Semiconductor Technology from A to Z

Optoelectronics & Photonics

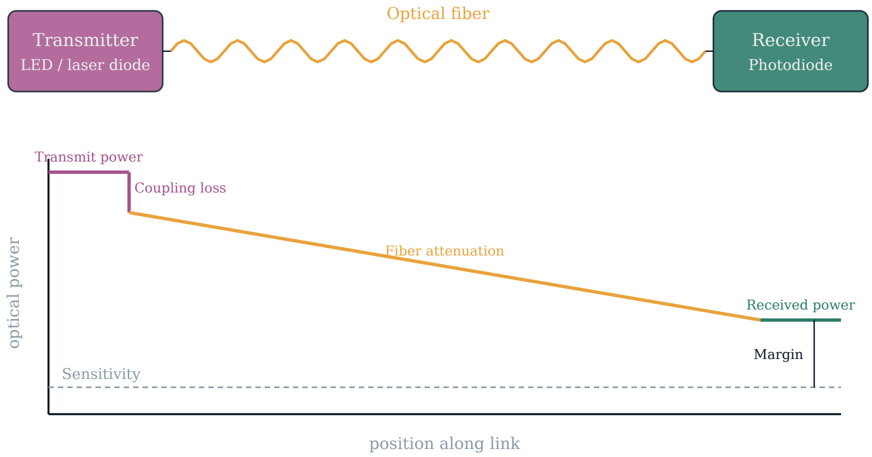
Integration & Applications

The Optical Transmission Chain

The previous three chapters treated the LED, laser diode, and photodiode as individual devices – in practice, however, they almost never work in isolation but as links in a transmission chain: transmitter (LED or laser diode) → transmission medium (optical fiber or free space) → receiver (photodiode). This chain clarifies why material choice in the previous chapters was so tightly coupled: an InGaAsP DFB laser at 1.55 µm only yields a working system if an InGaAs photodiode with matching responsivity sits at the other end, in exactly this wavelength window – transmitter and receiver aren't a random material pairing but a coordinated system component.

In system design, the efficiencies and losses of each stage add up: the transmitter's wall-plug efficiency, the fiber coupling efficiency (typically the lossiest step for edge emitters, one reason for the growing use of VCSELs with their round, easily coupled beam profile), fiber attenuation over the link length, and finally the photodiode's receiver sensitivity. The power budget (link budget) – transmit power minus all losses – must ultimately exceed the photodiode's minimum detectable power; if the margin isn't sufficient, intermediate amplifiers (optical fiber amplifiers) or more sensitive APD receivers are used.

Optical Transmission Chain and Link Budget
Transmitter, fiber and receiver as a coordinated system chain



The power budget — transmit power minus all losses — must exceed the photodiode's minimum detectable power.

Display Technology: LED Backlighting, µLED, and OLED Compared

In display technology, LEDs serve in several, technically quite different roles. In conventional LCD screens, a row of white InGaN LEDs (see Chapter 2) merely serves as backlighting – the actual image is formed by downstream liquid crystal cells that transmit or block the LED light pixel by pixel. In OLED displays, by contrast, each pixel is itself a light emitter: organic semiconductor layers emit light directly, substantially improving contrast (true black by fully switching off individual pixels) and viewing-angle stability – though at the cost of maximum brightness and long-term stability compared to inorganic semiconductors.

µLED displays pursue a third approach: instead of organic emitters, tiny inorganic InGaN/AlGaInP LED chips (edge length often below 50 µm) are used directly as individually addressable pixels – the same semiconductor technology from Chapter 2, just massively miniaturized and transferred in extremely high volumes onto a carrier substrate ("mass transfer," one of the biggest manufacturing bottlenecks of this technology). µLEDs thereby combine the contrast advantages of self-emitting pixels with the brightness, lifetime, and material stability of inorganic III-V semiconductors, but due to manufacturing complexity are currently still limited to premium applications and large display diagonals.

Sensing: LiDAR and Time-of-Flight

LiDAR systems (Light Detection and Ranging) use the devices covered in Chapters 3 and 4 in a precise timing application: a laser diode – usually a VCSEL or edge emitter in the near infrared (905 nm or the more eye-safe 1550 nm) – emits a short light pulse, and a fast photodiode (often an APD, due to the weak return signal) registers the reflection from the target object. The time-of-flight Δt between emission and reception directly yields the distance via $d = c \cdot \Delta t/2$ – at the speed of light, this corresponds to picosecond-range timing resolution for centimeter-level distance accuracy, placing high demands on the switching speed of both the laser diode and the photodiode readout electronics.

Automotive LiDAR systems scan an entire field of view, either mechanically (rotating mirror) or increasingly solid-state via VCSEL arrays that address different angles electronically instead of mechanically – a direct application of the VCSEL array capability described in Chapter 3. In 1550 nm systems, the advantage of the InGaAsP/InP technology already established for telecommunications comes into play: this wavelength can be operated at substantially higher power than 905 nm without exceeding eye-safety limits, since it's absorbed by the cornea rather than focused onto the retina.

Sensing: Pulse Oximetry and Proximity Sensors

A medical application example combining the materials from Chapters 2 and 4 is pulse oximetry: a fingertip clip sensor shines two LEDs of different wavelengths (red, ≈660 nm, and infrared, ≈940 nm) through tissue and measures the transmitted light intensity with a photodiode behind it. Oxygenated and deoxygenated hemoglobin absorb these two wavelengths to different degrees; from the ratio of the pulsating absorption signals (caused by arterial blood volume with each heartbeat), the device calculates blood oxygen saturation, entirely without drawing blood.

Proximity sensors in smartphones work on a similar but simpler principle: an IR LED (usually GaAs-based, see Chapter 2) emits invisible light, and an adjacent silicon photodiode measures the reflection – if an object (such as an ear during a call) is close enough, the reflected intensity rises sharply and switches off the screen. The same basic architecture, extended with structured light from VCSEL arrays (see Chapter 3), also forms the basis for 3D facial recognition systems, which reconstruct a complete depth image of the scene instead of a simple yes/no proximity measurement.

Photonic Integrated Circuits (PICs) – Outlook

All the devices covered so far – lasers, photodiodes, and to some extent modulators – today exist predominantly as discrete, individually packaged components connected to each other via fiber or free space. Photonic integrated circuits (PICs) pursue the same miniaturization and integration philosophy that has shaped microelectronics for decades: several optical functions – lasers, waveguides, modulators, photodetectors – are combined on a single chip, connected by structured waveguides instead of discrete fibers.

Silicon photonics is currently the most important trend in this space: since silicon itself doesn't emit light (Chapter 1) but is excellently suited as a waveguide and detector material (combined with germanium, see Chapter 4) and can additionally be manufactured on established CMOS production lines, passive and detecting photonic functions can be integrated cost-effectively. The light source itself typically remains a separately fabricated III-V laser chip (InP-based), subsequently bonded onto the silicon chip or coupled via hybrid integration – an active research field that directly links the III-V material systems covered in this section with the silicon manufacturing world of the site's other chapters. The main application driver is data centers, where PICs are increasingly replacing electrical cabling between servers with optical links offering higher bandwidth and lower energy consumption per bit.