How optoelectronic components fit in the optical spectrum

As optoelectronic applications multiply, optical sources, detectors, and transmission media are becoming increasingly available; this guide relates the more important of them by their operating wavelengths

by Lyman Hardeman, *Communications & Microwave Editor*

☐ Many optoelectronic devices that till recently were the playthings of a few curious researchers have by now become standard building blocks to a good many design engineers. And as the growing demand further lowers prices, still more EEs will want to exploit the interaction of light and electronics in industrial and consumer as well as military equipment.

A convenient approach to surveying the optoelectronic technologies and devices that are available today is to categorize them as optical sources, optical detectors, and materials through which optical waves are transmitted. The portion of the electromagnetic spectrum over which they function extends from ultraviolet wavelengths of a few nanometers, through the visible spectrum of about 400 to 700 nm, and far into infrared wavelengths that measure up to tens of thousands of nanometers (see foldout chart on p. 115).

Optical sources

The most important sources of light are the sun, various man-made lamps, lasers, and light-emitting diodes.

The sun operates as a blackbody, or thermal, radiator which emits broadband optical energy due to its inherent temperature. But in fact any substance is a blackbody radiator and emits light with a peak intensity that gets stronger and shorter in wavelength as temperature increases (see Fig. 1). At room temperature (300° K), the wavelength of peak light intensity of a blackbody radiator is about 10 microns (micrometers), while at 6,000° K, the peak occurs around 0.5 μm. The sun's peak corresponds to a temperature of 5,900° K.

Tungsten lamps are the chief sources of man-made visible light based on blackbody radiation principles. Depending on the amount of electrical power dissipated across its filament, the typical lamp will radiate with a blackbody temperature ranging from 2,500° K to over 3,000° K. The broadband nature of this radiation, however, is the major factor that reduces the lamp's over-all efficiency in the visible spectrum to only about 3%.

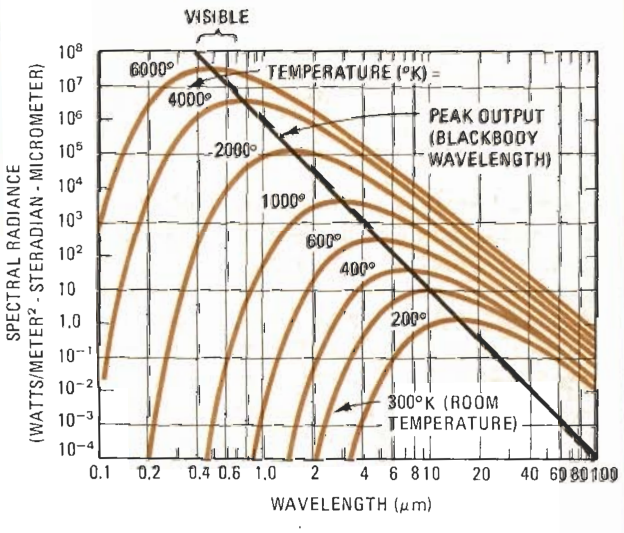
Thermal radiators are also very important in infrared applications—and becoming more so as the security barrier imposed on military infrared technology in World War II has gradually been lowered. In the last few years, many nonmilitary applications have emerged that exploit the natural infrared radiation of such sources as thermally polluted water, diseased crops in a field, or forest fires. In these applications, the sources are blackbody radiators and serve as inputs for highly sensitive remote sensors placed in aircraft or satellites.

Other artificial light sources include arc and glow discharge lamps, and fluorescent tubes. Almost all of these lamps emit in or near the visible spectrum, and each has its own applications niche. The arc and glow discharge types, for instance, are generally efficient sources of high-intensity light that serve both as illuminators in the visible spectrum and as exciters for laser sources.

Coherent sources

The only source of coherent light—the laser—yields extremely high radiance. But of the hundreds of different types of lasers that have been evaluated since the device was first shown to work in 1960, only a few have left the laboratory and entered general use.

Today's most common lasers are based on gasses such as carbon dioxide, helium-neon, argon, and krypton, or else are solid-state, using mainly either gallium-arsenide semiconductors or neodymium-doped yttrium-alumi-



1. Blackbodies. Substances emit broadband electromagnetic energy depending upon their temperature. At room temperature, the wavelength of peak intensity is in the infrared region, at about 10 micrometers, while at 5,900°K (about the temperature of the sun) peak intensity falls at just about the middle of the visible spectrum.

