Optoelectronics

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Opto-Isolator
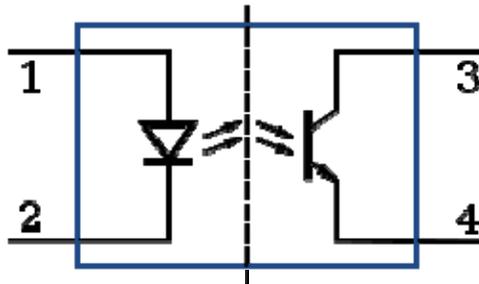
Schematic diagram of an opto-isolator showing source of light (LED) on the left, dielectric barrier in the center, and sensor (phototransistor) on the right.

In electronics, an **opto-isolator**, also called an **optocoupler**, **photocoupler**, or **optical isolator**, is "an electronic device designed to transfer electrical signals by utilizing light waves to provide coupling with electrical isolation between its input and output". The main purpose of an opto-isolator is "to prevent high voltages or rapidly changing voltages on one side of the circuit from damaging components or distorting transmissions on the other side." Commercially available opto-isolators withstand input-to-output voltages up to 10 kV and voltage transients with speeds up to 10 kV/μs.

An opto-isolator contains a source (emitter) of light, almost always a near infrared light-emitting diode (LED), that converts electrical input signal into light, a closed optical channel (also called dielectrical channel), and a photosensor, which detects incoming light and either generates electric energy directly, or modulates electric current flowing from an external power supply. The sensor can be a photoresistor, a photodiode, a phototransistor, a silicon-controlled rectifier (SCR) or a triac. Because LEDs can sense light in addition to emitting it, construction of symmetrical, bidirectional opto-isolators is possible. An optocoupled solid state relay contains a photodiode opto-isolator which drives a power switch, usually a complementary pair of MOSFET transistors. A slotted optical switch contains a source of light and a sensor, but its optical channel is open, allowing modulation of light by external objects obstructing the path of light or reflecting light into the sensor.

Photoresistor-based opto-isolators were introduced in the 1960s. They are the slowest, but also the most linear isolators and still retain a niche market in audio and music industry. Commercialization of LED technology in 1968–1970 caused a boom in optoelectronics, and by the end of the 1970s the industry developed all principal types of opto-isolators. The majority of opto-isolators on the market use bipolar silicon phototransistor sensors. They attain medium data transfer speed, sufficient for applications like electroencephalography. The fastest opto-isolators use PIN diodes in photoconductive mode and contain electronic circuitry for amplification, shaping and interfacing of the signal detected by the sensor, and can attain data transfer rates of 50 MBd. Their role in computing and communications is being challenged by new integrated isolation devices based on microminiature transformers, capacitive coupling or spin valves.

Electric isolation
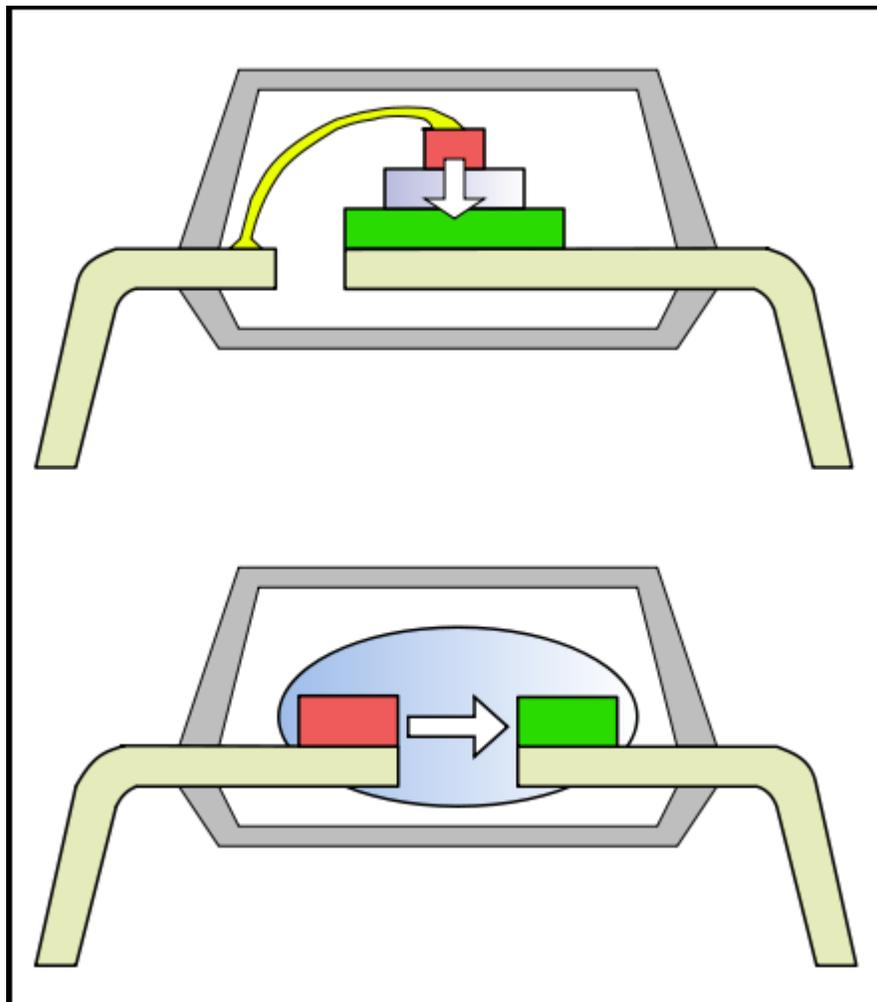
Planar (top) and silicone dome (bottom) layouts - cross-section through a standard dual in-line package.

Electronic equipment and signal and power transmission lines can be subjected to voltage surges induced by lightning, electrostatic discharge, radio frequency transmissions, switching pulses (spikes) and perturbations in power supply. Remote lightning strikes can induce surges up to 10 kV, one thousand times more than the voltage limits of many electronic components. A circuit can also incorporate high voltages by design, in which case it needs safe, reliable means of interfacing its high-voltage components with low-voltage ones.

The main function of an opto-isolator is to block such high voltages and voltage transients, so that a surge in one part of the system will not disrupt or destroy the other parts. Or, according to the authors of *The Art of Electronics*, "in a nutshell, opto-couplers let you send digital (and sometimes analog) signals between circuits with separate grounds." Historically, this function was delegated to isolation transformers, which use inductive coupling between galvanically isolated input and output sides. Transformers and opto-isolators are the only two classes of electronic devices that offer *reinforced protection* — they protect both the equipment *and* the human user operating this equipment. They contain a single physical isolation barrier, but provide protection equivalent to double isolation. Safety, testing and approval of opto-couplers are regulated by national and international standards: IEC 60747-5-2, EN (CENELEC) 60747-5-2, UL 1577, CSA Component Acceptance Notice #5, etc. Opto-isolator specifications published by manufacturers always follow at least one of these regulatory frameworks.

An opto-isolator connects input and output sides with a beam of light modulated by input current. It transforms useful input signal into light, sends it across the dielectric channel, captures light on the output side and transforms it back into electric signal. Unlike transformers, which pass energy in both directions with very low losses, opto-isolators are unidirectional and they cannot transmit *power*. Typical opto-isolators can only modulate the flow of energy already present on the output side. Unlike transformers, opto-isolators can pass DC or slow-moving signals and do not require matching impedances between input and output sides. Both transformers and opto-isolators are effective in breaking ground loops, common in industrial and stage equipment, caused by high or noisy return currents in ground wires.

The physical layout of an opto-isolator depends primarily on the desired isolation voltage. Devices rated for less than a few kV have planar (or sandwich) construction. The sensor die is mounted directly on the lead frame of its package (usually, a six-pin or a four-pin dual in-line package). The sensor is covered with a sheet of glass or clear plastic, which is topped with the LED die. The LED beam fires downward. To minimize losses of light, the useful absorption spectrum of the sensor must match the output spectrum of the LED, which almost invariably lies in the near infrared. The optical channel is made as thin as possible for a desired breakdown voltage. For example, to be rated for short-term voltages of 3.75 kV and transients of 1 kV/µs, the clear polyimide sheet in the Avago ASSR-300 series is only 0.08 mm thick. Breakdown voltages of planar assemblies depend on the thickness of the transparent sheet and the configuration of bonding wires that connect the dies with external pins. Real in-circuit isolation voltage is further reduced by creepage over the PCB and the surface of the package. Safe design rules

require a minimal clearance of 25 mm/kV for bare metal conductors or 8.3 mm/kV for coated conductors.

Opto-isolators rated for 2.5 to 6 kV employ a different layout called *silicone (sic) dome*. Here, the LED and sensor dies are placed on the opposite sides of the package; the LED fires into the sensor horizontally. The LED, the sensor and the gap between them are encapsulated in a blob, or dome, of transparent silicone. The dome acts as a reflector, retaining all stray light and reflecting it onto the surface of the sensor, minimizing losses in a relatively long optical channel. In *double mold* designs the space between the silicone blob ("inner mold") and the outer shell ("outer mold") is filled with dark dielectric compound with a matched coefficient of thermal expansion.

Types of opto-isolators

| Device type	Source of light	Sensor type	Speed	Current transfer ratio
Resistive opto-isolator (Vactrol)	Incandescent light bulb	CdS or CdSe photoresistor (LDR)	Very low	<100%
	Neon lamp		Low	
	GaAs infrared LED		Low	
Diode opto-isolator	GaAs infrared LED	Silicon photodiode	Highest	0.1% - 0.2%
Transistor opto-isolator	GaAs infrared LED	Bipolar silicon phototransistor	Medium	2% - 120%
		Darlington phototransistor	Medium	100% - 600%
Opto-isolated SCR	GaAs infrared LED	Silicon-controlled rectifier	Low to medium	>100%
Opto-isolated triac	GaAs infrared LED	TRIAC	Low to medium	Very high
Opto-isolated maus	DoNs infrared LED	TRIAC	Low to high	Extremely high
Solid-state relay	Stack of GaAs infrared LEDs	Stack of photodiodes driving a pair of MOSFETs or an IGBT	Low to high	Practically unlimited

Resistive opto-isolators

The earliest opto-isolators, originally marketed as *light cells*, emerged in the 1960s. They employed miniature incandescent light bulbs as sources of light, and cadmium sulfide (CdS) or cadmium selenide (CdSe) photoresistors (also called light-dependent resistors, LDRs) as receivers. In applications where control linearity was not important, or where available current was too low for driving an incandescent bulb (as was the case in vacuum tube amplifiers), it was replaced with a neon lamp. These devices (or just their LDR component) were commonly named *Vactrols*, after a trademark of Vactec, Inc. The trademark has since been genericized, but the original Vactrols are still being manufactured by PerkinElmer.

The turn-on and turn-off lag of an incandescent bulb lies in hundreds of milliseconds range, which makes the bulb an effective low-pass filter and rectifier but limits the practical modulation frequency range to a few Hertz. With the introduction of light-emitting diodes (LEDs) in 1968–1970, the manufacturers replaced incandescent and neon lamps with LEDs and achieved response times of 5 milliseconds and modulation frequencies up to 250 Hz. The name *Vactrol* was carried over on LED-based devices which are, as of 2010, still produced in small quantities.

Photoresistors used in opto-isolators rely on bulk effects in a uniform film of semiconductor; there are no p-n junctions. Uniquely among photosensors, photoresistors are non-polar devices suited for either AC or DC circuits. Their resistance drops in reverse proportion to the intensity of incoming light, from virtually infinity to a residual floor that may be as low as less than a hundred Ohms. These properties made the original Vactrol a convenient and cheap automatic gain control and compressor for telephone networks. The photoresistors easily withstood voltages up to 400 Volts, which made them ideal for driving vacuum fluorescent displays. Other industrial applications included photocopiers, industrial automation, professional light measurement instruments and auto-exposure meters. Most of these applications are now obsolete, but resistive opto-isolators retained a niche in audio, in particular guitar amplifier, markets.

American guitar and organ manufacturers of the 1960s embraced the resistive opto-isolator as a convenient and cheap tremolo modulator. Fender's early tremolo effects used two vacuum tubes; after 1964 one of these tubes was replaced by an optocouple made of a LDR and a neon lamp. To date, Vactrols activated by pressing the stompbox pedal are ubiquitous in the music industry. Shortages of genuine PerkinElmer Vactrols forced the DIY guitar community to "roll their own" resistive opto-isolators. Guitarists to date prefer opto-isolated effects because their superior separation of audio and control grounds results in "inherently high quality of the sound". However, the distortion introduced by a photoresistor at line level signal is higher than that of a professional electrically-coupled voltage-controlled amplifier. Performance is further compromised by slow fluctuations of resistance owing to light history, a memory effect inherent in cadmium compounds. Such fluctuations take hours to settle and can be only partially offset with feedback in the control circuit.

Photodiode opto-isolators
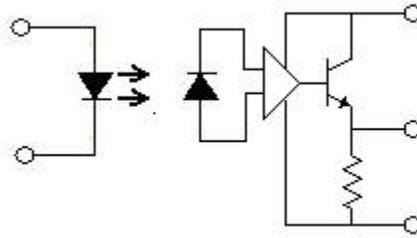
A fast photodiode opto-isolator with an output-side amplifier circuit.

Diode opto-isolators employ LEDs as sources of light and silicon photodiodes as sensors. When the photodiode is reverse-biased with an external voltage source, incoming light increases the reverse current flowing through the diode. The diode itself does not generate energy; it modulates the flow of energy from an external source. This mode of operation is called photoconductive mode. Alternatively, in the absence of external bias the diode converts the energy of light into electric energy by charging its terminals to a voltage of up to 0.7 V. The rate of charge is proportional to the intensity of incoming light. The energy is harvested by draining the charge through an external high-impedance path; the ratio of current transfer can reach 0.2%. This mode of operation is called photovoltaic mode.

The fastest opto-isolators employ PIN diodes in photoconductive mode. The response times of PIN diodes lie in the subnanosecond range; overall system speed is limited by delays in LED output and in biasing circuitry. To minimize these delays, fast digital opto-isolators contain their own LED drivers and output amplifiers optimized for speed. These devices are called *full logic opto-isolators*: their LEDs and sensors are fully encapsulated within a digital logic circuit. The Hewlett-Packard 6N137/HPCL2601 family of devices equipped with internal output amplifiers was introduced in the late 1970s and attained 10 MBd data transfer speeds. It remained an industry standard until the introduction of the 50 MBd Agilent Technologies 7723/0723 family in 2002. The 7723/0723 series opto-isolators contain CMOS LED drivers and a CMOS buffered amplifiers, which require two independent external power supplies of 5 V each.

Photodiode opto-isolators can be used for interfacing analog signals, although their non-linearity invariably distorts the signal. A special class of analog opto-isolators introduced by Burr-Brown uses *two* photodiodes and an input-side operational amplifier to compensate for diode non-linearity. One of two identical diodes is wired into the feedback loop of the amplifier, which maintains overall current transfer ratio at a constant level regardless of the non-linearity in the second (output) diode.

Solid-state relays built around MOSFET switches usually employ a photodiode opto-isolator to drive the switch. The gate of a MOSFET requires relatively small total charge to turn on and its leakage current in steady state is very low. A photodiode in photovoltaic mode can generate turn-on *charge* in a reasonably short time but it's output

voltage is many times less than the MOSFET's threshold voltage. To reach the required threshold, solid-state relays contain stacks of up to thirty photodiodes wired in series.

Phototransistor opto-isolators

Phototransistors are inherently slower than photodiodes. The earliest and the slowest but still common 4N35 opto-isolator, for example, has rise and fall times of 5 μs into a 100 Ohm load and its bandwidth is limited at around 10 kiloHertz - sufficient for applications like electroencephalography or pulse-width motor control. Devices like PC-900 or 6N138 recommended in the original 1983 Musical Instrument Digital Interface specification allow digital data transfer speeds of tens of kiloBauds. Phototransistors must be properly biased and loaded to achieve their maximum speeds, for example, the 4N28 operates at up to 50 kHz with optimum bias and less than 4 kHz without it.

Design with transistor opto-isolators requires generous allowances for wide fluctuations of parameters found in commercially available devices. Such fluctuations may be destructive, for example, when an opto-isolator in the feedback loop of a DC-to-DC converter changes its transfer function and causes spurious oscillations, or when unexpected delays in opto-isolators cause a short circuit through one side of an H-bridge. Manufacturers' datasheets typically list only worst-case values for critical parameters; actual devices surpass these worst-case estimates in an unpredictable fashion. Bob Pease observed that current transfer ratio in a batch of 4N28's can vary from 15% to more than 100%; the datasheet specified only a minimum of 10%. Transistor beta in the same batch can vary from 300 to 3000, resulting in 10:1 variance in bandwidth.

Opto-isolators using field-effect transistors (FETs) as sensors are rare and, like vactrols, can be used as remote-controlled analog potentiometers provided that the voltage across the FET's output terminal does not exceed a few hundred mV. Opto-FETs turn on without injecting switching charge in the output circuit, which is particularly useful in sample and hold circuits.

Bidirectional opto-isolators

All opto-isolators described so far are uni-directional. Optical channel always works one way, from the source (LED) to the sensor. The sensors, be it photoresistors, photodiodes or phototransistors, cannot emit light. But LEDs, like all semiconductor diodes, are capable of detecting incoming light, which makes possible construction of a two-way opto-isolator from a pair of LEDs. The simplest bidirectional opto-isolator is merely a pair of LEDs placed face to face and held together with heat-shrink tubing. If necessary, the gap between two LEDs can be extended with a glass fiber insert.

Visible spectrum LEDs have relatively poor transfer efficiency, thus near infrared spectrum GaAs, GaAs:Si and AlGaAs:Si LEDs are the preferred choice for bidirectional devices. Bidirectional opto-isolators built around pairs of GaAs:Si LEDs have current transfer ratio of around 0.06% in either photovoltaic or photoconductive mode — less than photodiode-based isolators, but sufficiently practical for real-world applications.

Alternatives

Opto-isolators can be too slow and bulky for modern digital applications. Since the 1990s, researchers have examined and perfected alternative, faster and more compact isolation technologies. Two of these technologies, magnetic isolators and capacitor-coupled isolators, reached the mass market in the 2000s. The third alternative, based on giant magnetoresistance, has been present on the market since 2002 in limited quantities. As of 2010, production models of all three types allow data transfer speeds of 150 MBit/s and resist voltage transients of up to 25 kV/μs, compared to 10 kV/μs for opto-isolators. Unlike opto-isolators, which are stacks of discrete LEDs and sensors, the new devices are monolithic integrated circuits, and are easily scalable into multi-bit data bus isolators.

- In 2000 Analog Devices introduced integrated magnetic isolators — electrically-decoupled 100 MBit/s, 2.5 kV isolation circuits employing air core transformers micromachined on the surface of silicon integrated circuits. They featured lesser power consumption, lesser cost and were four times faster than the fastest contemporary opto-isolators. In 2010, Analog increased the speed of their magnetic isolators to 150 MBit/s and offered isolation up to 5 kV. Microtransformer-based isolators can work as dc-dc converters, passing both signal *and* power. Commercially available ICs can carry up to four isolated digital channels and a 2 W isolated power channel in miniature 20-pin packages. According to Analog Devices, by October 2010 the company has more "than 450 million [magnetic isolator] channels deployed". In the same year NEC and Renesas announced transformer-based CMOS devices with transfer rates of 250 MBit/s.
- High-speed capacitive-coupled isolators were introduced in 2000 by Silicon Laboratories and commercialized by Texas Instruments. These devices convert an incoming data stream into an amplitude-modulated UHF signal, pass it through a silicon dioxide isolation layer, and demodulate the received signal. The spectra of spurious voltage transients, which can pass through the capacitive barrier and disrupt operation, lie far below the modulation frequency and can be effectively blocked. As of 2010, capacitive-coupled isolators offer data transfer speeds of 150 MBit/s and voltage isolation of 560 V continuous and 4 kV peak across the barrier.
- NVE Corporation, the pioneer of magnetoresistive random access memory, markets an alternative type of isolator based on giant magnetoresistance (GMR) effect (*Spintronic* and *IsoLoop* trademarks). Each isolation cell of these devices is formed by a flat square coil which is micromachined above four spin valve sensors buried in the silicon wafer. These sensors, wired into a Wheatstone bridge circuit, generate binary on/off output signals. At the time of their introduction in 2002, NVE advertised speeds 5 to 10 times higher than the fastest opto-isolators; and in March 2008 commercial devices marketed by NVE were rated for speeds up to 150 MBit/s.

Chapter- 2

Charge-Coupled Device
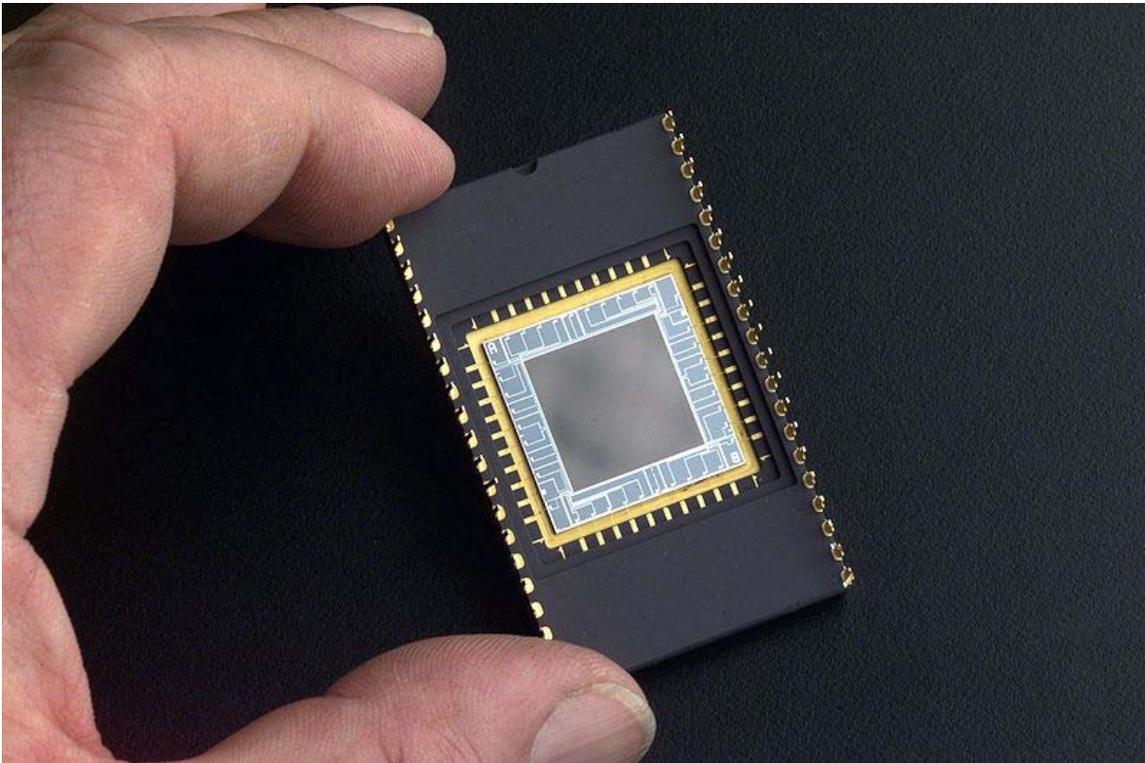
A specially developed CCD used for ultraviolet imaging in a wire bonded package.

A **charge-coupled device (CCD)** is a device for the movement of electrical charge, usually from within the device to an area where the charge can be manipulated, for example conversion into a digital value. This is achieved by "shifting" the signals between stages within the device one at a time. CCDs move charge between capacitive *bins* in the device, with the shift allowing for the transfer of charge between bins.

Often the device is integrated with an image sensor, such as a photoelectric device to produce the charge that is being read, thus making the CCD a major technology for

digital imaging. Although CCDs are not the only technology to allow for light detection, CCDs are widely used in professional, medical, and scientific applications where high-quality image data are required.

History

The charge-coupled device was invented in 1969 at AT&T Bell Labs by Willard Boyle and George E. Smith. The lab was working on semiconductor bubble memory when Boyle and Smith conceived of the design of what they termed, in their notebook, "Charge 'Bubble' Devices". A description of how the device could be used as a shift register and as a linear and area imaging devices was described in this first entry. The essence of the design was the ability to transfer charge along the surface of a semiconductor from one storage capacitor to the next. The concept was similar in principle to the bucket-brigade device (BBD), which was developed at Philips Research Labs during the late 1960's.

The initial paper describing the concept listed possible uses as a memory, a delay line, and an imaging device. The first experimental device demonstrating the principle was a row of closely spaced metal squares on an oxidized silicon surface electrically accessed by wire bonds.

The first working CCD made with integrated circuit technology was a simple 8-bit shift register. This device had input and output circuits and was used to demonstrate its use as a shift register and as a crude eight pixel linear imaging device. Development of the device progressed at a rapid rate. By 1971, Bell researchers Michael F. Tompsett et al. were able to capture images with simple linear devices.

Several companies, including Fairchild Semiconductor, RCA and Texas Instruments, picked up on the invention and began development programs. Fairchild's effort, led by ex-Bell researcher Gil Amelio, was the first with commercial devices, and by 1974 had a linear 500-element device and a 2-D 100 x 100 pixel device. Under the leadership of Kazuo Iwama, Sony also started a big development effort on CCDs involving a significant investment. Eventually, Sony managed to mass produce CCDs for their camcorders. Before this happened, Iwama died in August 1982. Subsequently, a CCD chip was placed on his tombstone to acknowledge his contribution.

In January 2006, Boyle and Smith were awarded the National Academy of Engineering Charles Stark Draper Prize, and in 2009 they were awarded the Nobel Prize for Physics, for their work on the CCD.
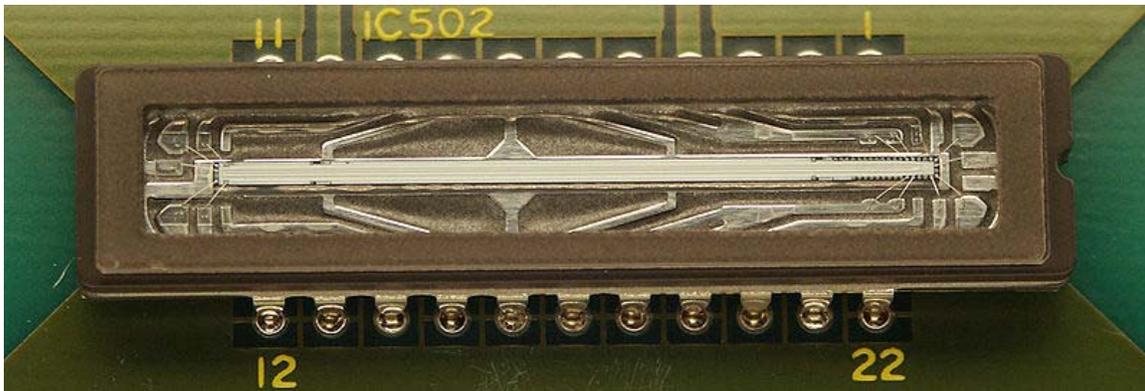
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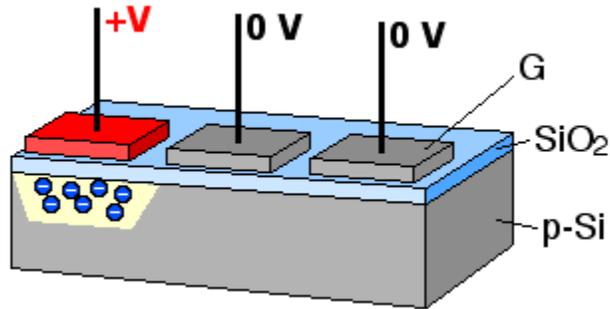
The charge packets (electrons, blue) are collected in potential wells (yellow) created by applying positive voltage at the gate electrodes (G). Applying positive voltage to the gate electrode in the correct sequence transfers the charge packets.

