Photonics—Light in the Twenty-First Century

13

When first invented, the laser was described as an invention in search of an application. Few predicted that lasers would ultimately have applications in medicine, agriculture, commerce, optical communication, astronomy, manufacturing, and security. With light now having uses in almost every area of human endeavor, it's no wonder that it is said that we have entered the *photonic* age, a time in which photons are used in a manner similar to the way electrons are employed in electronics.

In this chapter, you will learn the science behind the practical applications of optics that have become a part of our daily lives. They include optical data storage, fiber-optic data transmission, optical scanning, and solar energy collection. You will also get a glimpse into the future when such things as optical computing, holographic data storage, and holographic television may become commonplace.

13.1 Optical Data Storage

Optical data storage systems have, in most instances, now been supplanted by hard-disk drives (HDDs), solid-state drives (SSDs), and cloud storage. That said, using light as a means of recording and retrieving data was an innovation that was the first to offer high-capacity data storage and the promise of archival permanence, the ability of a medium to remain stable over a long period of time. The technology involved in optical storage devices is quite sophisticated and, at the time of its introduction, groundbreaking.

Compact Discs

For years the most widely used optical storage system was the *compact disc* (CD), which made its debut in 1982. The CD provided a means for storing music in a digital format, thus achieving a level of high fidelity reproduction never attainable in an analog format. Shortly after the introduction of the CD, the CD-ROM became

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a valuable data storage option for microcomputers, as did optical laser discs for storing movies for use in home theaters.

Optical storage systems use a focused laser beam to read and write data. The smallest achievable spot size is determined largely by the wavelength of the laser light. For the widely used red/infrared diode laser with a 790-nm wavelength, the minimum spot size is about 1 μm, which allows a maximum storage density of about 10^8 bits/cm^2. Green and blue diode lasers, with shorter wavelengths, allow even greater storage densities.

Only 12 cm in diameter, a compact disc can store more than six billion bits of binary data, which is equivalent to 782 megabytes, or more than the capacity of 390 two-megabyte floppy disks. Over 275,000 pages of text, each holding 2000 characters, can be stored on a compact disc. Used for digital audio, a compact disc stores 74 min of digitally encoded music that can be reproduced with very high fidelity through the full audible range of 20–20,000 Hz. The dynamic range and the signal-to-noise ratios can both exceed 90 dB, and the sound is virtually unaffected by dust, scratches, and fingerprints on the disc.

Recorded information is contained in pits impressed into the plastic surface, which is then coated with a thin layer of aluminum to reflect the laser beam, as shown in Fig. 13.1. The pits are about 0.5 μm wide and 0.11 μm deep, arranged in a spiral track similar to the spiral groove on a phonograph record but much narrower. The track spacing on a compact disc is about 1.6 μm, compared to about 0.1 mm (100 μm) for the groove of a long-play phonograph record.

The track on a compact disc, which spirals from the inside out, is about three miles in length. The track of pits is recorded and read at a constant 1.25 m/s, so the rotation rate of the disc must change from about 8 to 3.5 revolutions per second as the spiral diameter changes. Each pit edge represents a binary 1, whereas flat areas within or between the pits are read as binary 0 s.

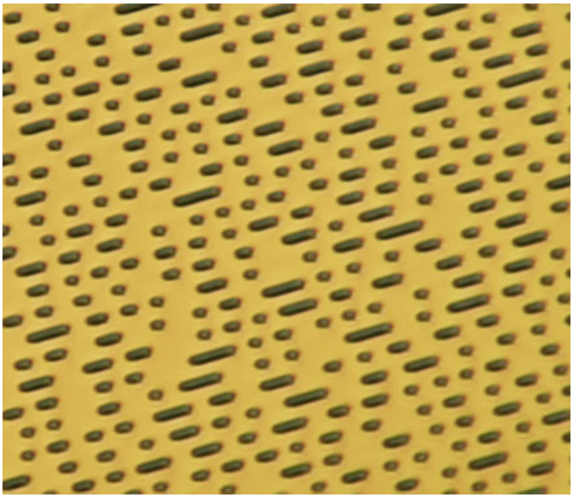

Fig. 13.1 Electron micrograph of pits on a compact disc (Gerd Guenther/Science Source)

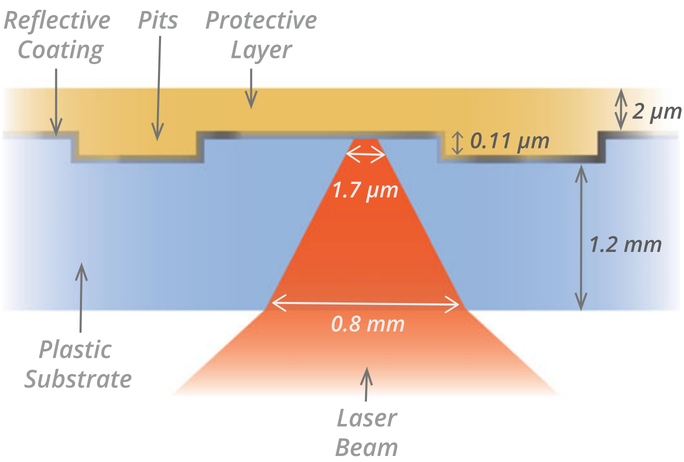

Fig. 13.2 Cross section of a compact disc (not to scale)

The laser beam, applied from below the compact disc as it lies on a turntable, passes through a transparent layer 1.2 mm thick and focuses on the aluminum coating, as shown in Fig. 13.2. The spot size of the laser on the transparent layer is 0.8 mm, but at the signal surface where the pits are recorded, its diameter is only 1.7 μm. Thus, any dust particles or scratches smaller than 0.5 mm will not cause a readout error because the laser/spot is out of focus. Larger blemishes are handled by error-correcting codes.

Pits are made approximately a quarter-wavelength ($\lambda/4$) thick so that the edge can be detected by means of optical interference (see Sect. 5.3). When the laser beam crosses the edge, the light reflected from the pit will be opposite in phase to that reflected from the adjacent area (because it has traveled $\lambda/2$ farther), and destructive interference results. The refractive index of the plastic substrate is about 1.5, so $\lambda/4$ is 790 nm/(4)(1.5) or 0.13 μm, just a little larger than the pit thickness.

The optical pickup used to read a compact disc is shown in Fig. 13.3. A semiconductor laser emits a beam of red/infrared light (790-nm wavelength) that is eventually focused to a tiny spot 1.7 μm in diameter. The reflected beam is directed to a photodiode that generates an electrical signal to be amplified and decoded. Included in the sophisticated optical pickup are a diffraction grating (see Sect. 5.9), a polarization beam splitter, a quarter-wavelength plate (see Sect. 6.5), and several lenses. A semiconductor diode laser (see Sect. 7.9) employs an aluminum–gallium–arsenide (AlGaAs) junction, similar to that in a light-emitting diode.