TABLE: LASER SUMMARY

TYPE	PRIMARY WAVELENGTHS (μm)	TYPICAL EFFICIENCY (%)	TYPICAL POWER (W) CW/PEAK	COMMENTS/PRINCIPAL APPLICATIONS
Argon	0.49 0.52	0.1	5/100	Emits at visible blue-green; used in cutting films in artwork design; efficiency and wavelength make it useful as pump for dye lasers for tuning in the visible spectrum.
He-Ne	0.63 1.15 3.39	0.01	0.1/2	Primary spectral line at 0.63 micrometer convenient and inexpensive source of red light for precision distance measuring, communications, and plasma physics studies.
Nd: YAG	1.06 1.30	3	50/1,000	High-power laser that is easy to control; used in cutting and welding and has potential in communications.
CO_2	10.6	20	200/75,000	Practical high-power laser; used extensively in cutting and welding; possible source for nuclear fusion
HeCd	0.44 0.33	0.5	0.1/2	Recently became commercially available for applications requiring blue light; is being considered for use as light source in facsimile equipment.
Ruby	0.69	1	5/50	Material used in first laser demonstrated in 1960; used some in cutting and melting.
GaAs	0.91	1	0.04/1	Promising solid-state laser for communications, but must improve reliability.
Krypton	0.64	0.1	5/100	Source of red and green light.

num-garnet. Primary operating wavelengths of each of these sources, along with their main application features, are summarized in the table.

Lasers are finding the bulk of their commercial applications in manufacturing and the construction industry. Here, they are useful for drilling holes, cutting, measuring precise distances, and surveying. But as optical component performance and modulation techniques advance, lasers will be used more in such areas as communications, optical data storage, and pollution control.

LEDs offer lower costs, higher speed

Light-emitting diodes have also made remarkable inroads the last few years. They are found in displays for everything from digital panel meters to pocket calculators. Their low cost, high reliability, and switching speeds on the order of a few tens of nanoseconds also make them attractive for use in optical isolators and as transmitters in fiber-optic communications systems.

While light-emitting diodes can be made from many semiconductor materials, gallium-arsenide-phosphide and gallium-phosphide diodes are much the most advanced. The wavelength of GaAsP LEDs can theoretically be varied from about 560 to 910 nanometers by growing crystals of varying ratios of concentration of arsenide and phosphide. But practical GaAsP devices—those used in most of today's LED displays—are constructed to operate in the red region, at 655 nanometers, a wavelength that represents the optimum tradeoff between the device's operating efficiency and the response of the human eye. Bandwidth of the light emitted from GaAsP devices is approximately 30 nm.

GaP diodes, however, are being made in increasing quantities, for green and yellow as well as for red displays. GaP is always doped, partly to increase its illuminating efficiency and partly to extend the bandwidth or alter the wavelength of the light it can emit. Doped with nitrogen, it will emit a broad range of wavelengths in the green and yellow portion of the visible spectrum. Doped with zinc-oxygen, it emits red light.

Another important type of LED is made from GaAlAs and is found in fiber-optic communication systems. The operating wavelength of this semiconductor is determined by the particular combination of aluminum and arsenide chosen. In these devices, practical efficiencies of approximately 3% are achieved over a range of wavelengths from 800 to 900 nm.

Optical detectors

Light sensors fall into three basic categories—photoemitters, photoconductors, and junction devices. In addition, several broadband temperature-sensing devices, such as the thermocouple, bolometer, and Golay cell, are used in light measurements, but these serve mainly laboratory and calibration purposes.

The photoemissive-type light sensor measures light by converting the energy of incident photons directly into free electrons, which are then accelerated in a vacuum under a strong electric field. Applications are chiefly in the visible and ultraviolet region—examples are the photocathode coating at the input of photomultiplier tubes, image-converter tubes, and low-light-level image intensifiers.

