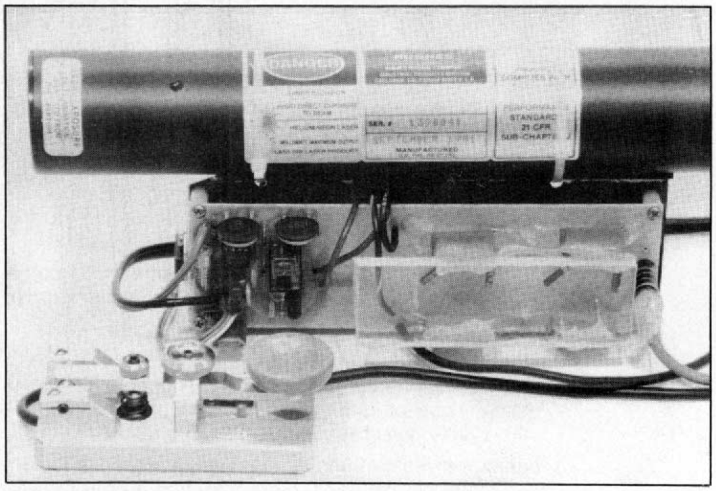
A Laser-Communications Primer—*Part 1*



Been looking for a new frontier in Amateur Radio? Give *optical* communications a try!

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Few technologies developed less than 30 years ago have permeated our lives as much as the laser. The most obvious applications of the now-commonplace laser range from bar-code scanners used in neighborhood grocery stores to CD (compact-disc) players, high-resolution printers and high-capacity computer disk drives. Less widely known, but perhaps even more significant, are the many varied commercial applications of lasers, including the fabrication and testing of ICs and precision resistors, geographical distance measurement, circuit-board drilling, eye surgery, motion detection for surveillance, high-temperature spot soldering, telecommunications and image digitization.

For the radio amateur interested in experimenting with optical communications, there has never been a more opportune time to enter the field. This article, the first in a two-part series, provides a modest introduction to the fundamentals of optical communications, including a discussion of laser light, laser-light sources and detectors, and optics, and includes a glossary of optical-communications terms. Part 2 builds upon this knowledge, describing how, with a small investment in time and money, you can build your own voice or CW optical communications system.

Optical Versus RF Communications

Although present-day, free-space optical communication suffers from atmospheric attenuation and is constrained to line-of-sight paths, it has a number of advantages over conventional RF communications. Perhaps the most notable feature of optical communications media—especially when you consider the current state of the crowded HF bands—is its practically unlimited bandwidth. Given the appropriate hardware, one could transmit the contents of the entire amateur MF/HF spectrum over a single beam of light! For example, laser diodes have a potential bandwidth in excess of *10 GHz*.[1]

From the radio amateur's perspective, optical communications represents a largely unexplored frontier. And, unlike microwave communications, it is currently free of FCC restrictions and license requirements. As was noted in several New Frontier columns in *QST*, laser-based optical communication using surplus, inexpensive components is not only challenging, but can also be fun and educational. In order to become proficient at optical communications—especially if you plan to design and build your own equipment—you need to adequately appreciate laser light and how it can be generated, modulated, directed and detected. This article contains an introduction to these concepts, including practical examples of their applications.

Laser Light

As any 5-year-old who has seen Saturday morning cartoons can tell you, one of the most significant characteristics of laser (an acronym for *light amplification by stimulated emission of radiation)* light is its intensity. Laser light is able to burn holes through metal bulkheads (whether real or imaginary) because it can deliver a large amount of light energy to a very small area. Even the most powerful laser beams can be focused on a spot of a size that's limited only by the wavelength of the light used. As shown in Fig 1, lasers can operate not only in the visible spectrum, but well below (infrared—IR) and above (ultraviolet—UV) this range as well.

In addition to intensity, laser light has a number of characteristics that make it useful for communications. First, laser light is usually generated at a single wavelength, or color. Although single-color—monochromatic—light can be generated from nonlaser sources such as monochromatic spectrum lamps containing cadmium, mercury, potassium or sodium, the light from these nonlaser sources does not share other significant

[1]Notes appear on page 24.

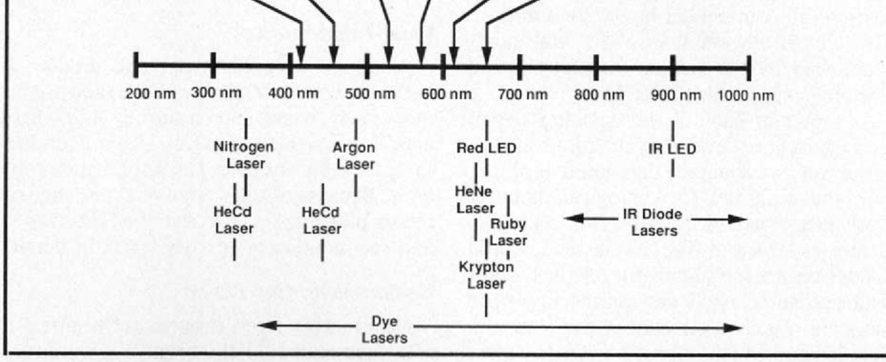

Fig 1—Spectral sensitivities (top) for common photodetectors and characteristic output wavelengths for selected laser sources (bottom).