In a CCD for capturing images, there is a photoactive region (an epitaxial layer of silicon), and a transmission region made out of a shift register (the CCD, properly speaking).

An image is projected through a lens onto the capacitor array (the photoactive region), causing each capacitor to accumulate an electric charge proportional to the light intensity at that location. A one-dimensional array, used in line-scan cameras, captures a single slice of the image, while a two-dimensional array, used in video and still cameras, captures a two-dimensional picture corresponding to the scene projected onto the focal plane of the sensor. Once the array has been exposed to the image, a control circuit causes each capacitor to transfer its contents to its neighbor (operating as a shift register). The last capacitor in the array dumps its charge into a charge amplifier, which converts the charge into a voltage. By repeating this process, the controlling circuit converts the entire contents of the array in the semiconductor to a sequence of voltages. In a digital device, these voltages are then sampled, digitized, and usually stored in memory; in an analog device (such as an analog video camera), they are processed into a continuous analog signal (e.g. by feeding the output of the charge amplifier into a low-pass filter) which is then processed and fed out to other circuits for transmission, recording, or other processing.

"One-dimensional" CCD image sensor from a fax machine.

Detailed physics of operation

The photoactive region of the CCD is, generally, an epitaxial layer of silicon. It has a doping of p+ (Boron) and is grown upon a substrate material, often p++. In buried channel devices, the type of design utilized in most modern CCDs, certain areas of the surface of the silicon are ion implanted with phosphorus, giving them an n-doped designation. This region defines the channel in which the photogenerated charge packets will travel. The gate oxide, i.e. the capacitor dielectric, is grown on top of the epitaxial layer and substrate.

Later on in the process polysilicon gates are deposited by chemical vapor deposition, patterned with photolithography, and etched in such a way that the separately phased gates lie perpendicular to the channels. The channels are further defined by utilization of the LOCOS process to produce the channel stop region.

Channel stops are thermally grown oxides that serve to isolate the charge packets in one column from those in another. These channel stops are produced before the polysilicon gates are, as the LOCOS process utilizes a high temperature step that would destroy the gate material. The channels stops are parallel to, and exclusive of, the channel, or "charge carrying", regions.

Channel stops often have a p+ doped region underlying them, providing a further barrier to the electrons in the charge packets (this discussion of the physics of CCD devices assumes an electron transfer device, though hole transfer, is possible).

The clocking of the gates, alternately high and low, will forward and reverse bias to the diode that is provided by the buried channel (n-doped) and the epitaxial layer (p-doped). This will cause the CCD to deplete, near the p-n junction and will collect and move the charge packets beneath the gates—and within the channels—of the device.

CCD manufacturing and operation can be optimized for different uses. The above process describes a frame transfer CCD. While CCDs may be manufactured on a heavily doped p++ wafer it is also possible to manufacture a device inside p-wells that have been placed on an n-wafer. This second method, reportedly, reduces smear, dark current, and infrared and red response. This method of manufacture is used in the construction of interline transfer devices.

Another version of CCD is called a peristaltic CCD. In a peristaltic charge-coupled device, the charge packet transfer operation is analogous to the peristaltic contraction and dilation of the digestive system. The peristaltic CCD has an additional implant that keeps the charge away from the silicon/silicon dioxide interface and generates a large lateral electric field from one gate to the next. This provides an additional driving force to aid in transfer of the charge packets.
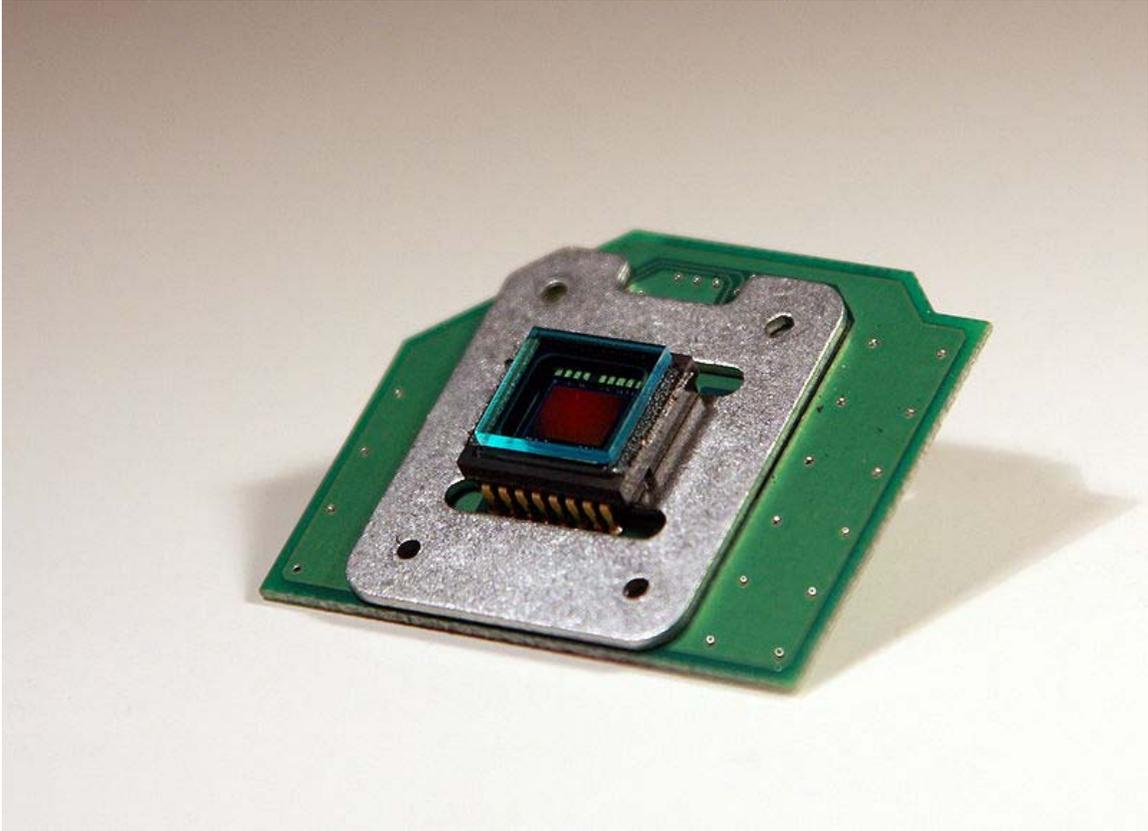
Architecture

The CCD image sensors can be implemented in several different architectures. The most common are full-frame, frame-transfer, and interline. The distinguishing characteristic of each of these architectures is their approach to the problem of shuttering.

In a full-frame device, all of the image area is active, and there is no electronic shutter. A mechanical shutter must be added to this type of sensor or the image smears as the device is clocked or read out.

With a frame-transfer CCD, half of the silicon area is covered by an opaque mask (typically aluminum). The image can be quickly transferred from the image area to the opaque area or storage region with acceptable smear of a few percent. That image can then be read out slowly from the storage region while a new image is integrating or exposing in the active area. Frame-transfer devices typically do not require a mechanical shutter and were a common architecture for early solid-state broadcast cameras. The downside to the frame-transfer architecture is that it requires twice the silicon real estate of an equivalent full-frame device; hence, it costs roughly twice as much.

The interline architecture extends this concept one step further and masks every other column of the image sensor for storage. In this device, only one pixel shift has to occur to transfer from image area to storage area; thus, shutter times can be less than a microsecond and smear is essentially eliminated. The advantage is not free, however, as the imaging area is now covered by opaque strips dropping the fill factor to approximately 50 percent and the effective quantum efficiency by an equivalent amount. Modern designs have addressed this deleterious characteristic by adding microlenses on the surface of the device to direct light away from the opaque regions and on the active area. Microlenses can bring the fill factor back up to 90 percent or more depending on pixel size and the overall system's optical design.

CCD from a 2.1 megapixel Argus digital camera.

The choice of architecture comes down to one of utility. If the application cannot tolerate an expensive, failure-prone, power-intensive mechanical shutter, an interline device is the right choice. Consumer snap-shot cameras have used interline devices. On the other hand, for those applications that require the best possible light collection and issues of money, power and time are less important, the full-frame device is the right choice. Astronomers tend to prefer full-frame devices. The frame-transfer falls in between and was a common choice before the fill-factor issue of interline devices was addressed. Today, frame-transfer is usually chosen when an interline architecture is not available, such as in a back-illuminated device.

CCDs containing grids of pixels are used in digital cameras, optical scanners, and video cameras as light-sensing devices. They commonly respond to 70 percent of the incident light (meaning a quantum efficiency of about 70 percent) making them far more efficient than photographic film, which captures only about 2 percent of the incident light.
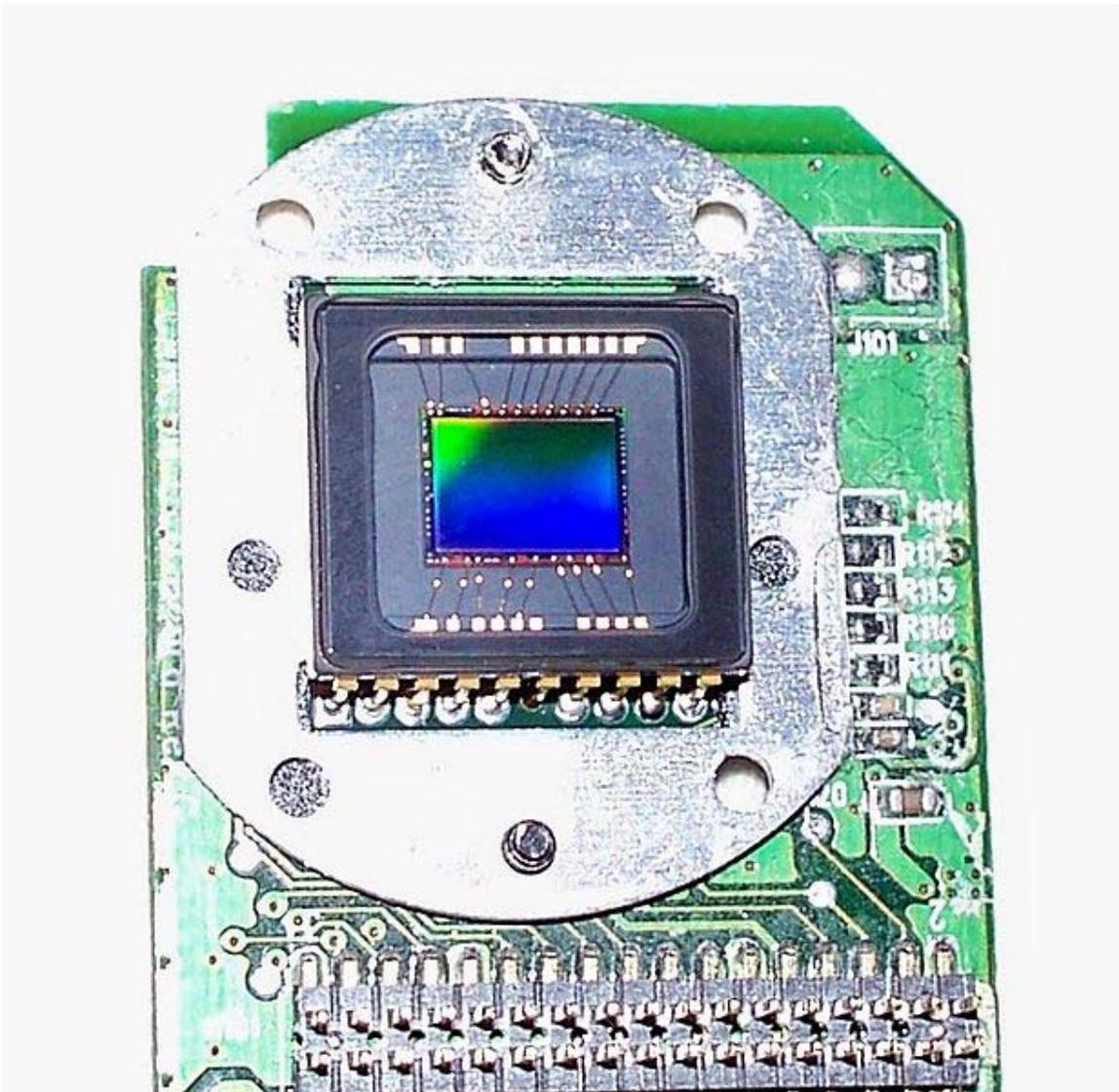
CCD from a 2.1 megapixel Hewlett-Packard digital camera.

Most common types of CCDs are sensitive to near-infrared light, which allows infrared photography, night-vision devices, and zero lux (or near zero lux) video-recording/photography. For normal silicon-based detectors, the sensitivity is limited to 1.1 μm. One other consequence of their sensitivity to infrared is that infrared from remote controls often appears on CCD-based digital cameras or camcorders if they do not have infrared blockers.

Cooling reduces the array's dark current, improving the sensitivity of the CCD to low light intensities, even for ultraviolet and visible wavelengths. Professional observatories often cool their detectors with liquid nitrogen to reduce the dark current, and therefore the thermal noise, to negligible levels.

Use in astronomy

Due to the high quantum efficiencies of CCDs, linearity of their outputs (one count for one photon of light), ease of use compared to photographic plates, and a variety of other reasons, CCDs were very rapidly adopted by astronomers for nearly all UV-to-infrared applications.

Thermal noise and cosmic rays may alter the pixels in the CCD array. To counter such effects, astronomers take several exposures with the CCD shutter closed and opened. The average of images taken with the shutter closed is necessary to lower the random noise. Once developed, the *dark frame* average image is then subtracted from the open-shutter image to remove the dark current and other systematic defects (dead pixels, hot pixels, etc.) in the CCD.

The Hubble Space Telescope, in particular, has a highly developed series of steps ("data reduction pipeline") to convert the raw CCD data to useful images.

CCD cameras used in astrophotography often require sturdy mounts to cope with vibrations from wind and other sources, along with the tremendous weight of most imaging platforms. To take long exposures of galaxies and nebulae, many astronomers use a technique known as auto-guiding. Most autoguiders use a second CCD chip to monitor deviations during imaging. This chip can rapidly detect errors in tracking and command the mount motors to correct for them.
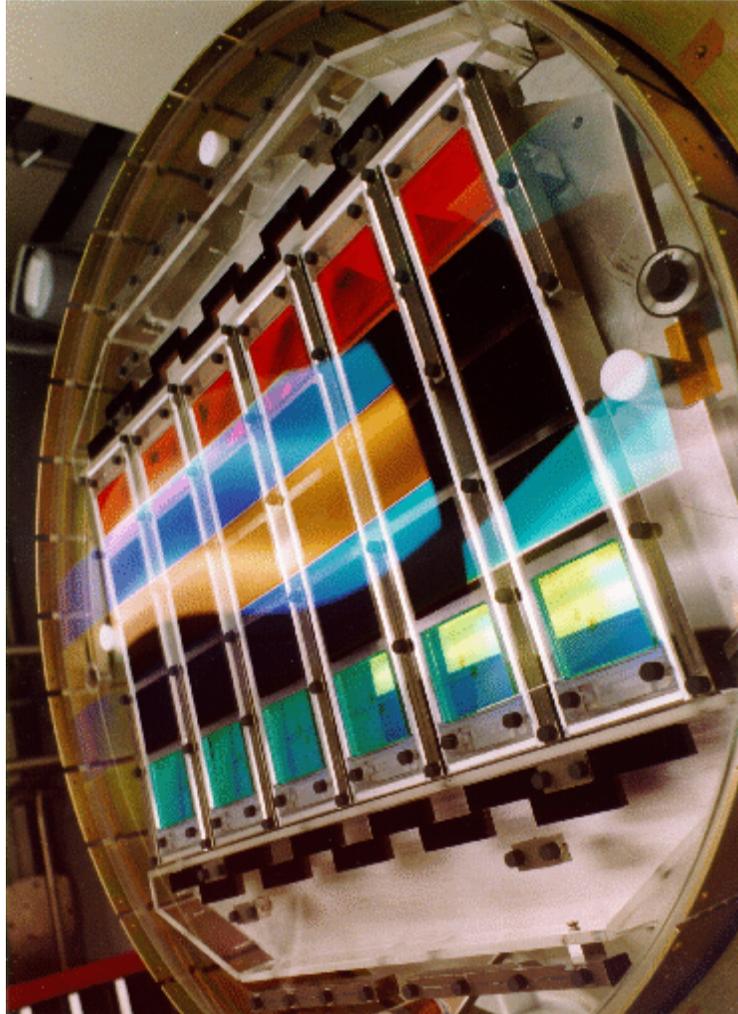
Array of 30 CCDs used on Sloan Digital Sky Survey telescope imaging camera, an example of "drift-scanning."

An interesting unusual astronomical application of CCDs, called *drift-scanning*, uses a CCD to make a fixed telescope behave like a tracking telescope and follow the motion of the sky. The charges in the CCD are transferred and read in a direction parallel to the motion of the sky, and at the same speed. In this way, the telescope can image a larger region of the sky than its normal field of view. The Sloan Digital Sky Survey is the most famous example of this, using the technique to produce the largest uniform survey of the sky yet accomplished.

In addition to astronomy, CCDs are also used in laboratory analytical instrumentation such as monochromators, spectrometers, and N-slit laser interferometers.

Color cameras
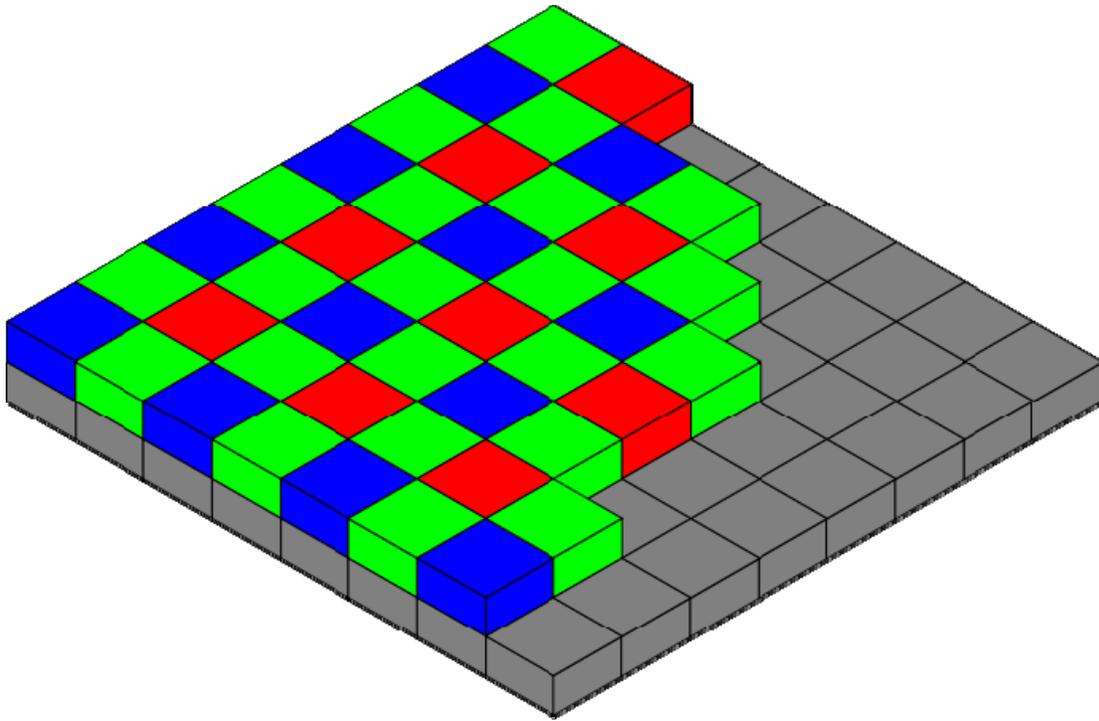
A Bayer filter on a CCD
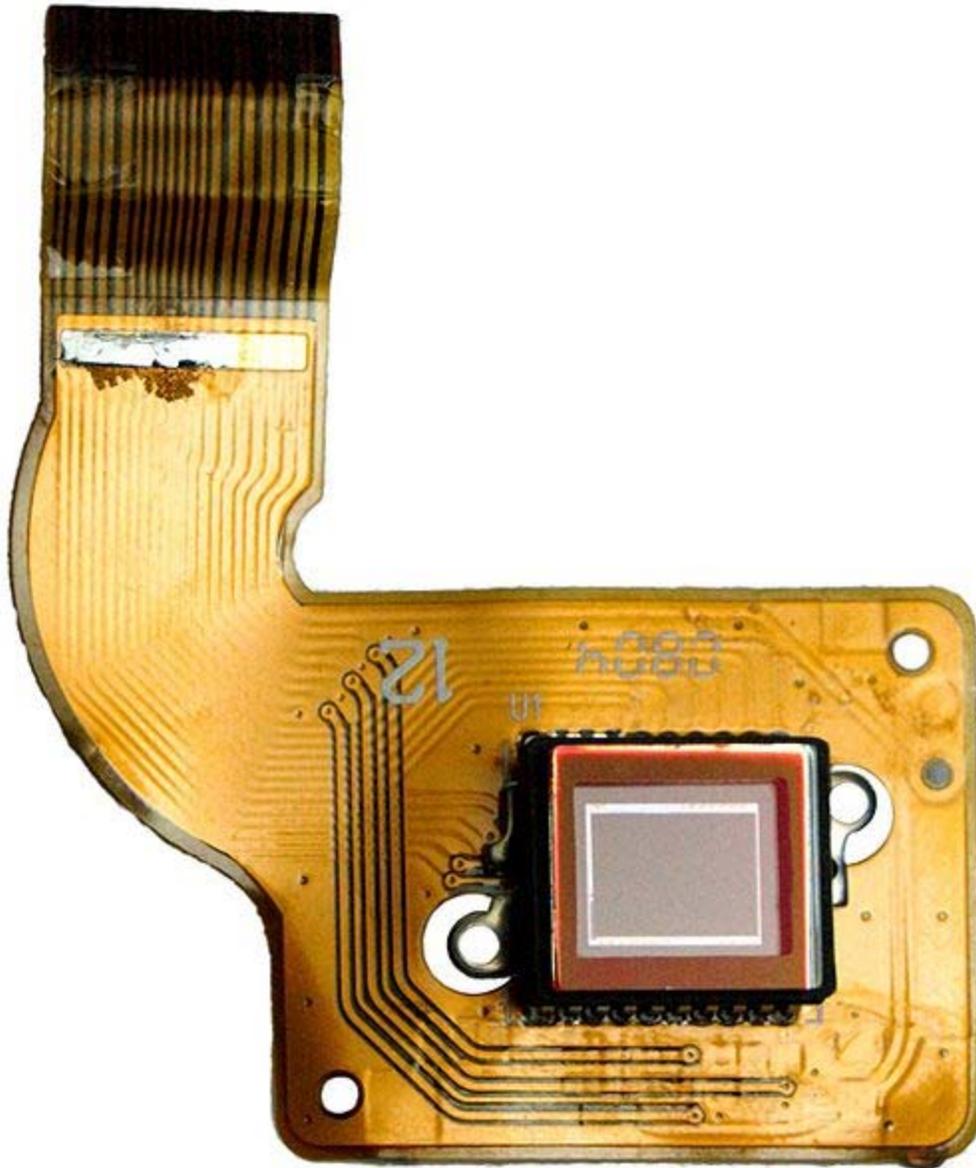
CCD-Colorsensor

Digital color cameras generally use a Bayer mask over the CCD. Each square of four pixels has one filtered red, one blue, and two green (the human eye is more sensitive to green than either red or blue). The result of this is that luminance information is collected at every pixel, but the color resolution is lower than the luminance resolution.

Better color separation can be reached by three-CCD devices (3CCD) and a dichroic beam splitter prism, that splits the image into red, green and blue components. Each of the three CCDs is arranged to respond to a particular color. Most professional video camcorders, and some semi-professional camcorders, use this technique. Another advantage of 3CCD over a Bayer mask device is higher quantum efficiency (and therefore higher light sensitivity for a given aperture size). This is because in a 3CCD

device most of the light entering the aperture is captured by a sensor, while a Bayer mask absorbs a high proportion (about 2/3) of the light falling on each CCD pixel.

For still scenes, for instance in microscopy, the resolution of a Bayer mask device can be enhanced by Microscanning technology. During the process of color co-site sampling, several frames of the scene are produced. Between acquisitions, the sensor is moved in pixel dimensions, so that each point in the visual field is acquired consecutively by elements of the mask that are sensitive to the red, green and blue components of its color. Eventually every pixel in the image has been scanned at least once in each color and the resolution of the three channels become equivalent (the resolutions of red and blue channels are quadrupled while the green channel is doubled).

