LIGHTWAVE DEVICE TECHNOLOGY

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High-performance, reliable lightwave devices are the foundation of the current lightwave revolution in communications. The advances in semiconductor laser, LED (light-emitting diode), and photodetector technologies and their role in the evolution of lightwave system architecture are described.

Introduction

The widespread installation of lightwave transmission systems is a result of their enormous information carrying capacity at relatively low cost. The systems currently being installed throughout the world are the result of two major technological advances. One is the development of low-loss silica (glass) fibers that act as the transmission medium. The other is the development of high-performance, reliable lightwave devices (i.e., semiconductor lasers, LEDs, and photodetectors). The interdependence of lightwave device technology, optical fiber technology, and lightwave system architecture can be traced back to the earliest commercial lightwave transmission in 1977 in Chicago. Lightwave device technologies are evolving along with lightwave system architectures.

First-generation lightwave systems use multimode fibers and an operating wavelength of about 0.8 μm. Semiconductor lasers or LEDs fabricated using the aluminum gallium arsenide (AlGaAs) material system are the light source. Silicon photodiodes detect light in these systems.

Second-generation systems using single-mode fibers and an operating wavelength of about 1.3 μm offer larger regenerator spacings because of the lower silica fiber loss at 1.3 μm than at 0.8 μm. Semiconductor lasers or LEDs fabricated using the indium gallium arsenide phosphide (InGaAsP) material system are both light sources and photodetectors in these systems.

Third-generation systems operating at wavelengths of about 1.56 μm, where fiber loss is minimum, offer even greater regenerator spacing, thereby reducing the overall cost for long-haul transmission systems.

As lightwave systems move toward higher data rates, chromatic dispersion of the fiber becomes important. In addition, the

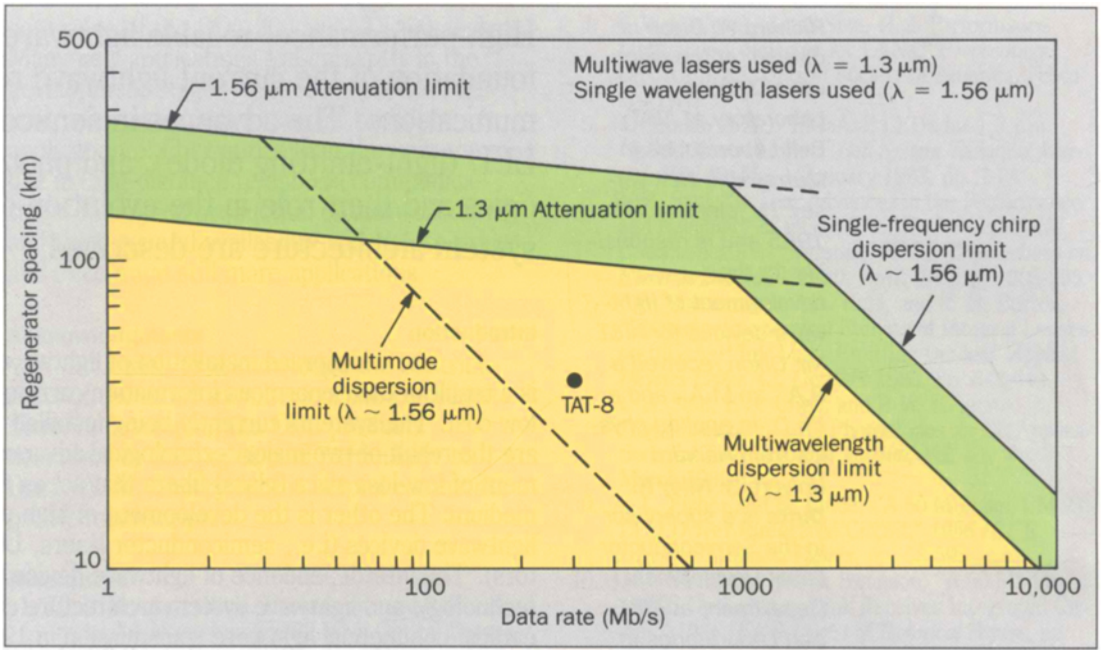
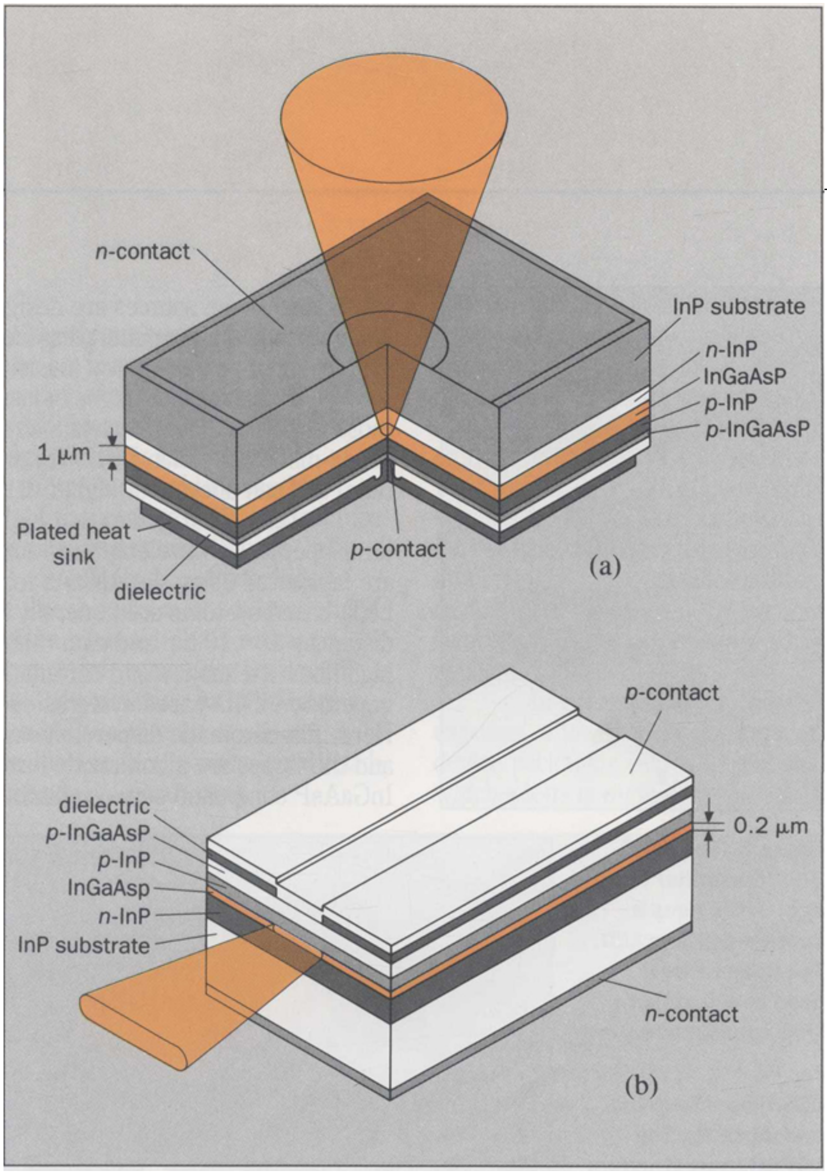