Table 1

Center for Devices and Radiological Health (CDRH) Laser-Device Classifications†

Class	*CDRH Criteria*
I	Emits energy in the UV, visible or IR spectrum (400-1400 nm) at levels below which biological hazards have been established. Up to 0.39 μW output.
IIA	Low-energy emissions in the visible spectrum (400-710 nm), but not intended for direct viewing, eg, bar-code scanners. No hazard from direct viewing for less than 1000 seconds. Up to 3.9 μW output.
II	Visible emissions only (400-710 nm). Beam must not be on or motionless for more than 0.25 second. Potential chronic hazard. Up to 1 mW output.
IIIA	Visible emissions only (400-710 nm). Potential acute (immediate) or chronic hazard. Up to 5 mW output. (Most NeHe lasers fall into this category.)
IIIB	Emits energy in the UV, visible or IR spectrum (400-1400 nm). Acute eye and skin hazard on direct exposure. Maximum output between 5 and 500 mW in the visible spectrum, less in the IR and UV regions.
IV	High-power lasers that are extremely hazardous to eyes and skin upon direct or scattered exposure. More than 500 mW in the visible and IR regions and more than 1.5 mW in the UV region. (Heavy duty, commercial cutting and soldering lasers fall into this category.)

†The classification criteria are for continuous lasers only; pulsed lasers are subject to different requirements. For more information on CDRH classifications, see the *Federal Register,* Vol 50, No. 161, Aug 20, 1985, pp 33688-33702.

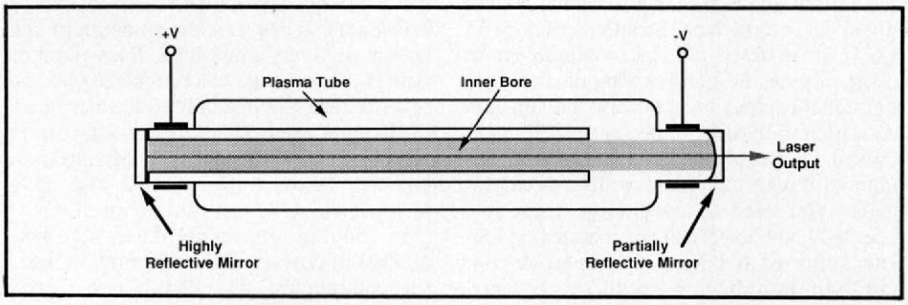

Fig 2—Cross-sectional view of a typical HeNe laser tube. Note that the partially reflective output mirror is curved inward slightly to provide a more parallel output beam. Although direct HV-supply connections are shown, a series ballast resistor is usually inserted in one power-supply lead to limit current.

properties of laser light. For example, unlike other types of light, laser light is both spatially and temporally *coherent*. That is, its component waves are all unvaryingly *in phase*.

Lasers and laser light are classified based on a variety of factors, but the most common classification schemes are based on the composition of the lasing medium (gas, dye, chemical, solid state, semiconductor), the output wavelength (IR, visible, UV), tunability (fixed or variable wavelength) and output power. Whatever the scheme used for classification, all commercial lasers are additionally classified according to standards established by the Center for Devices and Radiological Health (CDRH).

As shown in Table 1, the six categories of laser devices are defined as functions of output power, wavelength, maximum exposure time and potential for biological damage. Most lasers useful to amateurs fall into categories IIIA and IIIB, as classes I, II and IIA devices are useful only for relatively short distances, and class IV devices are simply too dangerous for communications use. (Carbon-dioxide lasers, with output powers in excess of 5 kW, as well as tunable titanium-sapphire solid-state units with more than *25 kW* output, are examples of class IV lasers.)

Whatever the CDRH classification, laser light, like all forms of radiation, is potentially very dangerous. Although the unfocused beam from a typical 1- or 2-mW gas laser is not likely to cause any injury to your hair or skin, it can damage your eyes, especially the retinae. *Treat a laser as you would the sun: Never look directly at a laser beam or a reflection of the beam, and always wear appropriate eye protection.* Even for low-power visible laser work (a 1- or 2-mW, unfocused beam), I wear high-quality dark sunglasses.

Laser-Light Sources

Although over 200 types and models of lasers are commercially available, you are far more likely to encounter a surplus visible-light helium-neon (HeNe) gas or IR semiconductor laser than, for example, a solid-state ruby laser. Because of their relative abundance on the surplus market, I'll describe HeNe lasers and semiconductor (diode) lasers in detail.

Helium-Neon Gas Lasers

Helium-neon lasers (known as "heenees"), with their characteristic bright red output at approximately 633 nm (see Fig 1), are the most abundant visible-light laser devices on the surplus market. HeNe lasers are especially attractive to the experimenter. Unlike many of the higher-power gas lasers, such as krypton units, low-power (1-5 mW) HeNe lasers are physically compact (see the title photograph) and do not require forced-air or liquid cooling.