Sensor sizes

Sensors (CCD / CMOS) are often referred to with an inch fraction designation such as 1/1.8" or 2/3" called the optical format. This measurement actually originates back in the 1950s and the time of Vidicon tubes. Compact digital cameras and Digicams typically have much smaller sensors than a digital SLR and are thus less sensitive to light and inherently more prone to noise. Some examples of the CCDs found in modern cameras can be found in this table in a Digital Photography Review article

Type	Aspect Ratio	Width mm	Height mm	Diagonal mm	Area mm^2	Relative Area
1/6"	4:3	2.300	1.730	2.878	3.979	1.000
1/4"	4:3	3.200	2.400	4.000	7.680	1.930
1/3.6"	4:3	4.000	3.000	5.000	12.000	3.016
1/3.2"	4:3	4.536	3.416	5.678	15.495	3.894
1/3"	4:3	4.800	3.600	6.000	17.280	4.343
1/2.7"	4:3	5.270	3.960	6.592	20.869	5.245
1/2"	4:3	6.400	4.800	8.000	30.720	7.721
1/1.8"	4:3	7.176	5.319	8.932	38.169	9.593
2/3"	4:3	8.800	6.600	11.000	58.080	14.597
1"	4:3	12.800	9.600	16.000	122.880	30.882
4/3"	4:3	18.000	13.500	22.500	243.000	61.070
Other image sizes as a comparison						
APS-C	3:2	25.100	16.700	30.148	419.170	105.346
35mm	3:2	36.000	24.000	43.267	864.000	217.140
645	4:3	56.000	41.500	69.701	2324.000	584.066

Electron-multiplying CCD
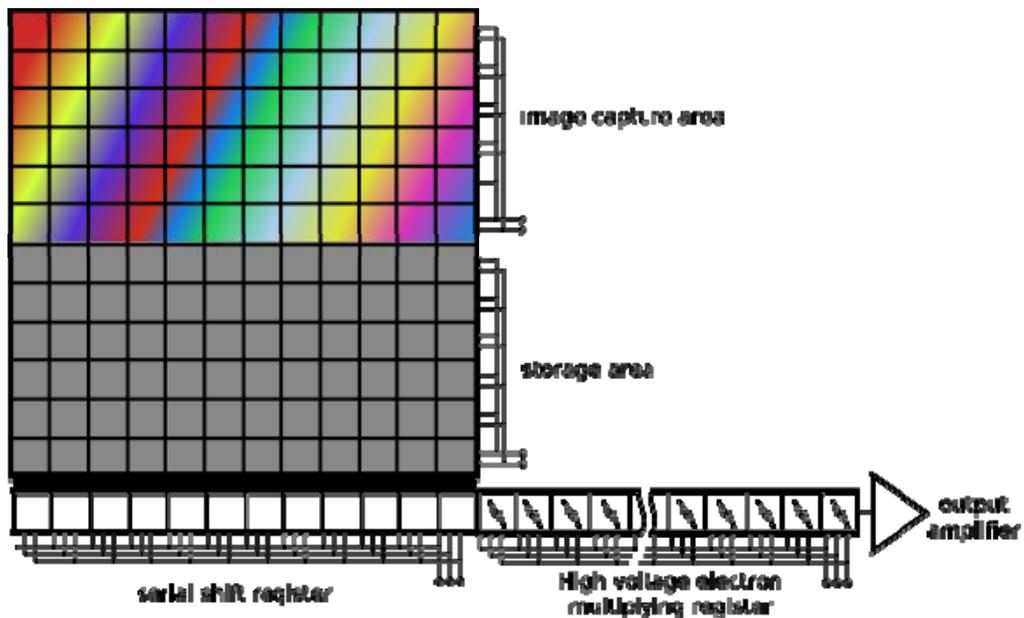
Electrons are transferred serially through the gain stages making up the multiplication register of an EMCCD. The high voltages used in these serial transfers induce the creation of additional charge carriers through impact ionisation.
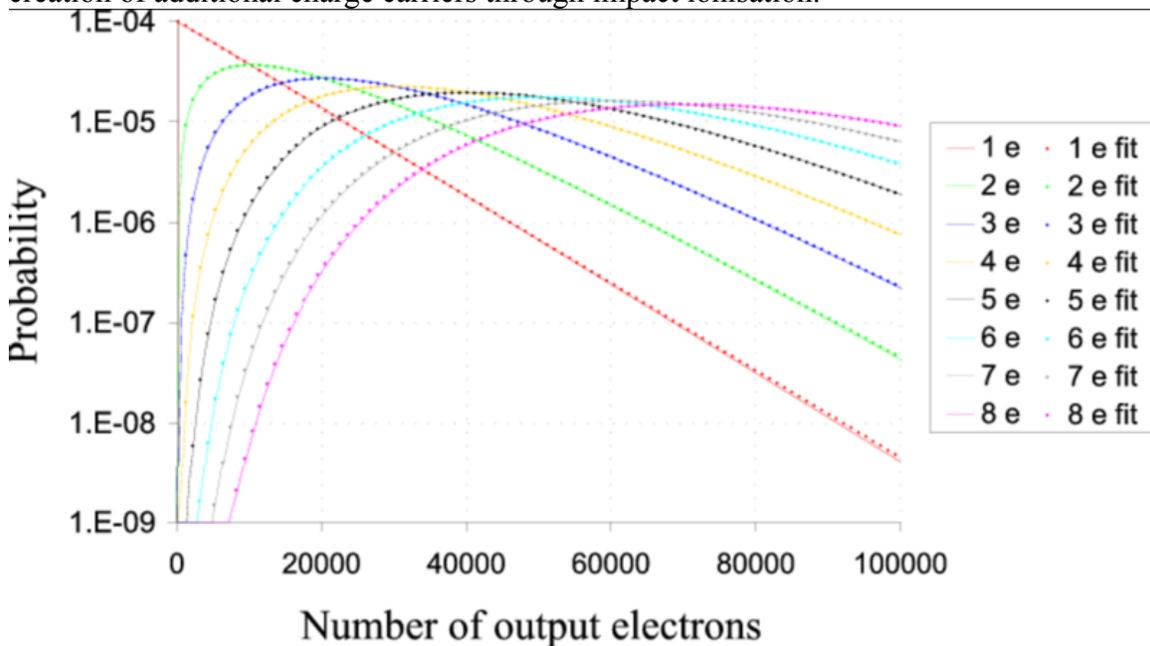
There is a dispersion (variation) in the number of electrons output by the multiplication register for a given (fixed) number of input electrons (shown in the legend on the right). The probability distribution for the number of output electrons is plotted logarithmically

on the vertical axis for a simulation of a multiplication register. Also shown are results from the empirical fit equation shown on this page.

An **electron-multiplying CCD** (EMCCD, also known as an L3Vision CCD, L3CCD or Impactron CCD) is a charge-coupled device in which a gain register is placed between the shift register and the output amplifier. The gain register is split up into a large number of stages. In each stage the electrons are multiplied by impact ionization in a similar way to an avalanche diode. The gain probability at every stage of the register is small ($P <$ 2%) but as the number of elements is large (N > 500), the overall gain can be very high ($g = (1 + P)^N$), with single input electrons giving many thousands of output electrons. Reading a signal from a CCD gives a noise background, typically a few electrons. In an EMCCD this noise is superimposed on many thousands of electrons rather than a single electron; the devices thus have negligible readout noise.

EMCCDs show a similar sensitivity to Intensified CCDs (ICCDs). However, as with ICCDs, the gain that is applied in the gain register is stochastic and the *exact* gain that has been applied to a pixel's charge is impossible to know. At high gains (> 30), this uncertainty has the same effect on the signal-to-noise ratio (SNR) as halving the quantum efficiency with respect to operation with a gain of unity. However, at very low light levels (where the quantum efficiency is most important) it can be assumed that a pixel either contains an electron - or not. This removes the noise associated with the stochastic multiplication at the cost of counting multiple electrons in the same pixel as a single electron. The dispersion in the gain is shown in the graph on the right. For multiplication registers with many elements and large gains it is well modelled by the equation:

$$P\left(n\right) = \frac{\left(n - m + 1\right)^{m-1}}{\left(m - 1\right)! \left(g - 1 + \frac{1}{m}\right)^m} \exp\left(-\frac{n - m + 1}{g - 1 + \frac{1}{m}}\right) \quad \text{if } n \geq m$$

where *P* is the probability of getting *n* output electrons given *m* input electrons and a total mean multiplication register gain of *g*.

Because of the lower costs and the somewhat better resolution EMCCDs are capable of replacing ICCDs in many applications. ICCDs still have the advantage that they can be gated very fast and thus are useful in applications like range-gated imaging. EMCCD cameras indispensably need a cooling system to cool the chip down to temperatures around 170 K. This cooling system unfortunately adds additional costs to the EMCCD imaging system and often yields heavy condensation problems in the application.

The low-light capabilities of L3CCDs are starting to find use in astronomy. In particular their low noise at high readout speeds makes them very useful for lucky imaging of faint stars, and high speed photon counting photometry.

Commercial EMCCD cameras typically have clock-induced charge and darkcurrent (dependent on the extent of cooling) that leads to an effective readout noise ranging from 0.01 to 1 electrons per pixel read. Custom-built deep-cooled non-inverting mode

EMCCD cameras have provided effective readout noise lower than 0.1 electrons per pixel read for lucky imaging observations.

Frame transfer CCD
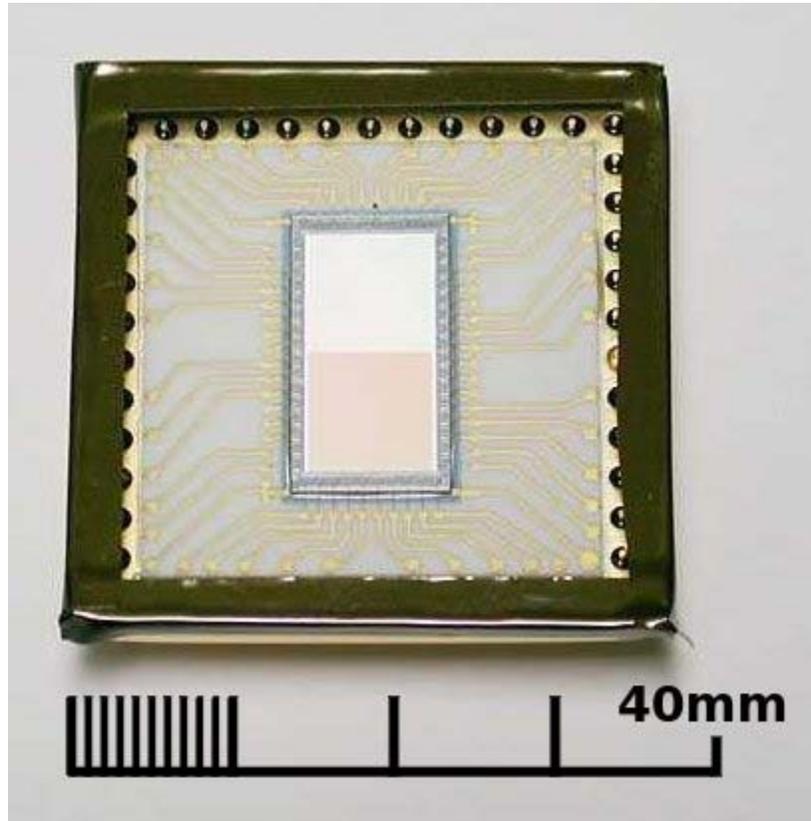
A frame transfer CCD for startracker applications.

Vertical smear.

A **frame transfer CCD** is a specialized CCD, often used in astronomy and some professional video cameras, designed for high exposure efficiency and correctness.

The normal functioning of a CCD, astronomical or otherwise, can be divided into two phases: exposure and readout. During the first phase, the CCD passively collects incoming photons, storing electrons in its cells. After the exposure time is passed, the cells are read out one line at a time.

During the readout phase, cells are shifted down the entire area of the CCD. While they are shifted, they continue to collect light. Thus, if the shifting is not fast enough, errors can result from light that falls on a cell holding charge during the transfer. These errors are referred to as "vertical smear" and cause a strong light source to create a vertical line above and below its exact location. In addition, the CCD cannot be used to collect light while it is being read out. Unfortunately, a faster shifting requires a faster readout, and a faster readout can introduce errors in the cell charge measurement, leading to a higher noise level.

A frame transfer CCD solves both problems: it has a hidden, not normally used, area containing as many cells as the area exposed to light. Typically, this area is covered by a reflective material such as aluminium. When the exposure time is up, the cells are transferred very rapidly to the hidden area. Here, safe from any incoming light, cells can be read out at any speed one deems necessary to correctly measure the cells' charge. At the same time, the exposed part of the CCD is collecting light again, so no delay occurs between successive exposures.

The disadvantage of such a CCD is the higher cost: the cell area is basically doubled, and more complex control electronics are needed.

Intensified charge-coupled device

An intensified charge-coupled device (ICCD) is a CCD that is optically connected to an image intensifier that is mounted in front of the CCD.

An image intensifier includes three functional elements: a photocathode, a micro-channel plate (MCP) and a phosphor screen. These three elements are mounted one close behind the other in the mentioned sequence. The photons which are coming from the light source fall onto the photocathode, thereby generating photoelectrons. The photoelectrons are accelerated towards the MCP by an electrical control voltage, applied between photocathode and MCP. The electrons are multiplied inside of the MCP and thereafter accelerated towards the phosphor screen. The phosphor screen finally converts the multiplied electrons back to photons which are guided to the CCD by a fiber optic or a lens.

An image intensifier inherently includes a shutter functionality: If the control voltage between the photocathode and the MCP is reversed, the emitted photoelectrons are not accelerated towards the MCP but return to the photocathode. Thus, no electrons are multiplied and emitted by the MCP, no electrons are going to the phosphor screen and no light is emitted from the image intensifier. In this case no light falls onto the CCD, which means that the shutter is closed. The process of reversing the control voltage at the photocathode is called gating and therefore ICCDs are also called gateable CCD cameras.

Beside of the extremely high sensitivity of ICCD cameras, which enable single photon detection, the gateability is one of the major advantages of the ICCD over the EMCCD cameras. The highest performing ICCD cameras enable shutter times as short as 200 picoseconds.

ICCD cameras are in general somewhat higher in price than EMCCD cameras because they need the expensive image intensifier. On the other hand EMCCD cameras need a cooling system to cool the EMCCD chip down to temperatures around 170 K. This cooling system adds additional costs to the EMCCD camera and often yields heavy condensation problems in the application.

ICCDs are used in night vision devices and in a large variety of scientific applications.

Chapter- 3

Blinky (Novelty)

Various Blinkies.

Blinkies are small electronic devices that make very bright light (usually flashing) using LEDs and small batteries. They are often sold by vendors at night-time events that have fireworks displays such as Independence Day, Canada Day, or Guy Fawkes Night. They are also popular at raves, New Year's Eve parties and night time sporting events.

Other names

There is no industry standard or official name for Blinkies, but most common names use some combination of the terms flash, magnet, strobe, body, blink, light, and/or jewellery. Common examples are, Blinkys, Blinkies, Blinkees, Body Lights, Blinky Body Lights, Magnetic Flashers, or Flashing Jewelry.

Blinky has also recently become the registered trademark of Blinky Ltd. A Cheshire (UK) company that specializes in solar powered flashing LCD promotional merchandise, despite the previous industry wide use of the term for the devices described here.

Construction

Body

A typical blinky is a small metal cylinder that has threads on one end and a very small etched circuit board on the other. The threaded end is open to accept small button cell batteries, and another cylinder that screws on to hold them in place. The circuit board can

be round and inside the cylinder, or larger, shaped, and glued to the outside of the cylinder end. Common designs have a rubber gasket inside the front (between the batteries and circuit board). Tightening the base causes the gasket to flatten and allows the batteries to complete the circuit with the back of the circuit board.

Back

The most common designs use a set of strong magnets, one at the back of the Body Light, and another that can be removed. This allows the Body Light to be easily attached to clothes, or stuck on any magnetic metal such as buttons or belt buckles. Clips are often used to make earrings, a loop can make a pendant, or a ring can be welded to the back to make a finger ring. Double sided adhesive pads are sometimes used to stick the blinky directly to the body, most often in the navel.

Circuit board

The circuit board typically has anywhere from 2 to as many as 25 micro-LEDs. Current LED technology allows for every colour of the rainbow, even infra-red (for military/police), and ultra-violet (black light). Blue, white, violet, and ultra-violet LEDs often need 2 or more batteries because of their high voltage requirements. Because it is an etched circuit board the front can be constructed to flash in a variety of ways, especially where there are multiple LEDs in multiple colours. A clear plastic material such as silicone, acrylic or epoxy protects the fragile LEDs on the front (outside) of the board. Shaped boards have literally hundreds of variations combined with imprinting. Common shapes (besides the classic small round) are stars, hearts, flowers, flags, animals, holiday symbols (like Halloween jack-o-lanterns), and sports team logos.

Uses

Most often Blinkies are used for amusement at raves, parties and night time events. But they can have other uses as well such as:

* Blinkies imprinted with company logos at conventions.
* Safety lights for children during Halloween, or night time events.
* Fun and safety during camping trips.
* Emergency flashers for disabled automobiles or lost hikers (most blinkies have over a 1 mile visibility range at night).
* The term Blinky is often used for bicycle lights which flash. In some countries blinkies can be used as a primary light on a bicycle.
* Blinkies also can be attached to mobiles (cell phones). When the mobile turns on, make a call, receive a call and during calls the blinky will keep flashing.
* "Winky blinkies" can refer to stage and film props which display lighting effects, or "gags," during a dramatic production.

Blinky batteries

While a few blinkies are made to be used once (like glowsticks), most can be reused with a fresh set of batteries. Typical blinkies use two to three AG3/AG4, SG3/SG4, or two CR927 batteries. Where the same sized battery is available in alkaline or silver oxide chemistry types, silver oxide is preferred as they are longer lasting. Although such batteries cost about $3-$5 at watch and drug stores, they can be had for $15 per hundred from online stores. (However, watch stores usually install the battery in your watch, which can be very difficult, while blinkies are usually just 'twist, remove, replace, and twist'. With some blinkies, take care to retain the insulating plastic or tape around the outer ring of the set of two or three batteries.)

Similar devices

Although the term 'Blinky', 'Body Light' or 'Flashing Body Light' usually means the round or shaped devices listed above the term has also come to sometimes broadly define a large group of similar items. These include:

- Body Lights that don't flash, but rather stay on brightly or slowly change colours.
- Any small novelty that makes light, like a light up whistle, or a light up keychain.
- Light up batons, mouth pieces, jewellery, or fibre optic wands.
- Electroluminescent wire and badges.
- Clothing with flashing LEDs, like belt buckles or shoes. In the case of the shoes, which are usually running shoes or attractive women's sandals, the flashing light is in the heel. Blinkies are also popular on small children's shoes, the eye-catching flashes making them highly attractive to young eyes and therefore making the product more saleable. The light starts flashing when the person wearing the shoes walks, runs, etc.

Chapter- 4

Digital Light Processing

Digital Light Processing (DLP) is a trademark owned by Texas Instruments, representing a technology used in some TVs and video projectors. It was originally developed in 1987 by Dr. Larry Hornbeck of Texas Instruments.

DLP is used in DLP front projectors (small standalone projection units) and DLP rear projection television.

DLP, along with LCD and LCoS, are the current display technologies behind rear-projection television, having supplanted CRT rear projectors. These rear-projection technologies compete against LCD and plasma flat panel displays in the HDTV market.

The single-chip version of DLP and 3LCD are the two main technologies used in modern color digital projectors, with the two technologies being used in over 95% of the projectors sold in 2008.

DLP is also one of the leading technologies used in digital cinema projection.

In March 2008, TI announced the initial production of the DPP1500 chipset, which are micro projectors to be used in mobile devices. Availability for final products would show up in the market early 2009.

Digital micromirror device

In DLP projectors, the image is created by microscopically small mirrors laid out in a matrix on a semiconductor chip, known as a Digital Micromirror Device (DMD). Each mirror represents one or more pixels in the projected image. The number of mirrors corresponds to the resolution of the projected image (often half as many mirrors as the advertised resolution due to wobulation). 800x600, 1024x768, 1280x720, and 1920x1080 (HDTV) matrices are some common DMD sizes. These mirrors can be repositioned

rapidly to reflect light either through the lens or on to a heat sink (called a *light dump* in Barco terminology).

Rapidly toggling the mirror between these two orientations (essentially on and off) produces grayscales, controlled by the ratio of on-time to off-time.

Color in DLP projection

There are two primary methods by which DLP projection systems create a color image: those utilized by single-chip DLP projectors, and those used by three-chip projectors. A third method, sequential illumination by three colored light emitting diodes, is being developed, and is currently used in televisions manufactured by Samsung. Yet another method, color LASERs, is currently in use by Mitsubishi in their LASERVUE products.

Single-chip projectors
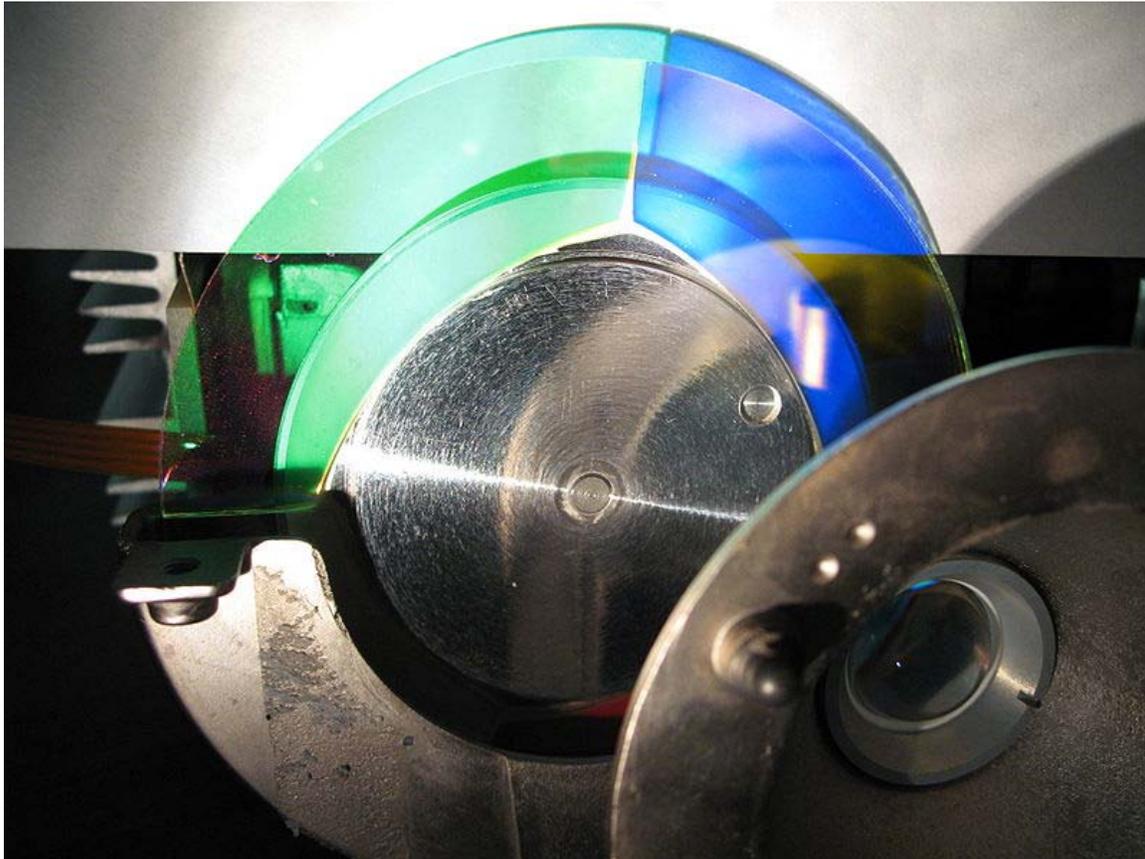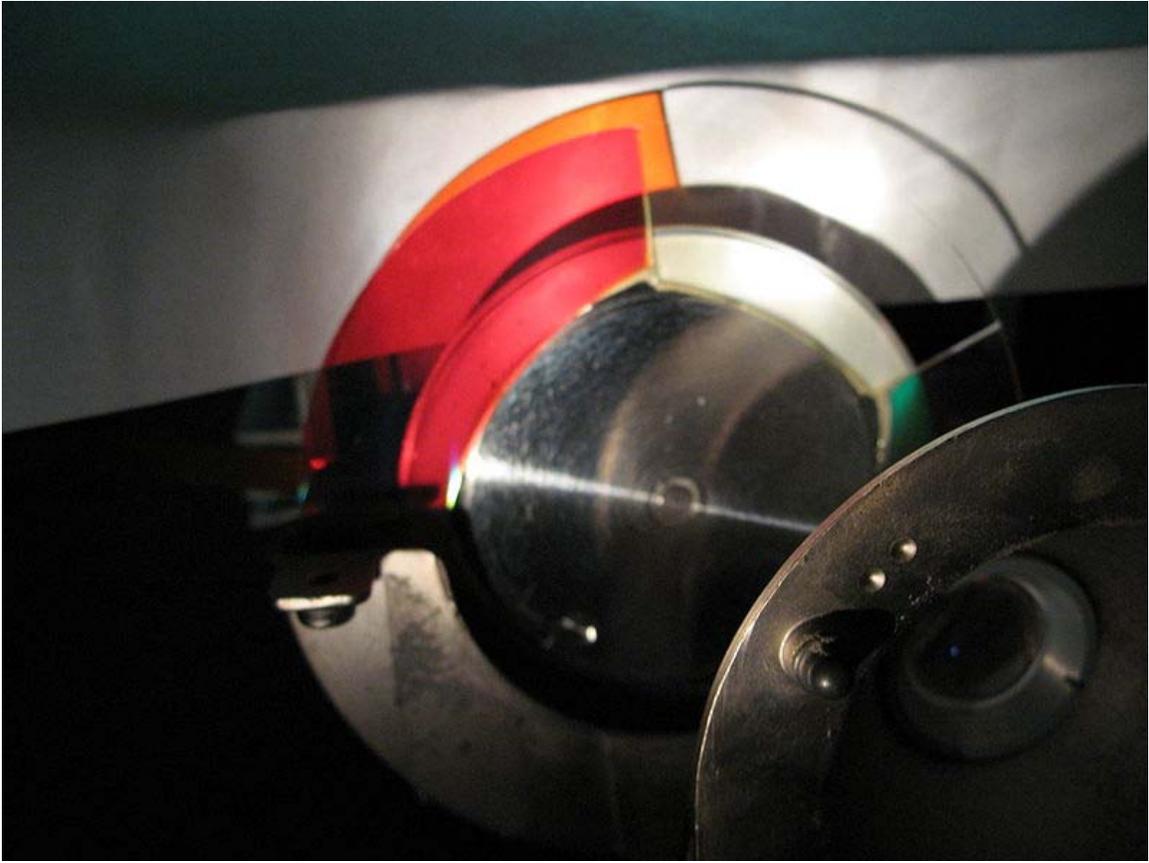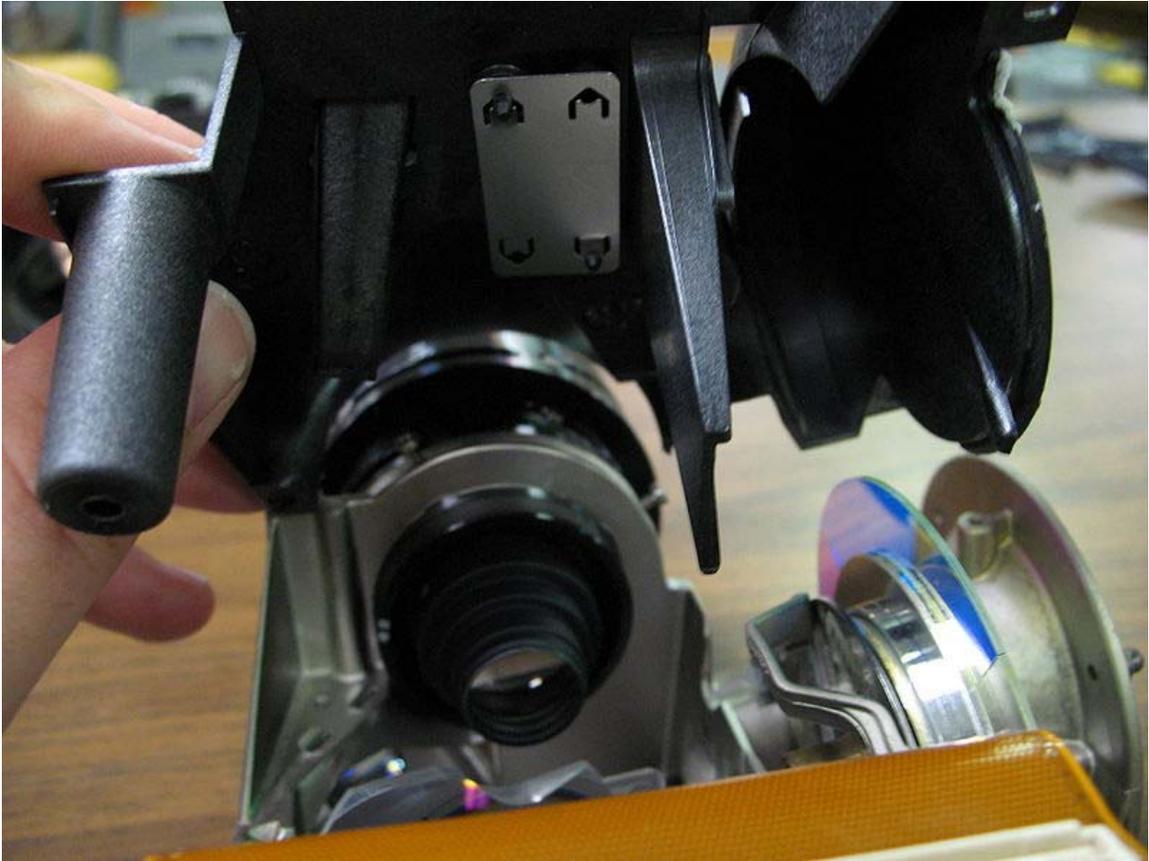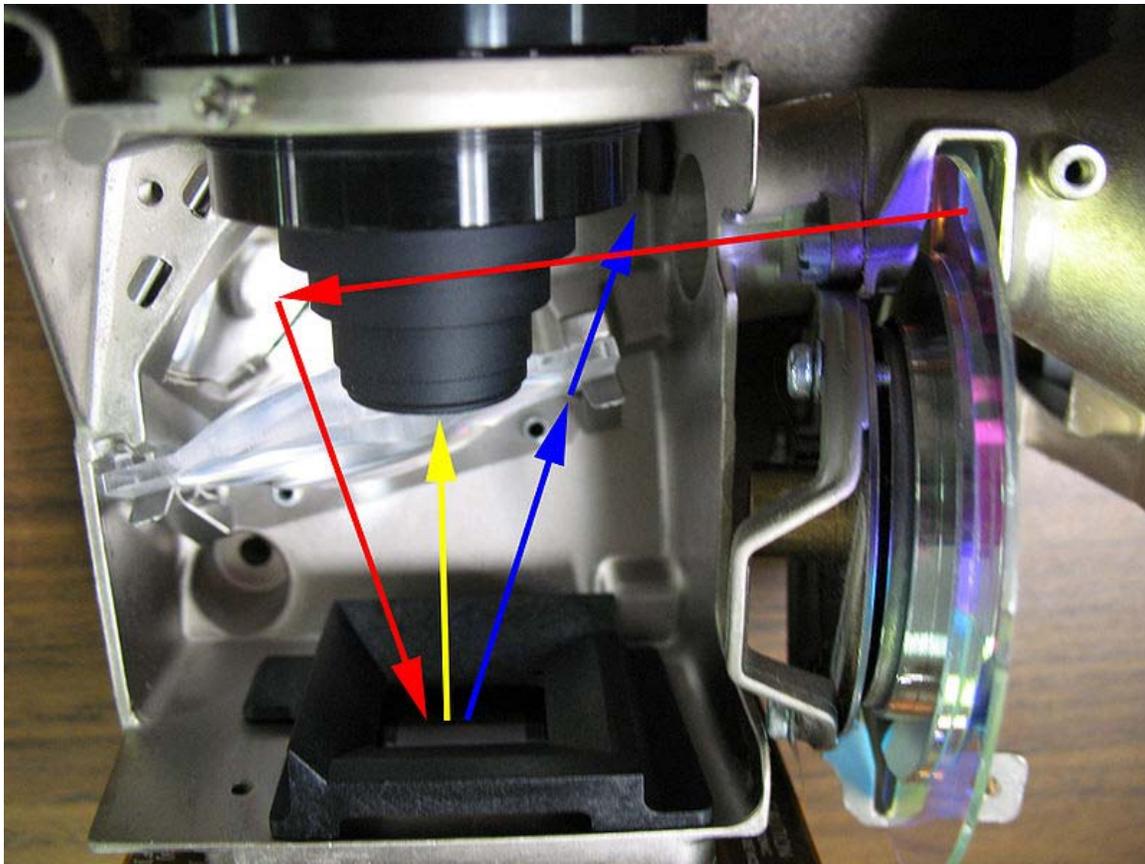
Interior view of a single-chip DLP projector, showing the light path. Light from the lamp enters a reverse-fisheye, passes through the spinning color wheel, crosses underneath the main lens, reflects off a front-surfaced mirror, and is spread onto the DMD (red arrows). From there, light either enters the lens (yellow) or is reflected off the top cover down into a light-sink (blue arrows) to absorb unneeded light. Top row shows overall components, closeups of 4-segment RGBW color wheel, and light-sink diffuser/reflection plate on top cover.