The more popular photoemissive materials today are silver-cesium oxide (AgCsO), cesium antimonide (CsSb), potassium-cesium-antimonide (K-Cs-Sb, referred to as a bialkali photoemitter) and sodium-potassium-cesium-antimonide (Na-K-Cs-Sb, a trialkali). Recently, GaAs photoemitters have become available and have stirred much interest among electro-optic system designers mainly because of their high sensitivity, especially at wavelengths between 600 and 900 nm.

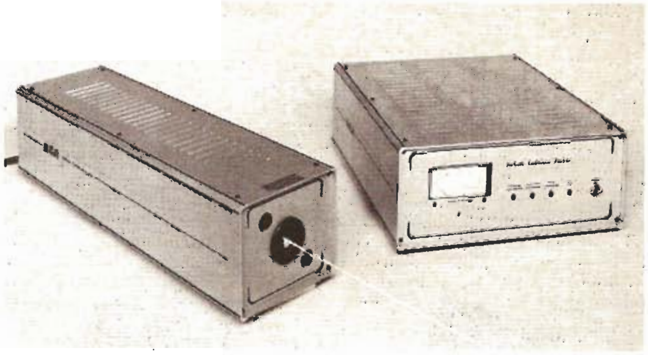
A convenient measure of performance of a photoemissive-type detector is its quantum efficiency, or ratio of output electrons to input photons. The theoretical maximum of one electron per photon defines a quantum efficiency of 100%. The quantum efficiencies for several commercially available photoemissive materials are plotted in Fig. 4 as a function of wavelength. The S-code numbers refer to standard devices defined by the Electronic Industries Association.

Both the quantum efficiency and the long wavelength cutoff of a photoemitter are determined by the semiconductor material it uses. Short wavelength cutoff is determined primarily by the cutoff wavelength of the window material through which light must pass before interacting with the photoemitter in a vacuum.

Photoconductors for longer wavelengths

As seen in Fig. 4, most photoemissive materials have a long-wavelength cutoff near the infrared edge of the visible spectrum, in the 600-800-nm region. Photoconductive-type detectors extend these detectable wavelengths well into the infrared range.

In a photoconductive detector, incident photons cause an increase in the current from an external biasing circuit to flow through the detector. The detector may be either intrinsic, with its sensing properties inherent in the photoconducting material itself, or extrinsic, in which case one material—usually germanium—is doped with one of a group of elements to make it sensitive to light at longer wavelengths.



2. Commercial lasers. Numerous lasers have been introduced in the past few years at prices below $3,000. The He-Cd unit shown can be operated at one of two spectral outputs (442 nm or 325 nm) and is expected to find applications in facsimile recording systems.

Intrinsic photoconductors include lead sulfide (PbS), lead selenide (PbSe), indium arsenide (InAs), and indium antimonide (InSb), all of which operate in the visible spectrum and to longer wavelengths out to about 3 to 5 μm at room temperature. The long-wavelength sensitivity of these detectors is increased when they are cooled to the temperatures of dry ice and liquid nitrogen. InAs and InSb are generally more expensive than PbS and PbSe, but take only microseconds instead of milliseconds to turn on.

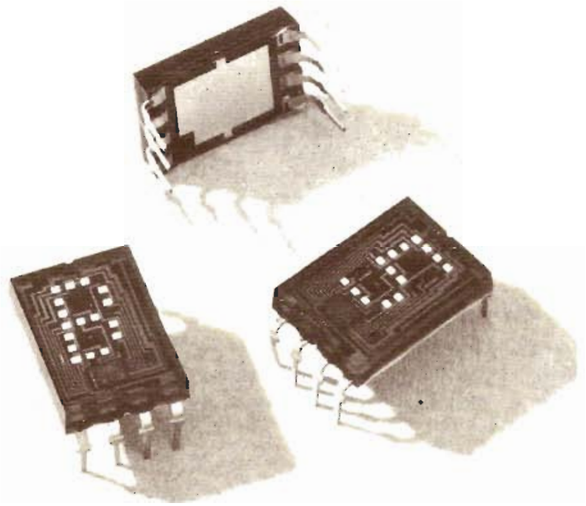
For applications in the visible spectrum—in camera light meters, home furnaces, and automatically operated street lights—cadmium sulfide (CdS) and cadmium

Photometry-radiometry units

The many terms that have been developed to define properties of propagating radiant energy are summarized in the table. For a detailed discussion of the units of photometry (light radiation normalized to the response of the human eye) and radiometry (radiation at any spectral frequency), and how these quantities are measured, see *Electronics,* Nov. 6, 1972, p. 91.