Figure 1. Maximum regenerator spacing is plotted as a function of data rate for commercially viable lightwave systems operating at about 1.3 μm and 1.56 μm. This example uses single-mode fiber with zero dispersion at about 1.3 μm and a directly modulated semiconductor laser. Loss-limited transmission data use 0-dBm (1 mW) power launched into the single-mode fiber. The chromatic dispersion limit is obtained from the relation $BL < 1/4\, D\, \sigma$ where B, L, D, and σ are data rate, regenerator spacing, chromatic dispersion of the fiber, and source linewidth, respectively. The first transatlantic lightwave transmission system (TAT 8, to be deployed in 1988) operates at 290 Mb/s with a regenerator spacing of 40 km.

sources evolve from multiwavelength lasers to single-wavelength lasers; and detectors evolve from PIN (positive-intrinsic-negative) photodiodes to avalanche photodiodes (APDs). Although it is difficult to predict the course of the current lightwave revolution, coherent lightwave transmission systems operating at about 1.56 μm are the next promising step. Such systems will require sources with very narrow spectral width and a whole new family of lightwave devices.

It is a common practice to characterize a digital transmission system by its data rate or bit rate (B) and its regenerator spacing (L). As the light pulse moves through the fiber, it loses intensity and broadens because of attenuation and chromatic dispersion in the fiber. Limits on transmission distance because of attenuation are determined by the minimum number of photons per bit needed by a photodetector at the receiver to detect the signal. Limits on transmission distance because of chromatic dis-



Illustrations: Ross Culbert Holland & Lavery, Inc.

Figure 2. The surface-emitting LED (a) and the edge-emitting LED (b) structures. The InGaAsP ($\lambda \sim$ 1.3 μm) layer surrounded by *p*-InP and *n*-InP layers is the light-emitting region. The surface-emitting LED is used as a source for multimode fiber systems; the edge-emitting LED for single-mode fiber systems.

persion occur when the broadening of the propagating pulses is such that they overlap with one another making the identification of the bit stream (pulses of 1s and 0s) impossible.

Because of the large chromatic dispersion of conventional single-mode fibers at about 1.56 μm, single wavelength sources are used for high data-rate transmission. Figure 1 shows the attenuation and dispersion limits on regenerator spacing as a function of data rate for systems using conventional single-mode fiber. Chromatic dispersion becomes an important limitation for multiwavelength lasers even near the zero-dispersion region of the fiber ($\lambda \sim$ 1.3 μm) so that single wavelength sources need to be used at very high data rates.