HeNe lasers, like many gas lasers, are energized by passing a current through a gas-filled tube with highly reflective ends (see Fig 2). This current, nominally in the range of 3 to 8 mA with a 2- to 4-kV supply, imparts energy to the helium-neon mixture, which in turn releases the energy in the form of red light. Although 1 or 2% of this light escapes through the less reflective output mirror, most of it is reflected back into the gas mixture, where it stimulates the emission of additional "particles" of light (photons) from other gas atoms. That is, a single photon may excite a gas atom already in an excited state as a result of the current passing through the gas, producing an additional photon, of the same energy content (wavelength) as the first. These two photons can similarly excite two additional gas atoms, producing four photons, and so on.

The result is an avalanche effect that generates large numbers of photons, all of the same wavelength. In this environment, out-of-phase waves (light has properties of both particles and waves) tend to cancel, so the resulting laser output is coherent. In addition, the reflective surfaces ensure that the photons traverse a parallel course within the laser tube, resulting in a parallel output beam (low beam divergence).

Because of their construction, HeNe lasers produce a bright red, cylindrically symmetrical output, without additional optics. The diameter of this cylinder is nominally 0.8 mm, with the exact value determined by the inner diameter of the laser-tube bore (see Fig 2).

Although mean-time-before-failure (MTBF—a catchphrase for service-life expectancy) figures for HeNe tubes range from only 10 to 20 thousand hours, a surplus tube with even 1% of its expected life remaining can be a good buy. Even a few hundred hours of tube life will go a long way in a communications system in which the laser is turned on for only a few minutes at a time.

Semiconductor (Diode) Lasers

Largely because of the electronics industry's need for compact, efficient laser-light sources, the gas laser is being supplanted by the semiconductor-diode laser (see Fig 3). The CD player, for example, would not be feasible without solid-state lasers.

A major advantage of diode lasers over HeNe lasers is their efficiency. Whereas typical HeNe lasers have efficiencies of only 1 or 2%, semiconductor laser diodes can be more than 60% efficient.[2] In addition, the power-supply requirements of a laser-diode system can often be satisfied by a compact low-voltage supply or battery, as the typical power consumption of a diode laser at room temperature is a mere 179 mW (2.1 V at 85 mA).[3]

In addition to their greater efficiency (and

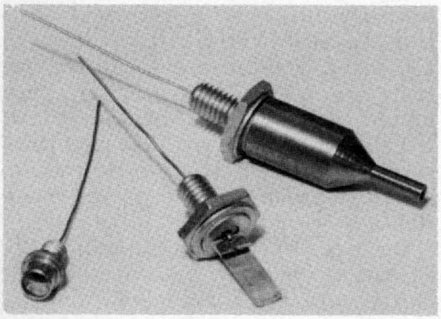

Fig 3—Gallium-arsenide (GaAs) IR laser diodes are both extremely compact and efficient laser-light sources. The small unit on the left, manufactured by RCA, is rated at 9 W output, and the two larger diodes on the right, manufactured by Laser Diode Laboratories, can provide up to 7 W of output power. The protective cover has been temporarily removed from the center diode to expose the GaAs substrate. *(NU1N photos)*

therefore cooler operation), semiconductor laser diodes offer additional advantages over their gas counterparts. Not only are they more mechanically rugged in general, but semiconductor diode lasers also offer greater reliability. For example, red-light semiconductor diode lasers have MTBFs in excess of 250 thousand hours—10 to 20 times that of typical HeNe lasers.

Although the composition of a diode laser is responsible for its compact size and reliability, it also introduces an important difference in the nature of the output beam, compared to the HeNe laser. Semiconductor laser-diode structures are rectangular, rather than cylindrically symmetric like those of an HeNe laser, and therefore produce a rectangular beam with two divergence angles. That is, over distance, the beam spreads more in one axis than in the other. The nearer the relative divergence angles (aspect ratio) is to unity, the better, for optical reasons.

In general, although the larger beam-divergence angle is temperature independent, the smaller divergence angle is affected by temperature. Typical initial spot (or rectangle) size for the output of a semiconductor diode laser is 2 μm × 5 μm, compared to a symmetrical 0.8 mm—800 μm—for a HeNe laser. Although optional on HeNe lasers, *collimating lenses* must be used with semiconductor-diode lasers to obtain a parallel beam.

Unlike HeNe lasers, with their fixed-wavelength, 633-nm outputs, the output wavelength of semiconductor diode lasers is temperature-dependent. Higher temperatures result in longer output wavelengths.[4]

Although the Japanese electronics firm NEC announced the first room-temperature visible light GaAs-diode laser in 1985, the majority of diode lasers in use today are silicon IR units. Market pressures are likely to change this situation in the near future. In fact, most of the major laser-diode manufacturers, including Toshiba, Sony, Hitachi and Philips, have announced production of visible-light diode lasers. Regardless of manufacturer, the current generation of visible-light laser diodes come in three-lead packages and include internal monitor photodiodes used in controlling output power.

