrical or hexagonal generating different cell shapes.

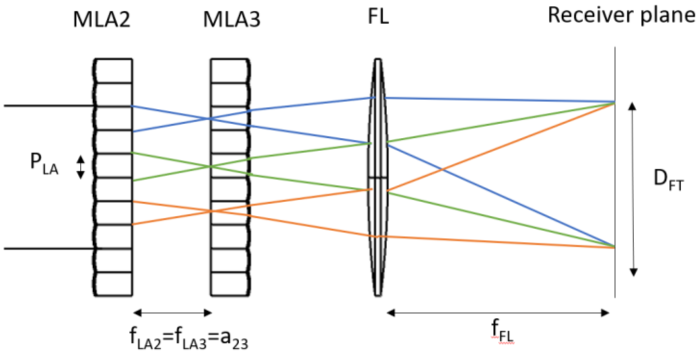

Figure 3. Structure of the beam homogeniser using a pair of microlens arrays.

3. RAY TRACING SIMULATIONS

3.1 Simulation results

The design of the optical transmitter system was verified with the ZEMAX ray tracing software using realistic parameters for the VCSEL pitch and beam output profile. A doughnut-shaped output beam profile was assumed for each VCSEL, while the VCSEL pitch of VCSEL was set to 250 µm to match the standard pitch of conventional VCSEL arrays [12]. The parameters of lens components are summarised in Table 1. Although such optical components could be custom-made, we matched the system design to use the closest available off-the-shelf optical components. The system using 'closed' off-the-shelf optical lens products is simulated and compared to the result based on the optimised lens components. In the simulation, the output power of each VCSEL is 6 mW and the distance from the VCSEL array to the imaging plane is 3 m.

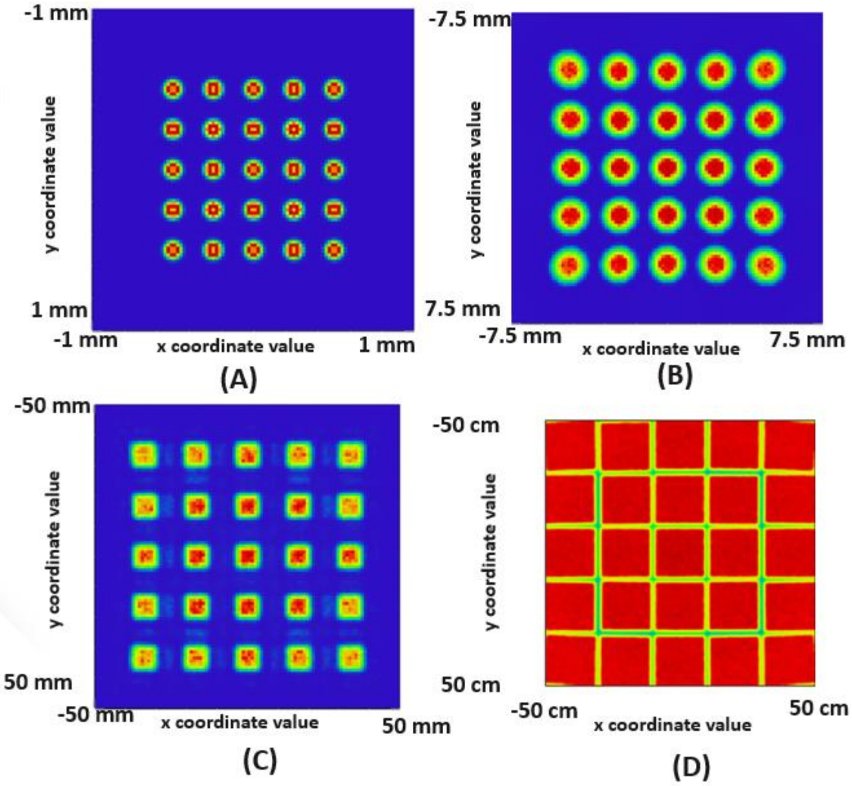

Figure 4. the 25 VCSEL beam spots aftereach stage of the transmitter (a) micrlens array (b) beam expander (c) homogeniser (d) receiver plane.