Sources

In lightwave transmission systems, lasers or LEDs are used as sources of light. These devices are fabricated from multilayered structures of doped compound semiconductors epitaxially grown over a single crystalline

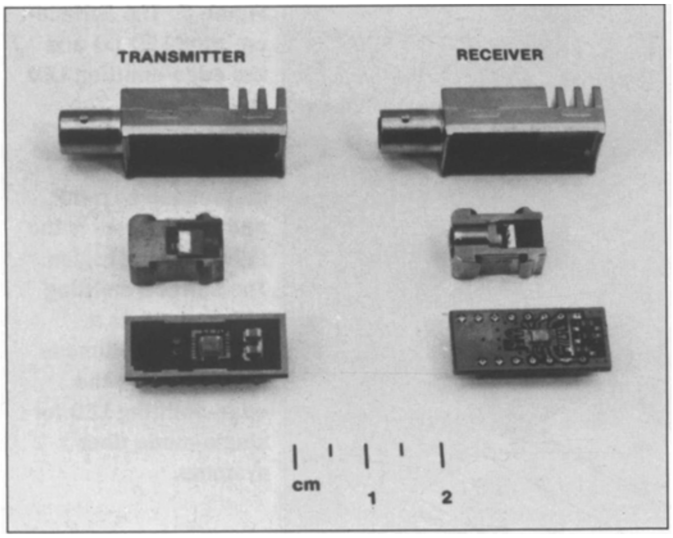


Figure 3. The ODL®-200 transmitter package, which uses a surface-emitting LED. The transmitter is used in subscriber loop applications.

substrate. These sources are designed to have a narrow beamwidth and a long operating life. In addition, laser sources must exhibit optical linearity and temporal stability.

Performance ranges of lasers are much wider than those of LEDs. Lasers can launch much more power into a single-mode fiber than LEDs (by several orders of magnitude) and can operate at higher data rates.

LEDs. First-generation LED-based lightwave systems operate at wavelengths of about 0.85 μm. The LEDs are fabricated using the AlGaAs material system. These LED-based systems are generally limited to transmission distances of <10 km and data rates <50 Mb/s because of high fiber attenuation and chromatic dispersion. Second-generation LED-based systems operate at about 1.3 μm. Here, the chromatic dispersion of the fiber is near zero and the losses are significantly lower than at 0.85 μm. The InGaAsP compound semiconductor is the light-emitting

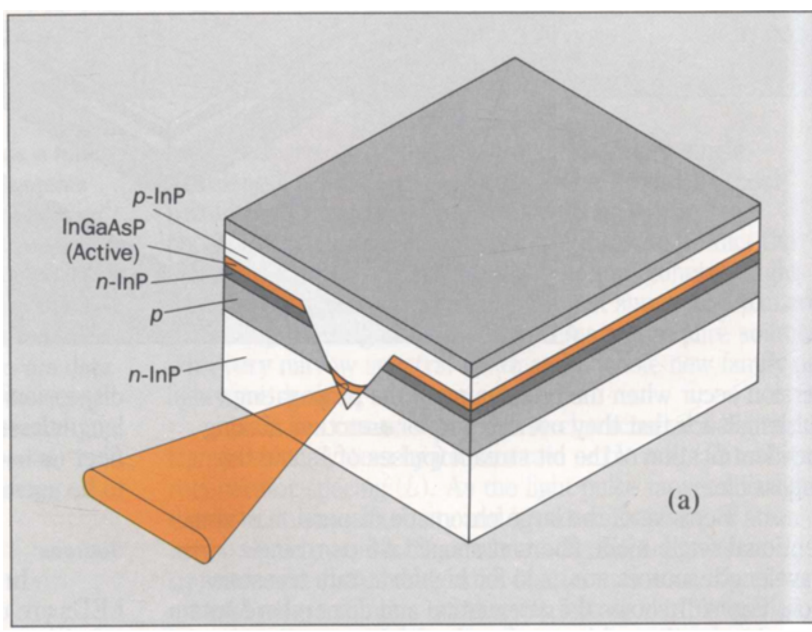


Figure 4. Shown are (a) the channeled substrate buried heterostructure (CSBH) and (b) the double channel buried heterostructure (DCPBH) lasers. The light-emitting region is the InGaAsP layer. The cleaved crystal facets at each end of the CSBH laser form the optical cavity. The DCPBH laser structure shown has a grating on the substrate that provides optical feedback at a fixed wavelength determined by the grating period. As a result, the laser emits in a single wavelength.

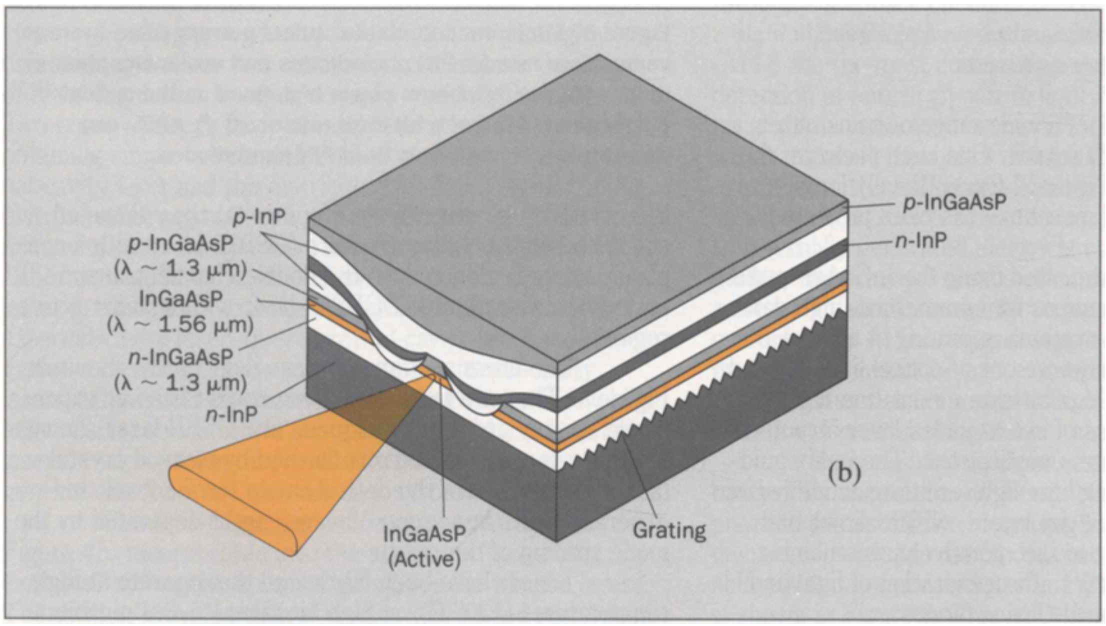
material for these LEDs.