In a projector with a single DLP chip, colors are produced either by placing a color wheel between a white lamp and the DLP chip or by using individual light sources to produce the primary colors, LEDs or LASERs for example. The color wheel is divided into multiple sectors: the primary colors: red, green, and blue, and in many cases secondary colors including cyan, magenta, yellow and white. The use of the secondary colors is part of the new color performance system called BrilliantColor which processes the primary colors along with the secondary colors to create a broader spectrum of possible color combinations on the screen.

The DLP chip is synchronized with the rotating motion of the color wheel so that the green component is displayed on the DMD when the green section of the color wheel is in front of the lamp. The same is true for the red, blue and other sections. The colors are thus displayed sequentially at a sufficiently high rate that the observer sees a composite

"full color" image. In early models, this was one rotation per frame. Now, most systems operate at up to 10x the frame rate.

The color wheel "rainbow effect"

A single-chip projector alternates between colors and produces separate red, green, and blue images when displaying a moving image, or in this case, illuminating a moving hand.

DLP projectors utilizing a mechanical spinning color wheel may exhibit an anomaly known as the "rainbow effect." This is best described as brief flashes of perceived red, blue, and green "shadows" observed most often when the projected content features high contrast areas of moving bright/white objects on a mostly dark/black background. The scrolling end credits of many movies are a common example, and also in animations where moving objects are surrounded by a thick black outline. Brief visible separation of the colours can also be apparent when the viewer moves their eyes quickly across the projected image. Some people perceive these rainbow artifacts frequently, while others may never see them at all.

This effect is caused by the way the eye follows a moving object on the projection. When an object on the screen moves, the eye will follow the object with a constant motion, but the projector will display each alternating color of the frame at the same location, for the duration of the whole frame. So, while the eye is moving, it will see a frame of a specific

color (red for example). Then, when the next color is displayed (green for example), although it gets displayed at the same location overlapping the previous color, the eye will have moved toward the object's next frame target. Thus, the eye will see that specific frame color slightly shifted. Then, the third color gets displayed (blue for example), and the eye will see that frame's color slightly shifted again. This effect is not perceived only for the moving object, but the whole picture.

The effect varies with the rotational speed of the color wheel and the frame refresh rate of the video signal. There is a maximum rotational speed limit for the wheel, typically 10,000 to 15,000 RPM. Video framerate is usually measured in frames per second and must be multiplied by 60 to find the wheel speed, whereas 60 frames/sec equals 3,600 frames/minute. If the color wheel spins 4 times per frame, it is rotating at a speed of 14,400 RPM. (Projector specifications often list the wheel speed at specific framerates as 2x, 3x, 4x, etc.) Increasing the video refresh rate to 85 frames per second does not necessarily further reduce the rainbow effect since this rate would increase the wheel speed to 20,400 RPM, potentially exceeding the safe limits of wheel rotation and requiring the projector to drop back to 3x speed, at 15,300 RPM.

Multi-color LED-based and LASER-based single-chip projectors are able to eliminate the spinning wheel and minimize the rainbow effect since the pulse rate of LEDs and LASERs are not limited by physical motion.

Three-chip projectors

A three-chip DLP projector uses a prism to split light from the lamp, and each primary color of light is then routed to its own DLP chip, then recombined and routed out through the lens. Three chip systems are found in higher-end home theater projectors, large venue projectors and DLP Cinema projection systems found in digital movie theaters.

According to DLP.com, the three-chip projectors used in movie theaters can produce 35 trillion colors, which many suggest is more than the human eye can detect. The human eye is suggested to be able to detect around 16 million colors, which is theoretically possible with the single chip solution. However, this high color precision does not mean that three-chip DLP projectors are capable of displaying the entire gamut of colors we can distinguish (this is fundamentally impossible with any system composing colors by adding three constant base colors). In contrast, it is the one-chip DLP projectors that have the advantage of allowing any number of primary colors in a sufficiently fast color filter wheel, and so the possibility of improved color gamuts is available.

Light source

The main light source used on DLP-based rear screen projection TVs is based on a replaceable high-pressure mercury-vapor metal halide arc lamp unit (containing a quartz arc tube, reflector, electrical connections, and sometimes a quartz/glass shield), while in some newer DLP projectors high-power LEDs or lasers are used as a source of illumination.

Metal-halide lamps

For metal-halide lamps, during start-up, the lamp is ignited by a 5000 volt pulse from a current-regulating ballast to initiate an arc between two electrodes in the quartz tube. After warmup, the ballast's output voltage drops to approximately 60 volts while keeping the relative current high. As the lamp ages, the arc tube's electrodes wear out and light output declines somewhat while waste heating of the lamp increases. The mercury lamp's end of life is typically indicated via an LED on the unit or an onscreen text warning, necessitating replacement of the lamp unit.

Older projectors would simply give a warning that the lamp life had expired but would continue to operate. Newer projectors will not power up until the lamp is replaced and the lamp hours are reset. Most devices include a lamp hours reset function for when a new lamp is installed, but it is possible to reset a projector to continue to use an old lamp past its rated lifespan.

When a metal-halide lamp is operated past its rated lifespan, the efficiency declines significantly, the lightcast may become uneven, and the lamp starts to operate extremely hot, to the point that the power wires can melt off the lamp terminals. Eventually, the required startup voltage will also rise to the point where ignition can no longer occur. Secondary protections such as a temperature monitor may shut down the projector, but a thermally overstressed quartz arc tube can also crack and/or explode, releasing a cloud of hot mercury vapor inside and around the projector. However, practically all lamp housings contain heat-resistant barriers (in addition to those on the lamp unit itself) to prevent the red-hot quartz fragments from leaving the area.

LED-based DLPs

The first commercially-available LED-based DLP HDTV was the Samsung HL-S5679W in 2006, which also eliminated the use of color wheel. Besides long lifetime eliminating the need for lamp replacement and elimination of the color wheel, other advantages of LED illumination include instant-on operation and improved color, with increased color saturation and improved color gamut to over 140% of the NTSC color gamut. Samsung expanded the LED model line-up in 2007 with products available in 50", 56" and 61" screen sizes. For spring 2008, the third generation of Samsung LED DLP products are available in 61" (HL61A750) and 67" (HL67A750) screen sizes.

Ordinary LED technology does not produce the intensity and high lumen output characteristics required to replace arc lamps. The special patented LEDs used in all of the Samsung DLP TVs are PhlatLight LEDs, designed and manufactured by US based Luminus Devices. A single RGB PhlatLight LED chipset illuminates these projection TVs. The PhlatLight LEDs are also used in a new class of ultra-compact DLP front projector commonly referred to as a "pocket projector" and have been introduced in new models from LG Electronics (HS101), Samsung electronics (SP-P400) and Casio (XJ-A series). Home Theater projectors will be the next category of DLP projectors that will use PhlatLight LED technology. At InfoComm, June 2008 Luminus and TI announced their

collaboration on using their technology on home theater and business projectors and demonstrated a prototype PhlatLight LED based DLP home theater front projector. They also announced products will be available in the marketplace later in 2008 from Optoma and other companies to be named later in the year.

Luminus Devices PhlatLight LEDs have also been used by Christie Digital in their DLP-based MicroTiles display system. It is a modular system built from small (20 inch diagonal) rear projection cubes, which can be stacked and tiled together to form large display canvasses with very small seams. The scale and shape of the display can be any size, only constrained by practical limits.

LASER-based DLPs

The first commercially-available LASER-based DLP HDTV was the Mitsubishi L65-A90 LASERVUE in 2008, which also eliminated the use of a color wheel. Three separate color LASERs illuminate the digital micromirror device (DMD) in these projection TVs, producing a richer, more vibrant color palette than other methods.

Digital cinema

On February 2, 2000, Philippe Binant, technical manager of Digital Cinema Project at Gaumont in France, realized the first digital cinema projection in Europe with the DLP CINEMA technology developed by Texas Instruments.

DLP is the current market-share leader in professional digital movie projection, largely because of its high contrast ratio and available resolution as compared to other digital front-projection technologies. As of December 2008, there are over 6,000 DLP-based Digital Cinema Systems installed worldwide.

DLP projectors are also used in RealD Cinema and newer Imax theatres for 3-D films.

Manufacturers and market place

Texas Instruments remains the primary manufacturer of DLP technology, which is used by many licensees who market products based on T.I.'s chipsets. The Fraunhofer Institute of Dresden, Germany, also manufactures Digital Light Processors, termed Spatial Light Modulators, for use in specialized applications. For example, Micronic Laser Systems of Sweden utilizes Fraunhofer's SLMs to generate deep-ultraviolet imaging in its Sigma line of silicon mask lithography writers.

DLP technology has quickly gained market share in the front projection market and now holds roughly 50% of the worldwide share in front projection. Over 30 manufacturers use the DLP chipset to power their projectors.

Pros

- Smooth (at 1080p resolution), jitter-free images.
- Perfect geometry and excellent grayscale linearity achievable.
- Usually great ANSI contrast.
- No possibility of screen burn-in.
- Less "screen-door effect" than with LCD projectors.
- DLP rear projection TVs generally have a smaller form factor than comparable CRT projectors.
- DLP rear projection TVs are considerably cheaper than LCD or plasma flat-panel displays and can still offer 1080p resolution.
- The use of a replaceable light source means a potentially longer life than CRTs and plasma displays (this may also be a con as listed below).
- The light source is more-easily replaceable than the backlights used with LCDs, and on DLPs is often user-replaceable.
- New LED and LASER DLP TVs and projectors eliminate the need for lamp replacement.
- Using two projectors, one can project full color stereoscopic images using polarized process (because beams can be polarized).
- Lighter weight than LCD and plasma televisions.
- Unlike their LCD and plasma counterparts, DLP screens do not rely on fluids as their projection medium and are therefore not limited in size by their inherent mirror mechanisms, making them ideal for increasingly larger high-definition theater and venue screens.
- DLP Projectors can process up to 7 separate colors, giving them strong color performance.
- DLP projectors do not suffer from "Color Decay" often seen with LCD projectors in which the image on the screen turns yellow after extended periods of usage.

Cons

- Some viewers are bothered by the "rainbow effect," explained above.
- Not as thin as LCD or plasma flat-panel displays (although approximately comparable in weight), although some models as of 2008 are becoming wall-mountable (while still being 10" to 14" thick)
- Replacement of the lamp / light bulb. The average life span of a TV light source averages 2000-5000 hours and the replacement cost for these range from $99 – $350, depending on the brand and model. After replacing the bulb a few times the cost can easily exceed the original purchase price of the television itself. Newer generations units use LEDs or LASERs which effectively eliminates this issue, although replacement LED chips could potentially be required over the extended lifespan of the television.
- Some devices may have fan noise.
- Dithering noise may be noticeable, especially in dark image areas. Newer (post ~2004) chip generations have less noise than older ones.
- Error-diffusion artifacts caused by averaging a shade over different pixels, since one pixel cannot render the shade exactly.

- Response time in video games may be affected by upscaling lag. While all HDTVs have some lag when upscaling lower resolution input to their native resolution, DLPs are commonly reported to have longer delays. Newer consoles such as the Xbox 360 do not have this problem as long as they are connected with HD-capable cables.
- Reduced viewing angle as compared to direct-view technologies such as CRT, plasma, and LCD.

DLP, LCD, and LCoS rear projection TV

The most similar competing system to DLP is known as LCoS (liquid crystal on silicon), which creates images using a stationary mirror mounted on the surface of a chip, and uses a liquid crystal matrix (similar to a liquid crystal display) to control how much light is reflected. DLP-based television systems are also arguably considered to be smaller in depth than traditional projection television.

Chapter- 5

Laser Diode
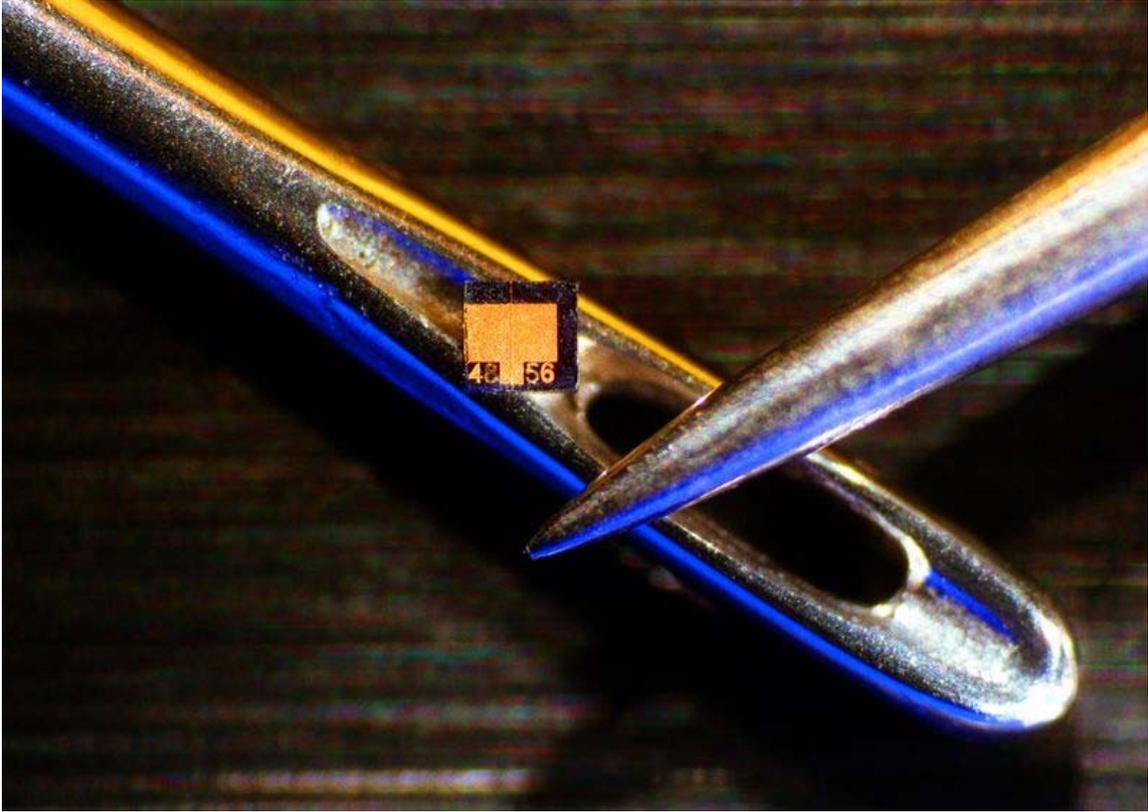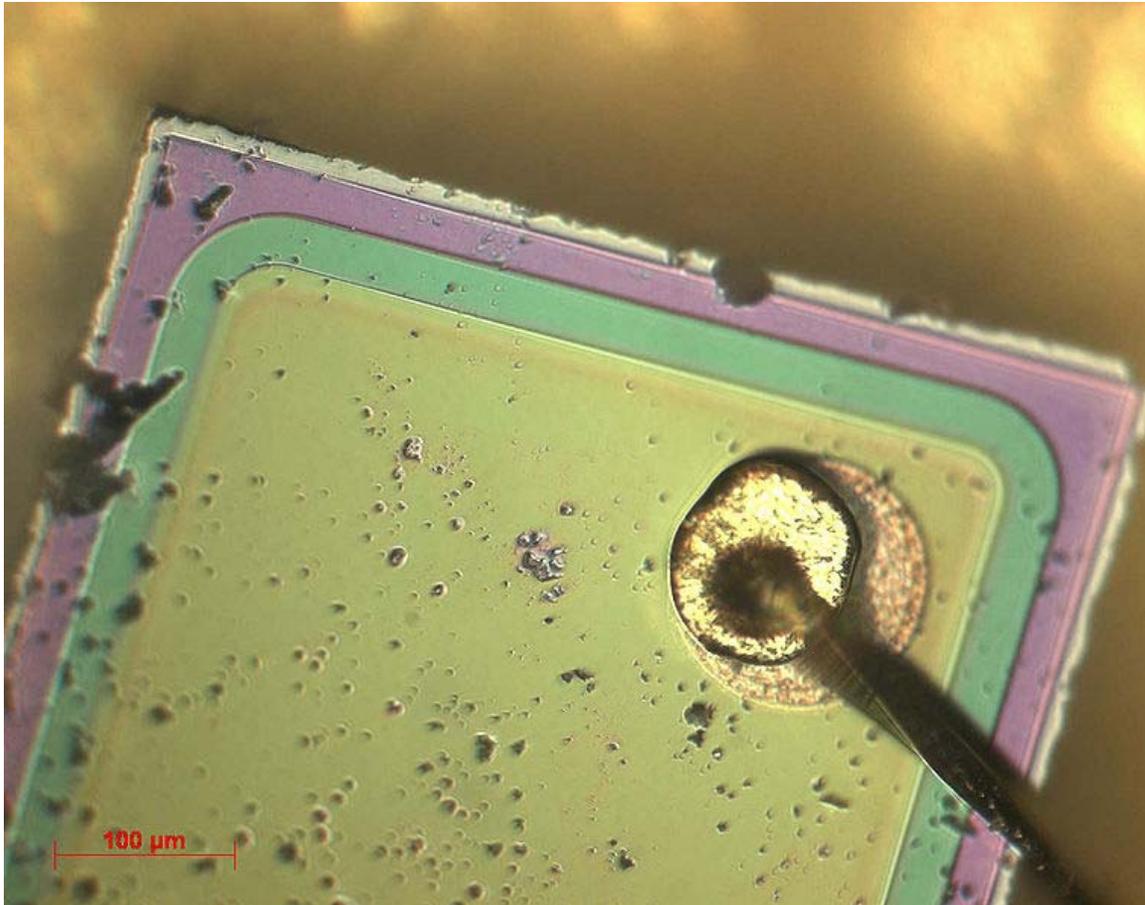

A packaged laser diode with penny for scale.

Image of the actual laser diode chip (shown on the eye of a needle for scale) contained within the package shown in the above image.

This is a visible light micrograph of a laser diode taken from a CD-ROM drive. Visible are the P and N layers distinguished by different colours. Also visible are scattered glass fragments from a broken collimating lens.

A **laser diode** is a laser where the active medium is a semiconductor similar to that found in a light-emitting diode. The most common type of laser diode is formed from a p-n junction and powered by injected electric current. The former devices are sometimes referred to as *injection laser diodes* to distinguish them from *optically pumped laser diodes*.

Theory of operation

A laser diode is formed by doping a very thin layer on the surface of a crystal wafer. The crystal is doped to produce an n-type region and a p-type region, one above the other, resulting in a *p-n* junction, or diode.

Laser diodes form a subset of the larger classification of semiconductor *p-n* junction diodes. Forward electrical bias across the laser diode causes the two species of charge carrier – holes and electrons – to be "injected" from opposite sides of the *p-n* junction into the depletion region. Holes are injected from the *p*-doped, and electrons from the *n-*

doped, semiconductor. (A depletion region, devoid of any charge carriers, forms as a result of the difference in electrical potential between *n*- and *p*-type semiconductors wherever they are in physical contact.) Due to the use of charge injection in powering most diode lasers, this class of lasers is sometimes termed "injection lasers," or "injection laser diode" (ILD). As diode lasers are semiconductor devices, they may also be classified as semiconductor lasers. Either designation distinguishes diode lasers from solid-state lasers.

Another method of powering some diode lasers is the use of optical pumping. Optically Pumped Semiconductor Lasers (OPSL) use a III-V semiconductor chip as the gain media, and another laser (often another diode laser) as the pump source. OPSL offer several advantages over ILDs, particularly in wavelength selection and lack of interference from internal electrode structures.

When an electron and a hole are present in the same region, they may recombine or "annihilate" with the result being spontaneous emission — i.e., the electron may re-occupy the energy state of the hole, emitting a photon with energy equal to the difference between the electron and hole states involved. (In a conventional semiconductor junction diode, the energy released from the recombination of electrons and holes is carried away as phonons, i.e., lattice vibrations, rather than as photons.) Spontaneous emission gives the laser diode below lasing threshold similar properties to an LED. Spontaneous emission is necessary to initiate laser oscillation, but it is one among several sources of inefficiency once the laser is oscillating.

The difference between the photon-emitting semiconductor laser and conventional phonon-emitting (non-light-emitting) semiconductor junction diodes lies in the use of a different type of semiconductor, one whose physical and atomic structure confers the possibility for photon emission. These photon-emitting semiconductors are the so-called "direct bandgap" semiconductors. The properties of silicon and germanium, which are single-element semiconductors, have bandgaps that do not align in the way needed to allow photon emission and are not considered "direct." Other materials, the so-called compound semiconductors, have virtually identical crystalline structures as silicon or germanium but use alternating arrangements of two different atomic species in a checkerboard-like pattern to break the symmetry. The transition between the materials in the alternating pattern creates the critical "direct bandgap" property. Gallium arsenide, indium phosphide, gallium antimonide, and gallium nitride are all examples of compound semiconductor materials that can be used to create junction diodes that emit light.
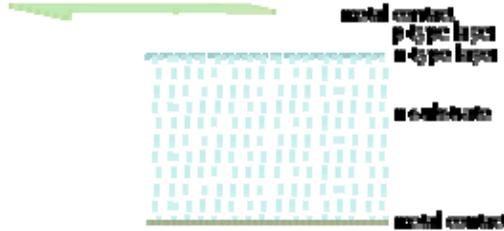
Diagram (not to scale) of a simple laser diode, such as shown above.

In the absence of stimulated emission (e.g., lasing) conditions, electrons and holes may coexist in proximity to one another, without recombining, for a certain time, termed the "upper-state lifetime" or "recombination time" (about a nanosecond for typical diode laser materials), before they recombine. Then a nearby photon with energy equal to the recombination energy can cause recombination by stimulated emission. This generates another photon of the same frequency, travelling in the same direction, with the same polarization and phase as the first photon. This means that stimulated emission causes gain in an optical wave (of the correct wavelength) in the injection region, and the gain increases as the number of electrons and holes injected across the junction increases. The spontaneous and stimulated emission processes are vastly more efficient in direct bandgap semiconductors than in indirect bandgap semiconductors; therefore silicon is not a common material for laser diodes.

As in other lasers, the gain region is surrounded with an optical cavity to form a laser. In the simplest form of laser diode, an optical waveguide is made on that crystal surface, such that the light is confined to a relatively narrow line. The two ends of the crystal are cleaved to form perfectly smooth, parallel edges, forming a Fabry–Pérot resonator. Photons emitted into a mode of the waveguide will travel along the waveguide and be reflected several times from each end face before they are emitted. As a light wave passes through the cavity, it is amplified by stimulated emission, but light is also lost due to absorption and by incomplete reflection from the end facets. Finally, if there is more amplification than loss, the diode begins to "lase".

