VCSEL-Based Optical Wireless Transmission: New Research Prospects

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Abstract: The fundamental features of VCSELs make them very suitable for various types of optical wireless communications, especially over short links. We present a range of promising applications for these devices in new OWC areas.

1. Introduction

Optical Wireless Communications (OWC) is increasingly investigated as a powerful complementary technology to RF wireless, with strong potential in various wireless communication areas [1]. Each of those can have very different requirements in terms of data rate, user mobility and specific optical properties of the operational environment. All the requirements contribute to determine the preferable OWC configuration, from directed line of sight (D-LoS, quite narrow beams) to non-directed line of sight (ND-LoS, wide-angle beam), to even non-line of sight (N-LoS, large beams exploiting scattering from walls and objects). A remarkable key point is that, in the different domains, we will prefer an OWC transmitter (TX) using a specific type of light source, among a wide choice of different devices: as an example, LEDs are proposed for high-speed indoor OWC, also indicated as LiFi [2], whereas 1550 nm lasers for fiber communications can be also exploited in high-speed satellite links [3].

In this framework, in some new and encouraging realizations, a key role is being played by commercial VCSELs, whose peculiar features make them promising candidates for selected OWC systems [4]. Mostly, they have circular beam with limited divergence (~10°) and, moreover, the large modulation bandwidth allows for compact high-speed TXs with direct modulation. Hence, VCSELs are particularly suited in D-LoS configurations, where we need quite accurate alignment, high data rate and limited size. Usually, the OWC system configuration includes a distance that is determined by the need of collecting a suitable level of optical power at the receiver (RX). As most of commercial VCSEL have limited power, the typical link distance is few meters. However, recent realizations show that high-bandwidth VCSEL arrays can also attain high output power: these are promising for further developments. Another important key parameter is the choice of the wavelength. As it is possible to produce VCSELs at different wavelengths, this allows the flexibility to choose the best option, depending on the specific application target, among, of course, the various devices meeting the transmission requirements.

In the following, we report recent research results about selected OWC system implementations, based on VCSELs, covering from High Energy Physics (HEP) to datacenter, till space applications. The OWC scenarios are very different and new, thus they are not yet deeply explored and limited literature is available. This leaves open the way to relevant innovation in OWC area.

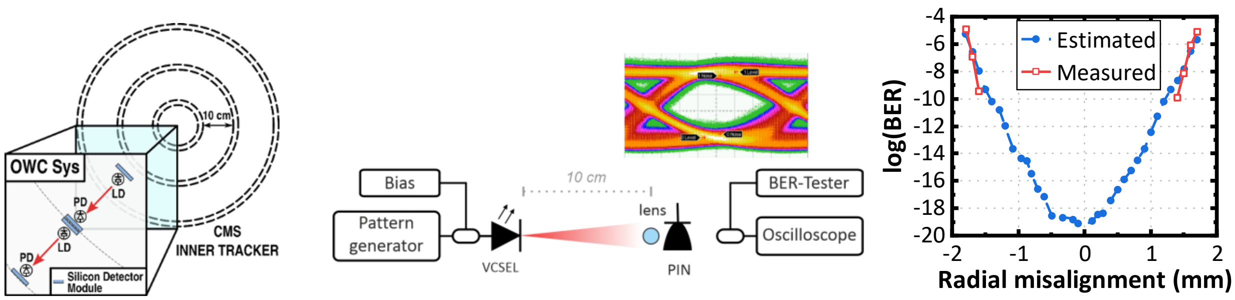
2. OWC Systems for High Energy Physics

A typical experiment in HEP, such as the Compact Muon Solenoid (CMS) at CERN, consists of about 10,000 silicon detector modules arranged in layers. These detector modules are fixed on concentric barrels, separated by few centimeters. Currently, the readout of data is performed by means of a huge number of optical fiber links (≈40,000), with a very high material budget and strong space limitations. Yet, future experiments will generate much higher data volumes: hence, OWC is currently being proposed for next-generation CERN experiments. Distances and data rates are fully compatible with VCSEL-based OWC: indeed, distances can range from few centimeters to some meters, whilst the signal bit rate is expected to be from few Gbit/s to tens of Gbit/s. Both features depend on the elements to be connected.