There is now considerable research and development activity to improve the performance of InGaAsP LEDs. For example, laboratory experiments have shown error-free transmission over 35-km single-mode fiber at 180 Mb/s using 1.3 μm edge-emitting LEDs.

Two basic LED structures are widely used for lightwave sources. These are the surface-emitter structure (Figure 2a) and the edge-emitter structure (Figure 2b). Both structures use an *n*-type InP (Indium Phosphide) substrate grown using the Czochralski method[1] over which four epitaxial layers are grown by liquid-phase or vapor-phase epitaxy. The first is an *n*-InP (generally tin-doped) buffer layer, followed by the light-emitting InGaAsP active region with the composition chosen to emit at about 1.3 μm. Next there is a *p*-type InP (generally zinc-doped) cladding layer and finally a *p*-InGaAsP contact layer.

For the surface emitter, the light is emitted perpendicular to the grown layer. A well is etched into the substrate so that the fiber is positioned close to the light-emitting region for maximum capture of the light by the fiber. The edge-emitter structure, in which the light is emitted along the plane of the epitaxially grown layer, is very similar to that of a laser. The lasing action is generally suppressed by using short cavities or by destroying the mirror facets using anti-reflection coatings or chemical etching. The basic surface-emitter and edge-emitter designs can be changed (by varying doping levels, active layer thickness, etc.) to suit a variety of commercial applications.

In general, higher coupled power comes at the expense of lower bandwidth and greater complexity in device packaging (external lens) or chip fabrication in which a lens is etched on the emitting surface of the LED



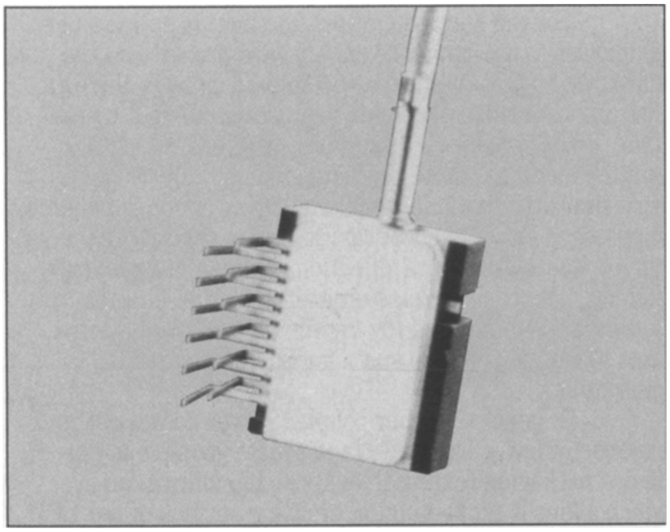


Figure 5. The ASTROTEC® transmitter package used in high-data-rate, single-mode-fiber systems.

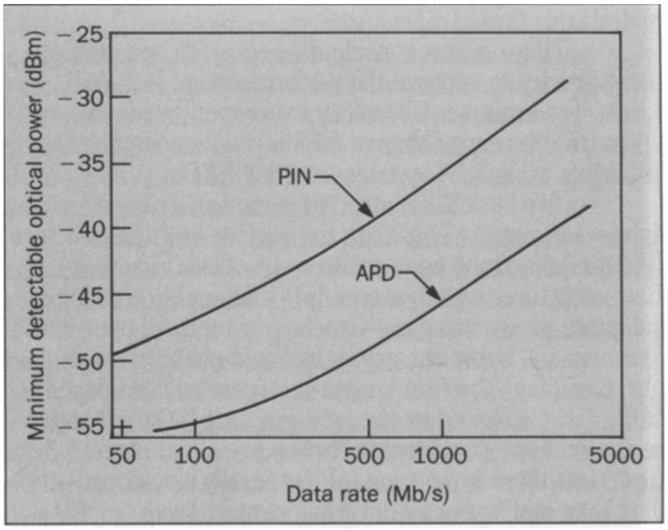


Figure 6. Minimum detectable optical powers (time-average) versus data rate for PIN photodiodes and avalanche photodiodes (APDs). Minimum power is defined as the optical power needed to get a bit error rate of 10^{-9}. APDs can detect lower signal levels than PIN photodiodes.

(integral lens). AT&T offers a wide range of transmitter packages that use an LED source. One such package, the ODL®-200, is shown in Figure 3. Exceptionally long life (> 10^8 hours at room temperature) has been projected for AT&T devices.