Definition	Radiometric			Photometric		
	Name	Symbol	Unit*	Name	Symbol	Unit*
Energy	radiant energy	Q	joule	luminous energy		lumen-s
Energy per unit time=power=flux	radiant flux	P	watt	luminous flux	F	lumen
Power input per unit area	irradiance	H	W/m^2	illuminance	E	lm/m^2 (lux)
Power output per unit area	radiant exitance	W	W/m^2	luminous exitance	L	lm/m^2
Power per unit solid angle	radiant intensity	J	W/steradian	luminous intensity	I	candela
Power per unit solid angle per unit projected	radiance	N	W/m^2 steradian	luminance	B	candela/m^2

*All units are metric.



3. Display breakthrough. Advances in semiconductor production techniques in the last few years have helped bring down the costs of GaAsP and GaP light-emitting diodes so that they are now widely used for display applications ranging from digital panel meters to pocket calculators. Recent alphanumerical digits come in many colors and sizes, some with built-in drive circuitry.

selenide (CdSe) are also used extensively and are supplied by several manufacturers. CdS has the greater sensitivity, CdSe responds at longer visible wavelengths, and both function at room temperature.

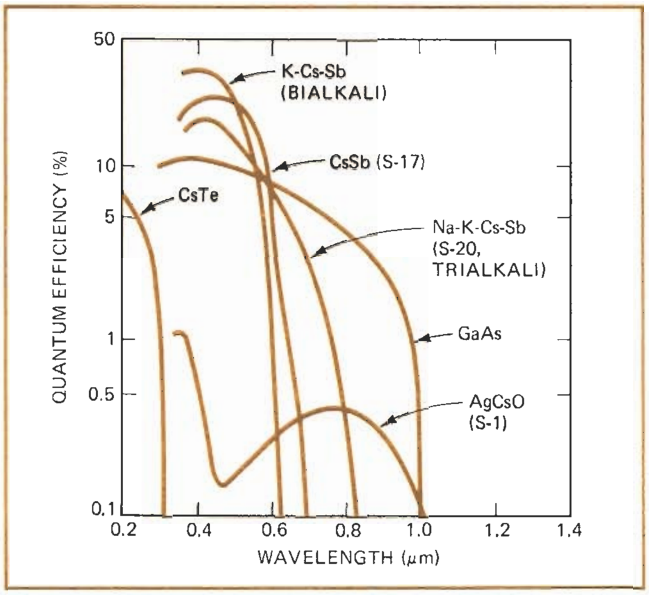
Two other intrinsic photoconductors—mercury cadmium telluride (Hg-Cd-Te) and lead tin telluride (Pb-Sn-Te)—have been developed more recently as detectors to operate to wavelengths out to about 14 μm when cooled to liquid-nitrogen temperatures (77° K). Such a spectral response makes these detectors attractive for use with the CO_2 laser, which emits at 10.6 μm.

Extrinsic photoconductors must usually be cooled to liquid-nitrogen temperatures or cooler and can be sensitive at still longer infrared wavelengths. Most practical extrinsic photoconductors employ a germanium host crystal. Depending on dopant and operating temperature, infrared wavelengths to over 100 μm can be detected (see foldout chart).