An interesting characteristic of visible-light diode lasers is that, unlike gas lasers, output wavelengths vary considerably from device to device.[5] The result, from a communications perspective, is that filters and detectors have to be carefully matched to individual laser diodes. For example, replacing a defective visible-light laser diode with a new one may require modifications in the optical systems of the transmitter *and* receiver in order to compensate for the wavelength difference.

Other limitations of current visible-light diode lasers include relatively low maximum output power. For instance, 680-nm GaAs laser diodes are available with output powers up to only 5 mW, compared to the 100 mW achievable with silicon IR laser diodes and HeNe lasers.[6] In addition, diode lasers with shorter wavelengths, eg, 670 nm (yellow), have somewhat shorter MTBFs than IR lasers, but still many times that of a typical HeNe laser.[7] Semiconductor-diode lasers are also less forgiving of voltage transients and overheating than their gas counterparts. As with the semiconductor finals in your radio-communications gear, good voltage regulation and heat dissipation will prolong the life of your laser communications system.

Laser Modulation

In order to carry information, a light beam must be modulated. The most appropriate form of modulation to employ is a function not only of the information to be communicated, but also of the type of laser system being used. For example, commercial IR laser-diode systems are available with modulation limits in excess of 90% with a 500-MHz bandwidth (Edmund Scientific Co, 101 E Gloucester Pike, Barrington, NJ 08007, tel 609-573-6250). HeNe lasers, however, have a modulation limit of only 15%, and a narrower bandwidth.

Although CW is by far the simplest mode to implement in conventional RF communications, it can be difficult to achieve with laser systems. HeNe lasers, for example, cannot be reliably switched on and off more than a few times per minute. Like fluorescent room lights, HeNe lasers require a brief stabilization period after power is applied. In addition, the thermal shock associated with each start and stop can eventually lead to a cracked laser tube.

Perhaps the best way to use an HeNe laser in CW work is to modulate the beam, after it has been generated, with a liquid-crystal shutter. For example, I have used the liquid-crystal display (LCD) from an inexpensive watch to successfully modulate a 5-mW HeNe laser beam. Unfortunately, there are both information-rate and communications-distance penalties associated with this approach. First, light transmission through an LCD in the clear state is at best only about 70%. In addition, LCD response time, a function of applied voltage and cell thickness, is on the order of 100-200 ms at room temperature, and considerably longer at lower temperatures.[8] You therefore end up with an attenuated beam that might, at best, support a 5-WPM CW QSO. Using more than a few milliwatts of laser energy is not advisable, because LCD failure occurs if the maximum operating temperature (near 120 °F) is exceeded.

The most practical means of working CW with an HeNe laser is to modulate the tube's supply voltage at a fixed audio-frequency rate. In modifiable switching power supplies, this is most easily done by changing the switching rate. Laser power-supply kits are most amenable to this approach, because they typically have a means of varying the switching rate to suit the needs of a particular laser tube.

Optics

Lenses, mirrors, fiber-optic cables and other optical devices are to light energy as antennas and coax are to RF energy. And like a radio antenna system, the quality and efficiency of the optical system can make the difference between a solid communications link and a worthless one, regardless of what signal generation and detection devices are employed. Given this scenario, you should have a good grasp of the types of optics available, and how they are best utilized in communications work.

Conventional Glass Lenses

The most basic optical element in laser communications is the common glass magnifying lens. For example, a simple magnifying glass, with its double convex lens, makes an excellent receiving lens. Simply mount the light detector (more on these later) at the lens's focal point and align the lens-detector axis with the target. A good rule of thumb is that doubling the receiving lens diameter doubles the maximum range of the receiver. You can easily determine the focal point of a lens by using the lens to focus a distant light source, such as the sun, on a sheet of white paper. When the distant object is in focus, the lens's focal length is the distance between the center of the lens and the paper.

Most inexpensive lenses, such as those used in hand-held magnifiers, display some degree of *chromatic aberration* (see Fig 4). That is, light of different wavelengths has different focal lengths, in part because light at each wavelength is refracted to a different degree by the glass that composes the lens. Expensive lenses, such as those used in better telescopes and binoculars, are coated to correct for this chromatic aberration. However, as shown in Fig 4, chromatic aberration can actually be of great benefit, because the optical detector can be positioned such that it encounters predominantly one segment of the spectrum, eg, primarily red light in a receiver system optimized to detect HeNe-laser light. Chromatic aberration increases nearly exponentially with increasing lens aperture,[9] so larger lenses provide more chromatic aberration, and therefore potentially better selectivi-

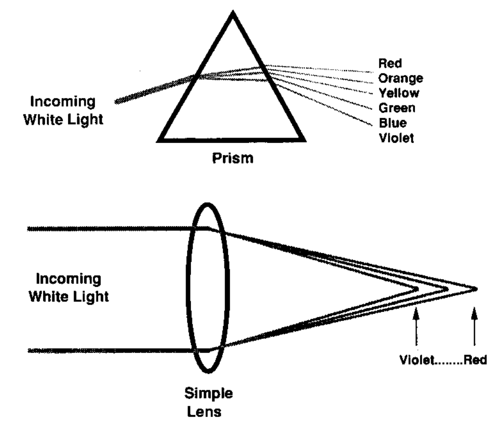

Fig 4—Light of various wavelengths is refracted differently by the glass in a prism (top) or lens (bottom). This *chromatic aberration* can be used as a means of selecting a particular wavelength, ie, an optical detector can be positioned to receive predominantly red or orange light, minimizing the effects of ambient yellow, blue and green light.