Recordable Compact Discs

The familiar *compact disc* digital audio (CD) and *compact disc–read-only memory* (CD-ROM) systems used in personal computers are both read-only devices. The pits are built in at the time of manufacture and cannot be altered by the user. Various techniques have been used to provide erasable compact discs. One

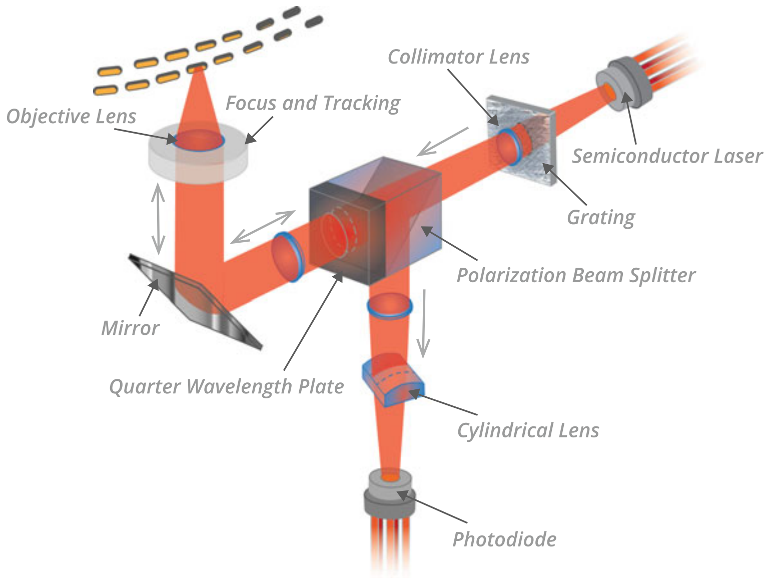

Fig. 13.3 Optical pickup in a compact disc player. Coherent light from a semiconductor diode laser is focused on one recorded track on the disc. The reflected light is directed to a photodiode

technique is to have the laser actually burn a tiny hole in the coating. This type of writing is suitable for data storage discs of the WORM ("write once, read many") type. More convenient, however, are *magneto-optical* (MO) discs.

Introduced in 1992, Sony's *MiniDisc* (MD) system uses either pre-recorded discs or recordable MO discs. MiniDiscs are only 64 mm (2½ in.) in diameter, but they can record the same amount of music (74 min) as a full-size compact disc by making use of adaptive coding to compress the audio signal by about a 4 to 1 ratio. Recording on MO discs is done thermomagnetically, and playback makes use of the *magneto-optical Kerr effect*. In thermomagnetic recording, a small spot is heated by the laser, while a magnetic field is applied by a recording head on the opposite side of the disc. As the spot cools, its magnetization remains in the direction of the field from the recording head.

Playback makes use of the MO Kerr effect, the rotation of the plane of polarization of light when it is reflected from the magnetized surface. The plane of polarization is rotated one direction if the MO layer is magnetized upward, and in the other direction if it is magnetized downward. Although the rotation is less than 1 degree, the sensitive optical pickup can distinguish between these two states, which represent recorded 1 and 0 s. The same optical playback system is used to read pre-recorded discs (as described in the previous section) and recordable MO discs.

Despite popularity among a relatively small following of primarily musicians and audio enthusiasts, the MiniDisc never achieved wide acceptance by the general public and was taken off the market in 2013. Its demise was hastened by the availability of solid-state digital MP3 audio players that employ a variety of compression schemes and mass storage offered by flash memory.

Digital Versatile Discs

The remarkable precision of the compact disc and its achievements as a data storage system are impressive indeed. But optical technology gave us an even more remarkable storage system. *Digital versatile discs* (DVDs), also 12 cm in diameter and designed to hold a full-length movie in digital video, can store up to 17 GB (gigabytes) of data, more than 20 times the capacity of a compact disc. These systems use red diode lasers (635–650 nm wavelength), allowing higher storage densities than CDs.

A DVD resembles a CD; like a CD, data is recorded on the disc in a spiral trail of tiny pits that are read by a laser beam. The larger capacity is achieved by making the pits smaller and the spiral tighter, and by recording data in as many as four layers, two on each side of the disc. Reading these smaller pits requires lasers with shorter wavelengths as well as more precise tracking and focusing mechanisms, and that is why DVDs use red diode lasers.

DVDs come in four different types with different storage capacities. The single-sided DVD with a single layer, having a storage capacity of 4.7 GB (seven times that of a CD), will hold a 135-min movie. Adding a second layer increases the storage capacity to 8.5 GB, and recording on both surfaces of the disc gives 17 GB. Reading a two-layer disc requires a focusing mechanism so accurate that it can focus on either of the two recorded layers.

DVD for Movies and Video

While any kind of digital data can be recorded on a DVD, its development was largely driven by the need for a high-quality medium for distributing movies using digital technology. In fact, DVD originally was an abbreviation for *digital video disc*, although in light of other applications, this has been changed to *digital versatile disc*.

Television pictures were originally transmitted only in black and white. When color was added in 1954, the National Television Standards Committee (NTSC) devised a standard designed to maintain compatibility with millions of black and white televisions already sold. The NTSC standard essentially grafted color information (chroma) onto the black and white signal (luma) by encoding it on a subcarrier. This was difficult to do within the 6-MHz bandwidth (i.e., the frequency spread) used for television broadcasting. NTSC limits resolution to about 300 lines and restricts color bandwidth. Other countries adopted different standards, and this made color television incompatible around the world (Most of Europe, e.g., uses the PAL standard or a variation called PAL-SECAM.).

Digital video keeps luma and chroma information separate at every stage of transmission from camera to monitor, which results in a much improved image. Viewers are able to see the full resolution that the camera captures with colors that have the same dynamic range as the brightness information. Furthermore, DVD adds digital audio using 5.1 surround sound (six-channel). It is possible for the viewer to seek any location on the disc to begin playing. It can pause, play in slow motion, or fast forward. These random-access features allow many interesting possibilities, such as selecting from multiple endings for a movie or selecting from multiple cameras to view a sporting event. DVD can support up to eight different languages for a single movie. Because of its compatibility with CD digital audio, home entertainment centers often have a single player for both audio and video.

DVD play/record features remain standard on most of today's desktop computers but, in many cases, are no longer included with laptop devices. As was mentioned previously, solid-state storage has, for the most part, replaced optical media in portable computers.