Junction-type detectors

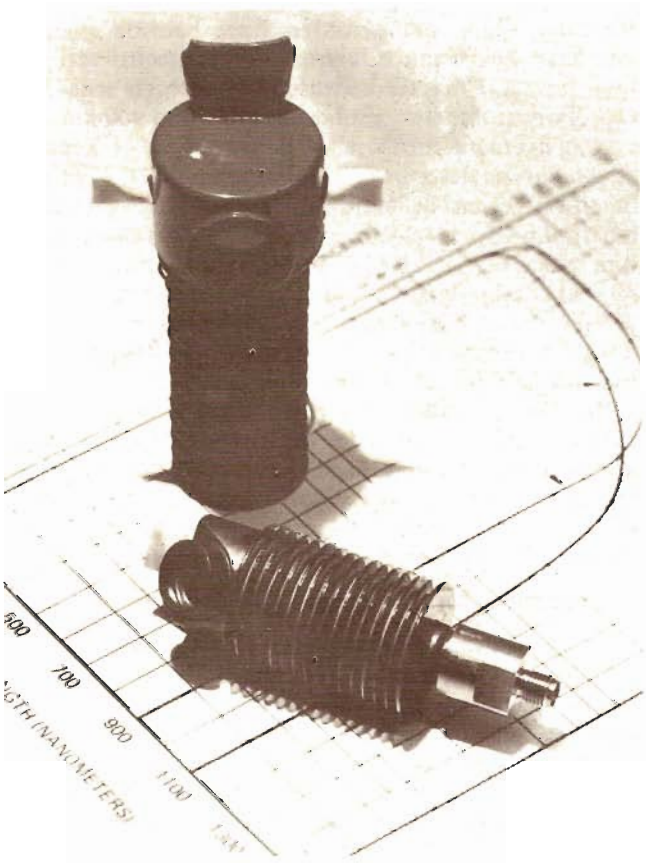
Light-sensing devices that depend on a semiconductor pn junction include photovoltaic devices, photodiodes, and phototransistors. In the photovoltaic sensor, a voltage is generated across the junction as a function of the light impinging on the junction. The photovoltaic cell, or simply photocell, is usually made of selenium or silicon and is most notably used in space, where the relatively high cost of the device is offset by the fact that it is the only self-generating light sensor available (i.e., one that requires no external power supply).

Photodiodes and phototransistors are finding increasing popularity at visible wavelengths. Because of their faster response and the high gains achievable when biased in a transistor circuit, these devices are competing more and more with photomultipliers operating to wavelengths as long as about 1.1 μm.



4. Photoemitter response. Photoemitter-type detectors are used at untraviolet and visible wavelengths. Material performance is typically compared in terms of quantum efficiency—the ratio of actual electron output to the maximum output possible determined by photon flux. S-code numbers refer to standards designated by the Electronic Industries Association.

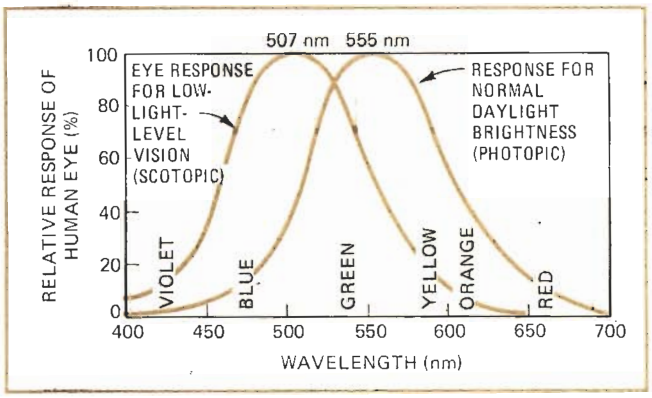
5. Photomultiplier edge. To stay half a step ahead of recent developments in solid-state detector technology, makers of photomultiplier tubes have recently introduced units with improved photocathode materials to achieve unprecedented combinations of speed, broad bandwidth and high quantum efficiency. Applications include optical-character readers and fiber-optic communications.



Reverse-biased silicon photodiodes typically respond to reset times of about 100 ns. Other semiconductor materials, including germanium, indium arsenide, and mercury-cadmium-telluride, are also used in making photodiodes, mainly to extend response to longer wavelengths, but often at a loss in response speed.

Seeing the light

As evident in the spectrum chart and the discussion so far, the wavelengths to which the human eye is sensitive form a middle reference area in the over-all optical spectrum. As a photodetector, the human eye has some peculiarities that become important in the context of photometry.



6. Day and night. Peak optical response of the human eye shifts about 50 nm as the eye adjusts from the brightness of normal daylight (photopic vision) to nighttime starlight levels (scotopic vision). There is no color perception under scotopic conditions.

The retina contains two types of receptors, responsive to two different ranges of wavelengths (Fig. 6). In daylight, one set of receptors responds to wavelengths from about 400 to 700 nanometers, with a peak response centered in the green region at 555 nanometers. This is the eye's light-adapted or photopic response.