Lasers. Lasers fabricated using the InGaAsP material system are used as sources for commercial, high-data-rate, long-haul lightwave systems operating at about 1.3 μm and 1.56 μm. The requirement of optical linearity and temporal stability under high bit-rate modulation has led to the development of a class of index-guided laser structures for current lightwave system applications. The index guiding is provided by "burying" the light-emitting active region in lower-index higher band gap layers, which allows both (a) electrical confinement to the radiatively recombining electrons and holes leading to the generation of light and (b) optical confinement of the lasing mode.

Two basic types of index-guided laser structures are the nonplanar active layer lasers and planar active layer lasers. AT&T is currently developing: (a) the channeled substrate buried heterostructure (CSBH) laser with a nonplanar active region and (b) the double channel planar buried heterostructure (DCPBH) laser with a planar active region.

The cross sections of these devices are shown in Figure 4. They are fabricated using liquid-phase or vapor-phase epitaxy growth techniques. The CSBH laser shown in Figure 4a relies on mirrors formed by cleaved crystal facets at each end of the optical cavity for feedback and generally emits in a group of wavelengths separated by the mode spacing of the cavity.

Lasers have been fabricated that operate at high temperatures (130° C), at high bit rates [> 3.4 gigabits per second (Gb/s)], at high powers [100 milliwatts (mW) near room temperature], and with extrapolated lifetimes in excess of 50 years at 25° C.

AT&T offers a family of laser transmitter packages in the ASTROTEC® module (Figure 5). These modules are available with different specifications for optical output, operating speed, and wavelength. They use a temperature-controlled InGaAsP injection laser as the source.

The transatlantic fiber optic cable system (TAT 8) currently being deployed operates at about 1.3 μm using a multiwavelength laser source with a regenerator spacing of 40 km. Larger regenerator spacings are possible at about 1.56 μm where fiber loss is minimum.

Multiwavelength lasers emitting at about 1.56 μm can be used as sources for regenerator spacings > 50 km and for repeaterless systems between remote islands separated by 50 to 100 km. Dispersion-shifted fibers (i.e., fibers whose zero-dispersion point and loss minimum are at about 1.56 μm) allow the use of multiwavelength lasers in high data-rate systems.

For larger regenerator spacings and for higher data-rate operation, it is necessary to eliminate the effect of fiber dispersion by using a single wavelength source. Two types of lasers have been extensively investigated for obtaining single wavelength emission. They are the external-cavity laser and the distributed feedback (DFB) or distributed Bragg reflector-type(DBR) laser. Several external-cavity laser designs have been studied at AT&T Bell Laboratories. They are the cleaved coupled-cavity (C^3) laser, graded index external-cavity laser, grating loaded external-cavity laser, fiber external-cavity laser and integrated external-cavity laser. The long external-cavity lasers exhibit continuous wave (CW) linewidths of few kilohertz (KHz) compared to few megahertz (MHz) for DFB lasers, making them more suitable for high-data-rate, next-generation, coherent transmission systems.

The DFB laser has a diffraction grating (see Figure 4b) incorporated into the structure (by etching, for example) before the epitaxial growth of the various layers. The grating provides optical feedback at a fixed wavelength determined by the periodicity of the grating. The planar active DCPBH laser structure allows good coupling of the grating to the lasing optical mode. The DFB lasers operate in a single wavelength over a wide temperature range and are being developed as a source for high-bit-rate (> 2 Gb/s) lightwave systems, wavelength multiplexed lightwave systems, and future coherent lightwave systems.

Photodetectors

The photodetector is an important component in a lightwave transmission system. Lightwave receivers use high-speed photodetectors for conversion of the incoming light pulses to electrical pulses. The photodetector transforms the input (or received) optical signal into an electrical signal, from which the original coded information is retrieved using a series of functions including amplification, equalization, filtering, and timing. Photodetectors are also used for monitoring the power output of the source at the transmitter and maintaining it within a specified range through a feedback circuit.

The PIN photodiode and the avalanche photodiode (APD) are the most commonly used photodetectors for the detection of optical signals in lightwave systems. The electrical signal generated in the APD is internally amplified, which makes it capable of detecting lower levels of optical signals than the PIN photodiode. The minimum detectable signal for both PIN photodiodes and APDs is determined by internally generated electrical noise. For PIN photodiodes, the principal source of noise is "shot noise," which arises from small, randomly varying thermally generated currents. For APDs, the principal source of noise is the probabilistic avalanche process, whereby a pair of photogenerated carriers undergo multiplication. This process also results in signal amplification.

Because total noise increases with increasing bandwidth, the minimum detectable signal for both PIN photodiodes and APDs increases (i.e., the sensitivity decreases) with increasing data rate. The minimum detectable power versus data rate for PIN photodiodes and APDs is shown in Figure 6. The APD can detect lower signal levels than the PIN photodiode.