Blu-ray Discs

Blu-ray is the name of an optical disc format capable of storing considerably larger amounts of data than is possible with either the CD or DVD. Blu-ray technology, which derives its name from the blue-violet laser used to record and read data, was developed jointly by a consortium of companies that included Sony, Panasonic, Phillips, and Samsung. The first Blu-ray recorder became available in 2003, but it was not until 2006 that Blu-ray players entered the commercial marketplace. Uses for the format include storing high definition and ultra-high definition video, home and commercial computer data, video game programs, and HD camcorder recordings.

The advantages of Blu-ray are many. Perhaps first and foremost is Blu-ray storage capacity. Blu-ray discs can store five to ten times more than a DVD. Key to the increased storage capacity of Blu-ray discs is the ability of blue-violet laser light to produce smaller and more densely packed pits on the surface of a disc than is possible with a red laser used with the standard DVD. The blue-violet laser light has a wavelength of 405 nm compared to the 650-nm wavelength of red light. It is this difference in wavelength that allows for a more tightly focused beam and, with it, a higher pit density. The basic single-sided Blu-ray disc can store up to 13 hours of standard video, compared to the 133 minutes possible with single-sided DVD. A comparison of optical disc characteristics is shown in Fig. 13.4.

Dual-Layer DVDs

As the name suggests, dual-layer DVDs have digital information on two recordable layers on one side of a DVD. This increases storage capacity from the standard DVDs 4.7 GB to 8.5 GB. The second, or top, layer on a dual-layer DVD is transparent to permit laser light to reach the lower layer.

There are two formats of DVD dual-layer disc, the DVD-R DL, developed by Pioneer, and the DVD+R DL, created by Mitsubishi and Philips. The latter format, which offers better error correction and hence improved writing to disc, is considered by many to be the better of the two. At first, the two formats were incompatible and each required a dedicated drive. However, hybrid drives and "super multidrives" have been developed that are capable of reading both types of discs.

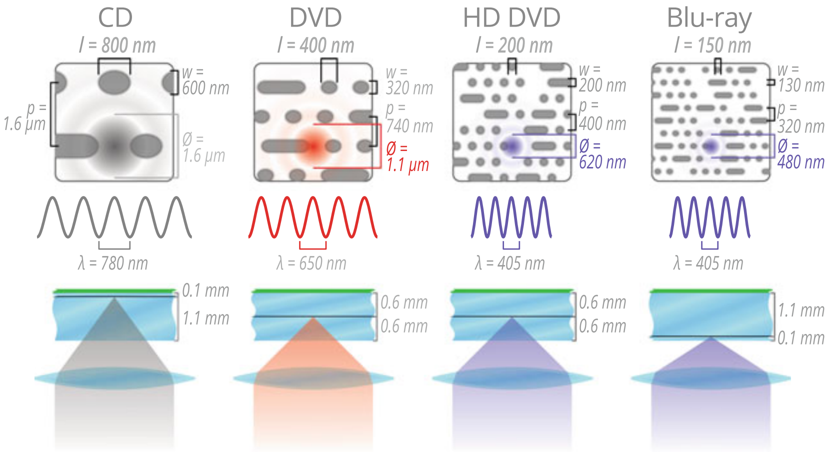

Fig. 13.4 Comparison of various characteristics of a compact disc, and single-layer digital versatile disc, high-definition/density digital versatile disc, and Blu-ray disc. Dimensions indicated are track pitch (p), pit width (w) and minimum length (l), and laser spot size (Ø) and wavelength (λ) (Cmglee [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0) or GFDL (http://www.gnu.org/copyleft/fdl.html)], from Wikimedia Commons)

Movies over two hours long must be recorded on dual-layer discs, as do most computer games. Consequently, all but first-generation computer drives and video players are capable of reading dual-layer DVDs. Dual-layer DVD burners are now becoming standard feature in most PCs.

13.2 Optical Communication

An “information superhighway” requires the ability to transmit data over large distances at very high bit rates. The ideal roadbed for such a superhighway is fiber-optic cable, over which large amounts of data can be carried by light waves. The greatest advantage of light waves is their enormous bandwidth, made possible by their very high frequency (5×10^{14} Hz or more), more than 10,000 times greater than microwaves. A single optical fiber can carry thousands of telephone messages along with dozens of TV programs at the same time.

Optical fibers guide light signals by means of total internal reflection, a phenomenon discussed in Chap. 4. An example of total internal reflection is shown in Fig. 13.5, where green laser light is totally internally reflected inside a Lucite rod. When used for communication purposes, fibers are made of fused silica (SiO_2) glass with dopants such as germania (GeO_2) added to produce small changes in the refractive index. A typical fiber shown in Fig. 13.6 has an 8-µm diameter core with

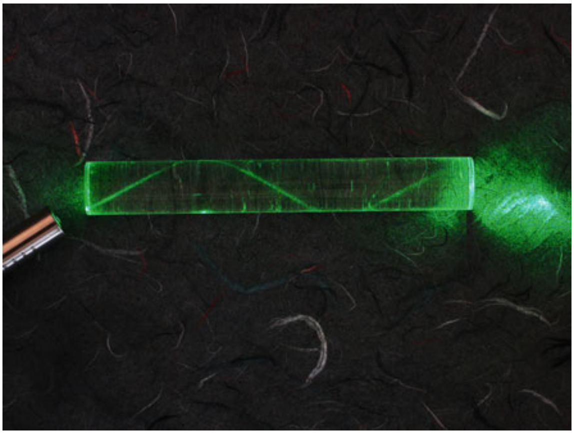

Fig. 13.5 The propagation of light through a Lucite rod models light transmission through an optical fiber (Timwether [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], from Wikimedia Commons)

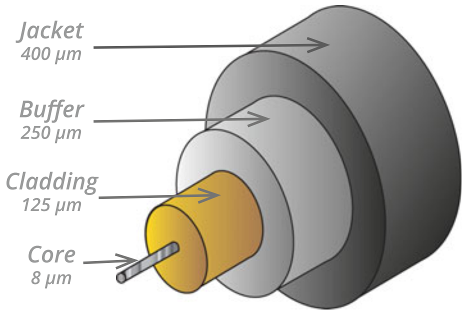

Fig. 13.6 Cross section of an optical fiber. The core material is doped to a higher refractive index than the cladding

a higher refractive index surrounded by a cladding 125 μm in diameter. Modern technology can produce fibers that attenuate the signals less than 0.2 dB (i.e., they lose less than 5% of their power) per kilometer.

Lasers generate radiation of the desired wavelength (typically 1.3 or 1.55 μm) for transmission through the optical fibers. To carry information, the light must be modulated, and this is done by direct modulation or by external modulation. In direct modulation, the drive current to the laser is varied in order to change the intensity of the light that is generated. External modulation is accomplished by passing the laser light through an electro-optic crystal such as lithium niobate ($LiNbO_3$) whose transmission can be varied by means of an electrical signal.