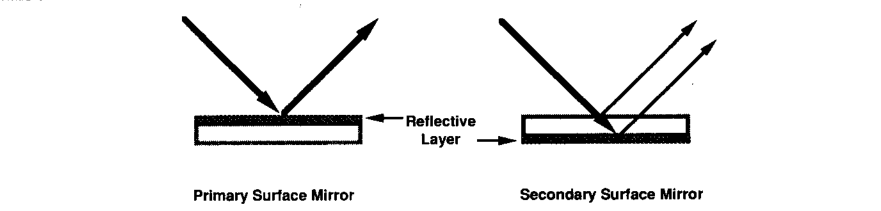

Fig 5—Primary-surface mirrors, in which the reflective coating is on top of the glass substrate (left) have less loss than common secondary-surface mirrors (right), because incident and reflected light don't have to travel through the lossy substrate.

ty, in addition to better light-gathering power.

Fresnel Lenses

Unfortunately, large-diameter glass lenses are expensive, heavy, difficult to produce, and generally difficult to work with. Luckily, lenses are available that not only provide large capture areas, but are also lightweight, easy to work with and easily affordable. *Fresnel* lenses are flat, thin pieces of plastic (commonly acetate butyrate) molded with a series of small, concentric, stepped zones, each of which acts as part of the lens. Unlike conventional lenses, Fresnel lenses are very thin—typically 1/8 to 1/4 inch thick.

Although Fresnel lenses offer advantages over conventional lenses in terms of cost, weight and size, they are somewhat less efficient than good-quality glass lenses. For example, Fresnel lenses made of acetate butyrate have a light transmissivity of about 92% in the visible spectrum, compared to about 98% for a good conventional glass lens. You can purchase a new 16-inch-diameter Fresnel lens for less than $20 (Edmund Scientific Co), but a good conventional lens of the same diameter would cost well over $1000, and would weigh tens of pounds.

Although the majority of Fresnel lenses on the market are designed for visible light, IR Fresnel lenses are also available. Composed of a whitish plastic, those of the IR variety craze rapidly when exposed to sunlight. However, they are somewhat more efficient than their visible-light counterparts, with typical light transmittances approaching 95%. Even IR Fresnel lenses are priced quite reasonably; 12- × 12-inch lenses sell for about $30 (Edmund Scientific Co).

Flat Mirrors and Prisms

Although lenses are useful for focusing light, flat mirrors and prisms are used primarily for redirecting the light beam once it has exited the laser source, or on its way to the optical detector. Mirrors can be classified as either primary- or secondary-surfaced.

Primary-surface mirrors have a reflective coating (usually aluminum) on the surface nearest the incident light, so that light is reflected without passing through any glass (see Fig 5). Reflectance figures for primary-surface mirrors approach 95% in the visible-light range. Single-lens-reflex (SLR) cameras commonly use primary-surface mirrors in their construction, and are a good source of these mirrors. Secondary-surface mirrors, typified by the common automobile rear-view mirror (which can be used for day- or night-time driving conditions by adjusting it such that the viewer encounters either the primary [night driving] or secondary [day driving] reflection), have losses associated with both light absorption from the glass and secondary reflection, with a reflectance figure approaching only 90%. Avoid lossy secondary-surface mirrors if possible.

Although aluminized primary and secondary-surface flat mirrors are effective at visible wavelengths, they tend to absorb energy in the IR spectrum. For IR laser work, you should use primary gold-surface mirrors, which are efficient at IR wavelengths. Similarly, if most of your work is centered around HeNe-laser light, you should consider a specially fabricated HeNe-laser mirror. These mirrors, with a reflectance of nearly 98% at 633 nm, can be purchased from most laser-supply houses. New 1- × 1-inch, primary-surface HeNe mirrors go for about $15 new (Edmund Scientific Co).

One type of mirror that can be useful in communications work is the so-called *cold mirror,* used in overhead projectors and projection microscopes. These mirrors reflect visible light while allowing IR light to pass, thereby minimizing heat buildup. Although expensive when purchased new ($50 for a 4- × 5-inch mirror [Edmund Scientific Co]), cold mirrors make excellent optical low-pass filters when used to protect sensitive IR detectors from daylight.

Although very dissimilar physically, prisms are functionally very similar to mirrors in that they are primarily useful for redirecting laser light. Instead of a reflective coating, prisms make use of total internal reflection to redirect the beam. Uncoated prisms, like uncoated simple glass lenses, tend to affect light of various wavelengths differently (see Fig 4), and can therefore be useful in providing some degree of optical selectivity. That is, the optical detector can be positioned such that it only receives light centered around a particular wavelength.

