VCSEL design and integration for high-capacity optical interconnects

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ABSTRACT

Vertical-cavity surface-emitting lasers and multi-mode fibers 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 Gbit/s. This is likely to continue at 50-56 Gbit/s. The technology shows potential for 100 Gbit/s.

Keywords: vertical-cavity surface-emitting laser, optical interconnect

1. 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 multi-mode 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. VCSELs also offer the highest energy efficiency and smallest footprint which is of great value for applications like HPC where power consumption and bandwidth density are important metrics [2].

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

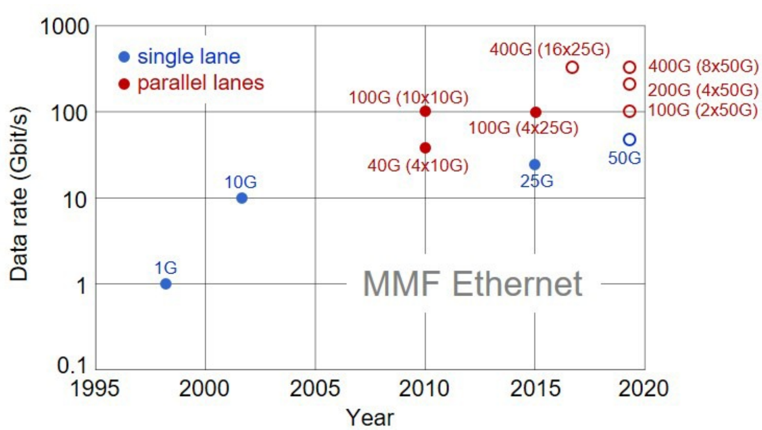

Figure 1. Evolution of the MMF Ethernet standard.

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At serial rates of 50-56 Gbit/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 demonstrations of 850 nm VCSEL-based links at or above this speed using OOK [4-6] and PAM modulation [7,8], with or without equalization and forward error correction (FEC). The use of such links 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 Gbit/s. Using parallel fibers this would enable an interconnect capacity of ~1 Tbit/s. Further use of multiple cores per fiber or multiple wavelengths per core would bring the aggregate capacity to ~10 Tbit/s, while a combination of these techniques could enable interconnects with ~100 Tbit/s capacity.

2. DATACOM VCSELS – STATE-OF-THE-ART

GaAs-based 850 nm MM-VCSELs for operation at 25 Gbit/s (Ethernet) and 28 Gbit/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 Gbit/s under OOK modulation without equalization [5]. A VCSEL energy dissipation below 100 fJ/bit has been demonstrated at 25-50 Gbit/s [10]. Transmitter and receiver equalization has enabled record speeds of 71 Gbit/s at 25°C [6] and 50 Gbit/s at 90°C [11]. State-of-the-art for GaAs-based VCSELs at other wavelengths include 980 nm VCSELs operating at 50 Gbit/s up to 75°C [12] and 1060 nm VCSELs operating at 28 Gbit/s up to 75°C [13] and 40 Gbit/s at 25°C [14].

Long wavelength (InP-based) single-mode VCSELs for longer reach single-mode fiber interconnects have reached data rates of 40 Gbit/s at 1525 nm [15] and 30 Gbit/s at 1270 nm [16] under OOK modulation without equalization. With transmitter and receiver equalization, 56 Gbit/s transmission at 1530 nm was recently demonstrated [17].

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 low complexity and power consumption. Most recent achievements include pre-FEC transmission at 112 Gbit/s using conventional PAM-4 [18] and 150 Gbit/s using Duobinary PAM-4 [19], both over 100 m OM4 fiber at 850 nm.

For DCs, it is likely that the 50 Gbit/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 brief discussion on VCSEL dynamics and speed limitations, some highlights from recent work at Chalmers on high speed 850 nm datacom VCSELs are presented.

3. 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 (ISI) [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 signal dependent noise (relative intensity noise and mode partition noise) become more important. Multilevel modulation formats are more sensitive to dynamic VCSEL nonlinearities as they are less robust to ISI [23].

4. 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 [24]. 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. The design is illustrated in Fig.2.

