High-Speed VCSELs for Datacom

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Abstract *VCSEL-MMF is the dominating technology for short-reach optical interconnects in datacenters and high performance computing systems at current serial rates of up to 25-28 Gb/s. This is likely to continue at 50-56 Gb/s. The technology shows potential for 100 Gb/s.*

Introduction

The short-reach optical interconnects used in datacenters (DCs) and high performance computing (HPC) systems are dominated by vertical-cavity surface-emitting laser (VCSEL) and multimode fiber (MMF) links[1]. The VCSEL-MMF technology is the most cost-efficient due to low VCSEL manufacturing and packaging costs enabled by wafer-scale testing and screening, the self-hermeticity of the VCSEL, the large alignment tolerance to the MMF and the use of plastic coupling optics. In addition, with a multimode (MM) VCSEL, there is no need for an optical isolator. VCSELs also offer the highest energy efficiency and smallest footprint which is of great value for applications where power consumption and bandwidth density are important metrics, such as HPC[2].

To meet demands for higher capacity, optical interconnects have evolved to higher lane rates and more parallel architectures. For Ethernet[3], the serial rate for MMF links has increased from 1 Gb/s in 1998 (1000BASE-SX) to 10 Gb/s in 2002 (10GBASE-SR) and 25 Gb/s in 2015 (100GBASE-SR4). The latter uses 4 parallel 25 Gb/s channels. Other examples of parallel solutions are 100GBASE-SR10 (10 x 10 Gb/s) and 40GBASE-SR4 (4 x 10 Gb/s). The next serial rate, expected to be implemented in 2019, is 50 Gb/s (50GBASE-SR) which will enable higher capacity and higher bandwidth density parallel solutions such as 200GBASE-SR4 (4 x 50 Gb/s). Other standards with a projected serial rate of 50-56 Gb/s are OIF CEI-56G, 64G Fibre Channel, and Infiniband HDR.

At serial rates of 50-56 Gb/s it is likely that VCSEL-MMF solutions will continue to dominate the DC and HPC short-reach optical interconnect markets[1]. This assumption is based on recent demonstrations of 850 nm VCSEL-based links at or above this speed under OOK[4-6] and PAM modulation[7,8], with or without equalization and forward error correction (FEC). It is also supported by the cost, volume and power consumption advantages of VCSEL-MMF links as well as the fact that 90% of the DC interconnects are shorter than 100 m[1].

Looking forward it is of interest to understand whether VCSELs can support even higher serial rates, such as 100 Gb/s. Using parallel fibers this would enable an interconnect capacity of ~1 Tb/s. Further use of multiple cores per fiber or multiple wavelengths per core would bring the aggregate capacity to ~10 Tb/s while a combination of these techniques would enable interconnects with ~100 Tb/s capacity.

Datacom VCSELs – state-of-the-art

GaAs-based MM 850 nm VCSELs operating at 25 Gb/s (Ethernet) and 28 Gb/s (Fibre Channel) under OOK modulation are now in production[9].

Research on 850 nm MM-VCSELs has pushed the modulation bandwidth to 30 GHz[10] and enabled data transmission at 57 Gb/s under OOK modulation without equalization[5]. A VCSEL energy dissipation below 100 fJ/bit has been demonstrated at 25-50 Gb/s[10]. Transmitter and receiver equalization has enabled record speeds of 71 Gb/s at 25°C[6] and 50 Gb/s at 90°C[11]. State-of-the-art for GaAs-based VCSELs at other wavelengths include 980 nm VCSELs operating at 50 Gb/s at 25°C and 46 Gb/s at 85°C[12], and 1060 nm VCSELs operating at 28 Gb/s up to 75°C[13].

Long wavelength (InP-based) single-mode VCSEL for longer reach single-mode fiber interconnects have reached data rates of 40 Gb/s at 1525 nm[14] and 30 Gb/s at 1270 nm[15] under OOK modulation without equalization. With transmitter and receiver equalization, 56 Gb/s transmission at 1530 nm was recently demonstrated[16].

To further improve speed and reach of bandwidth limited VCSEL-based links, various higher order modulation (HOM) formats together with FEC and digital signal processing (DSP) have been investigated. An attractive format is PAM-4 due to relatively low complexity and power consumption. Achievements include 70 Gb/s at 850 nm[8] and 50 Gb/s at 1060 nm[17].

Other HOMs together with FEC and DSP, such as Duobinary PAM-4[18] and MultiCAP[19], have enabled data rates above 100 Gb/s at 850 nm.

For DCs, it is likely that the 50 Gb/s serial rate will use PAM-4 and FEC since this enables the use of 850 nm MM-VCSELs already in production. For HPC, the latency associated with FEC is not acceptable and higher speed VCSELs together with equalization under OOK modulation is the most likely solution.

In the following, after a discussion on VCSEL dynamics and speed limitations, some highlights from recent work at Chalmers on high speed 850 nm datacom VCSELs are presented.

VCSEL dynamics and speed limitations

The modulation speed of a VCSEL, just like any other semiconductor laser, is limited by the damping of the intrinsic modulation response, thermal effects due to self-heating and device parasitics[20].

The intrinsic modulation bandwidth is favoured by an active (gain) region with high differential gain, low gain compression and fast transport and capture of carriers, and a cavity with high optical confinement and reduced photon lifetime. Since the photon lifetime has a strong impact on the damping of the modulation response[21] it has to be set to an optimum value at the intended data rate to provide sufficient bandwidth while also providing enough damping to minimize degradation of the signal quality caused by inter-symbol interference[22].

Current-induced self-heating is minimized in a VCSEL with low thermal impedance, low electrical resistance and low internal optical loss, which is a trade-off in the design. The impact of device parasitics is mitigated by a reduction of VCSEL resistance and capacitance.