Inexpensive, uncoated glass prisms are available from a number of sources, including most scientific supply houses, for $3-$5, depending on the size. Avoid the plastic prisms sold in some toy stores—they are generally less efficient than glass prisms, and scratch easily. High-quality coated-glass prisms are usually easy to come by surplus (from old binoculars and—my favorite source for optics—discarded SLR cameras.)

Curved Mirrors

Like lenses, parabolic, ellipsoidal and other curved mirrors can be used to collect and focus light. Lightweight, inexpensive parabolic reflectors of highly polished aluminum can be used to focus light on an optical detector, in a manner much like a conventional microwave dish. However, they are considerably less efficient than their glass counterparts. Edmund Scientific Co markets an 18-inch reflector for about $30.

An excellent source of a highly reflective, secondary-surface parabolic or ellipsoidal glass reflector is a discarded automobile headlight (unsealed) or spotlight. Simply replace the bulb with a suitable optical detector, and aim the assembly toward the laser-light source. You will have to experiment with the exact orientation of the detector for best results. Avoid spotlights and headlights with rectangular reflectors in favor of those of the more efficient round shape.

If you can't find a source of surplus parabolic mirrors, or if you need a larger capture area than a discarded automobile headlight can provide, you can buy secondary-surface parabolic mirrors in sizes up to about 20 inches (for about $50 from Edmund Scientific Co). Primary-surface mirrors of more than 2 inches in diameter are relatively rare, and are found mainly in reflecting telescopes.

Bandpass Filters

Optical bandpass filters can increase the range of both IR and visible-light lasers when used in daylight. New HeNe laser-light filters with a center wavelength of 632.8 (±2) nm, sell for about $30 (Edmund Scientific Co). Many telescope manufacturers and retail outlets (eg, Orion Telescope Center, 421 Soquel Ave, PO Box 1158, Santa Cruz, CA 95061) offer broadband light-pollution filters designed to eliminate the effects of mercury and sodium street lights on astronomical observations. These bandpass filters, usually centered on approximately 500 nm (blue-green), effectively eliminate reds and yellows, as well as violet and UV wavelengths. They are therefore useful when used in conjunction with HeCd, argon and other blue-green lasers, but not with red HeNe lasers.

Less expensive optical bandpass filters include heat-absorbing glass and colored acetate. Heat-absorbing glass, commonly used in overhead projectors and microscopes, passes visible light and absorbs IR light. Heat-absorbing glass is best used as part of a front-end system in a visible-light receiver in the presence of a high-IR-noise background. Colored acetate, although less efficient than glass bandpass filters or heat-absorbing glass, is an inexpensive and effective bandpass filter. For example, a small piece of red acetate (which passes only the red part of the visible spectrum) can be placed in front of an optical detector to minimize interference from environmental light outside the red part of the spectrum.

Optical Fiber

Optical fiber is the functional equivalent of RF waveguide, but operates with photons instead of electrical RF currents.[10] Like the prism, optical fiber relies on internal reflection for its operation. Light introduced into one end of an optical fiber propagates within the transparent, inner core to the other end of the fiber.

Like coaxial cable and waveguide, fiber-optic cable is available in a wide variety of types. In small lengths, optical fiber can be purchased new for about 50 cents per foot. Surplus-market prices are comparable to those of coaxial cable.

For runs of only a few feet, the predominant loss in fiber-optic systems occurs at the interface between the laser source and the fiber aperture. Only laser radiation within a critical acceptance angle is admitted into the fiber. Even very small alignment errors or imperfections in the fiber entrance can result in significant signal losses. If you absolutely must locate your lens system some distance from your laser transmitter or receiver, use a fiber-optic pigtail—an optical fiber that has been accurately and permanently bonded to the active area of a laser diode, LED or photodetector during the manufacturing process.[11]

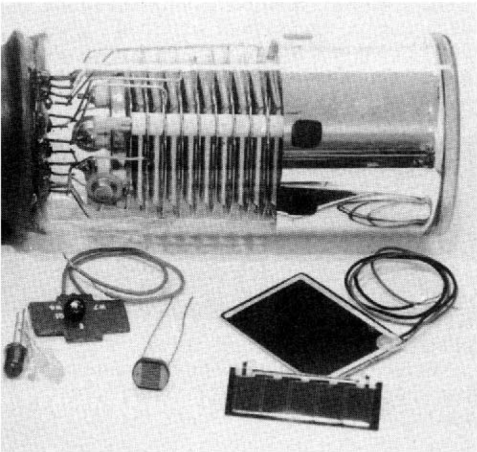

Fig 6—Examples of common visible-light and IR photodetectors. In the background is a photomultiplier tube. The photocathode is to the right, immediately adjacent to the transparent tube face, and the anode is visible near the tube base, to the left. In the foreground, from left to right, are: three common LEDs, an IR phototransistor assembly, a CdS photoresistor, and amorphous (front) and crystalline (rear, with leads) solar cells.

Optical Detectors

In order to extract audio or digital data from a modulated laser beam, a suitable optical-to-electrical transducer must be used. The detector's frequency response, bandwidth and sensitivity largely define the performance of the entire receiving system. Common optical detectors, described in more detail to follow, include solar cells, CdS photoresistors, LEDs, semiconductor and vacuum-tube photodiodes, phototransistors, and photomultiplier tubes.