First-generation lightwave systems operating at

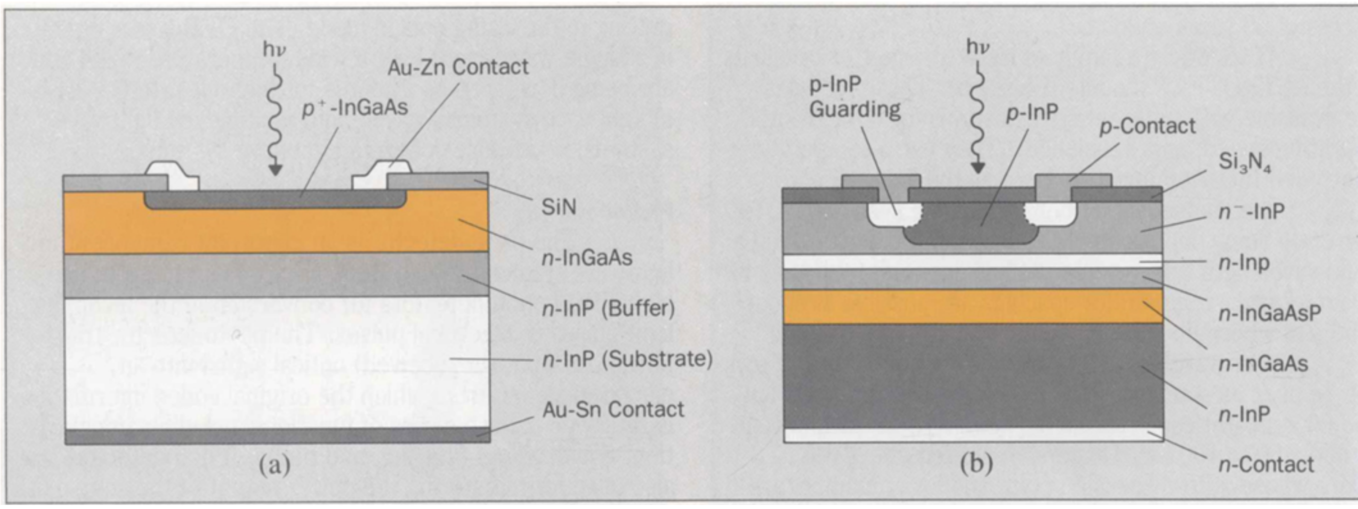


Figure 7. The commonly used (a) PIN photodiode and (b) avalanche photodiode (APD) structures. Light in both structures is absorbed at the low doped *n*-InGaAs layer. The APD structure has separate absorption and multiplication regions (SAM-APD).

about 0.8 μm use silicon PIN photodiodes for detecting light. Lightwave systems operating at about 1.3 μm and 1.56 μm use PIN photodiodes and APDs fabricated using the InGaAsP material system with an InGaAs absorbing region. Figure 7 shows the commonly used PIN photodiode (Figure 7a) and APD (Figure 7b) structures. The fabrication of these devices requires epitaxial growth of several layers on an *n*-InP substrate. The incident light is absorbed in the low-doped (10^{16} cm $^{-3}$) *n*-InGaAs layer, generating carriers that are collected at the external circuit. For the APD, the photogenerated carriers undergo multiplication via impact ionization at the *n*-InP multiplication layer before collection at the external circuit.

The PIN photodiodes are easier to fabricate and operate and are extensively used for low- and moderate-data-rate lightwave transmission systems. The PIN photodiodes manufactured at AT&T exhibit 1-FIT reliability (1 failure in 10^9 hours). Higher sensitivity APDs are advantageous in applications in which extreme regenerator spacings or higher data rates (> 1.5 Gb/s) in installed systems are desired.

Future Lightwave Devices

Extensive research and development of discrete lightwave sources and detectors has improved the performance and lowered the cost of current transmission systems. The regenerator packages in these systems are hybrid circuits in which the electronic functions use silicon technology. The photonic functions use GaAs or InP materials technology.

The exploratory work in lightwave device technology consists of:

- The development of devices for new lightwave system architectures such as multifiber loop applications for interconnection between computers, active star networks, parallel data transfer, or coherent detection lightwave systems.
- The monolithic integration of sources, detectors, amplifiers, and timing circuits leading to a single chip regenerator.