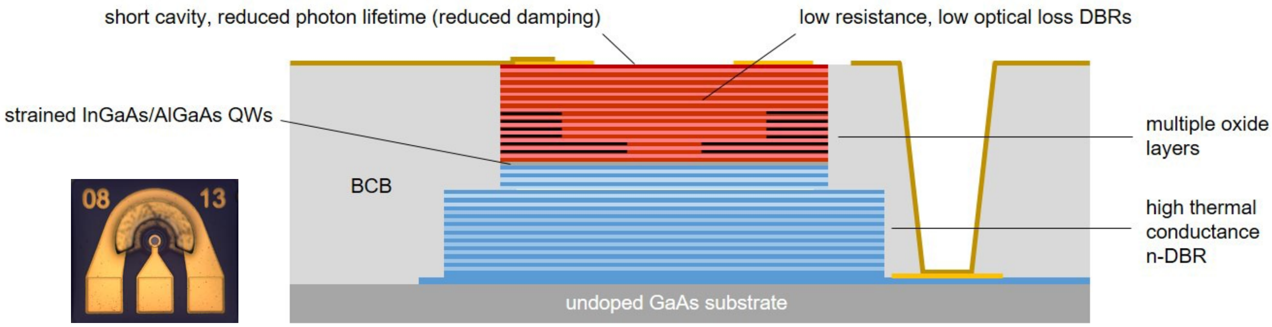

Figure 2. Cross-sectional view and microscope image of a high-speed oxide-confined VCSEL design.

With an adjustment of the photon lifetime, and therefore the damping of the modulation response, such VCSELs reach a modulation bandwidth of 28 GHz [25] and have enabled OOK data transmission up to 47(40) Gbit/s at 25(85)°C using a limiting optical receiver [26] and up to 57 Gbit/s using a linear receiver [5] without equalization. They have also been successfully used for real-time 60 Gbit/s PAM-4 transmission [7], 70 Gbit/s PAM-4 transmission with equalization and FEC [8], and 56 Gbit/s PAM-8 transmission with FEC [8]. With an analog pre-emphasis filter and off-line digital receiver equalization, the PAM-4 bit-rate could be increased to 94 Gbit/s [27].

More recently, by modifying the VCSEL design to improve the confinement of optical fields and carriers [28] 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 Gbit/s [10] (Fig.3).

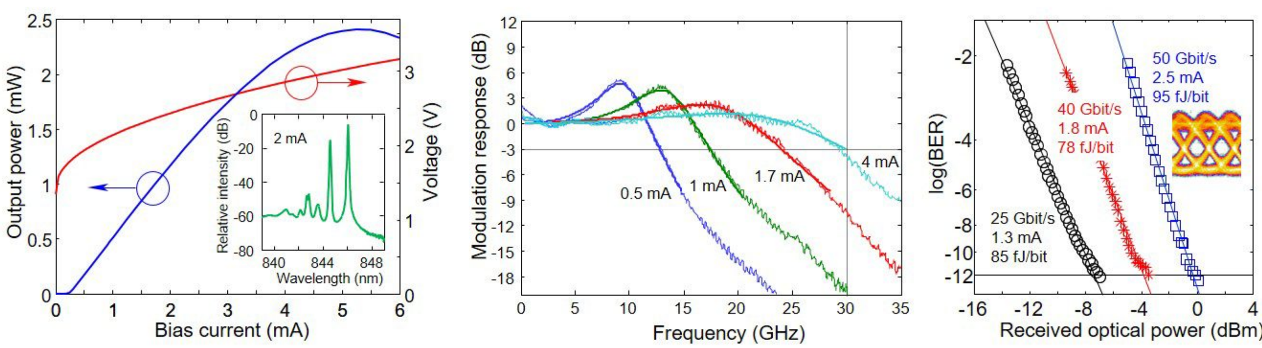

Figure 3. An 850 nm oxide-confined VCSEL with an aperture diameter of 3.5 µm. Left: output power and voltage vs. current, emission spectrum. Middle: modulation response at different bias currents. Right: data transmission at 25-50 Gbit/s under OOK-NRZ modulation with energy dissipation <100 fJ/bit.

Extending the reach of VCSEL-MMF optical interconnects to ~2 km would enable power and cost efficient interconnectivity in large-scale datacenters over all distances of interest. Therefore, longer wavelength GaAs-based VCSELs are of interest since the chromatic dispersion and attenuation in the MMF decrease rapidly with wavelength. It has been shown that extending the wavelength to 1060 nm (where chromatic dispersion is reduced by 50% and attenuation by 70% compared to 850 nm) is possible without compromising VCSEL reliability [13]. In collaboration with Hewlett Packard Enterprise (Palo Alto, CA, USA), we have therefore transferred our high-speed 850 nm VCSEL technology to 1060 nm and so far demonstrated modulation up to 40 Gbit/s at 25°C and 30 Gbit/s at 85°C [14]. Such VCSELs, together with high modal bandwidth 1060 nm MMF, hold promise for e.g. 50 Gbit/s PAM-4 transmission over 2 km of MMF.