Solar Cells

Solar cells (see Fig 6) are used in a variety of applications, from powering pocket calculators to charging batteries on communications satellites. As shown in Fig 1, typical silicon solar cells are sensitive to wavelengths from visible light to near IR. Silicon solar cells can generate about 0.5 V dc per cell at full illumination, and their current output is a linear function of light intensity. With a bandwidth of about 50 kHz, silicon solar cells are adequate for both voice and moderate-speed digital communications.

Cadmium-Sulfide (CdS) Photoresistors

As optical detectors go, CdS photoresistors (see Fig 6) are both inexpensive (Radio Shack sells a package of five, part no. 276-1657, for about $2) and fairly sensitive, with typical gains on the order of 10^4.[12] The resistance of these devices varies as a function of light intensity, within a range of about 100 Ω to 1 MΩ. As shown in Fig 1, CdS photoresistors respond to energy in the visible-light through near-IR range. They are, however, most sensitive to green light (approximately 520 nm). Like many photodetectors, CdS photoresistors exhibit a persistence effect—their sensitivity is reduced for 1 or 2 seconds after light is removed. Although the published bandwidth for CdS photoresistors is only about 100 Hz, I have used a CdS-photoresistor-based detector system to successfully recover 20-kHz signals from modulated HeNe-laser light.

LEDs

Primarily used to *generate* light, common LEDs also make fair optical *detectors.* Although I wouldn't recommend an LED-based detector for a long-distance communications link, LEDs make good, inexpensive detectors for close-range laser testing.

Vacuum Photodiodes

Vacuum photodiodes (see Fig 7) employ a relatively large, negatively biased photocathode and a smaller, positive anode to detect light. Current flow is directly proportional to the number of photons striking the photocathode. Although standard vacuum photodiodes have an efficiency range of only 0.5-20%, increased sensitivity (gains of five to ten) is possible when small amounts of argon gas are introduced into the partial vacuum. Vacuum-photodiode output is, like that of solar cells, a linear function of light intensity and, like CdS photoresistors,

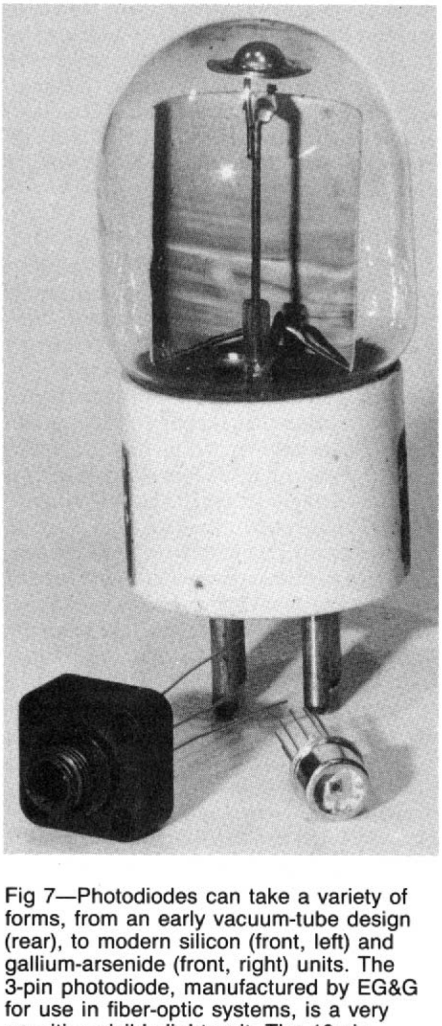

Fig 7—Photodiodes can take a variety of forms, from an early vacuum-tube design (rear), to modern silicon (front, left) and gallium-arsenide (front, right) units. The 3-pin photodiode, manufactured by EG&G for use in fiber-optic systems, is a very sensitive visible-light unit. The 10-pin photodiode from RCA, also sensitive primarily to visible light, has a built-in lens system.

vacuum photodiodes fatigue with exposure to light.

Semiconductor Photodiodes

Whereas vacuum photodiodes are practically antiques, semiconductor photodiodes are the most prevalent type of photodetector in use today (see Fig 7). Their extremely fast response times, good sensitivity and low cost make them excellent optical detectors for laser-light receiving systems. As shown in Fig 1, photo-diodes are available for visible through infrared wavelengths.[13]

The most common types of semiconductor photodiodes are the PN, PIN (P-intrinsic-N), and avalanche photodiodes. The common and inexpensive PN photodiode makes an excellent optical detector, especially at visible wavelengths, but PIN and avalanche diodes are even better.

PIN photodiodes, commonly used in fiber-optic communications systems, like vacuum photodiodes, respond linearly to incident light intensity. Normally operated with a reverse bias of 10 to 90 V, PIN photodiodes have typical bandwidths in excess of 1 GHz.