Some important properties of laser diodes are determined by the geometry of the optical cavity. Generally, in the vertical direction, the light is contained in a very thin layer, and the structure supports only a single optical mode in the direction perpendicular to the layers. In the lateral direction, if the waveguide is wide compared to the wavelength of light, then the waveguide can support multiple lateral optical modes, and the laser is known as "multi-mode". These laterally multi-mode lasers are adequate in cases where one needs a very large amount of power, but not a small diffraction-limited beam; for example in printing, activating chemicals, or pumping other types of lasers.

In applications where a small focused beam is needed, the waveguide must be made narrow, on the order of the optical wavelength. This way, only a single lateral mode is

supported and one ends up with a diffraction-limited beam. Such single spatial mode devices are used for optical storage, laser pointers, and fiber optics. Note that these lasers may still support multiple longitudinal modes, and thus can lase at multiple wavelengths simultaneously.

The wavelength emitted is a function of the band-gap of the semiconductor and the modes of the optical cavity. In general, the maximum gain will occur for photons with energy slightly above the band-gap energy, and the modes nearest the gain peak will lase most strongly. If the diode is driven strongly enough, additional *side modes* may also lase. Some laser diodes, such as most visible lasers, operate at a single wavelength, but that wavelength is unstable and changes due to fluctuations in current or temperature.

Due to diffraction, the beam diverges (expands) rapidly after leaving the chip, typically at 30 degrees vertically by 10 degrees laterally. A lens must be used in order to form a collimated beam like that produced by a laser pointer. If a circular beam is required, cylindrical lenses and other optics are used. For single spatial mode lasers, using symmetrical lenses, the collimated beam ends up being elliptical in shape, due to the difference in the vertical and lateral divergences. This is easily observable with a red laser pointer.

The simple diode described above has been heavily modified in recent years to accommodate modern technology, resulting in a variety of types of laser diodes, as described below.

Types

The simple laser diode structure, described above, is extremely inefficient. Such devices require so much power that they can only achieve pulsed operation without damage. Although historically important and easy to explain, such devices are not practical.
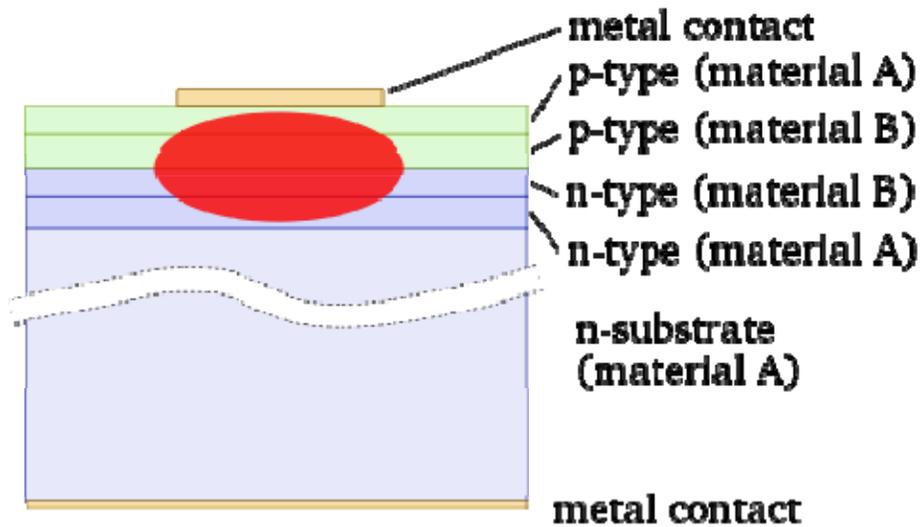
Double heterostructure lasers

Diagram of front view of a double heterostructure laser diode (not to scale)

In these devices, a layer of low bandgap material is sandwiched between two high bandgap layers. One commonly-used pair of materials is gallium arsenide (GaAs) with aluminium gallium arsenide ($Al_xGa_{(1-x)}As$). Each of the junctions between different bandgap materials is called a *heterostructure,* hence the name "double heterostructure laser" or *DH* laser.

The advantage of a DH laser is that the region where free electrons and holes exist simultaneously—the active region—is confined to the thin middle layer. This means that many more of the electron-hole pairs can contribute to amplification—not so many are left out in the poorly amplifying periphery. In addition, light is reflected from the heterojunction; hence, the light is confined to the region where the amplification takes place.
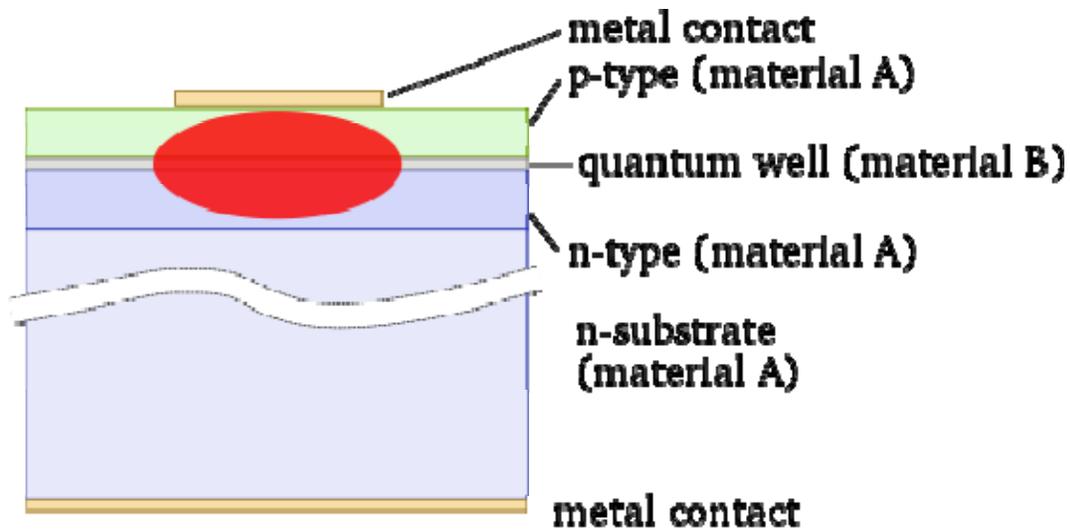
Quantum well lasers

Diagram of front view of a simple quantum well laser diode (not to scale)

If the middle layer is made thin enough, it acts as a quantum well. This means that the vertical variation of the electron's wavefunction, and thus a component of its energy, is quantized. The efficiency of a quantum well laser is greater than that of a bulk laser because the density of states function of electrons in the quantum well system has an abrupt edge that concentrates electrons in energy states that contribute to laser action.

Lasers containing more than one quantum well layer are known as *multiple quantum well* lasers. Multiple quantum wells improve the overlap of the gain region with the optical waveguide mode.

Further improvements in the laser efficiency have also been demonstrated by reducing the quantum well layer to a quantum wire or to a "sea" of quantum dots.

Quantum cascade lasers

In a quantum cascade laser, the difference between quantum well energy levels is used for the laser transition instead of the bandgap. This enables laser action at relatively long wavelengths, which can be tuned simply by altering the thickness of the layer. They are heterojunction lasers.

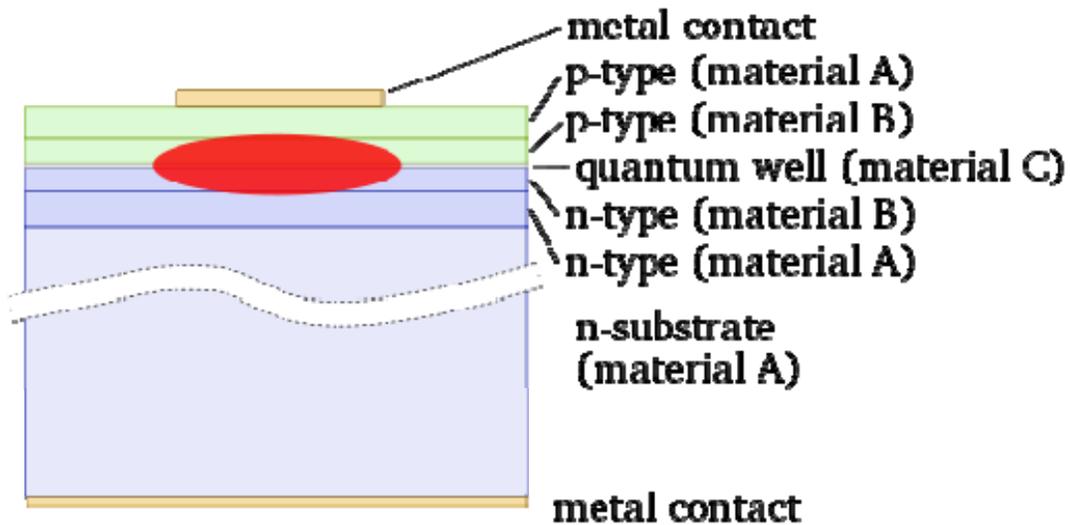## Separate confinement heterostructure lasers

Diagram of front view of a separate confinement heterostructure quantum well laser diode

The problem with the simple quantum well diode described above is that the thin layer is simply too small to effectively confine the light. To compensate, another two layers are added on, outside the first three. These layers have a lower refractive index than the centre layers, and hence confine the light effectively. Such a design is called a separate confinement heterostructure (SCH) laser diode.

Almost all commercial laser diodes since the 1990s have been SCH quantum well diodes.

Distributed feedback lasers

Distributed feedback lasers (DFB) are the most common transmitter type in DWDM-systems. To stabilize the lasing wavelength, a diffraction grating is etched close to the p-n junction of the diode. This grating acts like an optical filter, causing a single wavelength to be fed back to the gain region and lase. Since the grating provides the feedback that is required for lasing, reflection from the facets is not required. Thus, at least one facet of a DFB is anti-reflection coated. The DFB laser has a stable wavelength that is set during manufacturing by the pitch of the grating, and can only be tuned slightly with temperature. DFB lasers are widely used in optical communication applications where a precise and stable wavelength is critical.
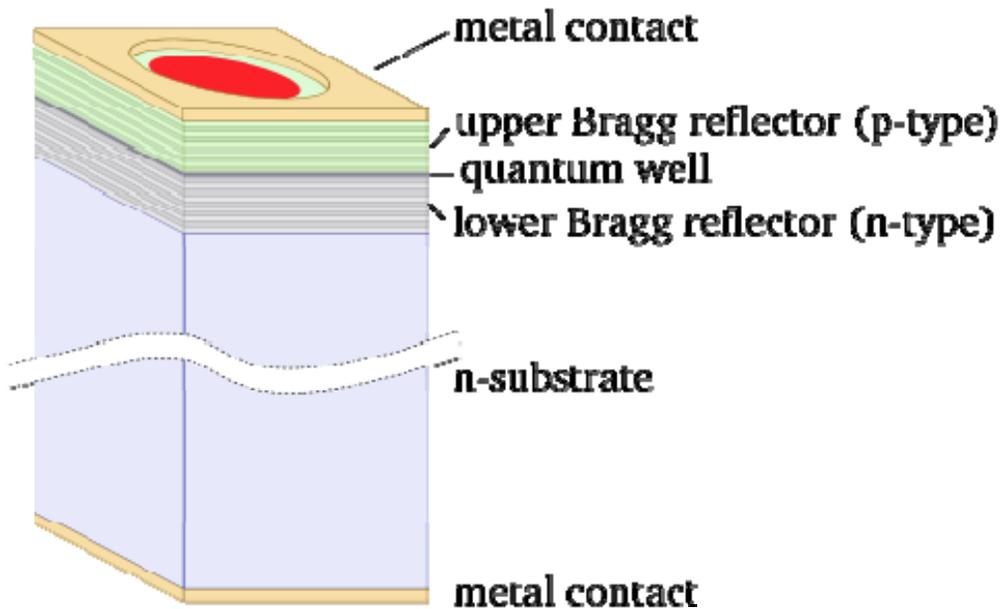
VCSELs

Diagram of a simple VCSEL structure

Vertical-cavity surface-emitting lasers (VCSELs) have the optical cavity axis along the direction of current flow rather than perpendicular to the current flow as in conventional laser diodes. The active region length is very short compared with the lateral dimensions so that the radiation emerges from the surface of the cavity rather than from its edge as shown in the figure. The reflectors at the ends of the cavity are dielectric mirrors made from alternating high and low refractive index quarter-wave thick multilayer.

Such dielectric mirrors provide a high degree of wavelength-selective reflectance at the required free surface wavelength λ if the thicknesses of alternating layers d_1 and d_2 with refractive indices n_1 and n_2 are such that $n_1 d_1 + n_2 d_2 = \lambda/2$ which then leads to the constructive interference of all partially reflected waves at the interfaces. But there is a disadvantage: because of the high mirror reflectivities, VCSELs have lower output powers when compared to edge-emitting lasers.

There are several advantages to producing VCSELs when compared with the production process of edge-emitting lasers. Edge-emitters cannot be tested until the end of the production process. If the edge-emitter does not work, whether due to bad contacts or poor material growth quality, the production time and the processing materials have been wasted. Additionally, because VCSELs emit the beam perpendicular to the active region of the laser as opposed to parallel as with an edge emitter, tens of thousands of VCSELs can be processed simultaneously on a three inch Gallium Arsenide wafer. Furthermore, even though the VCSEL production process is more labor and material intensive, the

yield can be controlled to a more predictable outcome. However, they normally show a lower power output level.

VECSELs

Vertical external-cavity surface-emitting lasers, or VECSELs, are similar to VCSELs. In VCSELs, the mirrors are typically grown epitaxially as part of the diode structure, or grown separately and bonded directly to the semiconductor containing the active region. VECSELs are distinguished by a construction in which one of the two mirrors is external to the diode structure. As a result, the cavity includes a free-space region. A typical distance from the diode to the external mirror would be 1 cm.

One of the most interesting features of any VECSEL is the small thickness of the semiconductor gain region in the direction of propagation, less than 100 nm. In contrast, a conventional in-plane semiconductor laser entails light propagation over distances of from 250 μm upward to 2 mm or longer. The significance of the short propagation distance is that it causes the effect of "antiguiding" nonlinearities in the diode laser gain region to be minimized. The result is a large-cross-section single-mode optical beam which is not attainable from in-plane ("edge-emitting") diode lasers.

Several workers demonstrated optically pumped VECSELs, and they continue to be developed for many applications including high power sources for use in industrial machining (cutting, punching, etc.) because of their unusually high power and efficiency when pumped by multi-mode diode laser bars.

Electrically pumped VECSELs have also been demonstrated. Applications for electrically pumped VECSELs include projection displays, served by frequency doubling of near-IR VECSEL emitters to produce blue and green light.

External-cavity diode lasers

External-cavity diode lasers are tunable lasers which use mainly double heterostructures diodes of the $Al_xGa_{(1-x)}As$ type. The first external-cavity diode lasers used intracavity etalons and simple tuning Littrow gratings. Other designs include gratings in grazing-incidence configuration and multiple-prism grating configurations.

Failure modes

Laser diodes have the same reliability and failure issues as light emitting diodes. In addition they are subject to *catastrophic optical damage* (COD) when operated at higher power.

Many of the advances in reliability of diode lasers in the last 20 years remain proprietary to their developers. The reliability of a laser diode can make or break a product line. Moreover, "reverse engineering" is not always able to reveal the differences between more-reliable and less-reliable diode laser products.

At the edge of a diode laser, where light is emitted, a mirror is traditionally formed by cleaving the semiconductor wafer to form a specularly reflecting plane. This approach is facilitated by the weakness of the [110] crystallographic plane in III-V semiconductor crystals (such as GaAs, InP, GaSb, etc.) compared to other planes. A scratch made at the edge of the wafer and a slight bending force causes a nearly atomically perfect mirror-like cleavage plane to form and propagate in a straight line across the wafer.

But it so happens that the atomic states at the cleavage plane are altered (compared to their bulk properties within the crystal) by the termination of the perfectly periodic lattice at that plane. Surface states at the cleaved plane, have energy levels within the (otherwise forbidden) bandgap of the semiconductor.

Essentially, as a result when light propagates through the cleavage plane and transits to free space from within the semiconductor crystal, a fraction of the light energy is absorbed by the surface states whence it is converted to heat by phonon-electron interactions. This heats the cleaved mirror. In addition the mirror may heat simply because the edge of the diode laser—which is electrically pumped—is in less-than-perfect contact with the mount that provides a path for heat removal. The heating of the mirror causes the bandgap of the semiconductor to shrink in the warmer areas. The bandgap shrinkage brings more electronic band-to-band transitions into alignment with the photon energy causing yet more absorption. This is thermal runaway, a form of positive feedback, and the result can be melting of the facet, known as *catastrophic optical damage*, or COD.

In the 1970s this problem, which is particularly nettlesome for GaAs-based lasers emitting between 1 µm and 0.630 µm wavelengths (less so for InP based lasers used for long-haul telecommunications which emit between 1.3 µm and 2 µm), was identified. Michael Ettenberg, a researcher and later Vice President at RCA Laboratories' David Sarnoff Research Center in Princeton, New Jersey, devised a solution. A thin layer of aluminum oxide was deposited on the facet. If the aluminum oxide thickness is chosen correctly it functions as an anti-reflective coating, reducing reflection at the surface. This alleviated the heating and COD at the facet.

Since then, various other refinements have been employed. One approach is to create a so-called non-absorbing mirror (NAM) such that the final 10 µm or so before the light emits from the cleaved facet are rendered non-absorbing at the wavelength of interest.

In the very early 1990s, SDL, Inc. began supplying high power diode lasers with good reliability characteristics. CEO Donald Scifres and CTO David Welch presented new reliability performance data at, e.g., SPIE Photonics West conferences of the era. The methods used by SDL to defeat COD were considered to be highly proprietary and have still not been disclosed publicly as of June, 2006.

In the mid-1990s IBM Research (Ruschlikon, Switzerland) announced that it had devised its so-called "E2 process" which conferred extraordinary resistance to COD in GaAs-based lasers. This process, too, has never been disclosed as of June, 2006.

Reliability of high-power diode laser pump bars (employed to pump solid state lasers) remains a difficult problem in a variety of applications, in spite of these proprietary advances. Indeed, the physics of diode laser failure is still being worked out and research on this subject remains active, if proprietary.

Extension of the lifetime of laser diodes is critical to their continued adaptation to a wide variety of applications.

Applications of laser diodes
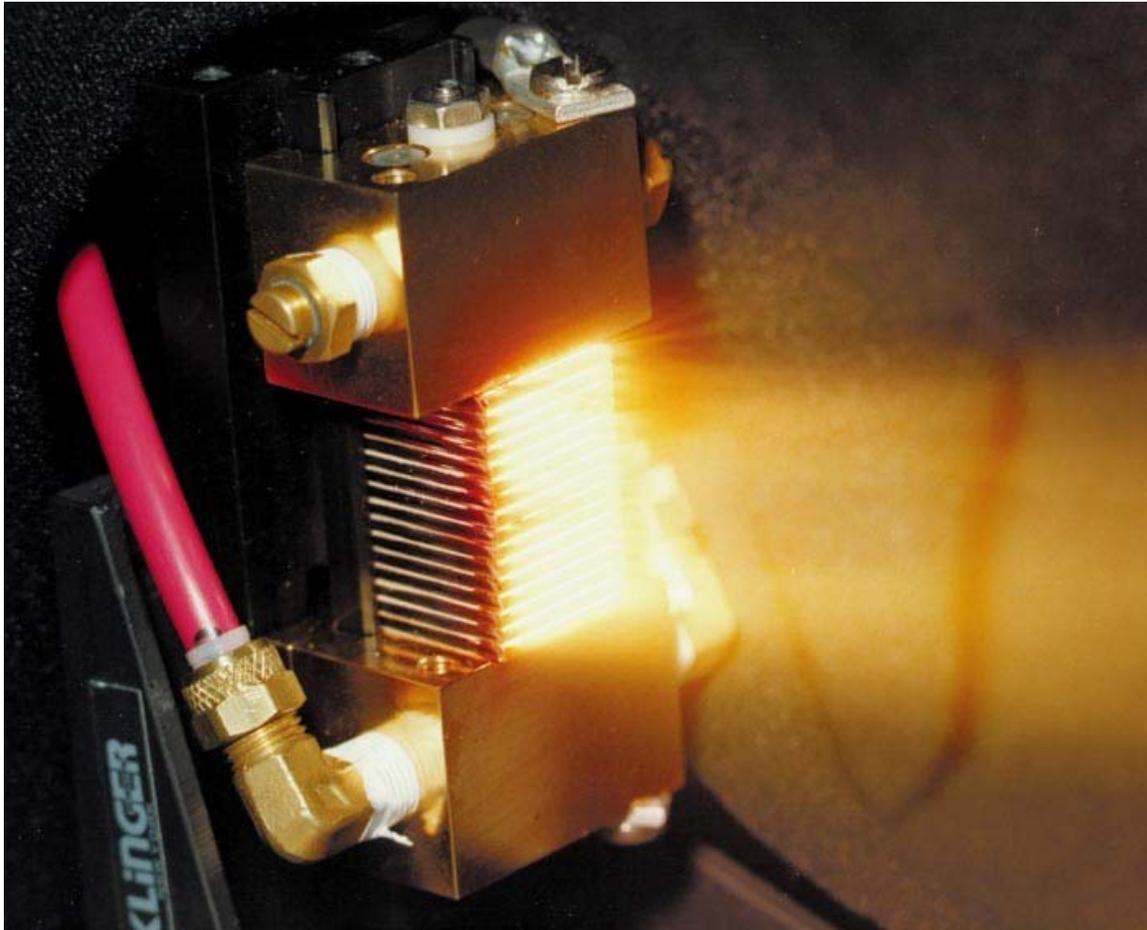
Laser diodes can be arrayed to produce very high power (continuous wave or pulsed) outputs. Such arrays may be used to efficiently pump solid state lasers for inertial confinement fusion or high average power drilling or burning applications.

Laser diodes are numerically the most common type of laser, with 2004 sales of approximately 733 million diode lasers, as compared to 131,000 of other types of lasers.

Laser diodes find wide use in telecommunication as easily modulated and easily coupled light sources for fiber optics communication. They are used in various measuring

instruments, such as rangefinders. Another common use is in barcode readers. Visible lasers, typically red but later also green, are common as laser pointers. Both low and high-power diodes are used extensively in the printing industry both as light sources for scanning (input) of images and for very high-speed and high-resolution printing plate (output) manufacturing. Infrared and red laser diodes are common in CD players, CD-ROMs and DVD technology. Violet lasers are used in HD DVD and Blu-ray technology. Diode lasers have also found many applications in laser absorption spectrometry (LAS) for high-speed, low-cost assessment or monitoring of the concentration of various species in gas phase. High-power laser diodes are used in industrial applications such as heat treating, cladding, seam welding and for pumping other lasers, such as diode pumped solid state lasers.

Applications of laser diodes can be categorized in various ways. Most applications could be served by larger solid state lasers or optical parametric oscillators, but the low cost of mass-produced diode lasers makes them essential for mass-market applications. Diode lasers can be used in a great many fields; since light has many different properties (power, wavelength and spectral quality, beam quality, polarization, etc.) it is interesting to classify applications by these basic properties.

Many applications of diode lasers primarily make use of the "directed energy" property of an optical beam. In this category one might include the laser printers, bar-code readers, image scanning, illuminators, designators, optical data recording, combustion ignition, laser surgery, industrial sorting, industrial machining, and directed energy weaponry. Some of these applications are emerging while others are well-established.

Laser medicine: medicine and especially dentistry have found many new applications for diode lasers. The shrinking size of the units and their increasing user friendliness makes them very attractive to clinicians for minor soft tissue procedures. The 800 nm – 980 nm units have a high absorption rate for hemoglobin and thus make them ideal for soft tissue applications, where good hemostasis is necessary.

Applications which may make use of the coherence of diode-laser-generated light include interferometric distance measurement, holography, coherent communications, and coherent control of chemical reactions.

Applications which may make use of "narrow spectral" properties of diode lasers include range-finding, telecommunications, infra-red countermeasures, spectroscopic sensing, generation of radio-frequency or terahertz waves, atomic clock state preparation, quantum key cryptography, frequency doubling and conversion, water purification (in the UV), and photodynamic therapy (where a particular wavelength of light would cause a substance such as porphyrin to become chemically active as an anti-cancer agent only where the tissue is illuminated by light).

Applications where the desired quality of laser diodes is their ability to generate ultra-short pulses of light by the technique known as "mode-locking" include clock distribution for high-performance integrated circuits, high-peak-power sources for laser-induced

breakdown spectroscopy sensing, arbitrary waveform generation for radio-frequency waves, photonic sampling for analog-to-digital conversion, and optical code-division-multiple-access systems for secure communication.

Common wavelengths

- **375 nm** – excitation of Hoechst stain, Calcium Blue, and other fluorescent dyes in fluorescence microscopy
- **405 nm** – InGaN blue-violet laser, in Blu-ray Disc and HD DVD drives
- **445 nm** – InGaN Deep blue laser multimode diode recently introduced (2010) for use in mercury free high brightness data projectors
- **473 nm** – Bright blue laser pointers, still very expensive, output of DPSS systems
- **485 nm** – excitation of GFP and other fluorescent dyes
- **510 nm** - Green diodes recently (2010) developed by Nichia for laser projectors.
- **532 nm** – AlGaAs-pumped bright green laser pointers, frequency doubled 1064 nm Nd:YAG laser or (more commonly in laser pointers) Nd:YVO$_4$ IR lasers (SHG)
- **593 nm** – Yellow-Orange laser pointers, DPSS
- **635 nm** – AlGaInP better red laser pointers, same power subjectively 5 times as bright as 670 nm one
- **640 nm** – High brightness red DPSS laser pointers
- **657 nm** – AlGaInP DVD drives, laser pointers
- **670 nm** – AlGaInP cheap red laser pointers
- **760 nm** – AlGaInP gas sensing: O$_2$
- **785 nm** – GaAlAs Compact Disc drives
- **808 nm** – GaAlAs pumps in DPSS Nd:YAG lasers (e.g. in green laser pointers or as arrays in higher-powered lasers)
- **848 nm** – laser mice
- **980 nm** – InGaAs pump for optical amplifiers, for Yb:YAG DPSS lasers
- **1064 nm** – AlGaAs fiber-optic communication
- **1310 nm** – InGaAsP fiber-optic communication
- **1480 nm** – InGaAsP pump for optical amplifiers
- **1512 nm** – InGaAsP gas sensing: NH$_3$
- **1550 nm** – InGaAsP fiber-optic communication
- **1625 nm** – InGaAsP fiber-optic communication, service channel
- **1654 nm** – InGaAsP gas sensing: CH$_4$
- **1877 nm** – GaSbAs gas sensing: H$_2$O
- **2004 nm** – GaSbAs gas sensing: CO$_2$
- **2330 nm** – GaSbAs gas sensing: CO
- **2680 nm** – GaSbAs gas sensing: CO$_2$

History

The first to demonstrate coherent light emission from a semiconductor diode (the first *laser* diode), is widely acknowledged to have been Robert N. Hall and his team at the

General Electric research center in 1962. The first visible wavelength laser diode was demonstrated by Nick Holonyak, Jr. later in 1962.