Even though the attenuation of fiber-optic cables is extremely small, there is some attenuation, and optical repeater amplifiers must be used to compensate for this attenuation in long-distance transmission. One type of amplifier makes use of fibers doped with active ions, which are optically pumped so that they add energy to the signals.

Optical receivers generally use either p-i-n photodiodes or avalanche photodiodes to detect the light signal. The detector produces a current that is proportional to the modulation and thus reconstructs the data signal. This signal can then be amplified electronically.

Charles Kuen Kao is attributed with making optical communications possible. Working for International Telephone and Telegraph in the 1960s, he discovered that if impurities are removed from glass, light would pass through it extremely efficiently. Prior to Kao's work, optical fibers were not suitable for communication purposes and were used primarily for decoration and some medical applications.

Kao received the Nobel Prize in 2009, at which time the fiber-optic network was heralded by the Royal Swedish Academy as "the circulatory system that nourishes our communication society." They further stated that "[i]f we were to unravel all the glass fibers that wind around the globe, we would get a single thread over one billion kilometers long… and is increasing by thousands of kilometers every hour." The rate of growth has increased exponentially since then. One result of this expansion is the dramatic increase in the availability of internet service. It is estimated that as of 2017, 3.58 billion people had access to the web as a result of this growth.

In addition to transmission of data and telephone messages, fiber-optic cables are widely used for applications such as file sharing, online gaming, and video-on-demand. High-definition television (HDTV) continues to be the stimulus for the improvement and expansion of fiber-optic communications networks.

A longtime goal of those in the communications industry, "Fiber to The Home," often referred to as FTTH, is becoming a reality in many communities. With FTTH, digital information is carried optically from the source directly to individual residences without intervening electrical conduits. The most important benefits of FTTH are that it provides for far faster connection speeds and carrying capacity than twisted pair conductors, DSL, or coaxial cable.

The implementation of FTTH continues to grow. These broadband connections already exist for more than one million consumers in the United States, more than six million in Japan, and ten million worldwide.

13.3 Optical Scanners

Optical scanners are used to interrogate a field of information for input to a computer and also for image recording, as in a laser printer. In most scanners, a laser beam is swept across the field of view by means of some type of device; in other scanners, an image is formed on an array of photosensitive elements that are then sequentially interrogated.

In a rotating mirror scanner, the laser beam is reflected from a continuously rotating mirror, often with several faces, so that the beam sweeps across the field of view. In a scanner with an electromagnetic or galvanometer-type drive, on the other hand, the beam can be swept at varying speeds, such as in a sawtooth waveform with very short retrace time, for example. Acousto-optic scanners use an acousto-optic cell in which the light beam is diffracted by a train of acoustic waves.

Barcode readers are found at supermarket checkout counters. To scan the barcode on an item, the clerk or customer moves it through a laser beam and a photodiode senses the reflected light and sends a series of electrical pulses to a microcomputer. The 6–13 digits in the universal product code (UPC) convey information about the brand name, type of article, and so on, which is combined with information about price that the merchant has entered into the computer.

Charge-coupled device (CCD) imagers are widely used in small video cameras as well as in a variety of scientific instruments. In addition to being very compact, CCDs offer low cost and high efficiency, broad spectral bandwidth, low noise, and large dynamic range. As shown in Fig. 13.7, flatbed scanners used to scan documents into computers generally employ one or more CCDs and an extended light source, such as a fluorescent lamp or a row of LEDs, that scans a thin strip of the document as it moves. Light reflected from the document is reflected by a movable mirror to the CCD. The optical resolution of a high-quality flatbed scanner is typically 600 × 1200 DPI (dots per inch) when scanning an ordinary 8½- × -11-inch page.

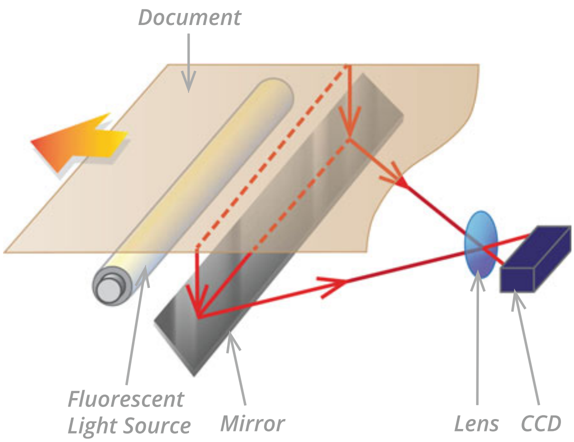

Fig. 13.7 Components found in a flatbed scanner

13.4 Optical Trapping and Tweezing

One half of the 2018 Nobel Prize in Physics was awarded to Arthur Ashkin for his invention of what is known as "optical tweezers." As the name suggests, optical tweezers use light to manipulate and trap objects such as microscopic glass and plastic beads, viruses, bacteria, living cells, and even strands of DNA.

The idea that light can exert force on matter is not new. In 1619, Johannes Kepler suggested that a comet's tail is created by solar radiation pressure pushing on particles expelled from a comet's core. Over two centuries later, the existence of light pressure was found to be a consequence of James Clerk Maxwell's theory of electromagnetism.

In 1901, Russian physicist Pytor Lebedev experimentally confirmed the existence of light pressure, but it was Ashkin who, in the 1980s, first used light to move and contain small physical objects. Ashkin found that micrometer-sized transparent

