Addressing the bandwidth density bottleneck: High-speed modulation, wavelength, and mode control in vertical-cavity surface-emitting lasers

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New processor technologies and advanced architectures continue to increase the productivity of the processors by three orders of magnitude per decade. To ensure the efficient exchange of data, the role of interconnects is growing at each level: from supercomputers and data-centers to consumer applications. Today, 4K and 5K displays are becoming broadly available and demand up to 80–100 Gb/s per screen for highest quality specs; 8K TV is coming next; while the IMAX-like bandwidth requires up to 175 Gb/s. The Thunderbolt 3 interface from Apple is due in 2015 at 40 Gb/s. Copper interfaces are steadily shrinking and optical links are exploding to tens of millions per single supercomputer.

We address recent achievements in VCSELs for data communication aimed at meeting the bandwidth demand.

- Recent concepts in high-speed VCSEL operation include anti-waveguiding cavity design with AlAs-rich core, further increased optical confinement factor, engineering of the density of states, and thick oxide apertures and superlattice barriers aimed at prevention of nonequilibrium carrier leakage. Serial data transmission up to 50 Gb/s has been realized in laser modules without any preemphasis and equalization. The expected lifetime of such VCSELs exceeds 10 years at 95 ^{o}C.
- Electrooptically-modulated VCSELs allow optical modulation bandwidths beyond 35 GHz and electrical bandwidths exceeding 60 GHz. So far, error-free digital data transmission at 10 Gb/s has been realized. With effort 100 Gb/s operation at a low current density and ultralow power consumption can become feasible.
- VCSEL design may allow uncooled wavelength multiplexing, for example within the narrow 840–860 nm spectral range of low modal dispersion of the standard multimode fiber (MMF). Complete temperature stability of the VCSEL is achieved due to the passive cavity concept. The gain medium is placed in the semiconductor region of the bottom distributed Bragg reflector (DBR) while another part of the bottom DBR, the cavity region and the top DBR are all made of dielectric materials. Due to the virtually no dependence of the refractive index on temperature at certain dielectric compositions, temperature-stabilized operation without cooling becomes possible. Further, dielectric DBRs and cavity make a high optical confinement factor possible even for InP-based 1300–1550 nm VCSELs, extending the range of VCSEL applications.
- Single-mode VCSELs at moderate oxide diameters of the oxide aperture (5–6 μm), fully compatible with standard technology, are feasible by the optical field engineering in the oxidized part. The leakage is engineered to suppress high-order transverse optical modes. The effect is achieved by a proper positioning of thick aperture oxide layers, inducing an optical leakage mode. Mode engineering can also be used to create a 3D optical mode confinement in the microcavity, resulting in long lifetimes for all VCSEL modes and allowing near-field surface-emitting lasers.
- Single-mode operation can overcome significant spectral dispersion of the MMF in the 840–860 nm range. A 1000 m error–free transmission at 25 Gb/s has been achieved in parallel MMF links using single-mode VCSEL arrays in combination with commercially available array electronics and standard optical couplers assembled into parallel 12-channel transceiver and receiver boards.