Ultrafast VCSELs for Datacom

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Abstract: Vertical-cavity surface-emitting lasers (VCSELs) are broadly used as low-cost reliable light sources for high-speed data communication in local area and storage area networks (LANs/SANs), as well as for computer and consumer applications. The rapid increase of the serial transmission speed and the limitations of copper-based links at bit rates beyond 10 Gb/s and distances beyond 1 m extend the applications of fiber-optic interconnects to progressively shorter distances. The wavelength of 850 nm is standard for LAN/SAN applications over OM3 and OM4 multimode fibers and will continue playing an important role in future standards. In the last year, impressive results were achieved with oxide-confined VCSELs emitting at 850 nm. The data transmission rate could be shifted from 30 to 38 Gb/s, which is presently the highest data rate for any oxide-confined VCSELs.

Index Terms: Data communication, interconnections, local area networks, optical interconnects, semiconductor lasers, storage area networks, vertical cavity surface emitting lasers.

Our modern communication society is increasingly hungry for bandwidth. Over the past few years, this hunger has been a driver for fast increases of memory capacity, in particular of flash memories, of the computational power of microprocessors, and the rapidly increasing demand for higher bit rates of data communication links. Interfaces for serial transmission at rates beyond 10 Gb/s are presently standardized for a variety of applications, including (with an expected data rate) Fibre Channel FC32G (34 Gb/s), InfiniBand (20 Gb/s), common electrical interface CEI (25–28 Gb/s), and universal serial bus protocol USB 4.0 (25 Gb/s or beyond). Because of the fundamental electro-magnetic limitations of copper-based links for bit rates beyond 10 Gb/s and distances beyond 1 m, fiber-based optics has now become indispensable for ultrafast data communication [1]–[4]. The rapidly increasing acceptance of short-reach optical interconnects and their penetration into traditional copper interconnect markets is enabled by the unique properties of advanced vertical-cavity surface-emitting lasers (VCSELs) such as a near-circular output beam with a small divergence angle, low threshold current and power consumption, planar processing and on-wafer characterization enabling inexpensive production and testing, high reliability, and easy packaging.

Oxide-confined VCSELs dominate today [5], [6]. Such devices have been available on the market for about 10 years, having established themselves as being very reliable, with impressive possibilities for high-volume, high-yield, and inexpensive manufacturing. Currently, up to 10-Gb/s oxide-confined VCSELs can be acquired from a variety of companies. Higher bit rates created a need for further research, and development in this area focused on increasing the modulation bandwidth, while

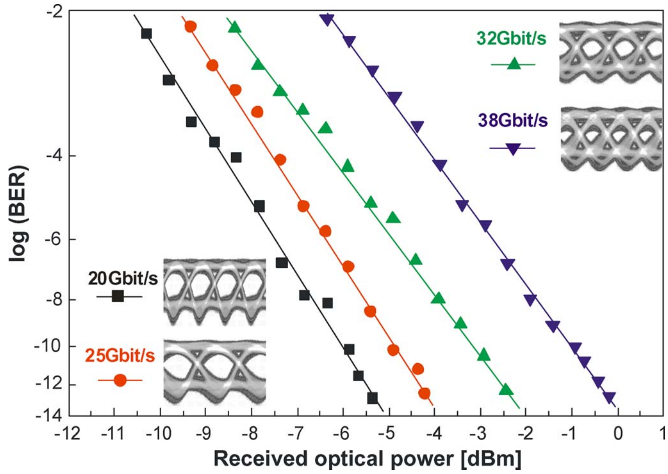

Fig. 1. Bit-error-rate measurements at 20 °C in a back-to-back configuration for the oxide-confined InGaAlAs VCSEL with the aperture diameter of 9 μm at 20, 25, 32, and 38 Gb/s for a bias current of 9 mA; the inset shows the corresponding optical eye diagrams.

simultaneously improving device reliability, power efficiency, modal and spectral characteristics, thermal management, and other figures of merit. The development of VCSELs at a few standard wavelengths (primarily around 850, 980, 1100, 1300 and 1550 nm) are presently in focus. The wavelength of 850 nm is particularly important, since it is the standard wavelength for local area and storage area networks (LANs/SANs) and is expected to play an increasingly important role for other standards.