Avalanche photodiodes, designed to operate with a high reverse bias (nominally 150 V), can provide gains of 50 to 2500.[14] With a typical sensitivity of 1 μA per μW of incident light and a bandwidth in excess of 1 GHz, avalanche photodiodes make very sensitive, wide-bandwidth optical detectors. On the negative side, avalanche photodiodes are both noisier than PIN and PN diodes, and more sensitive to temperature and voltage variations.[15]

Phototransistors

Like LEDs, most transistors are sensitive to incident light. A phototransistor is essentially a normal transistor with a transparent case that allows photons to interact with the collector-base junction. Most phototransistors are NPN devices with a base region somewhat larger than that of a standard transistor. Bandwidth—approximately 1 MHz—is more than adequate for most applications, but considerably less than that of a photodiode. Typical phototransistor sensitivities, a few microamperes per microwatt of incident light, are significantly greater than those of common PN photodiodes, however. Darlington phototransistors are even more sensitive, but have correspondingly narrower bandwidths (on the order of 10 kHz).

Most phototransistors are sensitive to energy in the IR region, with a peak at approximately 850 nm. For IR laser work, phototransistors offer an inexpensive, readily available photodetector alternative. Radio Shack offers a good IR phototransistor, the TIL414 (part no. 276-145), for less than a dollar.

Photomultiplier Tubes

Despite the advances in solid-state photodetection, photomultiplier tubes (PMTs) remain the most sensitive of the generally available detectors for visible light, with gains approaching 10^8.[16] If long-distance laser communication is your goal, a PMT-based receiver is a must. For example, the current laser DX record, 95.6 miles, held by KY7B and WA7LYI, was made with 30-mW HeCd lasers (operating at 442 nm) and receivers equipped with 19- × 24-inch Fresnel lenses and PMTs.[17] Similarly, a 125-mW HeNe laser, together with a receiver constructed from a 12-inch telescope and a PMT, has been used in one-way contacts of over 110 miles.[18]

As shown in Fig 6, PMTs are considerably bulkier than their semiconductor counterparts. For example, my 19-pin EMI (Emitronics, Inc) model 9558 PMT has a 2-inch-diameter flat face. This PMT was designed for use in the visible spectrum, but PMTs are also available with peak sensitivities in the IR region. The composition of the internal emitting surfaces largely defines the spectral sensitivity of a PMT, but it is also influenced by the composition of the transparent photocathode window. Therefore, when you shop around for a surplus PMT, make certain that you get a data sheet with your tube. Although new PMTs can be expensive (in the $100 range), I have picked up working surplus units at local swapfests for under $10.

PMTs can be difficult to work with, mainly because their anode-supply requirements range from 700 V to over 3 kV. Because gain is an exponential function of the applied voltage,[19] a well-regulated HV supply is a must. In addition, PMTs demand shielding and a controlled-temperature environment, as they are sensitive to both ambient-temperature variations and magnetic fields. Even in total darkness, PMTs exhibit a small anode current that can be attributed to thermally excited electrons. This source of noise can be reduced by cooling the PMT, and by holding any material in contact with the glass envelope at cathode potential.

PMTs should never be exposed to ordinary light levels, because after even a short exposure to normal daylight, the PMT may require a day or more to return to normal dark-current levels.[20] For example, the flash I used in taking the photo of Fig 6 resulted in an abnormally high dark current in that PMT for almost 2 days.

Despite the numerous precautions that must be observed with PMTs, their superb efficiency (in excess of 25%), sensitivity (typically *1 ampere* per μW of incident light), and bandwidth in excess of 500 MHz are simply hard to beat with any other technology.

Summary

There has never been a more opportune time to enter the field of light communications. Light-communications technology has advanced to the point where the required hardware is not only readily available, but is also affordable to the average amateur. Stay tuned: In Part 2, I'll review the basics of light propagation and describe affordable laser-based communications systems that you can build.

Notes

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18R. Atkins, "New World DX Record on 47 GHz," The New Frontier, *QST*, Dec 1988, p 87.
19P. Horowitz and W. Hill, "Measurement and Signal Processing," *The Art of Electronics* (Cambridge MA: Cambridge University Press, 1980).
20See Note 19.

Strays

I would like to get in touch with...

☐ anyone who has information or literature dealing with the medical condition "glass arm" of old-time telegraphers, or anyone who has personally suffered from this malady. David R. Pennes, MD, WA3LKN, 5220 Winterberry Dr, Apt C, Indianapolis, IN 46254.

☐ anyone who has a Master Crafters 24-hour clock, Model no. 1-2324. William Hanberry, K6MQT, PO Box 11, Avalon, CA 90704.

☐ anyone to regularly exchange ideas with about Amateur Radio in an elementary school. My students are eight and nine years old and we have a transceiver that covers 10 to 80 meters in our third-grade classroom. Brad Hammer, KC1RQ, John Ward School, 10 Dolphin Rd, Newton Center, MA 02159.

☐ anyone interested in participating in an architecture net to discuss the life and work of Frank Lloyd Wright. Ted Osborn, WN9PIQ, 30 Lamm St, Danville, IL 61832.

☐ anyone who worked at Wells-Gardner Radio Company when it made the military receiver BC-348 during WW II. Alan Mark, PO Box 372, Pembroke, MA 02359.