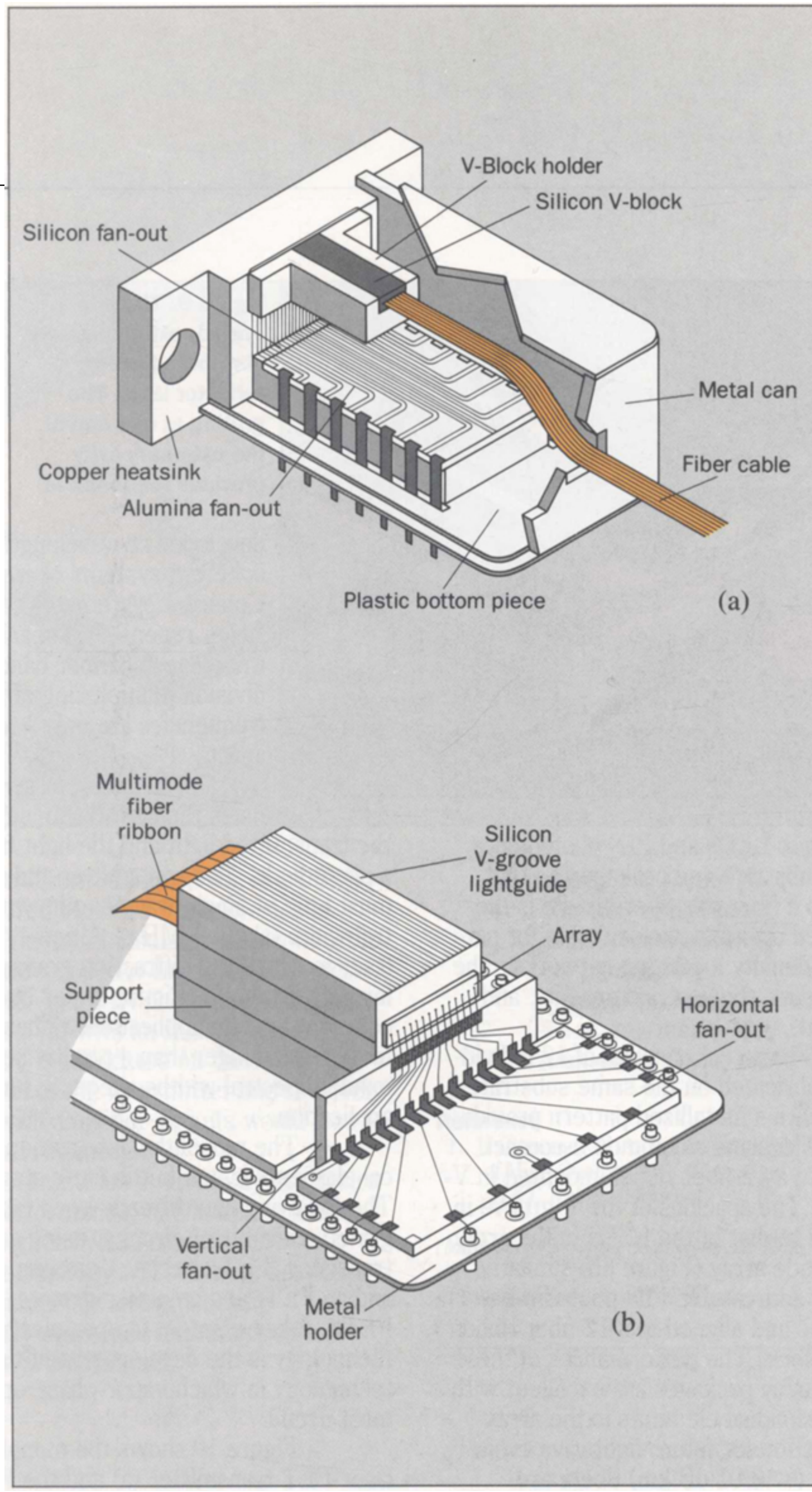


Figure 8. Schematic of (a) LED and (b) PIN photodiode array packages. Each array consists of 12 individually addressable elements with center-to-center spacings of 250 μm. The arrays are aligned to a 12-fiber ribbon using a silicon V-block.

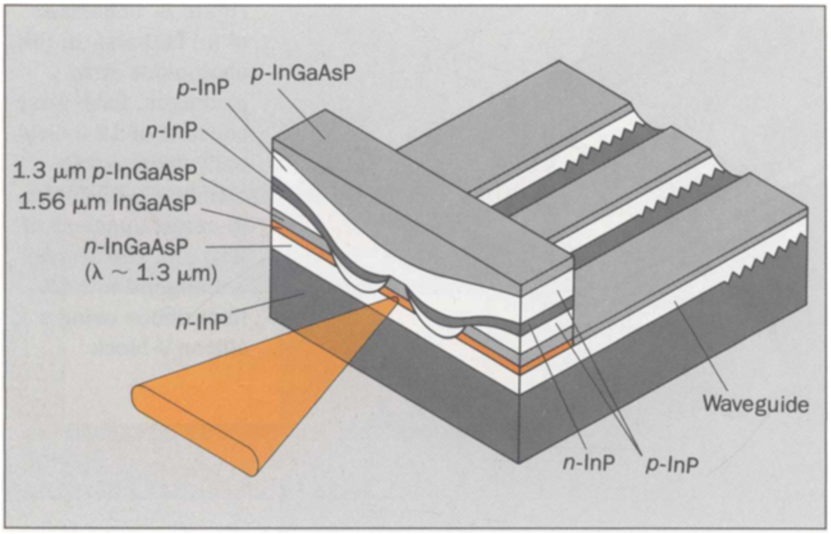


Figure 9. The integrated, external-cavity distributed Bragg reflector laser. The grating at one end of the external cavity provides feedback at a fixed wavelength. The laser emits in a single wavelength with narrow linewidth and is useful for next-generation coherent transmission systems.

An array of multiple LEDs and PIN photodiodes integrated onto a single substrate and packaged so that each element is aligned to a fiber of a fiber-bundle is the simplest form of integrated optical device suitable for parallel data transfer in high-density local area networks. The arrays are expected to reduce the cost, complexity, and size of terminal equipment.

The LED array (Figure 8a) consists of 12 individually addressable LEDs fabricated on the same substrate mounted on a submount with a metallized pattern providing *p*-contact to the 12 devices and a common *n*-contact. The submount is aligned to a 12-fiber ribbon mounted in V-grooves in a silicon block. The spacings of the V-groove in the silicon block are equal to that of the LEDs in the array.