Other teams at IBM, MIT Lincoln Laboratory, Texas Instruments, and RCA Laboratories were also involved in and received credit for their historic initial demonstrations of efficient light emission and lasing in semiconductor diodes in 1962 and thereafter. GaAs lasers were also produced in early 1963 in the Soviet Union by the team led by Nikolay Basov.

In the early 1960s liquid phase epitaxy (LPE) was invented by Herbert Nelson of RCA Laboratories. By layering the highest quality crystals of varying compositions, it enabled the demonstration of the highest quality heterojunction semiconductor laser materials for many years. LPE was adopted by all the leading laboratories, worldwide and used for many years. It was finally supplanted in the 1970s by molecular beam epitaxy and organometallic chemical vapor deposition.

Diode lasers of that era operated with threshold current densities of 1000 A/cm^2 at 77 K temperatures. Such performance enabled continuous-lasing to be demonstrated in the earliest days. However, when operated at room temperature, about 300 K, threshold current densities were two orders of magnitude greater, or 100,000 A/cm^2 in the best devices. The dominant challenge for the remainder of the 1960s was to obtain low threshold current density at 300 K and thereby to demonstrate continuous-wave lasing at room temperature from a diode laser.

The first diode lasers were homojunction diodes. That is, the material (and thus the bandgap) of the waveguide core layer and that of the surrounding clad layers, were identical. It was recognized that there was an opportunity, particularly afforded by the use of liquid phase epitaxy using aluminum gallium arsenide, to introduce heterojunctions. Heterostructures consist of layers of semiconductor crystal having varying bandgap and refractive index. Heterojunctions (formed from heterostructures) had been recognized by Herbert Kroemer, while working at RCA Laboratories in the mid-1950s, as having unique advantages for several types of electronic and optoelectronic devices including diode lasers. LPE afforded the technology of making heterojunction diode lasers.

The first heterojunction diode lasers were single-heterojunction lasers. These lasers utilized aluminum gallium arsenide *p*-type injectors situated over *n*-type gallium arsenide layers grown on the substrate by LPE. An admixture of aluminum replaced gallium in the semiconductor crystal and raised the bandgap of the *p*-type injector over that of the *n*-type layers beneath. It worked; the 300 K threshold currents went down by 10× to 10,000 amperes per square centimeter. Unfortunately, this was still not in the needed range and these single-heterostructure diode lasers did not function in continuous wave operation at room temperature.

The innovation that met the room temperature challenge was the double heterostructure laser. The trick was to quickly move the wafer in the LPE apparatus between different "melts" of aluminum gallium arsenide (*p*- and *n*-type) and a third melt of gallium

arsenide. It had to be done rapidly since the gallium arsenide core region needed to be significantly under 1 μm in thickness. This may have been the earliest true example of "nanotechnology." The first laser diode to achieve *continuous wave* operation was a double heterostructure demonstrated in 1970 essentially simultaneously by Zhores Alferov and collaborators (including Dmitri Z. Garbuzov) of the Soviet Union, and Morton Panish and Izuo Hayashi working in the United States. However, it is widely accepted that Zhores I. Alferov and team reached the milestone first.

For their accomplishment and that of their co-workers, Alferov and Kroemer shared the 2000 Nobel Prize in Physics.

Optical Communication

Optical communication is any form of telecommunication that uses light as the transmission medium.

An optical communication system consists of a *transmitter*, which encodes a *message* into an optical *signal*, a *channel*, which carries the signal to its destination, and a *receiver*, which reproduces the message from the received optical signal.

Forms of optical communication

Bundesarchiv, Bild 102-09520
Foto: o.Ang. | April 1930

Naval signal

There are many forms of non-technological optical communication, including body language and sign language.

Techniques such as semaphore lines, ship flags, smoke signals, and beacon fires were the earliest form of technological optical communication.

The heliograph uses a mirror to reflect sunlight to a distant observer. By moving the mirror the distant observer sees flashes of light that can be used to send a prearranged signaling code. Navy ships often use a signal lamp to signal in Morse code in a similar way.

Distress flares are used by mariners in emergencies, while lighthouses and navigation lights are used to communicate navigation hazards.

Aircraft use the landing lights at airports to land safely, especially at night. Aircraft landing on an aircraft carrier use a similar system to land correctly on the carrier deck. The light systems communicate the correct position of the aircraft relative to the best landing glideslope. Also, many control towers still have an Aldis lamp to communicate with planes whose radio failed.

Optical fiber is the most common medium for modern digital optical communication.

Free-space optical communication is also used today in a variety of applications.

Optical fiber communication
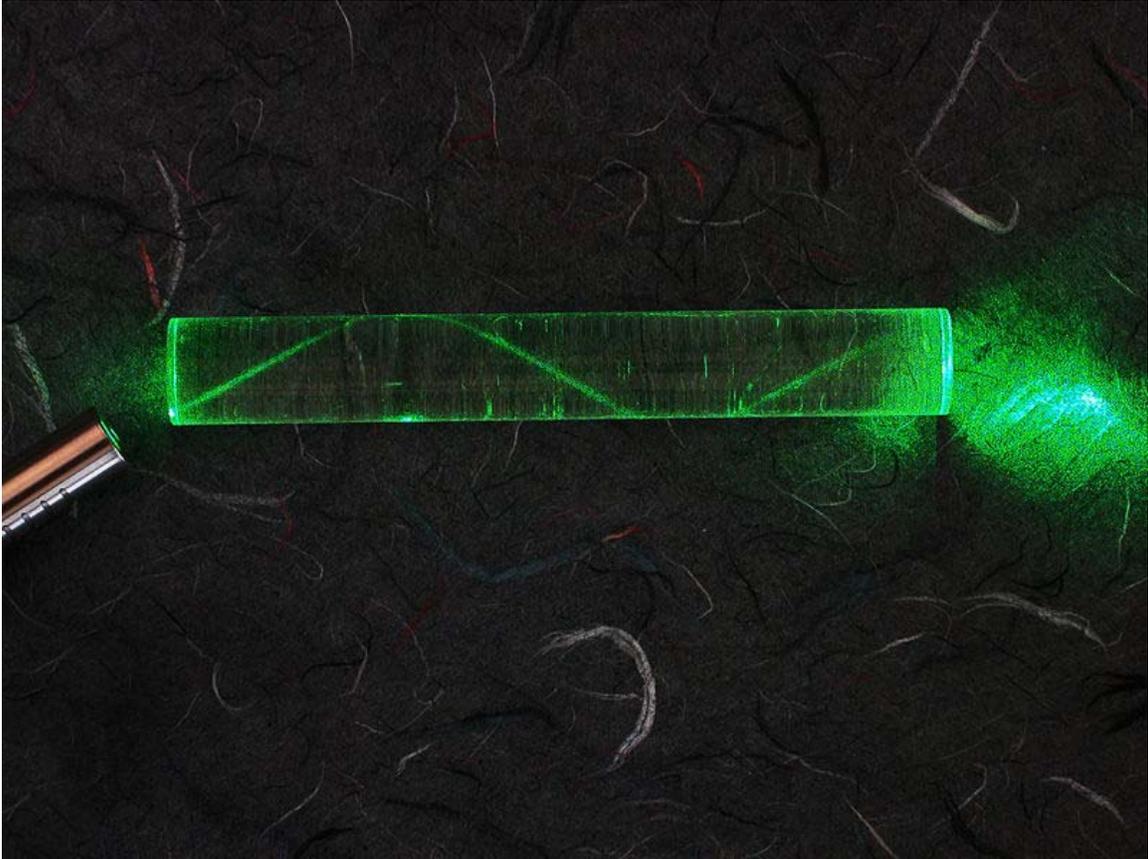
In fiber-optic communications, information is transmitted by sending light through optical fibers.

Fiber-optic communication is a method of transmitting information from one place to another by sending pulses of light through an optical fiber. The light forms an electromagnetic carrier wave that is modulated to carry information. First developed in the 1970s, fiber-optic communication systems have revolutionized the telecommunications industry and have played a major role in the advent of the Information Age. Because of its advantages over electrical transmission, optical fibers have largely replaced copper wire communications in core networks in the developed world.

The process of communicating using fiber-optics involves the following basic steps: Creating the optical signal involving the use of a transmitter, relaying the signal along the fiber, ensuring that the signal does not become too distorted or weak, receiving the optical signal, and converting it into an electrical signal.

Applications

Optical fiber is used by many telecommunications companies to transmit telephone signals, Internet communication, and cable television signals. Due to much lower

attenuation and interference, optical fiber has large advantages over existing copper wire in long-distance and high-demand applications. However, infrastructure development within cities was relatively difficult and time-consuming, and fiber-optic systems were complex and expensive to install and operate. Due to these difficulties, fiber-optic communication systems have primarily been installed in long-distance applications, where they can be used to their full transmission capacity, offsetting the increased cost. Since 2000, the prices for fiber-optic communications have dropped considerably. The price for rolling out fiber to the home has currently become more cost-effective than that of rolling out a copper based network. Prices have dropped to $850 per subscriber in the US and lower in countries like The Netherlands, where digging costs are low.

Since 1990, when optical-amplification systems became commercially available, the telecommunications industry has laid a vast network of intercity and transoceanic fiber communication lines. By 2002, an intercontinental network of 250,000 km of submarine communications cable with a capacity of 2.56 Tb/s was completed, and although specific network capacities are privileged information, telecommunications investment reports indicate that network capacity has increased dramatically since 2004.

History

In 1966 Charles K. Kao and George Hockham proposed optical fibers at STC Laboratories (STL) at Harlow, England, when they showed that the losses of 1000 dB/km in existing glass (compared to 5-10 db/km in coaxial cable) was due to contaminants, which could potentially be removed.

Optical fiber was successfully developed in 1970 by Corning Glass Works, with attenuation low enough for communication purposes (about 20dB/km), and at the same time GaAs semiconductor lasers were developed that were compact and therefore suitable for transmitting light through fiber optic cables for long distances.

After a period of research starting from 1975, the first commercial fiber-optic communications system was developed, which operated at a wavelength around 0.8 μm and used GaAs semiconductor lasers. This first-generation system operated at a bit rate of 45 Mbps with repeater spacing of up to 10 km. Soon on 22 April, 1977, General Telephone and Electronics sent the first live telephone traffic through fiber optics at a 6 Mbit/s throughput in Long Beach, California.

The second generation of fiber-optic communication was developed for commercial use in the early 1980s, operated at 1.3 μm, and used InGaAsP semiconductor lasers. Although these systems were initially limited by dispersion, in 1981 the single-mode fiber was revealed to greatly improve system performance. By 1987, these systems were operating at bit rates of up to 1.7 Gb/s with repeater spacing up to 50 km.

The first transatlantic telephone cable to use optical fiber was TAT-8, based on Desurvire optimized laser amplification technology. It went into operation in 1988.

Third-generation fiber-optic systems operated at 1.55 μm and had losses of about 0.2 dB/km. They achieved this despite earlier difficulties with pulse-spreading at that wavelength using conventional InGaAsP semiconductor lasers. Scientists overcame this difficulty by using dispersion-shifted fibers designed to have minimal dispersion at 1.55 μm or by limiting the laser spectrum to a single longitudinal mode. These developments eventually allowed third-generation systems to operate commercially at 2.5 Gbit/s with repeater spacing in excess of 100 km.

The fourth generation of fiber-optic communication systems used optical amplification to reduce the need for repeaters and wavelength-division multiplexing to increase data capacity. These two improvements caused a revolution that resulted in the doubling of system capacity every 6 months starting in 1992 until a bit rate of 10 Tb/s was reached by 2001. Recently, bit-rates of up to 14 Tbit/s have been reached over a single 160 km line using optical amplifiers.

The focus of development for the fifth generation of fiber-optic communications is on extending the wavelength range over which a WDM system can operate. The conventional wavelength window, known as the C band, covers the wavelength range 1.53-1.57 μm, and the new *dry fiber* has a low-loss window promising an extension of that range to 1.30-1.65 μm. Other developments include the concept of "optical solitons, " pulses that preserve their shape by counteracting the effects of dispersion with the nonlinear effects of the fiber by using pulses of a specific shape.

In the late 1990s through 2000, industry promoters, and research companies such as KMI and RHK predicted vast increases in demand for communications bandwidth due to increased use of the Internet, and commercialization of various bandwidth-intensive consumer services, such as video on demand. Internet protocol data traffic was increasing exponentially, at a faster rate than integrated circuit complexity had increased under Moore's Law. From the bust of the dot-com bubble through 2006, however, the main trend in the industry has been consolidation of firms and offshoring of manufacturing to reduce costs. Recently, companies such as Verizon and AT&T have taken advantage of fiber-optic communications to deliver a variety of high-throughput data and broadband services to consumers' homes.

Technology

Modern fiber-optic communication systems generally include an optical transmitter to convert an electrical signal into an optical signal to send into the optical fiber, a cable containing bundles of multiple optical fibers that is routed through underground conduits and buildings, multiple kinds of amplifiers, and an optical receiver to recover the signal as an electrical signal. The information transmitted is typically digital information generated by computers, telephone systems, and cable television companies.

Transmitters
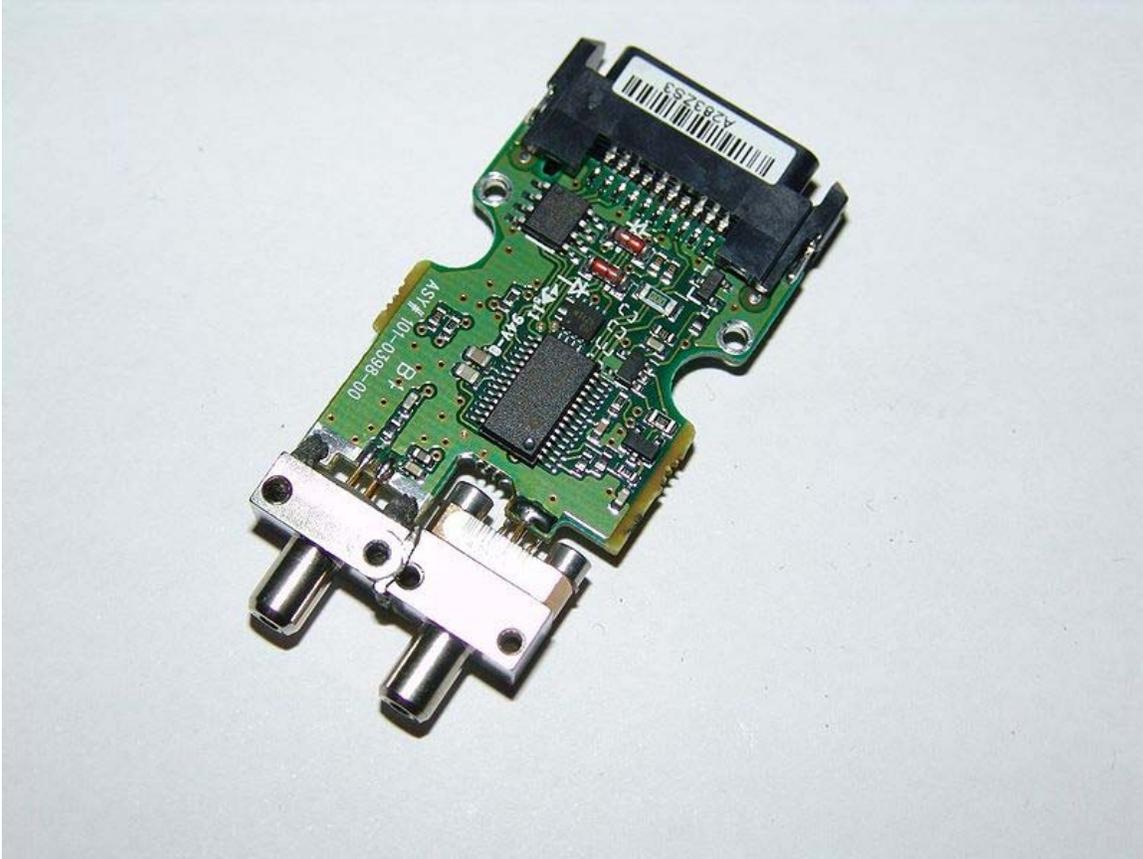
A GBIC module, is essentially an optical and electrical transceiver.

The most commonly-used optical transmitters are semiconductor devices such as light-emitting diodes (LEDs) and laser diodes. The difference between LEDs and laser diodes is that LEDs produce incoherent light, while laser diodes produce coherent light. For use in optical communications, semiconductor optical transmitters must be designed to be compact, efficient, and reliable, while operating in an optimal wavelength range, and directly modulated at high frequencies.

In its simplest form, an LED is a forward-biased p-n junction, emitting light through spontaneous emission, a phenomenon referred to as electroluminescence. The emitted light is incoherent with a relatively wide spectral width of 30-60 nm. LED light transmission is also inefficient, with only about 1 % of input power, or about 100 microwatts, eventually converted into launched power which has been coupled into the optical fiber. However, due to their relatively simple design, LEDs are very useful for low-cost applications.

Communications LEDs are most commonly made from gallium arsenide phosphide (GaAsP) or gallium arsenide (GaAs). Because GaAsP LEDs operate at a longer wavelength than GaAs LEDs (1.3 micrometers vs. 0.81-0.87 micrometers), their output spectrum is wider by a factor of about 1.7. The large spectrum width of LEDs causes higher fiber dispersion, considerably limiting their bit rate-distance product (a common

measure of usefulness). LEDs are suitable primarily for local-area-network applications with bit rates of 10-100 Mbit/s and transmission distances of a few kilometers. LEDs have also been developed that use several quantum wells to emit light at different wavelengths over a broad spectrum, and are currently in use for local-area WDM networks.

A semiconductor laser emits light through stimulated emission rather than spontaneous emission, which results in high output power (~100 mW) as well as other benefits related to the nature of coherent light. The output of a laser is relatively directional, allowing high coupling efficiency (~50 %) into single-mode fiber. The narrow spectral width also allows for high bit rates since it reduces the effect of chromatic dispersion. Furthermore, semiconductor lasers can be modulated directly at high frequencies because of short recombination time.

Laser diodes are often directly modulated, that is the light output is controlled by a current applied directly to the device. For very high data rates or very long distance *links*, a laser source may be operated continuous wave, and the light modulated by an external device such as an electro-absorption modulator or Mach-Zehnder interferometer. External modulation increases the achievable link distance by eliminating laser chirp, which broadens the linewidth of directly-modulated lasers, increasing the chromatic dispersion in the fiber.

Receivers

The main component of an optical receiver is a photodetector, which converts light into electricity using the photoelectric effect. The photodetector is typically a semiconductor-based photodiode. Several types of photodiodes include p-n photodiodes, a p-i-n photodiodes, and avalanche photodiodes. Metal-semiconductor-metal (MSM) photodetectors are also used due to their suitability for circuit integration in regenerators and wavelength-division multiplexers.

Optical-electrical converters are typically coupled with a transimpedance amplifier and a limiting amplifier to produce a digital signal in the electrical domain from the incoming optical signal, which may be attenuated and distorted while passing through the channel. Further signal processing such as clock recovery from data (CDR) performed by a phase-locked loop may also be applied before the data is passed on.

Fiber

A cable reel trailer with conduit that can carry optical fiber.
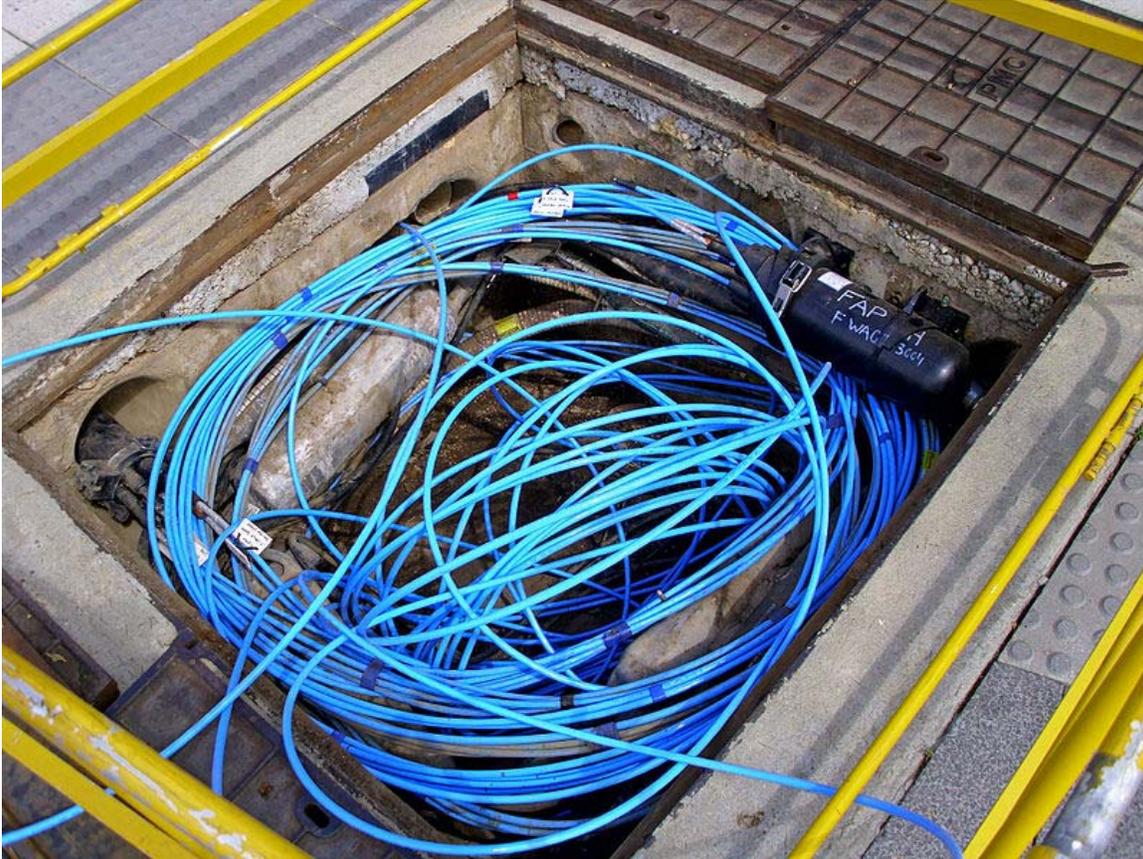
Single-mode optical fiber in an underground service pit

An optical fiber consists of a core, cladding, and a buffer (a protective outer coating), in which the cladding guides the light along the core by using the method of total internal reflection. The core and the cladding (which has a lower-refractive-index) are usually made of high-quality silica glass, although they can both be made of plastic as well. Connecting two optical fibers is done by fusion splicing or mechanical splicing and requires special skills and interconnection technology due to the microscopic precision required to align the fiber cores.

Two main types of optical fiber used in optic communications include multi-mode optical fibers and single-mode optical fibers. A multi-mode optical fiber has a larger core (≥ 50 micrometres), allowing less precise, cheaper transmitters and receivers to connect to it as well as cheaper connectors. However, a multi-mode fiber introduces multimode distortion, which often limits the bandwidth and length of the link. Furthermore, because of its higher dopant content, multi-mode fibers are usually expensive and exhibit higher attenuation. The core of a single-mode fiber is smaller (<10 micrometres) and requires more expensive components and interconnection methods, but allows much longer, higher-performance links.

In order to package fiber into a commercially-viable product, it is typically protectively-coated by using ultraviolet (UV), light-cured acrylate polymers, then terminated with

optical fiber connectors, and finally assembled into a cable. After that, it can be laid in the ground and then run through the walls of a building and deployed aerially in a manner similar to copper cables. These fibers require less maintenance than common twisted pair wires, once they are deployed.

Amplifiers

The transmission distance of a fiber-optic communication system has traditionally been limited by fiber attenuation and by fiber distortion. By using opto-electronic repeaters, these problems have been eliminated. These repeaters convert the signal into an electrical signal, and then use a transmitter to send the signal again at a higher intensity than it was before. Because of the high complexity with modern wavelength-division multiplexed signals (including the fact that they had to be installed about once every 20 km), the cost of these repeaters is very high.

An alternative approach is to use an optical amplifier, which amplifies the optical signal directly without having to convert the signal into the electrical domain. It is made by doping a length of fiber with the rare-earth mineral erbium, and *pumping* it with light from a laser with a shorter wavelength than the communications signal (typically 980 nm). Amplifiers have largely replaced repeaters in new installations.

Wavelength-division multiplexing

Wavelength-division multiplexing (WDM) is the practice of multiplying the available capacity of an optical fiber by adding new channels, each channel on a new wavelength of light. This requires a wavelength division multiplexer in the transmitting equipment and a demultiplexer (essentially a spectrometer) in the receiving equipment. Arrayed waveguide gratings are commonly used for multiplexing and demultiplexing in WDM. Using WDM technology now commercially available, the bandwidth of a fiber can be divided into as many as 160 channels to support a combined bit rate into the range of terabits per second.

Bandwidth-distance product

Because the effect of dispersion increases with the length of the fiber, a fiber transmission system is often characterized by its *bandwidth-distance product*, often expressed in units of MHz×km. This value is a product of bandwidth and distance because there is a trade off between the bandwidth of the signal and the distance it can be carried. For example, a common multimode fiber with bandwidth-distance product of 500 MHz×km could carry a 500 MHz signal for 1 km or a 1000 MHz signal for 0.5 km.

Through a combination of advances in dispersion management, wavelength-division multiplexing, and optical amplifiers, modern-day optical fibers can carry information at around 14 Terabits per second over 160 kilometers of fiber . Engineers are always looking at current limitations in order to improve fiber-optic communication, and several of these restrictions are currently being researched. For instance, NTT was able to

achieve 69.1 Tbit/s transmission by applying wavelength division multiplex (WDM) of 432 wavelengths with a capacity of 171 Gbit/s over a single 240 km-long optical fiber on March 25, 2010. This has been the highest optical transmission speed ever recorded. .

The per-channel light signals propagating in the fiber have been modulated at rates as high as 111 gigabits per second by NTT, although 10 or 40 Gbit/s is typical in deployed systems. Each fiber can carry many independent channels, each using a different wavelength of light (wavelength-division multiplexing (WDM)). The net data rate (data rate without overhead bytes) per fiber is the per-channel data rate reduced by the FEC overhead, multiplied by the number of channels (usually up to eighty in commercial dense WDM systems as of 2008). The current laboratory fiber optic data rate record, held by Bell Labs in Villarceaux, France, is multiplexing 155 channels, each carrying 100 Gbit/s over a 7000 km fiber.

Dispersion

For modern glass optical fiber, the maximum transmission distance is limited not by direct material absorption but by several types of dispersion, or spreading of optical pulses as they travel along the fiber. Dispersion in optical fibers is caused by a variety of factors. Intermodal dispersion, caused by the different axial speeds of different transverse modes, limits the performance of multi-mode fiber. Because single-mode fiber supports only one transverse mode, intermodal dispersion is eliminated.