Rate equation theory [7] predicts that the high-frequency properties of a semiconductor laser are described by the small-signal modulation transfer function, which depends on three parameters: relaxation oscillation frequency, damping, and the cutoff frequency of electric parasitics. Consequently, three types of limits exist, which can prevent high-speed operation: the thermal limit, the damping or internal limit, and the limit caused by electrical parasitics. Commonly, all three types of limitations are of importance, such that combined concepts must be developed to increase the laser bandwidth. Additionally, practical requirements like device reliability and simple fabrication technology must be considered as well.

Over the past few years, immense progress has been made and concepts have been developed to shift the limits to ever higher speed. Small-signal modulation bandwidths of 21 GHz and 24 GHz have been demonstrated for 4-μm-aperture-diameter VCSELs emitting at 850-nm [8] and 1100-nm devices based on a buried tunnel junction [9]. Thermal, intrinsic, and parasitic properties of the VCSELs were improved simultaneously. Large signal modulation at 35 Gb/s using 980-nm VCSELs with a tapered oxide aperture and deep oxidation layers [10] at 40 Gb/s using 1100-nm VCSELs with tunnel junctions [11] and at 22 Gb/s using 1550-nm VCSELs with a buried tunnel junction [12] have been reported. No data rates at or beyond 30 Gb/s were reported until 2008 for the commercially most relevant wavelength of 850 nm. Progress at 850 nm is more difficult to achieve, since e.g., the depth of the potential localizing the carriers is minimal.

Eventually, in 2008, large signal modulation at 30 Gb/s was demonstrated for oxide-confined VCSELs emitting at 850 nm [13]. Data rates higher than 30 Gb/s with 850-nm oxide-confined VCSELs were then reported last year by the group of A. Larsson the Chalmers University of Technology and by the Technical University of Berlin. 32-Gb/s error-free operation was demonstrated at sensationally low current densities of $\sim$10 kA/cm^2 [14], [15]. The main concepts used for these devices were double oxide apertures to reduce parasitic capacitance and InGaAs strained quantum wells (QWs) for the active layer to increase the differential gain and binary alloys in most of the bottom mirror to decrease the thermal resistance of the laser. It appeared that the 40-Gb/s directly modulated VCSELs were still a long way off.

A little bit later, a big step forward followed. The Technical University of Berlin and VI Systems GmbH demonstrated 38-Gb/s error-free operation of 850-nm oxide-confined VCSELs [16], [17]. By applying several concepts, among other strained InGaAs QWs in the active region, optimized device design with thick dielectric layers for smaller parasitic capacitances, and two mesas for better thermal conductivity, it was possible to demonstrate the first oxide-confined VCSELs ever operating at data rates up to 38 Gb/s (see Fig. 1). These are the fastest 850-nm VCSELs in use today. Electrical parasitics and the thermal resistance of the laser were appreciably reduced, and the internal properties of the gain medium were improved. Optimization of both epitaxial structure and design has led to high-speed operation without increasing the current density beyond the range of $\sim$10 kA/cm^2, which is an important consideration for device reliability. Cutoff frequencies of electrical parasitics up to 27 GHz were extracted from the measurements, showing the positive impact of applying thick dielectric layers and small mesa sizes.

Thus, 2009 has seen great progress in the field of high-speed 850-nm VCSELs for datacom applications. Large-signal operation of oxide-confined VCSELs at or beyond 40 Gb/s, which seemed hardly possible at the beginning of the year, is now within reach. Oxide-confined VCSELs operating reliably at 25 and 40 Gb/s will be on the market in a few years time. This development will serve the need of society for faster communication and drive progress for a better future.

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