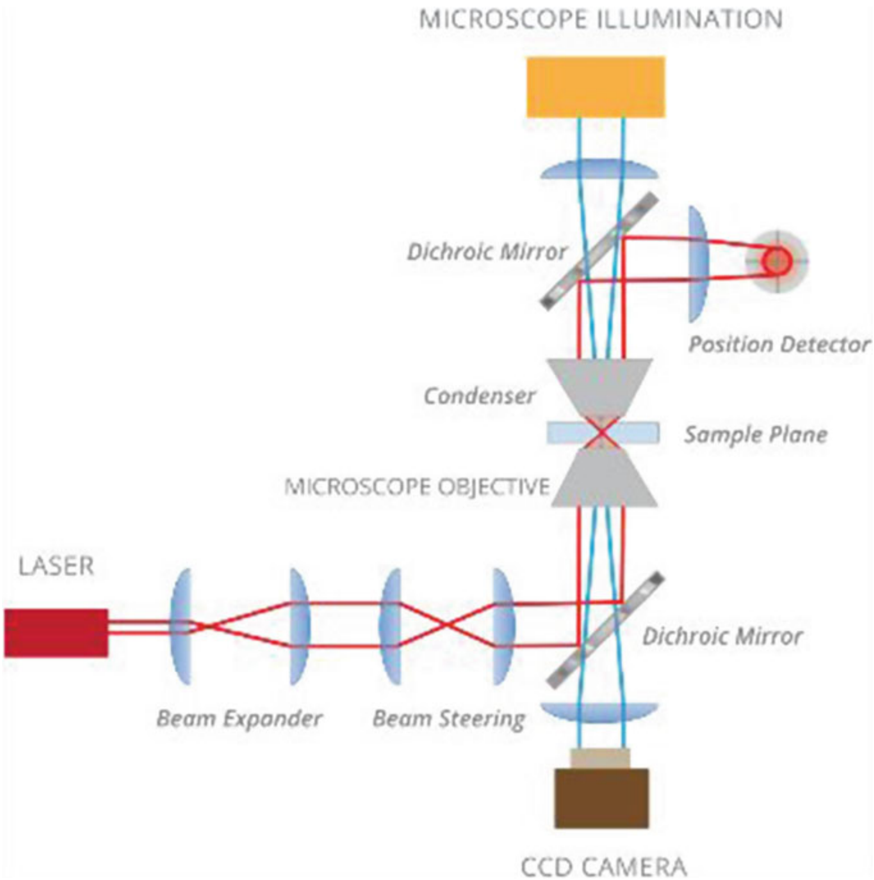

Fig. 13.8 Typical components in an optical tweezers system (public domain via Wikimedia Commons)

particles move to the center of a highly focused beam of laser light. Acted on by the light's electric field, particles can be either attracted or repelled depending on the difference in the indices of refraction between the particle and surrounding medium. The laser light also tends to apply a force on particles in the beam along the direction of beam propagation. By utilizing this force, it is possible to move and trap small particles.

Figure 13.8 shows the basic components found in an optical tweezers system. They include a laser, a beam expander, some optics used to direct the beam, a microscope objective and condenser to create the trap, a photodiode that serves as a position detector, and a microscope illumination source coupled to a CCD camera.

13.5 Photonics-Enabled Fields

Astronomy

Electromagnetic radiation is the source of virtually all that is known about the nature and history of the cosmos. Astronomers rely on optical and radio telescopes to make observations and collect data. In recent years, enormous strides have been made in observational technologies. Most notable among them have been space telescopes and adaptive optics. Both have greatly increased the performance of optical systems and have provided the most significant advance in astronomy since Galileo's telescope 400 years ago.

The largest and best known space observatory is the Hubble Space Telescope. Heralded as one of the greatest achievements of the twentieth-century astronomy, the Hubble orbits Earth at an altitude of 350 miles (569 km) and completes its orbital journey in 97 min. A 2.4-m mirror working in concert with an onboard camera capable of sensing infrared, visible, and ultraviolet radiation has captured light from more than 13 billion light-years from Earth. The combination of superior optics, sensitive detectors, and lack of atmospheric distortion gives the Hubble a view of the universe that exceeds that of most ground-based telescopes.

Electromagnetic radiation normally absorbed by Earth's atmosphere, but observable from space observatories, provides a more complete picture of the universe. In Fig. 13.9, three superimposed images from the Hubble and Spitzer Space Telescopes form a spectacular, multiwavelength view of the starburst galaxy M82. The photo combines visible light, seen as yellow and green, with images produced by infrared and X-ray radiation, which are shown as red and blue, respectively.

Many Earth-bound telescopes are now able to produce Hubble-quality images through the use of adaptive optics systems. Adaptive optics, a technology designed to improve the performance of astronomical optical systems, was first proposed in

Fig. 13.9 Superimposed images from the Hubble and Spitzer space observatories provide a multiwavelength view of starburst galaxy M82 (Smithsonian Institution from United States [No restrictions])

1953; however, it did not come into common usage until advances in computer technology during the 1990s made the technique possible. The use of adaptive optics avoids the enormous expense of launching a telescope into space, a task that can cost 10–20 times more than building the same size telescope on the ground.

Adaptive optics systems compensate for the blurring effect of Earth's atmosphere through the use of a wavefront sensor, which detects incoming light, a deformable mirror, and a computer. The wavefront sensor rapidly measures atmosphere-introduced distortion. From this information the computer calculates the mirror shape needed to correct for the distortion. Within milliseconds, the deformable mirror is reshaped to correct incoming light so that the telescope's images appear sharp (Fig. 13.10).

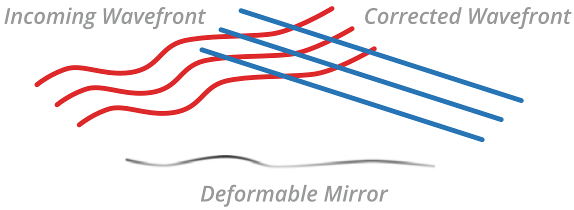

Fig. 13.10 A deformable mirror in an adaptive optics system is used to correct a distorted wavefronts

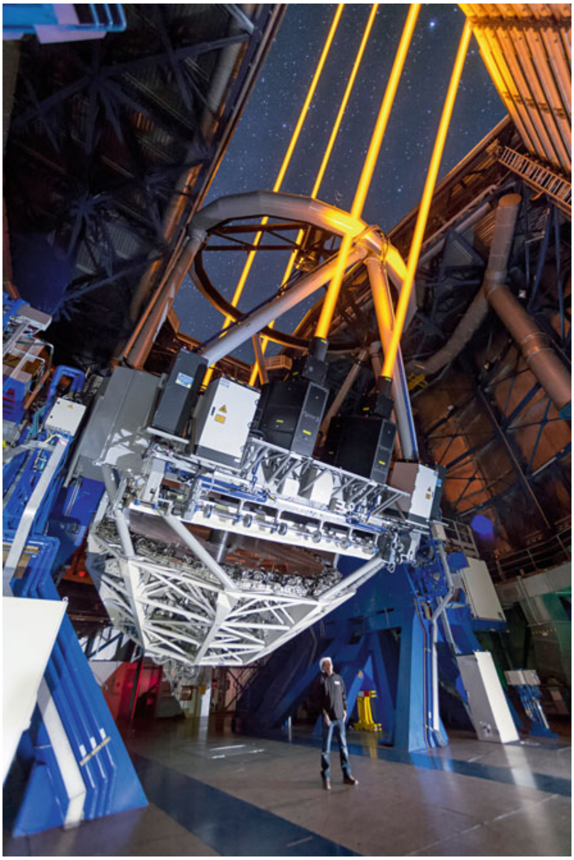

Fig. 13.11 Four laser beams are used in an adaptive optics system at the European Southern Observatory's Very Large Telescope in Paranal, Chile (ESO/F. Kamphues [CC BY 4.0 (https://creativecommons.org/licenses/by/4.0)], via Wikimedia Commons)

Because the celestial object being observed is often too faint to be used for measuring the shape of the wavefronts, a nearby, brighter "guide star" is used since light from both objects has passed through approximately the same atmospheric turbulence. When there is not a suitably bright star nearby, astronomers use lasers to create artificial stars. Sodium atoms high in the atmosphere, made to glow by the action of the lasers, form tiny patches of light that simulate actual stars. The use of several lasers, such as shown in Fig. 13.11, allows the atmosphere's properties to be better characterized, resulting in enhanced image quality.

