European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Demonstration of 1.75 Gbit/s VCSEL-based Non-Directed Optical Wireless Communications with OOK and FDE

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Abstract *We evaluate a high power on-off-keying transmitter for non-directed optical wireless communications based on VCSEL-arrays. Error-free transmission after FEC with a net data rate of 1.75 GBit/s is achieved across a distance of 2.5 m with a coverage area of 3 m². ©2022 The Author(s)*

Introduction

Optical Wireless Communications (OWC) are increasingly considered as a suitable alternative to radio based wireless solutions, especially in areas where electromagnetic interferences are an issue, e.g. in production facilities or for sensitive medical devices. Light has further unique properties. It can be used for ultra-dense deployment scenarios to define sharply limited optical communication cells with minor overlap. This keeps interference limited to adjacent cells only, thus making coordination less complex compared to radio frequencies. However, the widely used light-emitting diode (LED) based transmitters offer only around 100 MHz modulation bandwidth, even with optimized drivers. One can achieve few Gbit/s by means of spectrally efficient modulation, but this reduces the achievable range. This paper presents an alternative approach, i.e. increasing bandwidth by means of using vertical-cavity surface emitting laser (VCSEL) diode arrays instead of LEDs. VCSEL arrays are developed as flashlight sources for the emerging mass market of sensing applications, e.g. LIDAR. They have higher electro-optical conversion efficiency and higher modulation frequencies compared to LEDs, but similar optical properties. VCSEL arrays have enough power to illuminate large areas and the potential for modulation bandwidths in the GHz range. In this paper, we present for the first time a high-power VCSEL-based transmitter achieving more than 1 GHz cut-off frequency at an optical power of 0.56 W. With a special driver design, providing high bandwidth and high modulation current at the same time, we demonstrate a net data rate of 1.75 Gbit/s using OOK with frequency-domain equalization (FDE) over 2.5 m distance, covering an area of 3 m^2 with a bit error rate below 10^{-3}. Our results show that the mobility and bandwidth requirements to support OWC as a new physical layer in 6G can be met with components developed for LIDAR sensing applications.

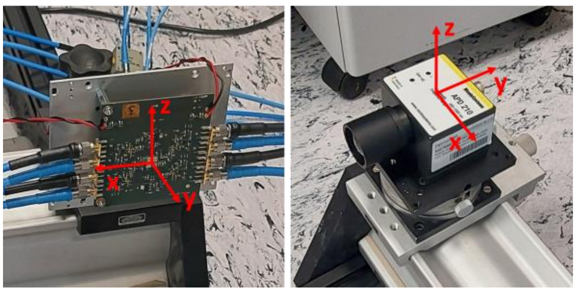

Fig. 1: Left: Transmitter prototype with four VCSEL arrays behind diffusors. Right: Commercial receiver (Thorlabs APD210) with 35 mm lens (diameter 25.4 mm).

State of the Art of VCSEL-Based OWC

In first VCSEL-based OWC trials, the optical emitters were coupled with commercial power line communication terminals [1], covering a distance below 40 cm. The transmission of 2.125 Gbit/s OOK signals over a distance of 2.8 m has been demonstrated in a static setup [2], but using a lens at the transmitter focusing the optical power onto the receiver. In a similar scenario, mobility of the receiving terminal was studied [3], demonstrating a covered area of 0.01 m^2 at 3 m distance at a data rate of 1.25 Gbit/s. Other works considered different lenses at the transmitter side and fiber-based beam steering to focus the transmitter power [4, 5]. Digital pre-equalization also achieved promising results reported in [6].

However, while Gbit/s data rates can already be achieved with VCSEL arrays, the coverage of larger areas has only been addressed by forming a narrow beam and steering it towards the receiver. These systems tend to have a high complexity and large form factors, which makes

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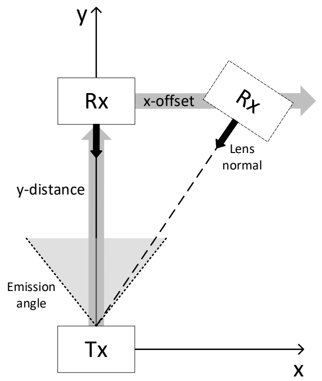

Fig. 2: Drawing of the experimental setup.

future integration challenging.

In this work, we follow the classical approach in mobile communications, i.e. provide enough power to cover a large area and increase the bandwidth to enhance performance. We demonstrate that high transmitter power can be reached by means of a limiting amplifier driver, which enables OOK at high symbol rates covering a 300-times larger area than the work mentioned above [3]. In contrast to the aforementioned works, moreover, our transmitter uses no lens and provides a wide beam. Emission is shaped by a diffusor attached to each VCSEL array. We use post- instead of pre-equalization to simplify the transmitter.