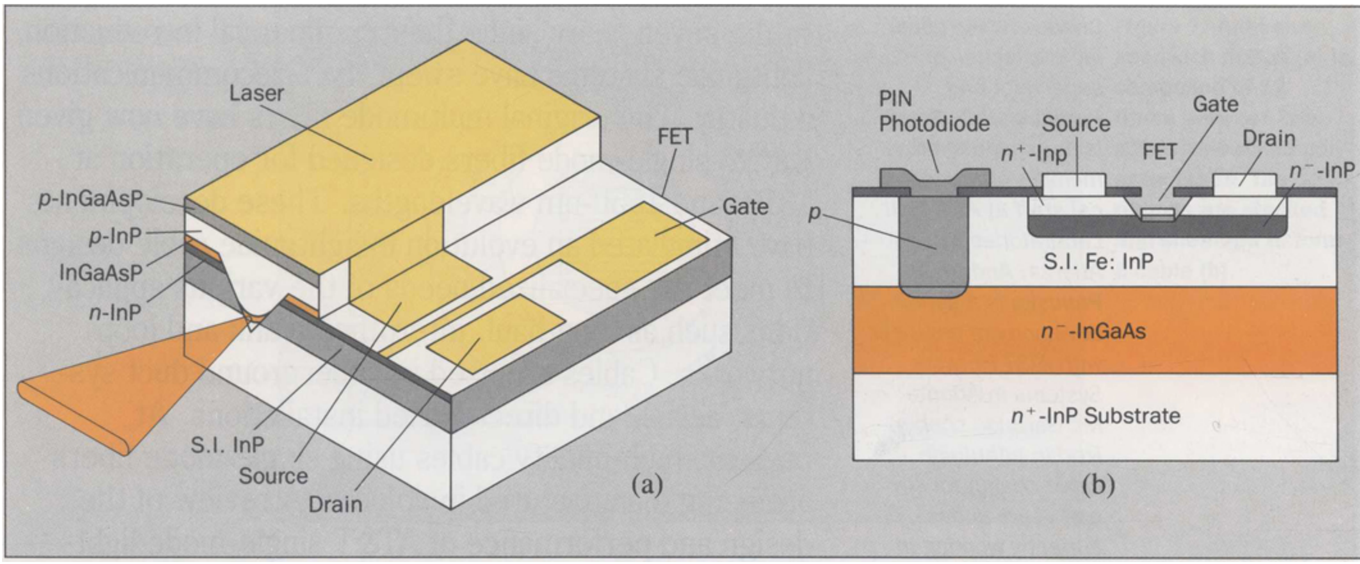
The PIN photodiode array (Figure 8b) similarly consists of 12 individually addressable PIN photodiodes fabricated on the substrate and aligned to a 12-fiber ribbon using a silicon V-groove block. The performances of these transmitter and receiver array packages are excellent with little crosstalk between individual elements in the array.

A promising direction for future lightwave evolution [unless very low-loss (< 0.01 dB/km) fibers are developed at wavelengths beyond 2 μm] is in coherent systems operating at about 1.56 μm. Coherent systems promise not only much larger regenerator spacings but also the use of the enormous fiber bandwidth using wavelength division multiplexing of sources whose emission frequencies are only a few gigahertz (GHz) apart.

In coherent systems, the detector signal is the beat frequency generated by mixing the transmitted light and the light from a local oscillator on a photodiode. The transmitter and the local oscillator laser must emit at single wavelengths with a very narrow spectral width (about 1 MHz). A new type of single wavelength laser in which the diffraction grating is external to the lasing active volume (Figure 9) has been developed for coherent system applications. These lasers are typically 20 to 30 times longer than a regular semiconductor laser and exhibit spectral widths adequate for coherent system application.

The monolithic integration of electronic and optical elements is still in the early stages of investigation. The following have already been fabricated: simple integrated transmitter circuits, using a laser and a field effect transistor (FET); receiver circuits, using a PIN photodiode and an FET; and amplifier circuits, using several InP FETs. A key element in opto-electronic integrated-circuit technology is the development of the materials growth technology in which vapor-phase epitaxy is expected to be most useful.

Figure 10 shows the monolithically integrated laser-FET transmitter (a) and the PIN photodiode-FET



receiver (b). The laser structure in Figure 10a is a CSBH laser currently manufactured at AT&T Technologies in Reading, Pennsylvania. The metal-insulator-semiconductor FET is fabricated on the low doped *n*-InP layer and operates in the depletion mode. The PIN photodiode is of the standard structure (Figure 7a) with an InGaAs absorbing layer and the junction FET is fabricated on the low doped *n*-InP layer. An integration of the transmitter and receiver structures of Figure 10 with amplifier circuits would lead to a monolithically integrated regenerator.

Opto-electronic integration is driven by the desire to lower cost, improve performance, and increase functionality compared to discrete hybrid component technology. Integrated technology will reach its full potential only after lightwave materials and processing technologies are more fully developed and the need for larger volumes of devices is established.

Figure 10. Monolithically integrated simple laser transmitter (a) and PIN receiver (b) front ends. The field effect transistors (FETs) fabricated on *n*-InP provide the electronic functions and the laser and the PIN photodiode provide the photonic functions.

Reference

1. J. Clemans, W. A. Gault, and E. M. Monberg, "The Production of High Quality, III-V Compound Semiconductor Crystals," *The AT&T Technical Journal,* Vol. 65, No. 4, July 1986, pp. 86-98.

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