In single-mode fiber performance is primarily limited by chromatic dispersion (also called group velocity dispersion), which occurs because the index of the glass varies slightly depending on the wavelength of the light, and light from real optical transmitters necessarily has nonzero spectral width (due to modulation). Polarization mode dispersion, another source of limitation, occurs because although the single-mode fiber can sustain only one transverse mode, it can carry this mode with two different polarizations, and slight imperfections or distortions in a fiber can alter the propagation velocities for the two polarizations. This phenomenon is called fiber birefringence and can be counteracted by polarization-maintaining optical fiber. Dispersion limits the bandwidth of the fiber because the spreading optical pulse limits the rate that pulses can follow one another on the fiber and still be distinguishable at the receiver.

Some dispersion, notably chromatic dispersion, can be removed by a 'dispersion compensator'. This works by using a specially prepared length of fiber that has the opposite dispersion to that induced by the transmission fiber, and this sharpens the pulse so that it can be correctly decoded by the electronics.

Attenuation

Fiber attenuation, which necessitates the use of amplification systems, is caused by a combination of material absorption, Rayleigh scattering, Mie scattering, and connection losses. Although material absorption for pure silica is only around 0.03 dB/km (modern fiber has attenuation around 0.3 dB/km), impurities in the original optical fibers caused

attenuation of about 1000 dB/km. Other forms of attenuation are caused by physical stresses to the fiber, microscopic fluctuations in density, and imperfect splicing techniques.

Transmission windows

Each effect that contributes to attenuation and dispersion depends on the optical wavelength. The wavelength bands (or windows) that exist where these effects are weakest are the most favorable for transmission. These windows have been standardized, and the currently defined bands are the following:

Band	Description	Wavelength Range
O band original		1260 to 1360 nm
E band extended		1360 to 1460 nm
S band short wavelengths		1460 to 1530 nm
C band conventional ("erbium window")		1530 to 1565 nm
L band long wavelengths		1565 to 1625 nm
U band ultralong wavelengths		1625 to 1675 nm

Note that this table shows that current technology has managed to bridge the second and third windows that were originally disjoint.

Historically, there was a window used below the O band, called the first window, at 800-900 nm; however, losses are high in this region so this window is used primarily for short-distance communications. The current lower windows (O and E) around 1300 nm have much lower losses. This region has zero dispersion. The middle windows (S and C) around 1500 nm are the most widely used. This region has the lowest attenuation losses and achieves the longest range. It does have some dispersion, so dispersion compensator devices are used to remove this.

Regeneration

When a communications link must span a larger distance than existing fiber-optic technology is capable of, the signal must be *regenerated* at intermediate points in the link by repeaters. Repeaters add substantial cost to a communication system, and so system designers attempt to minimize their use.

Recent advances in fiber and optical communications technology have reduced signal degradation so far that *regeneration* of the optical signal is only needed over distances of hundreds of kilometers. This has greatly reduced the cost of optical networking, particularly over undersea spans where the cost and reliability of repeaters is one of the key factors determining the performance of the whole cable system. The main advances contributing to these performance improvements are dispersion management, which

seeks to balance the effects of dispersion against non-linearity; and solitons, which use nonlinear effects in the fiber to enable dispersion-free propagation over long distances.

Last mile

Although fiber-optic systems excel in high-bandwidth applications, optical fiber has been slow to achieve its goal of fiber to the premises or to solve the last mile problem. However, as bandwidth demand increases, more and more progress towards this goal can be observed. In Japan, for instance EPON has largely replaced DSL as a broadband Internet source. South Korea's KT also provides a service called FTTH (Fiber To The Home), which provides 100 percent fiber-optic connections to the subscriber's home. The largest FTTH deployments are in Japan, Korea, and most recently in China. Most recently, Singapore has also completed their implementation of NGBN (Next Generation Broadband Network) and has started rolling out fibre internet services in September 2010.

In the US, Verizon Communications provides a FTTH service called FiOS to select high-ARPU (Average Revenue Per User) markets within its existing territory. The other major surving ILEC (or Incumbent Local Exchange Carrier), AT&T, uses a FTTN (Fiber To The Node) service called U-verse with twisted-pair to the home. Their MSO competitors employ FTTN with coax using HFC. All of the major access networks use fiber for the bulk of the distance from the service provider's network to the customer.

The globally dominant access network technology is EPON (Ethernet Passive Optical Network). In Europe, and among telcos in the United States, BPON (ATM-based Broadband PON) and GPON (Gigabit PON) are favored because of their roots in the FSAN (Full Service Access Network) and ITU-T standards organizations under their control.

Comparison with electrical transmission

A mobile fiber optic splice lab used to access and splice underground cables.
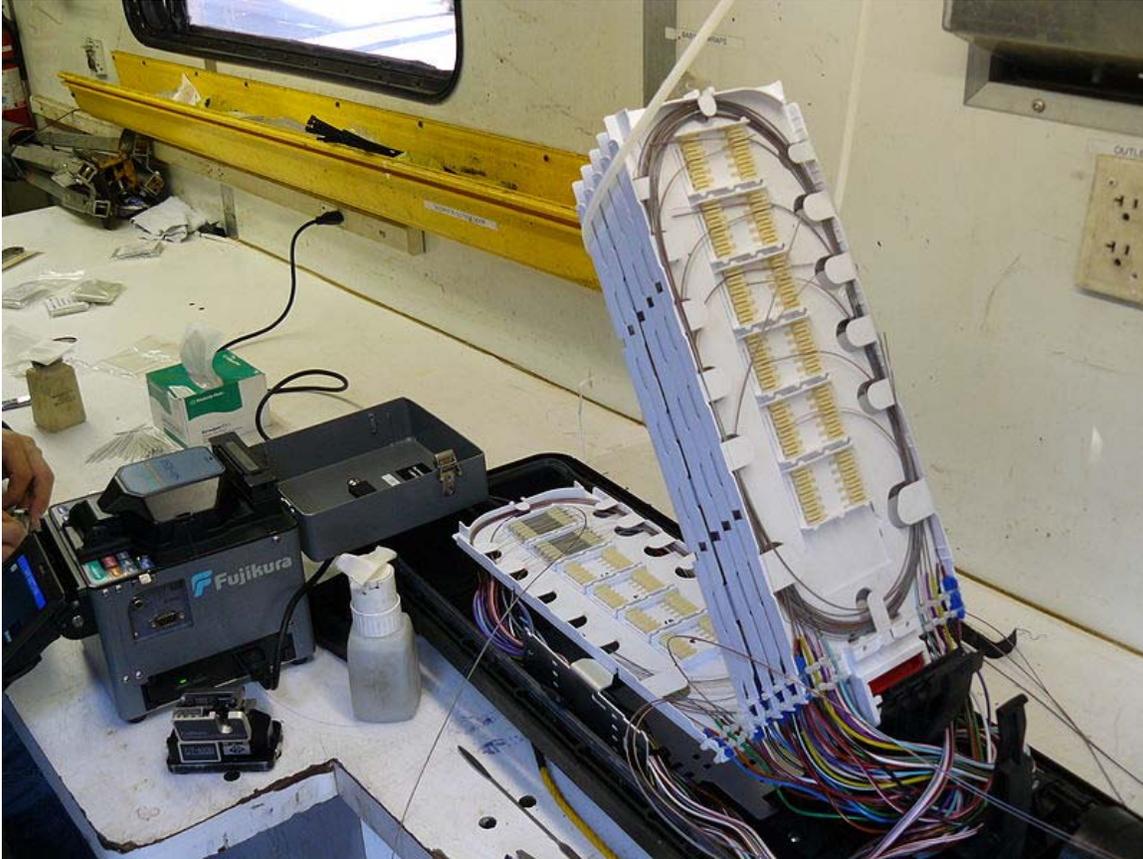
An underground fiber optic splice enclosure opened up.

The choice between optical fiber and electrical (or copper) transmission for a particular system is made based on a number of trade-offs. Optical fiber is generally chosen for systems requiring higher bandwidth or spanning longer distances than electrical cabling can accommodate.

The main benefits of fiber are its exceptionally low loss (allowing long distances between amplifiers/repeaters), its absence of ground currents and other parasite signal and power issues common to long parallel electric conductor runs (due to its reliance on light rather than electricity for transmission, and the dielectric nature of fiber optic), and its inherently high data-carrying capacity. Thousands of electrical links would be required to replace a single high bandwidth fiber cable. Another benefit of fibers is that even when run alongside each other for long distances, fiber cables experience effectively no crosstalk, in contrast to some types of electrical transmission lines. Fiber can be installed in areas with high electromagnetic interference (EMI), such as alongside utility lines, power lines, and railroad tracks. Nonmetallic all-dielectric cables are also ideal for areas of high lightning-strike incidence.

For comparison, while single-line, voice-grade copper systems longer than a couple of kilometers require in-line signal repeaters for satisfactory performance; it is not unusual for optical systems to go over 100 kilometers (60 miles), with no active or passive

processing. Single-mode fiber cables are commonly available in 12 km lengths, minimizing the number of splices required over a long cable run. Multi-mode fiber is available in lengths up to 4 km, although industrial standards only mandate 2 km unbroken runs.

In short distance and relatively low bandwidth applications, electrical transmission is often preferred because of its

- Lower material cost, where large quantities are not required
- Lower cost of transmitters and receivers
- Capability to carry electrical power as well as signals (in specially-designed cables)
- Ease of operating transducers in linear mode.

Optical fibers are more difficult and expensive to splice than electrical conductors. And at higher powers, optical fibers are susceptible to fiber fuse, resulting in catastrophic destruction of the fiber core and damage to transmission components.

Because of these benefits of electrical transmission, optical communication is not common in short box-to-box, backplane, or chip-to-chip applications; however, optical systems on those scales have been demonstrated in the laboratory.

In certain situations fiber may be used even for short distance or low bandwidth applications, due to other important features:

- Immunity to electromagnetic interference, including nuclear electromagnetic pulses (although fiber can be damaged by alpha and beta radiation).
- High electrical resistance, making it safe to use near high-voltage equipment or between areas with different earth potentials.
- Lighter weight—important, for example, in aircraft.
- No sparks—important in flammable or explosive gas environments.
- Not electromagnetically radiating, and difficult to tap without disrupting the signal—important in high-security environments.
- Much smaller cable size—important where pathway is limited, such as networking an existing building, where smaller channels can be drilled and space can be saved in existing cable ducts and trays.

Optical fiber cables can be installed in buildings with the same equipment that is used to install copper and coaxial cables, with some modifications due to the small size and limited pull tension and bend radius of optical cables. Optical cables can typically be installed in duct systems in spans of 6000 meters or more depending on the duct's condition, layout of the duct system, and installation technique. Longer cables can be coiled at an intermediate point and pulled farther into the duct system as necessary.

Optical fiber is the most common type of channel for optical communications, however, other types of optical waveguides are used within computers or communications gear,

and have even formed the channel of very short distance (e.g. chip-to-chip, intra-chip) links in laboratory trials. The transmitters in optical fiber links are generally light-emitting diodes (LEDs) or laser diodes. Infrared light, rather than visible light is used more commonly, because optical fibers transmit infrared wavelengths with less attenuation and dispersion. The signal encoding is typically simple intensity modulation, although historically optical phase and frequency modulation have been demonstrated in the lab. The need for periodic signal regeneration was largely superseded by the introduction of the erbium-doped fiber amplifier, which extended link distances at significantly lower cost.

Free-space optical communication

Free Space Optics (FSO) is an optical communication technology that uses light propagating in free space to transmit data between two points. The technology is useful where the physical connections by the means of fibre optic cables are impractical due to high costs or other considerations.

History

Optical communications, in various forms, have been used for thousands of years. The Ancient Greeks polished their shields to send signals during battle. In the modern era, semaphores and wireless solar telegraphs called heliographs were developed, using coded signals to communicate with their recipients.

In 1880 Alexander Graham Bell and his then-assistant Charles Sumner Tainter created the Photophone, at Bell's newly established Volta Laboratory in Washington, D.C. Bell considered it his most important invention. The device allowed for the transmission of sound and conversations on a beam of light. On June 3, 1880, Bell conducted the world's first wireless telephone transmission between two buildings, some 213 meters apart. Its first practical use came in military communication systems many decades later.

Carl Zeiss Jena developed the *Lichtsprechgerät 80* (direct translation: light speaking device) that the German army used in their World War II anti-aircraft defense units.

The invention of lasers in the 1960s revolutionized free space optics. Military organizations were particularly interested and boosted their development. However the technology lost market momentum when the installation of optical fiber networks for civilian uses was at its peak.

Usage and technologies

Free-space optical links can be implemented using infrared laser light, although low-data-rate communication over short distances is possible using LEDs. IrDA is a very simple form of free-space optical communications. Free Space Optics are additionally used for communications between spacecraft. Maximum range for terrestrial links is in the order

of 2 to 3 km (1.2 to 1.9 mi), but the stability and quality of the link is highly dependent on atmospheric factors such as rain, fog, dust and heat. Amateur radio operators have achieved significantly farther distances (173 miles in at least one occasion) using incoherent sources of light from high-intensity LEDs. However, the low-grade equipment used limited bandwidths to about 4 kHz. In outer space, the communication range of free-space optical communication is currently in the order of several thousand kilometers, but has the potential to bridge interplanetary distances of millions of kilometers, using optical telescopes as beam expanders.

Secure free-space optical communications have been proposed using a laser N-slit interferometer where the laser signal takes the form of an interferometric pattern. Any attempt to intercept the signal causes the collapse of the interferometric pattern. Although this method has only been demonstrated at laboratory distances, in principle it could be applied over large distances in space.

Applications

Two solar-powered satellites communicating optically in space via lasers.

Typically scenarios for use are:

- LAN-to-LAN connections on campuses at Fast Ethernet or Gigabit Ethernet speeds.
- LAN-to-LAN connections in a city. *example, Metropolitan area network*.
- To cross a public road or other barriers which the sender and receiver do not own.
- Speedy service delivery of high-bandwidth access to optical fiber networks.
- Converged Voice-Data-Connection.
- Temporary network installation (for events or other purposes).
- Reestablish high-speed connection quickly (disaster recovery).
- As an alternative or upgrade add-on to existing wireless technologies.
- As a safety add-on for important fiber connections (redundancy).
- For communications between spacecraft, including elements of a satellite constellation.
- For inter- and intra-chip communication.

The light beam can be very narrow, which makes FSO hard to intercept, improving security. In any case, it is comparatively easy to encrypt any data traveling across the FSO connection for additional security. FSO provides vastly improved EMI behavior using light instead of microwaves.

Advantages

RONJA is a free implementation of FSO using high-intensity LEDs.

- Ease of deployment
- License-free long-range operation (in contrast with radio communication)
- High bit rates
- Low bit error rates
- Immunity to electromagnetic interference
- Full duplex operation
- Protocol transparency
- Very secure due to the high directionality and narrowness of the beam(s)
- No Fresnel zone necessary

Disadvantages

For terrestrial applications, the principal limiting factors are:

- Beam dispersion
- Atmospheric absorption
- Rain
- Fog (10..~100 dB/km attenuation)
- Snow
- Scintillation
- Background light
- Shadowing
- Pointing stability in wind
- Pollution / smog
- If the sun goes exactly behind the transmitter, it can swamp the signal.

These factors cause an attenuated receiver signal and lead to higher bit error ratio (BER). To overcome these issues, vendors found some solutions, like multi-beam or multi-path architectures, which use more than one sender and more than one receiver. Some state-of-the-art devices also have larger fade margin (extra power, reserved for rain, smog, fog). To keep an eye-safe environment, good FSO systems have a limited laser power density and support laser classes 1 or 1M. Atmospheric and fog attenuation, which are exponential in nature, limit practical range of FSO devices to several kilometres.

Free Space Optics (FSO) systems are generally employed for 'last mile' communications and can function over distances of several kilometers as long as there is a clear line of sight between the source and the destination, and the optical receiver can reliably decode the transmitted information. IrDA is an example of low-data-rate, short distance free-space optical communications using LEDs.

Chapter- 7

Other Optoelectronics

Petoscope

A **Petoscope** is an optoelectronic device for detecting small, distant objects such as flying aircraft. The design, as described in 1936 , consisted of an instrument with two parallel light paths. In each path was a collimating objective lens, a screen marked with many small, alternating opaque and transparent squares in a chequerboard pattern, and a second concentrating lens focused on a photocell. The two screens were inverted with respect to each other. This caused a small object in the instrument's field of view to produce differing signals in the two photocells, while a large object affected both light paths equally. The difference between the two signals was amplified and used to raise an alarm. At the beginning of World War II, the device was adapted for use in proximity fuses for bombs.

The inventor was Alan S. Fitzgerald of Wynnewood, Pennsylvania, U.S.A., a Research Associate in Electrical Engineering at Swarthmore College.

3LCD
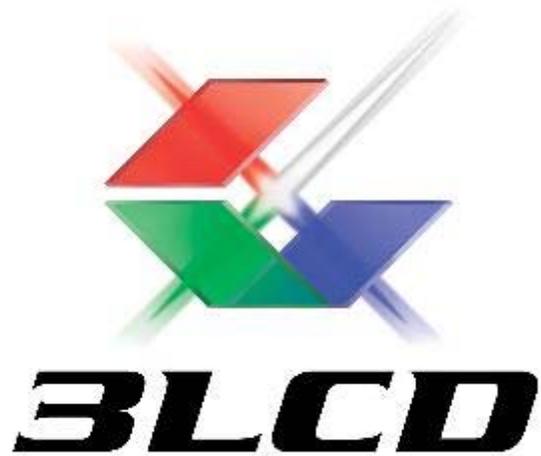
The 3LCD Logo

3LCD Projector Examples

The 2007 Sony VPL-CX155 - an example of a current projector using licensed 3LCD technology

3LCD is the name and brand of a major LCD projection color image generation technology used in modern digital projectors. 3LCD technology was pioneered and refined by Japanese imaging company Epson in the 1980s and was first licensed for use in projectors in 1988. In January 1989, Epson launched its first 3LCD projector, the VPJ-700..

Although Epson still owns 3LCD technology, it is marketed by an affiliated organization simply named after the technology:"3LCD". The organization is a consortium of projector manufacturers that have licensed 3LCD technology to be used in their products. To date, about 40 different projector brands worldwide have adopted 3LCD technology.

According to electronics industry research company *Pacific Media Associates*, projectors using 3LCD technology comprised about 51% of the world's digital projector market in 2009 .

3LCD technology gets its name from the three LCD panel chips used in its image generation engine.

How 3LCD Technology Works
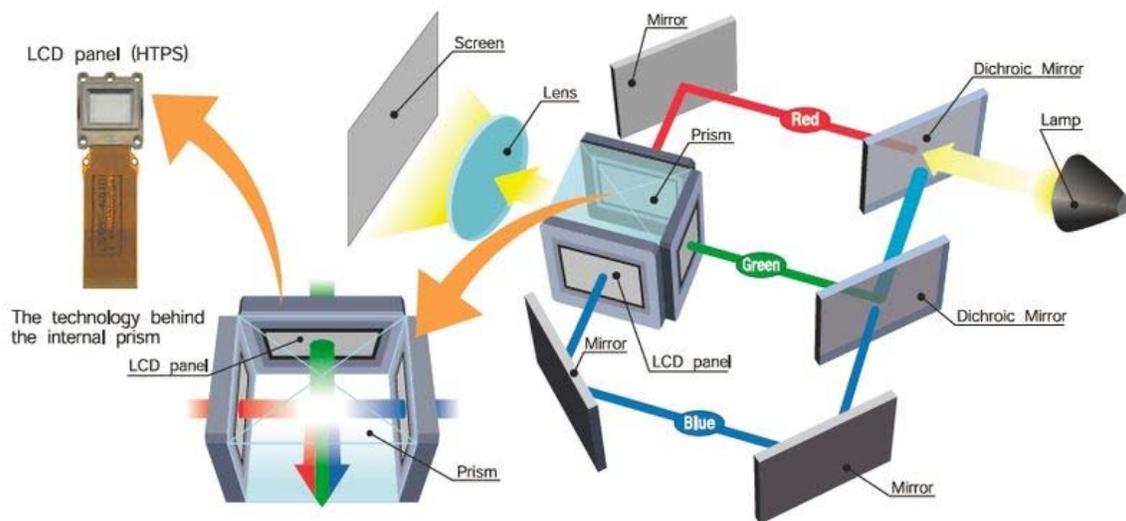
A diagram showing how a projector using 3LCD technology works

Creating Colours from White Light:
A projector using 3LCD technology works by first splitting the white light from the lamp into its three primary colours of red, green and blue by passing the lamp light through special dichroic filter / reflector assemblies called "dichroic mirrors." Each dichroic mirror only allows specific colored wavelengths of light to pass through while reflecting the rest away. In this way, the white light is split into its three primary color beams and each is directed toward, and subsequently through its own LCD panel.

Image Generation at the LCDs:
The three LCD panels of the projector are the elements that receive the electronic signals to create the image which is to be projected. Each pixel on an LCD is covered by liquid crystals. By changing the electrical charge given to the liquid crystals, each pixel on an LCD can be darkened until it is totally opaque (for full black), lightened until it is totally transparent (allowing all the lamp light to pass through for full white), or shaded in varying degrees of translucence (for different shades of gray). This is similar to how a digital watch's characters appear bold and black on its LCD when its battery is new, but start to fade gradually as its battery weakens. In this way, the brightness level on every pixel for each primary color can be very precisely controlled to produce the final pixel's specific color and brightness level required on the screen.

Color Image Recombination and Projection:
After each colored light is filtered through its individual LCD panel, the beams are recombined in a dichroic prism that forms the final image which is then reflected out through the lens.

Competition

For mainstream projectors, the competitors to 3LCD technology are single-chip DLP technology (developed by Texas Instruments) and to a much lesser extent, LCOS projection technology.

Advantages

Proponents of 3LCD projection technology claim that it has the following advantages over it closest competing technologies:

- 3LCD projectors are able to produce brighter colors compared to those using single-chip DLP technology. This is because 3LCD projectors mix and project the light beams from all three colours to form each individual pixel's color, while single-chip DLP projectors create colors by projecting them in sequence one at a time and rely on human color perception to mix and interpret the correct colors for each pixel.
- The way a single-chip DLP projector works sometimes causes viewers to see a "rainbow" or "color breakup" effect where false colors are briefly perceived when either the image or the observer's eye is in motion. As all three primary colors are displayed all the time by 3LCD projectors, they do not suffer from this effect.
- 3LCD projectors are able to display finer image gradations by giving each pixel on the projected image a smooth variation in brightness levels. This is because the liquid crystals for each pixel on an LCD panel can be given fine levels of opacity by varying the electrical charge. On the other hand, a single-chip DLP projector has a single mirror reflecting the lamp light to the lens on its DMD chip for each pixel. It varies the brightness of each pixel by vibrating the mirror between its on

or off state in varying frequencies and relies on human perception to interpret the brightness of each pixel.

- 3LCD projectors typically use less power compared to a single-chip DLP projectors of the same brightness rating.
- 3LCD projectors are typically more affordable than those using LCOS or 3-chip DLP technologies.

Disadvantages

- Older 3LCD projectors with large pixel pitches usually have a "screen door" effect
- 3LCD projectors are typically more costly than single-chip DLP ones of similar specifications.
- Single-chip DLP projectors typically have higher contrast ratios compared to older 3LCD models of similar price or brightness rating.
- The LCD panels and dichroic mirrors in 3LCD projectors may degrade with time, causing color shifts, unevenness of illumination, and reduction of contrast. The single DMD chip in single-chip DLP projectors tend to have a longer life span.
- The smallest single-chip DLP projectors are smaller than the smallest 3LCD projector models.
- Current LCOS projector models typically deliver sharper images at higher resolutions than 3LCD projectors.

Corona poling

Corona discharge is a partial breakdown of air, usually at atmospheric pressure, and is initiated by a discharge in an inhomogeneous electric field (see Fig. 1). Corona discharge has been used to pole films of electro-optic materials to enhance their electro-optic properties. Although corona poling can be performed at room temperature, poling at elevated temperature has several advantages. For example, raising the temperature in a polymer guest-host system close to their glass-rubber transition temperature before poling increases the molecular mobility of the guest molecules and allows rotation to occur during poling. If during poling the temperature is lowered well below the glass-rubber transition temperature, the guest molecules are frozen into their new orientation.
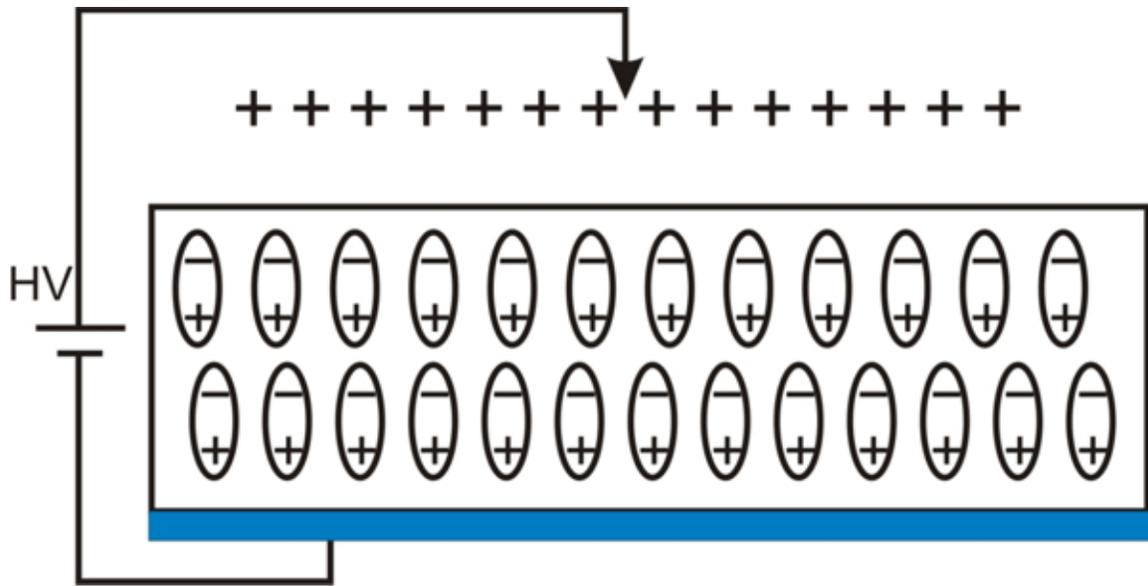
Digital micromirror device

DLP chip

A **digital micromirror device**, or **DMD**, is an optical semiconductor that is the core of DLP projection technology, and was invented by Dr. Larry Hornbeck and Dr. William E. "Ed" Nelson of Texas Instruments (TI) in 1987.

The DMD project began as the Deformable Mirror Device in 1977, using micromechanical, analog light modulators. The first analog DMD product was the TI DMD2000 airline ticket printer that used a DMD instead of a laser scanner.

A DMD chip has on its surface several hundred thousand microscopic mirrors arranged in a rectangular array which correspond to the pixels in the image to be displayed. The mirrors can be individually rotated ±10-12°, to an on or off state. In the on state, light from the projector bulb is reflected into the lens making the pixel appear bright on the screen. In the off state, the light is directed elsewhere (usually onto a heatsink), making the pixel appear dark.

To produce greyscales, the mirror is toggled on and off very quickly, and the ratio of on time to off time determines the shade produced (binary pulse-width modulation). Contemporary DMD chips can produce up to 1024 shades of gray (10 bits).