Based on our preliminary analysis, we selected the configuration of direct OWC links among two neighbor elements along the same radial direction in two concentric barrels. This solution enables to collect data locally, either for further processing (and size-shrinking) or direct high-speed wired link. The distance is then quite limited, i.e., 10 cm at maximum. In Fig. 1, we show the selected configuration in a typical HEP experiment (a), then we report the scheme of our lab setup (b). Here, we have demonstrated transmission up to 2.5 Gbit/s using a single off-the-shelf VCSEL (1550 nm wavelength, 1 mW output power and 16◦full width divergence at half-maximum) at the

TX. The RX consisted of a pin and a ball lens. The photodiode has 3-dB bandwidth of 1.8 GHz and a trans-impedance amplifier (TIA).

The on-axis performance is practically error-free: we measure a Q factor of around 9, which would correspond to 10^{-19} BER. However, a key parameter is the tolerance to misalignment, because TX and RX should be mounted in precise positions of the boards and could not be moved. Hence it is important that TX and RX will properly work, once placed at their optimal points within the mechanical tolerance. Noteworthy, the HEP mechanical precision is around 100 µm. In all experimental realizations we never found a tolerance to misalignment lower than 1 mm: this value indicates that the expected system is compatible with the above requirements. Further studies have finally confirmed that the used OWC devices (both pin and VCSEL) are tolerant to large X-ray irradiation (tests carried out with total dose of 238 Mrad) [5].



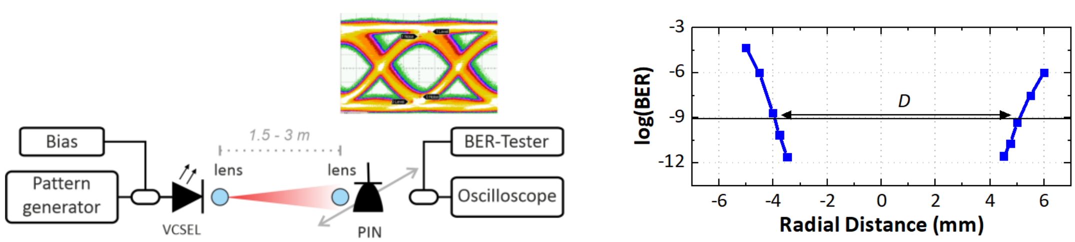
(a) (b) (c)

Fig. 1. Selected configuration for OWC in HEP (a); experimental setup with eye diagram (b), BER measurements (c)

3. OWC Systems for Data Centers

Data Centers (DC) are growing at steady pace [6]. Yet, the rise of intra-DC traffic comes with dramatic issues about connectivity, reconfigurability and power consumption: these links use today optical fibers, which give practical issues, e.g., about large amounts of fiber cables in limited spaces or reduced air recirculation for thermal dissipation. Therefore, alternative types of high-speed wireless systems are attracting attention. Whereas radio-frequency (RF) systems cannot reach the needed data rates, OWC indeed has demonstrated the potential for huge capacities [7], thus it is an attractive solution; as example, OWC can connect Top-of-the Racks (ToR) switches. Among the various OWC-DC network architectures proposed, straight connection of ToR by VCSEL-based OWC could be particularly effective. Indeed, VCSELs are particularly suited to get these high-rates, thanks to limited divergence and high modulation bandwidth. First, we used a 1310 nm-VCSEL (6 GHz bandwidth) with OOK modulation to transmit 10 Gbit/s over up to 3 meters [8]. The setup now included ball lenses at TX and at RX, as shown in Fig. 2 (a). Without Forward Error Correction (FEC), the alignment tolerance was around ±4 mm at 3-meter distance. Noteworthy, longer distances could be achieved, though not yet measured, whilst the bit rate was limited by the modulation bandwidth: this was overcome by means of Discrete Multi-Tone (DMT) modulation. Namely, using again a 1310 nm-VCSEL we achieved 24 Gbit/s DMT transmission over 1.5 m [9], finally, by a 1550 nm VCSEL with DMT we reached 40 Gbit/s over 80 cm.

