Semiconductor Technology from A to Z

Optoelectronics & Photonics

Laser Diodes

From LED to Laser: Population Inversion and Stimulated Emission

The fundamental difference between an LED and a laser diode lies not in the basic structure – both are based on a pn junction made from a direct-bandgap semiconductor – but in the emission mechanism. An LED generates light through spontaneous emission: an excited electron recombines with a hole at a random point in time, and the resulting photon has a random phase and direction. A laser, by contrast, relies on stimulated emission: a photon that already exists strikes an excited electron-hole pair and triggers its recombination – the newly generated photon is then identical in phase, direction, and wavelength to the triggering photon. This amplification mechanism (Light Amplification by Stimulated Emission of Radiation) produces coherent light, in contrast to the incoherent light of an LED.

For stimulated emission to dominate over absorption, the active medium must exhibit population inversion: more electrons must occupy the higher-energy conduction band state than the lower valence band state – a condition that never occurs in thermal equilibrium and must therefore be actively forced through high injection current density. In semiconductor lasers, the strongly forward-biased pn junction performs this role: above a certain threshold current, the ratio flips, optical gain sets in, and spontaneous emission increasingly gives way to stimulated emission.

The Optical Resonator and Mode Formation

Population inversion alone doesn't yet produce a laser – only an optically amplifying medium. The actual lasing effect additionally requires feedback: an optical resonator, usually realized as two parallel, partially reflective mirror facets on either side of the active region. In simple edge emitters, these mirrors form from the semiconductor's natural crystal cleavage planes (fracture surfaces along specific crystal planes), which already provide a reflectivity of 30–35% due to the refractive-index step to air – enough to circulate light repeatedly through the gain medium.

Only light whose wavelength forms an integer multiple of the resonator length (a standing wave between the mirrors) is amplified constructively – all other wavelengths interfere destructively and are suppressed. This produces a laser's characteristic longitudinal mode structure: instead of a broad, continuous spectrum as with an LED, a comb of sharp, closely spaced emission lines appears, with spacing set by the resonator length. Once the optical gain within the resonator exceeds the sum of all losses (mirror transmission, internal absorption, scattering), laser oscillation begins – the threshold current I_{th} marks exactly this transition point and is one of the most important parameters of any laser diode.

Edge Emitters: Fabry-Pérot and DFB Lasers

The simplest design is the Fabry-Pérot laser: two parallel cleaved facets serve as resonator mirrors, and light is coupled out sideways from the chip edge (hence "edge-emitting laser"). Since the resonator is usually several hundred micrometers long, it simultaneously supports multiple longitudinal modes, whose wavelength spacing is inversely proportional to the resonator length – a Fabry-Pérot laser therefore typically emits multimode, with several spectral lines spaced roughly 0.1–0.3 nm apart.

For applications requiring a single, extremely stable wavelength – chiefly fiber-optic communication, where chromatic dispersion would otherwise smear the signal – the DFB laser (Distributed Feedback) is used. Instead of simple end mirrors, a periodic diffraction grating is integrated directly into the layer structure near the active region (grating period on the order of a few hundred nanometers, typically fabricated by electron-beam lithography). This grating provides wavelength-selective reflection distributed along the entire resonator length rather than only at the end facets, forcing longitudinal single-mode operation with a side-mode suppression ratio typically above 30–40 dB. InGaAsP/InP-based DFB lasers at 1.55 µm are the industry standard for long-haul fiber-optic transmission.

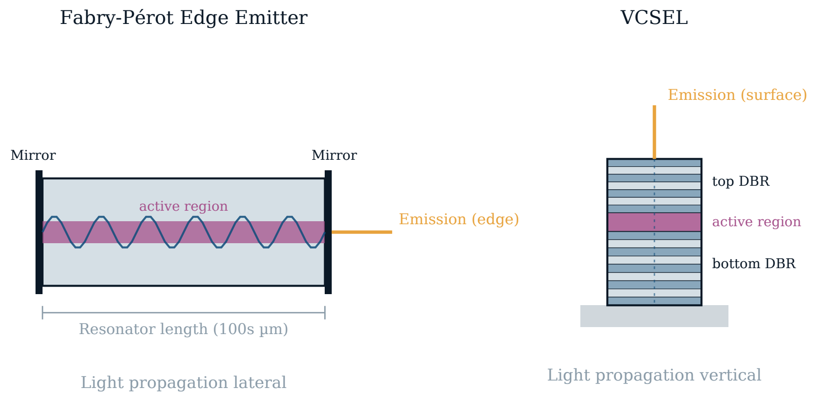
VCSEL: Structure and Advantages

The VCSEL (Vertical-Cavity Surface-Emitting Laser) follows a fundamentally different geometry: instead of coupling light out sideways from the edge, it emits perpendicular to the wafer surface. The resonator is vertical, formed by two DBR mirrors (Distributed Bragg Reflector) – stacks of alternating layers with different refractive indices, each a quarter-wavelength thick, which through constructive interference can achieve reflectivities above 99%, since a single semiconductor interface reflection would be far too low for a usable resonator. Because the active region is only a few micrometers long rather than several hundred micrometers as in edge emitters, extremely high mirror reflectivities are needed to reach the lasing threshold despite the short gain length.

The vertical design brings decisive practical advantages: VCSELs can be tested at the wafer level before being singulated (with edge emitters this is only possible after cleaving), they emit a round, low-divergence beam profile (instead of the elliptical beam of edge emitters, which simplifies fiber coupling), and they can be densely packed into two-dimensional arrays. These properties make VCSELs the dominant technology for short datacom links (data centers, 850 nm GaAs VCSELs over multimode fiber) and, in high volume, for 3D sensing such as facial recognition and LiDAR illumination in smartphones, where arrays of thousands of VCSELs jointly project structured light.

Optical Resonator: Edge Emitter vs. VCSEL

Lateral resonator (Fabry-Pérot) vs. vertical DBR resonator (VCSEL)



Short gain length in a VCSEL requires mirror reflectivities > 99% – hence DBR stacks instead of simple cleaved facets.

Material Systems and Applications

Material choice follows the same principles as for LEDs, supplemented by resonator-specific requirements. GaAs/AlGaAs systems cover 780–980 nm (historically CD/DVD lasers, today mainly pump lasers for fiber lasers and VCSELs for datacom/sensing). InGaAsP/InP dominates at 1.3 µm and 1.55 µm for telecommunications, since these wavelengths coincide with the attenuation and dispersion minima of silica fiber. GaN-based laser diodes cover the blue-violet range around 405 nm and enabled high-density Blu-ray storage technology, since shorter wavelengths allow a smaller diffraction limit and thus higher storage density.

Beyond conventional data transmission, laser diodes have established themselves in three further fields: in materials processing, high-power diode laser bars (arrays of edge emitters) are increasingly replacing gas lasers for welding, cutting, and as pump sources for solid-state lasers, thanks to high electrical efficiency (conversion efficiency often above 50%). In sensing, LiDAR (Light Detection and Ranging) uses short laser pulses for time-of-flight distance measurement in automotive and robotics applications – here VCSELs are increasingly displacing conventional edge emitters. And in display technology, red, green, and blue laser diodes serve as light sources for laser projectors, where their high spectral purity enables a significantly wider color gamut than LED or lamp-based projectors.