Experimental Setup

Our transmitter (Fig. 1, left) carries four VCSEL arrays, each with a nominal power of 140 mW and 10 emission apertures each. Diffusors are mounted on each VCSEL array, with an emission angle of 60° in the x-direction and 45° in the z-direction. The VCSEL arrays are driven by limiting amplifiers. They are biased at the threshold current and a modulation current of 170 mA is used.

On the receiver side, a commercial avalanche photodiode (APD) receiver with a 3 dB bandwidth of 5 to 1000 MHz is used (Thorlabs APD210, Fig. 1, right). It is combined with a lens with a diameter of 25.4 mm and a focal length of 34.9 mm located at a distance of 30 mm from the APD. To focus the optical power on the photodiode, alignment of the receiver is required in the lab. A receiver design with a large area photodiode with wide field-of-view, relaxing this requirement, is subject of ongoing research.

A drawing of the experimental setup is shown in Fig. 2. The receiver (Rx) is placed at distances of 1, 1.75, and 2.5 m from the transmitter (Tx), denoted as y-distance, and then moved at distances between 0 and 1.2 m from the y-axis, denoted x-offset. At every position, the receiver is rotated so that the lens is aligned with the transmitter, as shown by the dashed Rx.

The transmitted OOK-signals follow the PM-PHY defined in IEEE P802.15.13 [7]. 8B10B line coding is used to minimize high-pass distortions. Blocks of 1024 symbols are formed and cyclic prefixes (CPs) of 128 symbols are inserted to enable FDE, yielding an additional overhead of 12.5%. Overall, this results in a net data rate of 70% of the symbol rate. For channel estimation, balanced Gold sequences [8] are inserted. Zero-forcing FDE is used at the receiver. Digital signal processing is carried out offline in MATLAB, with signals being transmitted from a Keysight M8190A AWG and recorded on a LeCroy WavePro 804HD oscilloscope with a sample rate of 20 GS/s. Per measurement, 65.536 data bits are transmitted in the payload.

Results and Discussion

In a first step, signals are transmitted across 1 m y-distance without x-offset for symbol rates of 1, 1.5, 2, 2.5, and 3 GBd, corresponding to net data rates of 0.7, 1.05, 1.4, 1.75 and 2.1 Gbit/s, respectively. The spectra of received signals with 1 and 2.5 GBd are shown in Fig. 3a. Beyond 1 GHz, strong attenuation can be observed due to the limited bandwidth of the receiver. In the 1 GBd spectrum, a distinct line is observed at the clock rate.

Figs. 3b and 3c show the distortions occurring on the time-domain representation of received signals at symbol rates of 1 and 2.5 GBd,

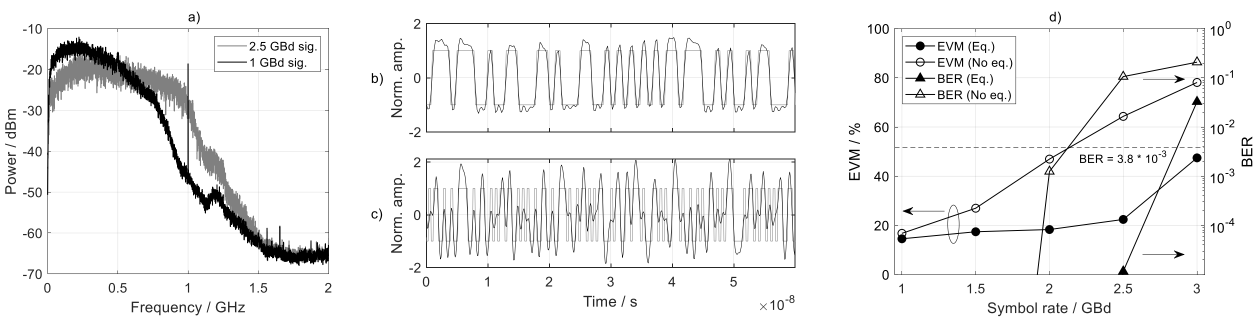

Fig. 3: Baseline performance over y-distance 1 m without x-offset. (a) Spectrum of received signals (incl. estim. sequences). Transmitted (gray) and received (black) waveforms for (b) 1 GBd and (c) 2.5 GBd. (d) EVM and BER over symbol rate.