In all above cases, the OWC performance was affected by the VCSELs limited bandwidth and low emission power. Recently, VCSELs are available with much improved features [10], thus we can correctly expect that DC-OWC links will achieve much higher rates and longer distances, in the near future.



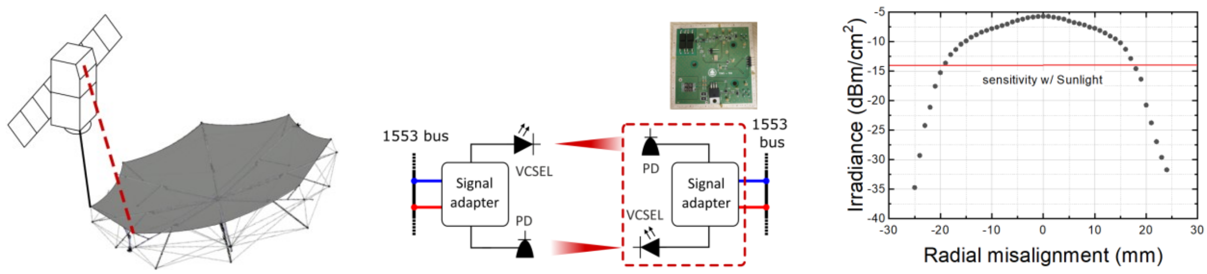
(a) (b)

Fig. 2. Setup of 10 Gb/s OWC for DCs (inset: 10 Gb/s eye diagram) (a), and BER values vs. misalignment (b)

4. OWC Systems for short-distance space links

A new emerging area for OWC is in space communications. Namely, the recent developments of intra-spacecraft (I-SC) and extra-spacecraft (E-SC) OWC links allows to design spacecraft networks that can transfer data without wires, with enhanced flexibility and lower costs [12]. This requires to realize OWC systems that support the bus types currently deployed on board, such as MIL-STD-1553. E-SC links are used to connect different external elements (e.g., star tracker, advanced smart active antennas, deployable reflectors) to the outer hub, which is then connected to the inner central unit. Whilst intra-spacecraft links rely on high-power LEDs at 850 nm [13], E-SC OWC links need low power, and high directionality. Moreover, in E-SC, narrow optical spectrum is required, to allow for narrow filtering at the RX, which removes most of the strong background Sunlight. Thus, a VCSEL-based TX is the most suitable choice. In this case, we realized an OWC TX emitting at 850 nm (0.85 nm spectral width, 4 deg. divergence and 1 mW output power). This allows to realize a MIL-STD-1553 link that is robust to the Sunlight conditions and provides good tolerance to misalignment. The system was indeed assessed in the lab, using an auxiliary source emulating the sunlight intensity (after optical filter), giving a misalignment tolerance of ±20 mm in the worst-case condition (sun aligned to the TX-RX axis).

Finally, we tested various VCSEL devices, emulating the typical space-grade qualifications, thus assessing their tolerance to strong mechanical stress, high temperature variations and strong X-ray irradiation. After (and during) all tests, the VCSELs were successfully tested with no significant degradation [14].



(a) (b) (c)

Fig. 3. Example of E-SC OWC link (dashed red line) (a); experimental setup for E-SC OWC (inset: OWC board) (b) BER measurements taken with auxiliary source emulating the sunlight (c).

3. Conclusion

VCSEL-based OWC systems have a strong potential for future deployment in new application areas: the obtained results confirm that VCSEL sources can be fruitfully exploited to solve the user needs, as they can provide wireless transmission of data, in compliance with strict and very specific requirements. This further supported by strong tolerance to X-ray radiations and extreme space conditions [14]. Moreover, the recent advancements in VCSEL technology [10] allow to expect that very interesting opportunities and applications are still to be explored

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