The beam spot shape transformation at each stage of the transmitter is illustrated in figure 4. In figures, the red area indicates high intensity and grean area indicates low intensity. The VCSEL laser provides a doughnut-shaped beam profile (figure 4a). However, a nearly gaussian beam profile is generated after the beam expander because it is set at the focal point of the microlens array (figure 4b). The beam spot is transformed into square beams with uniform power intensity after the homogeniser (figure 4c). Finally, a 1x1 m square coverage area is shown at the receiver plane at 3 m consisting of 25 square beams. The gap between the beams is around 3 cm from the full width at half maximum (FWHM) to the adjacent beam's FWHM to provide near ubiquitous coverage with minimal interference. The average irradiance of each cell is 11 mW/cm^2.

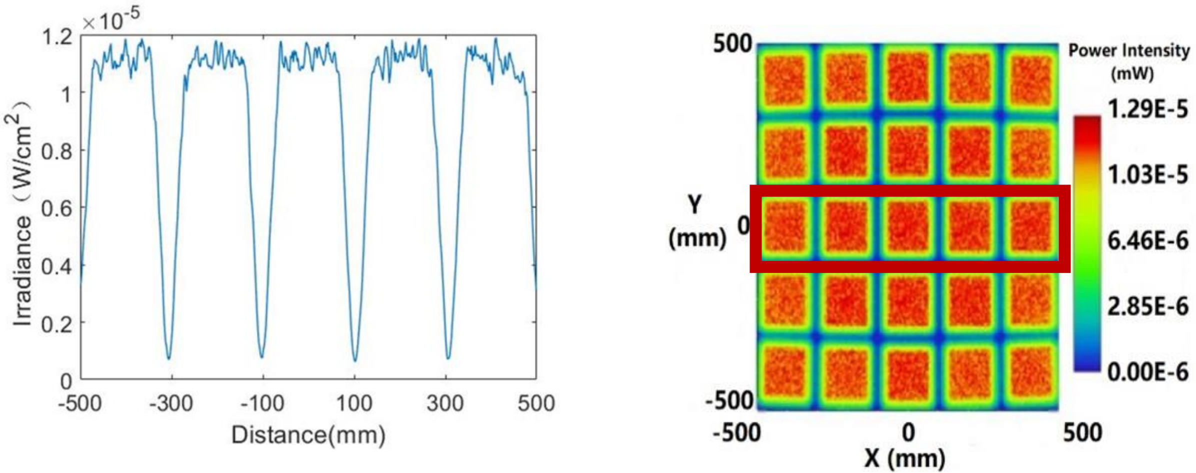

Figure 5. The cross-section of power intensity distribution and full map

Table 1. the parameters of the off-the-shelf components and optimised components (ROC: radius of curvature).

Components	**Optimised components**		**Off-the-shelf components**	
Parameter	ROC (mm)	Diameter (mm)	ROC (mm)	Diameter (mm)
1. Microlens array	0.22	0.25	0.25	0.25
2. Plano-Concave lens	5	3	4.71	3
3. Plano-Concave lens	10	9	9.42	9
4. Plano-Convex lens	15.5	4.9	15.5	5
5. Microlens arrays 1&2	3.5	0.52	2.2	0.3

4. EXPERIMENT RESULT

To experimentally test the transmitter designed in Zemax, 3D holders are designed for mounting optics. For MLA1, a metallic holder is designed as it requires very high precision and needs to be positioned just 0.16 mm away from the VCSEL active area. 3D holders for beam expander and homogenizer are formed by SLA printing with the precision of 0.1 mm. To provide proof of concept and avoid complexity, homogenizer is designed for three channels, out of which two channels coverage is verified due to setup limitations.