For multilevel modulation (e.g. PAM-4), other VCSEL parameters such as output power, slope efficiency and noise (relative intensity noise and mode partition noise) become more important.

High speed and high efficiency VCSELs

Our GaAs-based oxide-confined VCSELs at 850 nm (the standard wavelength for VCSEL-MMF interconnects) are designed with all speed limiting effects in mind[23]. The active region has strained InGaAs/AlGaAs quantum wells to enhance differential gain and is designed for fast transport and capture of carriers. A short optical cavity provides high optical confinement. Advanced interface grading and modulation doping schemes are used in the distributed Bragg reflectors (DBRs) to reduce resistance and optical loss while the bottom DBR is also designed for low thermal impedance. Multiple oxide apertures are used to reduce capacitance.

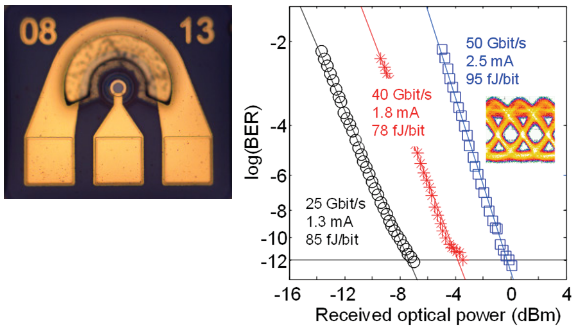

Fig. 1: A 30 GHz bandwidth 850 nm VCSEL with <100 fJ/bit energy dissipation at 25-50 Gb/s under OOK-NRZ modulation.

With an adjustment of the photon lifetime, such VCSELs reach a modulation bandwidth of 28 GHz[24] and have enabled OOK data transmission up to 47(40) Gb/s at 25(85)°C using a limiting optical receiver[25] and up to 57 Gb/s using a linear receiver[5] without equalization. They have also been successfully used for real-time 60 Gb/s PAM-4 transmission[7], 70 Gb/s PAM-4 transmission with equalization and FEC[8], and 56 Gb/s PAM-8 transmission with FEC[8].

More recently, by modifying the VCSEL design to improve the confinement of optical fields and carriers[26] we were able to reach a bandwidth of 30 GHz[10]. This also led to a large improvement of efficiency, with a VCSEL energy dissipation less than 100 fJ/bit at 25-50 Gb/s[10] (Fig.1).

Transmitter integration and equalization

For applications in optical interconnects, the high speed VCSEL is integrated with a driver IC in a transmitter module. Co-design and optimization and the use of pre-emphasis and equalization techniques to compensate for bandwidth limitations imposed by the VCSEL, fiber and photodetector have a tremendous impact on link performance and can enable data rates far beyond 50 Gb/s under OOK modulation.

In a collaborative effort with IBM (Yorktown Heights, NY, USA), a 26 GHz bandwidth 850 nm VCSEL was integrated with a SiGe BiCMOS driver IC with two-tap feed-forward equalization. This enabled 71(64) Gb/s OOK transmission over 7(57) m of OM4 MMF with the transmitter held at 25°C[4,6]. At a higher temperature of 90°C, data could be transmitted at a rate of 50 Gb/s[11].

With further improvements of VCSEL speed and dynamics, co-design and optimization of VCSELs and drivers, and the use of electronic compensation techniques (pre-emphasis, equalization, etc.) and HOMs together with FEC and DSP, a serial rate of 100 Gb/s over temperature seems feasible.

ISBN 978-3-8007-4274-5

VCSEL arrays for multicore fiber interconnects

A promising solution for higher aggregate capacity and higher bandwidth density optical interconnects is the use of multicore fibers (MCFs). With the VCSEL being a surface emitting laser it is ideal for this application as it enables dense 2D integration of VCSELs in a configuration that matches the distribution of cores in the MCF for direct butt-coupling.

To this end we have designed and fabricated dense 6-channel VCSEL arrays (Fig.2) for a 6-core MCF with 26 µm graded index multimode cores in a circular configuration. The core-to-core (and VCSEL-to-VCSEL) spacing is 39 µm.

Each VCSEL in the array supports 40 Gb/s transmission up to 85°C for an aggregate capacity of 240 Gb/s per fiber[27] (Fig.2) at no measurable crosstalk between channels[28].

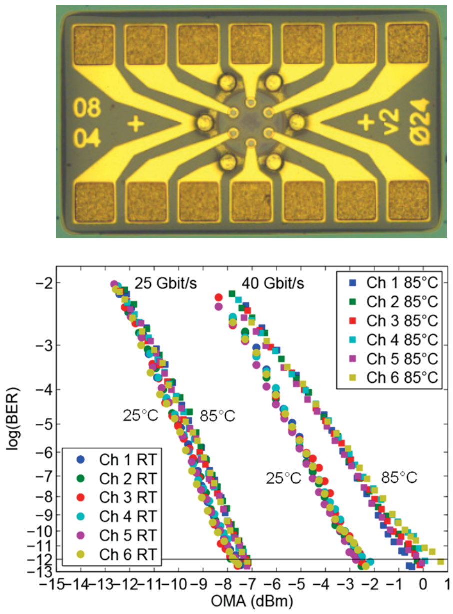

Fig. 2: 6-channel VCSEL array for a 240 Gb/s (40 Gb/s/channel) MCF optical interconnect.

Acknowledgement

This work was supported by the Swedish Foundation for Strategic Research (SSF), the Wallenberg Foundation, and the European FP7 project MERLIN (grant 607274).

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ISBN 978-3-8007-4274-5