Capturing the first-ever visual evidence of a black hole in 2019 by an international team of researchers, members of the Event Horizon Telescope project, stands out as one of the most important and impressive achievements of modern day astronomy. In order to obtain the resolution needed to observe a black hole 55 million light-years from Earth, a world-wide system of eight synchronized radio telescopes was employed. The array of telescopes, which were located at various locations around the planet, was described as "a virtual telescope dish as large as the Earth itself."

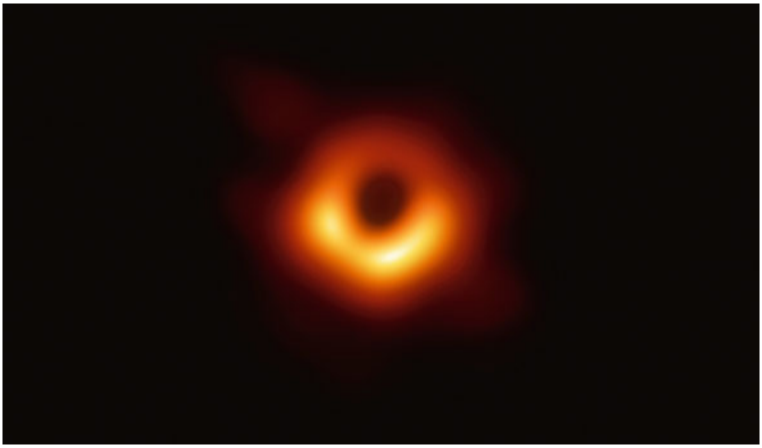

Fig. 13.12 Glowing material surrounding the black hole in galaxy M87 (Event Horizon Telescope Collaboration [CC BY 4.0 (https://creativecommons.org/licenses/by/4.0)])

To be observable from Earth, a super massive black hole was needed, such as one at the center of the Messier 87 (M87) galaxy. The image in Fig. 13.12 shows a ring of super-heated material swirling around the M87 black hole. Since no light can escape from a black hole, what is seen is not the black hole itself, but its shadow and the luminous matter that surrounds it.

Industry

Lasers have revolutionized manufacturing and are now used for anything from fabric cutting to automobile assembly. With industrial applications that include laser cutting, drilling, and welding, as well as optical imaging and analysis of product quality, the laser has become a versatile tool in modern manufacturing.

Lasers have several advantages in materials processing. Lasers obviate the need for contact tools in which the tool bit must be sharpened and often replaced. Brittle or very pliable materials that are very difficult or impossible to machine with tools can be processed using lasers. In addition, fiber optics allow access to previously inaccessible locations. Finally, and very importantly, laser processing is easily controlled by computer.

Light plays an important role in the burgeoning production process known as 3D printing. 3D printers employ an additive process, making things by building them up, a layer at a time, rather than by removing material through cutting, drilling, or machining. During production, ultraviolet light can be used to harden each layer of material as it is deposited. Laser sintering, another example of an additive 3D manufacturing process, uses high-powered lasers to harden powdered plastic, ceramic, or metal into a desired shape. Laser sintering has been increasingly utilized in industrial situations in which small quantities of high-quality parts, such as aerospace components, are needed.

Medicine

Photonics and medicine have partnered for thousands of years. As companions, they have contributed to the treatment as well as the diagnosis of a wide range of medical conditions.

Ancient Hindu writings suggest that sunlight was used for therapeutic purposes. The Greeks also realized that exposure to light could be beneficial to health, unaware of the skin's light-stimulated production of vitamin D. Much later, in the nineteenth century, English scientists found that bacteria died when exposed to sunlight. In 1893, a Danish physician demonstrated the light had beneficial effects in the treatment of a variety of skin conditions. Medical uses of light, both visible and invisible, increased as the century was winding down. In 1895 German physicist Wilhelm Roentgen serendipitously discovered X-rays. The high-energy photons were put to work almost immediately to reveal structures inside the body.

Over the course of the twentieth century, a wide range of noninvasive, photonic-based diagnostic tools were to follow X-rays. These include the use of radio waves in MRI (magnetic resonance imaging) and gamma rays in PET (positron emission tomography) scans.

With the advent of the laser, visible light would take center stage as a versatile tool for both the diagnosis and treatment of physical ailments. The applications of laser light range from dentistry to cancer therapy. Perhaps the most mature applications of lasers are in the field of ophthalmology. Lasers of various wavelengths are used in the treatment of glaucoma, diabetic retinopathy, macular degeneration, retinal breaks, and other ocular disorders. In addition, laser procedures such as LASIK eye surgery can correct vision problems including myopia or nearsightedness, farsightedness, and astigmatism by reshaping the cornea.

As the field of ophthalmic laser treatment has matured, the array of diagnostic tools has grown to include automated refractors, which can determine the correct eyeglass prescription, and fundus cameras, one of which is shown in Fig. 13.13, which are used to examine the eye's interior. Instruments such as the scanning laser ophthalmoscope and optical coherence tomography imagers are in general use to take three-dimensional pictures of the retina.

In dentistry, lasers are used to remove overgrown tissue, shape gums, or whiten teeth. Lasers are also used in filling procedures to remove decay and to kill bacteria. Hard tissue lasers, lasers that produce light absorbable by bone, are often used in the prepping or shaping of teeth for composite bonding, the removal of small amounts of tooth structure, and the repair of certain worn-down dental fillings.

Lasers are also now routinely employed to perform cosmetic surgery. Laser light has been found to be particularly effective in the removal of tattoos, scars, wrinkles, birthmarks, and unwanted hair. When done with a laser, general surgery, such as tumor removal, breast surgery, plastic surgery, and most other surgical procedures have improved outcomes and shortened recovery times.