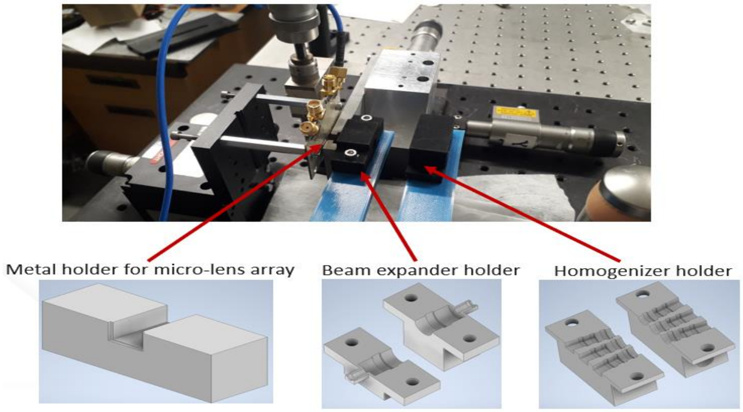

Figure 6. 3D housing lens holders for microlens array, beam expander and homogenizer

The holders for the MLA1, beam expander, homogeniser are shown in Figure 6. All holders are then mounted on the 3-axis stages for precise alignment. A 1×4 linear VCSEL array (ULM850-10-TN-N0104U) is integrated to a designed PCB for generating optical signal. The average output power of each individual VCSEL is 1.7 mW. VCSEL and lens holders are precisely positioned according to Zemax simulation values. An IR camera capture the beam profile projected onto a white screen at the 3m distance, the profile of two adjacent beams is shown in Figure 7 demonstrating 20cm x 20cm cells, where the receiver irradiance in the square area is 25.5 mW/m^2. Thetwo channels coverage clearly show that experimental results matched well with the simulation results

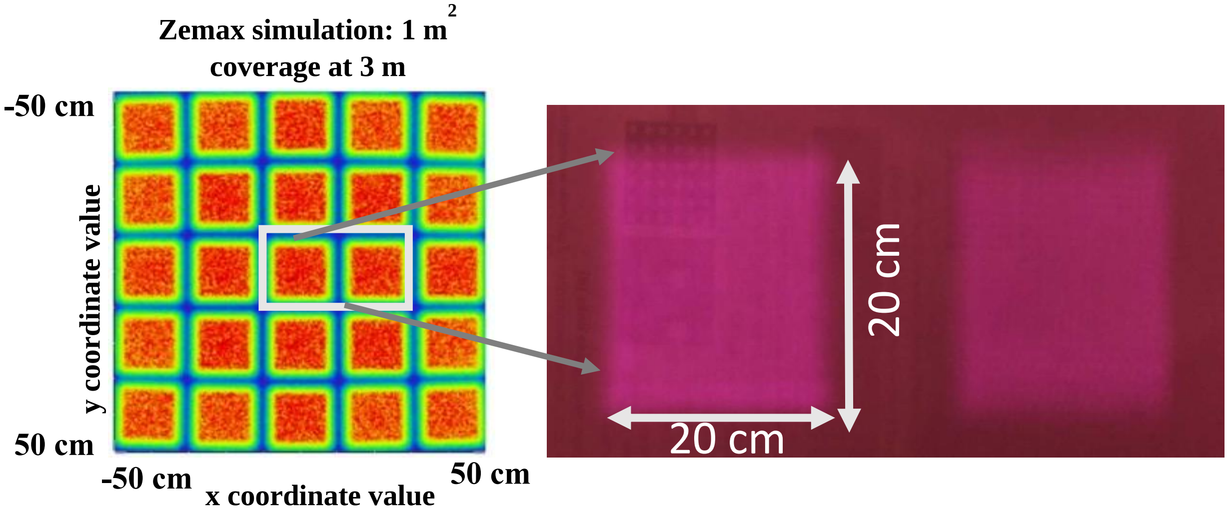

Figure 7. Two channels coverage at 3 m without FL lens (Image obtained using an IR Camera)