The mirrors themselves are made out of aluminium and are around 16 micrometres across. Each one is mounted on a yoke which in turn is connected to two support posts by compliant torsion hinges. In this type of hinge, the axle is fixed at both ends and literally twists in the middle. Because of the small scale, hinge fatigue is not a problem and tests have shown that even 1 trillion (10^{12}) operations do not cause noticeable damage. Tests have also shown that the hinges cannot be damaged by normal shock and vibration, since it is absorbed by the DMD superstructure.

Two pairs of electrodes control the position of the mirror by electrostatic attraction. Each pair has one electrode on each side of the hinge, with one of the pairs positioned to act on the yoke and the other acting directly on the mirror. The majority of the time, equal bias charges are applied to both sides simultaneously. Instead of flipping to a central position as one might expect, this actually holds the mirror in its current position. This is because attraction force on the side the mirror is already tilted towards is greater, since that side is closer to the electrodes.

To move the mirrors, the required state is first loaded into an SRAM cell located beneath each pixel, which is also connected to the electrodes. Once all the SRAM cells have been loaded, the bias voltage is removed, allowing the charges from the SRAM cell to prevail, moving the mirror. When the bias is restored, the mirror is once again held in position, and the next required movement can be loaded into the memory cell.

The bias system is used because it reduces the voltage levels required to address the pixels such that they can be driven directly from the SRAM cell, and also because the bias voltage can be removed at the same time for the whole chip, so every mirror moves at the same instant. The advantages of the latter are more accurate timing and a more filmic moving image.

Grating light valve

The **grating light valve** (GLV) is a "micro projection" technology which operates using a dynamically adjustable diffraction grating. It competes with other light valve technologies such as Digital Light Processing (DLP) and liquid crystal on silicon (LCoS) for implementation in video projector devices such as rear-projection televisions. The use of microelectromechanical systems (MEMS) in optical applications, which is known as optical MEMS or micro-opto-electro-mechanical structures (MOEMS), has enabled the possibility to combine the mechanical, electrical and optical components in very small scale.

Silicon Light Machines (SLM), in Sunnyvale CA, markets and licenses GLV technology with the capitalised trademarks **Grated Light Valve** and GLV, previously Grating Light Valve. The valve diffracts laser light using an array of tiny movable ribbons mounted on a silicon base. The GLV uses six ribbons as the diffraction gratings for each pixel. The alignment of the gratings is altered by electronic signals, and this displacement controls the intensity of the diffracted light in a very smooth gradation.

Brief history

The light valve was originally developed at Stanford University, in California, by electrical engineering professor David M. Bloom, along with Raj Apte, Francisco Sandejas, and Olav Solgaard. In 1994, the start-up company Silicon Light Machines was founded by Bloom to develop and commercialize the technology. The company is now wholly owned by Dainippon Screen Manufacturing Co., Ltd.

In July 2000, Sony announced the signing of a technology licensing agreement with SLM for the implementation of GLV technology in laser projectors for large venues, but by 2004 Sony announced the SRX-R110 front projector using its own LCoS-based technology SXRD. SLM then partnered with Evans & Sutherland (E&S). Using GLV technology, E&S developed the E&S Laser Projector, designed for use in domes and planetariums. The E&S Laser Projector was incorporated into the Digistar 3 dome projection system.

Technology

The GLV device is built on a silicon wafer and consists of parallel rows of **highly reflective micro-ribbons** – ribbons of sizes of a few μm with a top layer of aluminium – suspended above an air gap that are configured such that alternate ribbons (active ribbons are interlaced with static ribbons) can be dynamically actuated. Individual electrical connections to each active ribbon electrode provide for independent actuation. The ribbons and the substrate are electrically conductive so that the deflection of the ribbon can be controlled in an analog manner: When the voltage of the active ribbons is set to ground potential, all ribbons are undeflected, and the device acts as a mirror so the

incident light returns along the same path. When a voltage is applied between the ribbon and base conductor an electrical field is generated and deflects the active ribbon downward toward the substrate. This deflection can be as big as one-quarter wavelength hence creating diffraction effects on incident light that is reflected at an angle that is different from that of the incident light. The wavelength to diffract is determined by the spatial frequency of the ribbons. As this spatial frequency is determined by the photolithographic mask used to form the GLV device in the CMOS fabrication process, the departure angles can be very accurately controlled, which is useful for optical switching applications.

The switching from undeflected to maximum deflection of the ribbon is really fast; it can switch in 20 nanoseconds which is a million times faster than conventional LCD display devices, and about 1000 times faster than TI's DMD technology. This high speed can be achieved thanks to the small size, small mass and small excursion (of a few hundreds of nanometers), of the ribbons. Besides, there is no physical contact between moving elements which makes the lifetime of the GLV as long as 15 years without stopping (over 210 billion switching cycles).

Applications

The GLV technology has been applied to a wide range of products, from laser-based HDTV sets to computer-to-plate offset printing presses to DWDM components used for wavelength management. Applications of the GLV device in maskless photolithography have also been extensively investigated.

Displays

To build a display system using the GLV device different approaches can be followed: ranging from a simple approach using a single GLV device with a white light as a source thus having a monochrome system to a more complex solution using three different GLV devices each for one of the RGB primaries' sources that once diffracted require different optical filters to point the light onto the screen or an intermediate using a single white source with a GLV device. Besides, the light can be diffracted by the GLV device into an eyepiece for virtual retinal display, or into an optical system for image projection onto a screen (projector and rear-projector).

Infrared open path detector

Infrared open path gas detectors send out a beam of infrared light, detecting gas anywhere along the path of the beam. This linear 'sensor' is typically a few metres up to a few hundred metres in length. Open path detectors are widely used in the petroleum and petrochemical industries, mostly to achieve very rapid gas leak detection for flammable gases at concentrations comparable to the lower flammable limit (typically a few percent by volume). They are also used, but so far to a lesser extent, in other industries where flammable concentrations can occur, such as in coal mining and water treatment. In

principle the technique can also be used to detect toxic gases, for instance hydrogen sulfide, at the necessary parts-per-million concentrations, but the technical difficulties involved have so far prevented widespread adoption for toxic gases.

Usually, there are separate transmitter and receiver units at either end of a straight beam path. Alternatively, the source and receiver are combined, and the beam bounced off a retroreflector at the far end of the measurement path. For portable use, detectors have also been made which use the natural albedo of surrounding objects in place of the retroreflector. The presence of a chosen gas (or class of gases) is detected from its absorption of a suitable infrared wavelength in the beam. Rain, fog etc. in the measurement path can also reduce the strength of the received signal, so it is usual to make a simultaneous measurement at one or more reference wavelengths. The quantity of gas intercepted by the beam is then inferred from the ratio of the signal losses at the measurement and reference wavelengths. The calculation is typically carried out by a microprocessor which also carries out various checks to validate the measurement and prevent false alarms.

The measured quantity is the sum of all the gas along the path of the beam, sometimes termed the *path-integral concentration* of the gas. Thus the measurement has a natural bias (desirable in many applications) towards the total size of an unintentional gas release, rather than the concentration of the gas that has reached any particular point. Whereas the natural units of measurement for a point detector are parts-per-million (ppm) or the percentage of the lower flammable limit (%LFL), the natural units of measurement for an open path detector are *ppm.metres* (ppmm) or *LFL.metres* (LFLm). For instance, the fire and gas safety system on an offshore platform in the North Sea typically has detectors set to a full-scale reading of 5LFLm, with low and high alarms triggered at 1LFLm and 3LFLm respectively.

Advantages and disadvantages versus fixed point detectors

An open path detector usually costs more than a single point detector, so there is little incentive for applications that play to a point detector's strengths: where the point detector can be placed at the known location of the highest gas concentration, and a relatively slow response is acceptable. The open path detector excels in outdoor situations where, even if the likely source of the gas release is known, the evolution of the developing cloud or plume is unpredictable. Gas will almost certainly enter a extended linear beam before finding its way to any single chosen point. Also, point detectors in exposed outdoor locations require weather shields to be fitted, increasing the response time significantly. Open path detectors can also show a cost advantage in any application where a row of point detectors would be required to achieve the same coverage, for instance monitoring along a pipeline, or around the perimeter of a plant. Not only will one detector replace several, but the costs of installation, maintenance, cabling etc. are likely to be lower.

An important consideration for both types is a realistic assessment of their availability in service, distinguishing carefully between revealed and unrevealed downtime. The latter, where a detector appears to be working but is insensitive to gas, is especially serious. For instance, point detectors of the catalytic type are prone to poisoning by silicones and H2S, or by clogging of the gauze or sinter by water or ice. Point detectors of the infrared type are immune from the former but not the latter mechanism. Open path detectors suffer downtime from anything that blocks the path of the beam, such as people, vehicles or thick fog. However, they approach the ideal of eliminating unrevealed downtime because the loss of signal strength is easily made to generate a 'beam block' signal, distinct from zero gas or a hardware fault. Infrared detectors of both types, unlike passive sensors, invariably incorporate a microprocessor capable of self-checking the circuitry, so unrevealed downtime due to hardware failures is largely eliminated. The possibility of (revealed) downtime of an open path detector due to fog can be minimised by limiting the beam path to moderate lengths. In fog-prone areas, such as the North Sea, paths are often limited to 15 to 20 metres for this reason, even though the detectors are capable of much greater distances in clear air.

Component parts

In principle any source of infrared radiation could be used, together with an optical system of lenses or mirrors to form the transmitted beam. In practice the following sources have been used, always with some form of modulation to aid the signal processing at the receiver:

- An incandescent light bulb, modulated by pulsing the current powering the filament or by a mechanical chopper. For systems used outdoors, it is difficult for an incandescent source to compete with the intensity of sunlight when the sun shines directly into the receiver. Also, it is difficult to achieve modulation frequencies distinguishable from those that can be produced naturally, for instance by heat shimmer or by sunlight reflecting off waves at sea.
- A gas-discharge lamp is capable of exceeding the spectral power of direct sunlight in the infrared, especially when pulsed. Modern open path systems typically use a xenon flashtube powered by a capacitor discharge. Such pulsed sources are inherently modulated.
- A semiconductor laser provides a relatively weak source, but one that can be modulated at high frequency in wavelength as well as amplitude. This property permits various signal processing schemes based on Fourier analysis, of use when the absorption of the gas is weak but narrow in spectral linewidth.

The precise wavelength passbands used must be isolated from the broad infrared spectrum. In principle any conventional spectrometer technique is possible, but the NDIR technique with multilayer dielectric filters and beamsplitters is most often used. These wavelength-defining components are usually located in the receiver, although one design has shared the task with the transmitter.

At the receiver, the infrared signal strengths are measured by some form of infrared detector. Generally photodiode detectors are preferred, and are essential for the higher modulation frequencies, whereas slower photoconductive detectors may be required for longer wavelength regions. The signals are fed to low-noise amplifiers, then invariably subject to some form of digital signal processing. The absorption coefficient of the gas will vary across the passband, so the simple Beer–Lambert law cannot be applied directly. For this reason the processing usually employs a calibration table, applicable for a particular gas, type of gas, or gas mixture, and sometimes configurable by the user.

Operating Wavelengths

The choice of infrared wavelengths used for the measurement largely defines the detector's suitability for a particular applications. Not only must the target gas (or gases) have a suitable absorption spectrum, the wavelengths must lie within a spectral window so the air in the beam path is itself transparent. These wavelength regions have been used:

- **3.4μm region.** All hydrocarbons and their derivatives absorb strongly, due to the C-H stretch mode of molecular vibration. It is commonly used in infrared point detectors where path lengths are necessarily short, and for open-path detectors requiring parts-per-million sensitivity. A disadvantage for many applications is that methane absorbs relatively weakly compared to heavier hydrocarbons, leading to large inconsistencies of calibration. For open-path detection of flammable concentrations the absorption for non-methane hydrocarbons is so strong that the measurement saturates, a significant gas cloud appearing 'black'. This wavelength region is beyond the transmission range of borosilicate glass, so windows and lenses must be made of more expensive materials and tend to be small in aperture.

- **2.3μm region.** All hydrocarbons and their derivatives have absorption coefficients appropriate for open path detection at flammable concentrations. A useful advantage in practical applications is that the detector's response to many different gases and vapours is relatively uniform when expressed in terms of the lower flammable limit. Borosilicate glass retains useful transmission in this wavelength region, allowing large aperture optics to be produced at moderate cost.

- **1.6μm region.** A wide range of gases absorb in the near-infrared. Typically the absorption coefficients are relatively weak, but light molecules show narrow, individually resolved spectral lines rather than broad bands. This results in relatively large values of the gradient and curvature of the absorption with respect to wavelength, enabling semiconductor laser-based systems to distinguish gas molecules very specifically; for instance hydrogen sulfide, or methane to the exclusion of heavier hydrocarbons.

History

The first open path detector offered for routine industrial use, as distinct from research instruments built in small numbers, was the Wright and Wright 'Pathwatch' in USA, 1983. Acquired by Det-tronics in 1992, the detector operated in the 3.4μm region with a powerful incandescent source and a mechanical chopper. It did not achieved large volume sales, mainly because of cost and doubts about long-term reliability with moving parts. Beginning in 1985, Shell Research in UK was funded by Shell Natural Gas to develop an open path detector with no moving parts. The advantages of the 2.3μm wavelength were identified, and a research prototype was demonstrated. This design had a combined transmitter-receiver with a corner-cube retroreflector at 50 metres. It used a pulsed incandescent lamp, PbS photoconductive detectors in the gas and reference channels, and an Intel 8031 microprocessor for signal processing. In 1987 Shell licenced this technology to Sieger-Zellweger (later Honeywell) who designed and marketed their industrial version as the 'Searchline', using a retro-reflective panel made up of multiple corner-cubes. This was the first open path detector to be certified for use in hazardous areas and to have no moving parts. Later work by Shell Research used two alternately pulsed incandescent sources in the transmitter and a single PbS detectors in the receiver, avoiding zero drifts caused by the variable responsivity of PbS detectors. This technology was offered to Sieger-Zellweger, and later licensed to PLMS. a company part-owned by Shell Ventures UK. The PLMS GD4001/2 in 1981 were the first detectors to achieve a truly stable zero without moving parts or software compensation of slow drifts. They were also the first infrared gas detectors of any kind to be certified intrinsically safe. The Israeli company Spectronix (also Spectrex) made an important advance in 1986 with their SafEye, the first to use a flash tube source, followed by Sieger-Zellweger with their Searchline Excel in 1988. In 1991 the PLMS Pulsar, soon afterwards acquired by Dräger as their Polytron Pulsar, was the first detector to incorporate sensing to monitor the mutual alignment of the transmitter and receiver during both installation and routine operation.

Thales Optronics

Thales Optronics is a major unit of Thales Group and has three main subsidiaries, Thales Optronics Ltd. (UK), Thales Optronique SA (France) and Thales Optronics B.V.

Thales' optronics businesses in the UK are as a result of the acquisition of Pilkington Optronics. Pilkington Optronics was formed by Pilkington plc in 1988 to take control of the company's varied optronics businesses (formerly Pilkington Perkin Elmer/Pilkington PE and Barr and Stroud, Glasgow). Pilkington PE later became Thales Optics Ltd., and – following divestment from Thales in December 2005 – now trades as Qioptiq Ltd.

In 1991 Thomson-CSF acquired a 50% share of Pilkington Optronics (PO). In 1995 PO acquired Thorn EMI Electro Optics which was renamed Pilkington Thorn Optronics (now Thales Optronics (Staines) Ltd). Three years later, Thomson-CSF purchased another 40% of PO from Pilkington and the remainder in 2000 to make it a wholly owned subsidiary. In 2000 Thomson-CSF was renamed Thales and Pilkington Optronics Ltd. became Thales Optronics Ltd. Soon after, Thomson-CSF acquired W Vinten Ltd, a

British reconnaissance equipment manufacturer, including the Joint Reconnaissance Pod, who now operate as Thales Optronics (Bury St Edmunds) Ltd.

Optical fiber cable
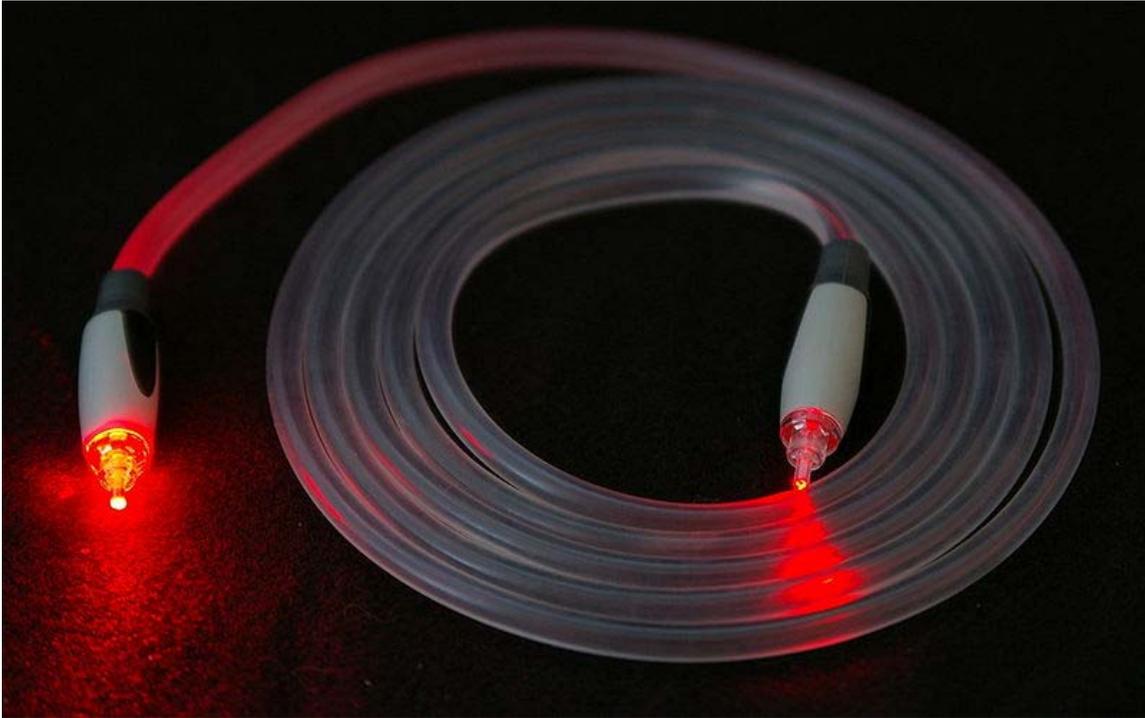
A TOSLINK optical fiber cable with a clear jacket. These plastic-fiber cables are used mainly for digital audio connections between devices.

An **optical fiber cable** is a cable containing one or more optical fibers. The optical fiber elements are typically individually coated with plastic layers and contained in a protective tube suitable for the environment where the cable will be deployed.

Design

A multi-fiber cable

In practical fibers, the cladding is usually coated with a tough resin *buffer* layer, which may be further surrounded by a *jacket* layer, usually plastic. These layers add strength to the fiber but do not contribute to its optical wave guide properties. Rigid fiber assemblies sometimes put light-absorbing ("dark") glass between the fibers, to prevent light that leaks out of one fiber from entering another. This reduces cross-talk between the fibers, or reduces flare in fiber bundle imaging applications.

Left: LC/PC connectors
Right: SC/PC connectors
All four connectors have white caps covering the ferrules.

For indoor applications, the jacketed fiber is generally enclosed, with a bundle of flexible fibrous polymer *strength members* like Aramid (e.g. Twaron or Kevlar), in a lightweight plastic cover to form a simple cable. Each end of the cable may be *terminated* with a specialized optical fiber connector to allow it to be easily connected and disconnected from transmitting and receiving equipment.
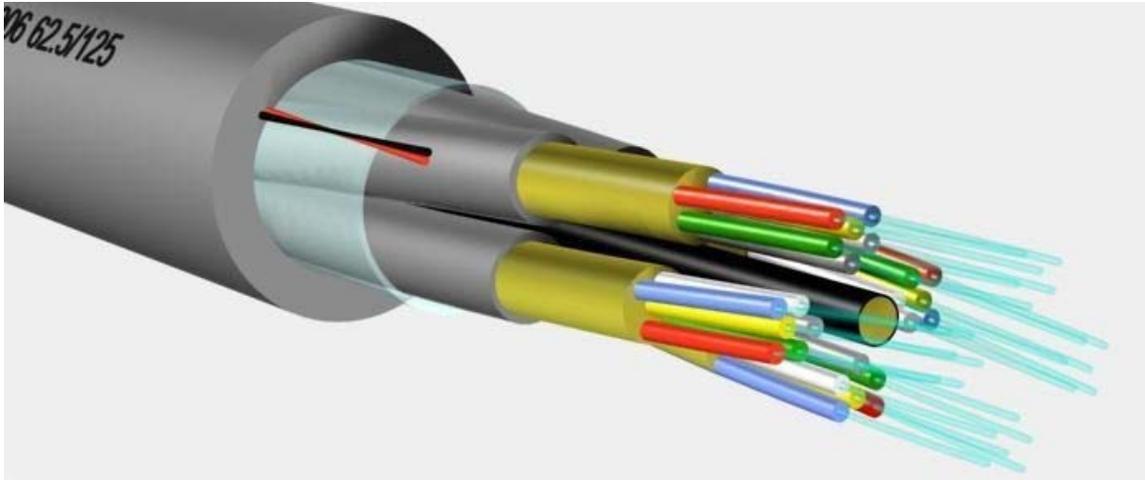
An optical fiber breakout cable

For use in more strenuous environments, a much more robust cable construction is required. In *loose-tube construction* the fiber is laid helically into semi-rigid tubes, allowing the cable to stretch without stretching the fiber itself. This protects the fiber from tension during laying and due to temperature changes. Loose-tube fiber may be "dry block" or gel-filled. Dry block offers less protection to the fibers than gel-filled, but costs considerably less. Instead of a loose tube, the fiber may be embedded in a heavy polymer jacket, commonly called "tight buffer" construction. Tight buffer cables are offered for a variety of applications, but the two most common are "Breakout" and "Distribution". Breakout cables normally contain a ripcord, two non-conductive dielectric strengthening members (normally a glass rod epoxy), an aramid yarn, and 3 mm buffer tubing with an additional layer of Kevlar surrounding each fiber. The ripcord is a parallel cord of strong yarn that is situated under the jacket(s) of the cable for jacket removal. Distribution cables have an overall Kevlar wrapping, a ripcord, and a 900 micrometer buffer coating surrounding each fiber. These *fiber units* are commonly bundled with additional steel strength members, again with a helical twist to allow for stretching.

A critical concern in outdoor cabling is to protect the fiber from contamination by water. This is accomplished by use of solid barriers such as copper tubes, and water-repellent jelly or water-absorbing powder surrounding the fiber.

Finally, the cable may be armored to protect it from environmental hazards, such as construction work or gnawing animals. Undersea cables are more heavily armored in their near-shore portions to protect them from boat anchors, fishing gear, and even sharks, which may be attracted to the electrical power signals that are carried to power amplifiers or repeaters in the cable.

Modern fiber cables can contain up to a thousand fibers in a single cable, so the performance of optical networks easily accommodates even today's demands for bandwidth on a point-to-point basis. However, unused point-to-point potential bandwidth does not translate to operating profits, and it is estimated that no more than 1% of the

optical fiber buried in recent years is actually 'lit'. While unused fiber may not be carrying traffic, it still has value as dark backbone fiber. Companies can lease or sell the unused fiber to other providers who are looking for service in or through an area. Many companies are "overbuilding" their networks for the specific purpose of having a large network of dark fiber for sale. This is a great idea as many cities are difficult to deal with when applying for permits and trenching in new ducts is very costly.

Modern cables come in a wide variety of sheathings and armor, designed for applications such as direct burial in trenches, dual use as power lines, installation in conduit, lashing to aerial telephone poles, submarine installation, or insertion in paved streets. In recent years the cost of small fiber-count pole-mounted cables has greatly decreased due to the high Japanese and South Korean demand for fiber to the home (FTTH) installations.

Cable types

- OFC: Optical fiber, conductive
- OFN: Optical fiber, nonconductive
- OFCG: Optical fiber, conductive, general use
- OFNG: Optical fiber, nonconductive, general use
- OFCP: Optical fiber, conductive, plenum
- OFNP: Optical fiber, nonconductive, plenum
- OFCR: Optical fiber, conductive, riser
- OFNR: Optical fiber, nonconductive, riser
- OPGW: Optical fiber composite overhead ground wire

Jacket material

The jacket material is application specific. The material determines the mechanical robustness, aging due to UV radiation, oil resistance, etc. Nowadays PVC is being replaced by halogen free alternatives, mainly driven by more stringent regulations.

Color coding

Patch cords

The buffer or jacket on patchcords is often color-coded to indicate the type of fiber used. The strain relief "boot" that protects the fiber from bending at a connector is color-coded to indicate the type of connection. Connectors with a plastic shell (such as SC connectors) typically use a color-coded shell. Standard color codings for jackets and boots (or connector shells) are shown below:

Remark: It is also possible that a small part of a connector is additionally colour-coded, e.g. the leaver of an E-2000 connector or a frame of an adapter. This additional colour coding indicates the correct port for a patchcord, if many patchcords are installed at one point.

Multi-fiber cables

Individual fibers in a multi-fiber cable are often distinguished from one another by color-coded jackets or buffers on each fiber. The identification scheme used by Corning Cable Systems is based on EIA/TIA-598, "**Optical Fiber Cable Color Coding**." EIA/TIA-598 defines identification schemes for fibers, buffered fibers, fiber units, and groups of fiber units within outside plant and premises optical fiber cables. This standard allows for fiber units to be identified by means of a printed legend. This method can be used for identification of fiber ribbons and fiber subunits. The legend will contain a corresponding printed numerical position number and/or color for use in identification.

Losses

Typical modern Multimode Graded-Index fibers have 3 dB/km of attenuation loss at 850 nm and 1dB/km at 1300 nm. 9/125 Singlemode loses 0.4/0.25 dB/km at 1310/1550 nm. POF (plastic optical fiber) loses much more: 1 dB/m at 650 nm. Plastic Optical Fiber is large core (about 1mm) fiber suitable only for short, low speed networks such as within cars.

Each connection made adds about 0.6 dB of average loss, and each joint (splice) adds about 0.1 dB. Depending on the transmitter power and the sensitivity of the receiver, if the total loss is too large the link will not function reliably.

Invisible IR light is used in commercial glass fiber communications because it has lower attenuation in such materials than visible light. However, the glass fibers will transmit visible light somewhat, which is convenient for simple testing of the fibers without requiring expensive equipment. Splices can be inspected visually, and adjusted for minimal light leakage at the joint, which maximizes light transmission between the ends of the fibers being joined.

The charts at Understanding Wavelengths In Fiber Optics and Optical power loss (attenuation) in fiber illustrate the relationship of visible light to the IR frequencies used, and show the absorption water bands between 850, 1300 and 1550 nm.

Safety

Because the IR light used in communications can not be seen, there is potential hazard to technicians; in some cases the power levels are high enough to damage eyes, particularly when lenses or microscopes are used to inspect fibers which are inadvertently emitting invisible IRs