5. 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 implementation of pre-emphasis and equalization in the driver and receiver ICs 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 Gbit/s under OOK modulation.

In collaboration 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(56) Gbit/s OOK transmission over 7(107) 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 Gbit/s [11].

Most of the power consumption of a VCSEL-MMF optical interconnect occurs in the driver and receiver ICs. While the use of power efficient CMOS ICs have enabled interconnects with low energy consumption (<3 pJ/bit up to 35 Gbit/s, 1 pJ/bit at 25 Gbit/s) [29], the need for higher speed IC technologies (e.g. SiGe BiCMOS) at higher data rates leads to an increase of the energy consumption [4,6,11]. Therefore, exploring new circuit technologies and developing new circuit architectures is as important as improving VCSEL performance. As a step in this direction we have implemented a 4-PAM VCSEL driver in 0.25 μm InP-DHBT technology. The high cut-off frequency and high breakdown voltage of this technology enable the implementation of high-bandwidth circuits at low power consumption. The driver consumes only 3.3 pJ/bit under 56 Gbit/s PAM-4 modulation. When integrated with a 24 GHz 850 nm VCSEL, the transmitter energy consumption is 3.7 pJ/bit [30].

With further improvements of VCSEL speed and dynamics and the development of new driver and receiver IC technologies/architectures with pre-emphasis and equalization, serial rates of 50 and 100 Gbit/s under OOK and PAM-4 modulation, respectively, without FEC/DSP and the associated latency seems feasible.

6. 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) [31]. 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 850 nm VCSEL arrays (Fig.4) 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. With a modulation bandwidth of 21 GHz at 25°C and 19 GHz at 85°C, each VCSEL in the array supports 40 Gbit/s transmission up to 85°C (Fig.4) for an aggregate capacity of 240 Gbit/s per fiber [32] at no measurable crosstalk between channels [33]. The use of such VCSEL arrays and MCFs in a parallel fiber cable would enable a multi-Tbit/s aggregate capacity.

This work is part of the European project MERLIN which aims at developing a technology platform for high capacity and low power consumption MCF optical interconnects. MCFs are developed by OFS (Denmark), detector arrays by Philips Photonics (Germany), and multi-channel driver and receiver ICs by IHP (Germany). The development and assembly of transceiver modules is performed by VTT (Finland).

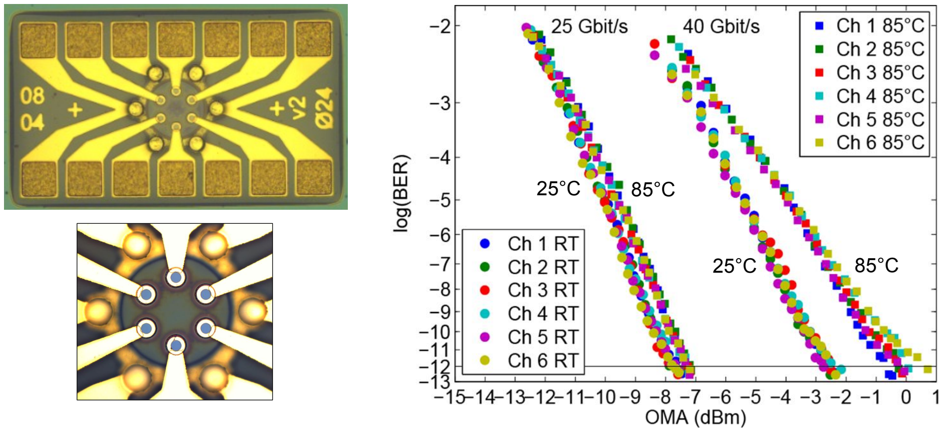

Figure 4. 6-channel VCSEL array for a 240 Gbit/s (6x40 Gbit/s) MCF optical interconnect. Left: microscope images of the array. Right: bit-error-ratio (BER) vs. optical modulation amplitude (OMA) for all 6 channels at 25 and 40 Gbit/s and 25 and 85°C.

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