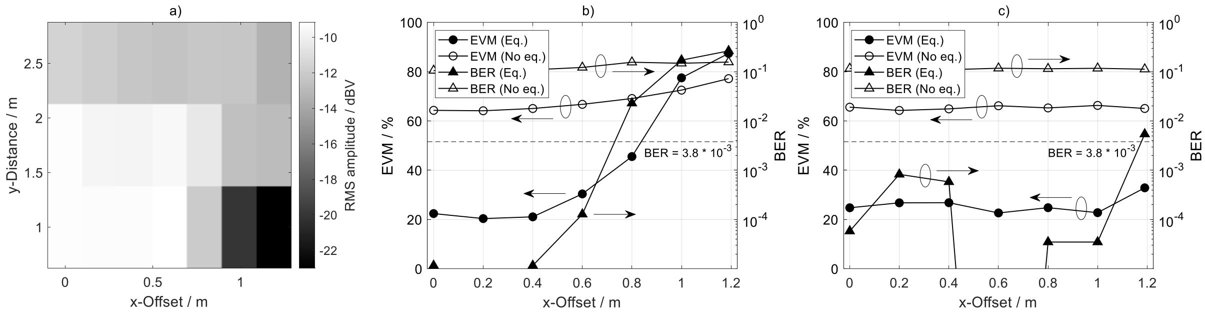

Fig. 4: (a) Measured RMS amplitude over x-offset and y-distances for symbol rate 1 GBd. BER and EVM for symbol rate 2.5 GBd over x-offset at y-distances (b) 1 m and (c) 2.5 m.

respectively. In the case of 1 GBd, the negative side of the waveform in comparison with the positive side shows lower variation of symbol amplitudes and no sloping “rooftops” of longer symbols. This is most likely due to the biasing of the VCSEL arrays at their threshold current. The additional baseline variation is caused by the high pass characteristic at the receiver. The 2.5 GBd waveform does not exhibit this effect, but clearly shows the attenuation of short pulses due to the low pass cut-off at around 1 GHz. Note that the displayed waveforms are normalized with respect to their RMS amplitude and zero-mean.

The EVM and BER metrics are shown over symbol rate in Fig. 3d, each for demodulation without equalization (No eq.) and zero-forcing equalization in the frequency domain (Eq.). Both metrics are shown, as the number of transmitted bits is limited. For reference, a BER limit of $3.8 * 10^{-3}$ is shown by a horizontal dashed line. Below this limit, error-free operation can be expected when using an adequate forward error correction (FEC). The graphs show that without equalizer, the BER stays under this limit up to a symbol rate of 2 GBd in our setup. Equalization enables symbol rates up to 2.5 GBd while maintaining a BER below 10^{-4}.

The performance variations over x- and y-distance are shown in Fig. 4. The optical power distribution is evaluated based on the RMS amplitude of the electrical output signals of the receiver in Fig. 4a. The brighter fields in the lower left corner show the highest signal power at a short y-distance and a small lateral x-offset. For x-offsets beyond 0.6 m, the received power drops at short y-distances, marking the edge of the emission cone. At the y-distance of 2.5 m, a significant decrease in received power is observed due the larger covered area. The uneven distribution of optical power is due to the propagation characteristics of the VCSEL arrays and the diffusors.

Fig. 4b shows EVM and BER values over x-offset at a y-distance of 1 m for a symbol rate of 2.5 GBd. The results without equalization show a consistently high error level, caused by the low-pass effect at higher symbol rates as observed in Fig. 3. At low lateral x-offset values, and correspondingly high signal power levels, the equalizer can compensate the low-pass distortions to a large extent, showing in the large margin between the equalized and non-equalized performance. The increasing EVM towards higher x-offsets aligns with the observed decay of signal power (see Fig. 4a).

At 2.5 m y-distance (Fig. 4c), the EVM of the equalized signal shows less variation, staying between 22 and 28% up to 1 m x-offset, with a smaller uptick for an x-offset of 1.2 m. This also aligns with the previous observations of signal power, which varies less across the x-offset range at the larger y-distance due to the transmission angles being smaller. The BER remains below 10^{-3} for x-offsets up to 1 m, but it varies notably over the whole range. Since the emission angle of the used diffusors in the z-direction (45°) is 75% of the angle in the x-direction (60°), the total covered area at which the BER limit is fulfilled amounts to 3 m^2 at the y-distance of 2.5 m.

Notably, the magnitude of EVM of equalized signals at 2.5 m y-distance is only slightly higher than the one observed at 1 m y-distance for low x-offsets. This implies that non-linear distortions may limit the performance at high signal power rather than receiver noise.

Conclusions

We demonstrate a VCSEL array based OWC transmitter that is capable of transmitting OOK signals with a symbol rate of 2.5 GBd, corresponding to a net data rate of 1.75 GBit/s, with a BER below 10^{-3}. A distance of 2.5 m is crossed, covering an area of 3 m^2. The integrated limiting amplifier driver allows low-power operation in future mobile devices. The main bandwidth-limiting factor is the commercial APD-receiver. We expect that a custom-made receiver can exceed the results shown here and will ease the requirement of receiver alignment.

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