The designed transmitter is then employed to perform data transmission using the experimental setup shown in Figure 8 (a). On-Off-Keying (OOK) modulation data with 8b10b coding is generated using Arbitrary Waveform Generator (AWG). An amplifier is used after AWG to provide peak-to-peak voltage of 600mV because AWG peak-to-peak voltage is limited to 500mV . A VCSEL in the 1x4 array VCSEL chip is biased at 4mA and directly modulated using signal from the AWG. The receiver consisting of a 1 mm^2 SiPM is placed at a 3 m distance. SiPM is selected due to its better sensitivity compared to APDs and PIN photodiodes [13]. The SiPM has a full-width and half maximum pulse width (FWHM) of 0.6ns and 3dB bandwidth of 310MHz but higher data rates can be obtained thanks to its slow frequency roll off. The SiPM is enclosed in a box while a colour glass filter RG-780 is placed in front of it to block any ambient light. A 5 cm plano-convex lens is placed in front of the SiPM receiver to focus light on its active area. The signal from the SiPM is then amplified and recorded in the real time oscilloscope. Finally, the signal from oscilloscope is post-processed offline. It was low-pass filtered to minimize noise and for reducing the Intersymbol interference (ISI), Decision Feedback Equalization (DFE) is applied.

The experimental setup provided data transmission of 8 Gbps at BER of < 3.8x10^{-3}. An eye diagram for 8 Gbps is shown in Figure 8 (c). As we assume that each VCSEL performs at its maximum data rate (8 Gbps), the transmitter can achieve an aggerated capacity of at least 200 Gbps. Eye safety of the transmitter is evaluated by measuring the irradiance from the transmitter at 10 cm distance. The measured irradiance value is 8.5 W/m^2 which is less than the maximum permissible exposure (MPE) class 1 eye-safe limit of 19.95 W/m^2 at 850 nm.

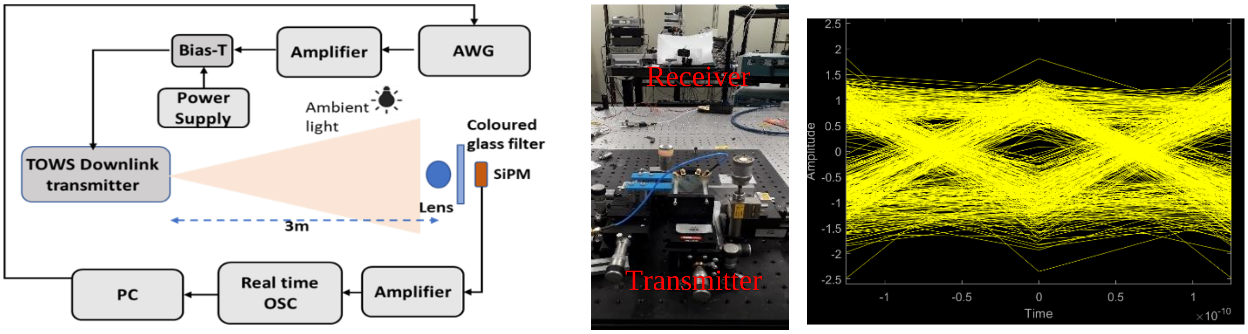

Figure 8. a) The VCSEL array based optical wireless experimental set up schematic, b) experimental setup, c) eye diagram for 8 Gbps at 3.8x10^{-3} BER.

5. CONCLUSION

We present a novel OWC transmitter employing a 5×5 multi-mode VCSEL array, plano-convex lenses and micro-lens arrays. It is shown that each VCSEL generates 90% beam uniformity across a square atto-cell of 20 cm × 20cm with low interference to adjacent cells. A single VCSEL experimentally achieves 8 Gb/s data transmission using OOK modulation and DFE over a 3 m link using a Silicon Photomultiplier (SiPM) receiver. The designed transmitter can therefore provide an aggregate capacity of up to 200 Gb/s over a 1 m² area, meeting future wireless demands.

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