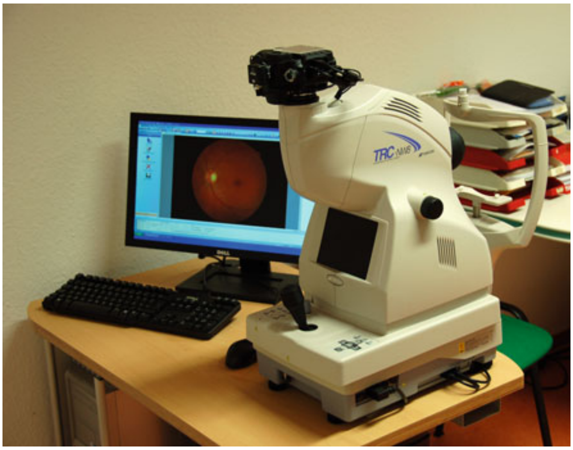

Fig. 13.13 Image of the interior of a human eye produced by a fundus camera (Ralf Roletschek (talk)—Fahrradtechnik auf fahrradmonteur.de [FAL or GFDL 1.2 (http://www.gnu.org/licenses/old-licenses/fdl-1.2.html)], from Wikimedia Commons)

Solar Energy

As we saw in Chap. 7, electrons are liberated when light shines on the surface of certain materials, such as silicon. This effect is the basis for the operation of photovoltaic cells, often referred to as solar cells, which produce electricity when exposed to light. Collections of such cells form the basis of photovoltaic solar panels, collection devices that serve as sources of sustainable power.

Currently, the vast majority of the world's solar cells are made from thin wafers of crystalline silicon; however, second-generation cells are made from materials such as cadmium telluride and copper indium gallium diselenide. While not as efficient as silicon-based solar cells, the newer solar cells are thin, light, flexible, and therefore well suited for attachment to a wide variety of substrates such as metal, glass, and plastic. The latest solar cell technology combines the best features of silicon and second-generation materials, resulting in higher efficiencies and lower cost.

According to the European Photovoltaic Industry Association, "The total solar energy that reaches the Earth's surface could meet existing global energy needs 10,000 times over." That said, solar energy remains to become widely accepted primarily because it is more expensive than energy produced by burning of fossil fuels. States such as California, North Carolina, and Arizona and countries like Germany and China that enjoy government support are outliers. In these areas the use of solar energy is showing strong signs of growth.

The Military

Photonics is of ever increasing importance in national defense. One key role is sensing. Multispectral imaging, capable of obtaining significantly more information about an area under surveillance than regular sensors, can be used for tasks such as locating explosives, revealing enemy movements, and determining the depth of hidden bunkers. Functioning as chemical sensors, specialized spectrometers can be used to detect explosives in liquids and solids.

Holographic imagers produce 3D visualizations of urban and mountainous areas. A major advantage of these photonic devices is that they are lightweight and small, making them easily portable for soldiers in the field. As mentioned in Chap. 12, virtual reality (VR) and augmented reality (AR) are important tools in pilot training and support of combat operations. VR and AR are also employed in conjunction with teleoperation, the ability to operate equipment and weapon systems, such as aerial drones, from a distance.

There are a variety of military laser applications. Lasers function as target designators, laser light sources, which are used to indicate a target, or laser sights. They are also used to "blind" sensors on heat-seeking anti-aircraft missiles. In relatively few cases, lasers are used as weapons. Some high-power lasers are under development for potential use on the battlefield or for destroying missiles, projectiles, and mines.

13.6 The Future of Photonics

Optical Computing

Optical computing, or photonic computing, is an area of technology that uses light for processing data. Although electronic digital computers have achieved very high speeds, they are ultimately limited by the time it takes electrical signals to travel from one component to another. Furthermore, electronic currents are affected by electromagnetic fields, so noise and cross-talk problems can become rather serious in high-speed operations.

Substituting light waves for electrical currents avoids such problems. Signals travel from one component to another at the maximum possible speed, that is the speed of light. Light waves can cross each other without interfering (see discussion of linear superposition in Sect. 2.4) , and they have extremely large bandwidths due to their high frequency (see Sect. 13.2). In addition, conventional computers operate in a serial manner with each operation being performed one after another. Optical computers execute instructions in parallel, allowing multiple operations to be performed simultaneously, which allows for more efficient and faster data processing.

While interest in optical computing dates from the 1980s, only limited prototypes have been constructed thus far. Among the challenges to optical computing, the creation of the photonic equivalent of the electronic transistor continues to be one of the most formidable.

It remains to be seen when fully functioning optical computers will become a reality. Researchers are motivated to achieve this goal, for they know when transistors can no longer be made smaller, an alternative to electronic computing will become necessary if processing speeds are to continue to increase.

Holographic Data Storage

The idea of storing data holographically has been around for decades. While it will be some time before holographic versatile disc (HVD) data storage systems will become commonplace, progress continues to be made. The goal is to develop HVD systems that can store 1000 times more data than a dual-layer DVD, roughly 8.5 terabytes. This level of storage is made possible by depositing information throughout a volume rather than just on the surface, as is the case with other optical storage methods.

The key components of holographic data systems currently under development include a green laser, a red laser, a beam splitter, a liquid crystal display called *spatial light modulator* (SLM), a photosensitive storage medium, such as a lithium-niobate crystal, and a photosensitive semiconductor detector, such as a CMOS or CCD sensor. The argon laser is used for writing and reading data, the red laser for tracking.

Information to be stored in the HVD's photosensitive crystal is first translated into binary code. The code is then displayed as what is known as a "page" of tiny translucent windows on the SLM. These windows can exist in two states, either open or closed, corresponding to a one or a zero. The condition and configuration of the windows at any given time reflect the data being stored on a page.

Following the creation of the data page, the green laser is pulsed and split into two beams. One beam, the signal beam, is directed toward the SLM; the other beam, the reference beam, is sent directly to the photosensitive crystal. After being processed by the SLM, the signal beam meets the reference beam at the crystal. The resulting interference pattern, which contains data carried by the signal beam, is stored in the form of a hologram. Each page of data is stored in a different location within the crystal.

Stored data is retrieved by directing the green laser into the hologram. This produces a diffraction pattern that is an optical replica of the original recorded data. The detector then converts the optical data into the original digital files.

Holographic Television

The dream of having Princess Leia-like images appear on your TV screen may become a reality sooner rather than later. Until now it hasn't been possible to display a succession of holographic images fast enough to realistically convey movement. However, recent developments in laser and screen technology make the projection of moving holographic images without flicker clearly within reach.

One scheme that has been used to capture and display holographic images with a relatively fast refresh rate involves using 16 conventional television cameras focused on a single subject. The camera images are sent to a computer, which combines them to form a holographic image. The computer then relays this image in the form of digital data to a nanosecond pulsed laser. A three-dimensional holographic image is formed when the laser light containing holographic pixels, or "hogels," is projected onto a photoreactive polymer screen. This approach has reduced the refresh rate from minutes to seconds.

While great strides have been made in projecting images at an acceptable rate, much work is yet to be done. The ability to reduce the refresh rate to a fraction of a second will be needed before holographic television will become a consumer item.

13.7 Summary

Lasers have applications in medicine, agriculture, alternate energy, commerce, optical communication, manufacturing, and security.

Optical storage systems, using focused laser beams to read and write data, are capable of very high storage densities. Optical discs are removable and easily transportable from one drive to another. Only 12 cm in diameter, a compact disc can store more than 780 megabytes (six billion bits) of binary data, which is equivalent to over 275,000 pages of text. Recordable compact discs and MiniDiscs generally make use of the Kerr magneto-optic effect.

Digital versatile discs (DVDs), which are similar to compact discs but have considerably greater storage capacity, are particularly attractive for digital recording of movies and video. Blu-ray discs are capable of storing substantially larger amounts of data than is possible with either the CD or DVD.

Optical fibers guide light by means of total internal reflection A single optical fiber can carry thousands of telephone messages and TV programs with relatively little loss. Modulation of the laser light source is done either directly, by modulating the drive current to the laser, or externally, by passing the laser light through an electro-optic crystal whose transmission can be changed with an electrical signal.

The entire electromagnetic spectrum is employed in the study of the cosmos. Adaptive optics, a technology designed to improve the performance of astronomical optical systems, compensate for the blurring effect of Earth's atmosphere. Optical tweezers use radiation pressure produced by high-intensity laser light to move and trap small particles such as cells, microbes, bacteria, and viruses.

Optical computers use light, rather than electrons, to process data. Holographic data storage uses the entire volume of a crystal to store data, resulting in enormous storage capacity. Holographic television will require a rapid succession of projected holographic images to realistically convey movement.

◆ Review Questions

1. Why are pits on a CD made of a quarter-wavelength thick?
2. What is the magneto-optical Kerr effect? How is it used in CDs?
3. Compare the storage capacity of a DVD with that of a CD. How is the DVD's expanded storage capacity achieved?

4. How are light waves transmitted over large distances in an optical communications system? Why are light waves able to transmit much more data than microwaves?
5. What is a photorefractive material? Give an example of a photorefractive material.
6. What are the two advantages of using light waves in a computer rather than electrical signals?
7. Describe the operation of optical tweezers.
8. How is the high level of holographic data storage achieved?

▼ Questions for Thought and Discussion

1. What are the advantages and disadvantages of a CD-ROM as compared to a magnetic floppy disk?
2. How long does it take for a light wave to travel between two components in an optical computer that are 1 cm apart? What frequency of oscillation has a period equal to this time? (The speed of light is 3×10^8 m/s in air.)
3. How do you think the laser beam in a compact disc pickup is kept precisely on the recorded track?
4. Why does the core of an optical fiber have a larger refractive index than the cladding that surrounds it?

■ Exercises

1. Find the frequency of a green laser with $\lambda = 650$ nm.
2. Measure the inner and outer diameters of the recorded area on a compact disc. If the track spacing is 1.6 μm, how many tracks are there? Multiply this times the circumference of the average track (π times the average diameter) to find the total track length from inside to outside.
3. Using the average rotation rate and the data in Exercise 2, estimate the total playing time of your CD.
4. A CD-ROM can store six billion bits. What is the average area taken up by each bit?
5. In Sect. 5.8, we learned that the limit of resolution of the eye is about 1.22 λ/D, where D is the diameter of the eye aperture. Without going into details, the same sort of argument predicts that laser light can be focused to a spot whose minimum size is 1.27 $f\lambda/D$, where D is now the diameter of the laser beam and f is the focal length of the lens used to focus it. Show that if f is roughly equal to D, this predicts a minimum spot size of about 1 μm when the wavelength is 790 nm. What minimum size is predicted for $\lambda = 650$ nm (green laser)?
6. Show that a laser spot size of 1 μm allows a storage density of about 10^8 bits/cm^2. (Hint: Assuming the bits to be square, what is the length of the square?)

7. Assuming that polypropylene has a refractive index of about 1.55, what is the wavelength in a CD of laser light whose wavelength in air is 780 nm? What fraction of a wavelength is the 0.11-μm pit depth? Why do you think this pit depth was selected?

● Experiments for Home, Laboratory, and Classroom Demonstration

Home and Classroom Demonstration

1. **Alexander Graham Bell's photophone**. Remove the bottom of a Styrofoam cup with a utility knife and tape a piece of aluminum foil over the open bottom. A modulated light beam is produced by directing a flashlight or a laser beam at the foil while someone speaks into the top of the cup. Use a solar cell or a photodiode connected to a piezo-electric earphone or an amplifier/loudspeaker to receive the modulated signal.
2. **Music on a beam of light**. With an audio cable, connect an LED to the earphone jack of a portable radio or iPod to obtain a modulated light beam. Use a solar cell or photodiode, connected to a piezoelectric earphone or an amplifier/loudspeaker to receive the modulated signal. Try transmitting the light beam by means of an inexpensive optical fiber.

Glossary of Terms

acousto-optic modulator Acoustic (sound) waves diffract light waves to produce a modulated signal.

***adaptive* optics** A technology designed to improve the performance of astronomical optical systems by compensating for distortions introduced by medium between object and image.

compact disc (CD) Optical storage device that uses a laser to write and read data stored as small pits on a reflecting surface.

compact disc read-only memory (CD-ROM) Compact disc used for computer input.

digital versatile disc (DVD) Optical disc capable of storing full-length movies.

diode laser Semiconductor junction diode that produces coherent light.

hogel A computer-generated holographic pixel.

holographic data storage A data storage system in which information is stored throughout a volume rather than just on the surface, as is the case with other optical storage methods.

light-emitting diode (LED) Semiconductor junction diode that emits light of a particular color when excited by an electric current.

magneto-optical (MO) disc Stores data that can be read out using the Kerr magneto-optical effect.

magneto-optical Kerr effect Rotation of the plane of polarization when reflected by a magnetic surface. Direction of rotation depends on direction of magnetization.

MiniDisc (MD) Miniature compact disc for recording digital audio.

multiwavelength astronomy The study of the universe using a wide range of wavelengths.

optical computer A device that uses visible or infrared light, rather electric current, to perform digital computations.

optical fiber Glass fiber capable of transmitting data optically.

optical tweezers Instruments that employ laser light to manipulate and trap micro particles.

photodiode Semiconductor junction that conducts electricity when illuminated by light. Used to detect reflected signals from an optical storage disc.

photonics A branch of physics and technology that deals with the properties and applications of photons.

spatial light modulator A device used in holographic data storage systems to modulate amplitude, phase, or polarization of light waves in space and time.

Further Reading

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