When adapted to darkness, the other set of receptors comes into play, with a peak response at 507 nm. This dark-adapted or scotopic eye is color-blind, whereas the light-adapted eye is able to discriminate between color wavelengths. Photometric units of light intensity (see "Photometry and radiometry defined," p. 111) are weighted by the photopic eye's normalized response.

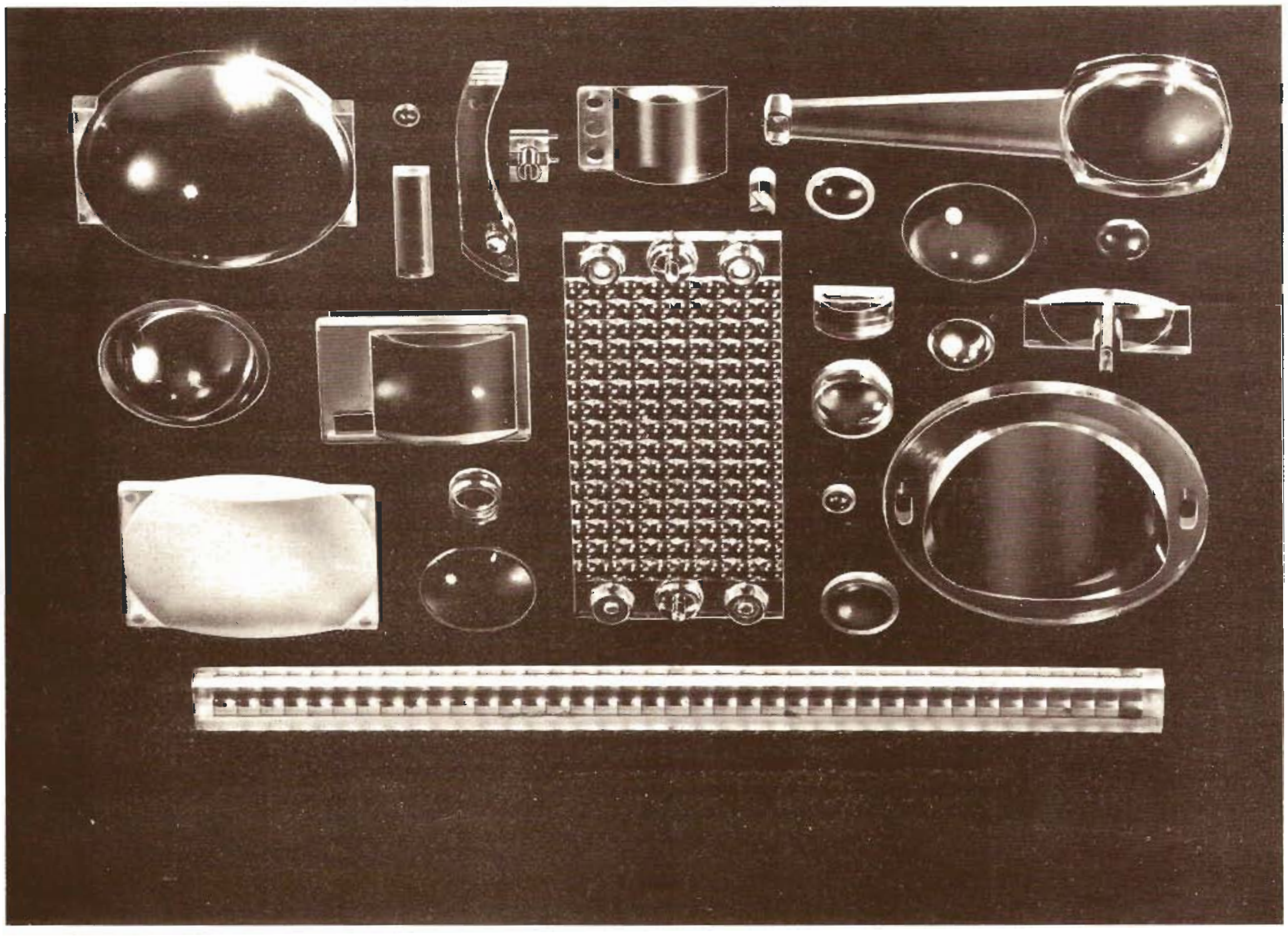
Transmission materials

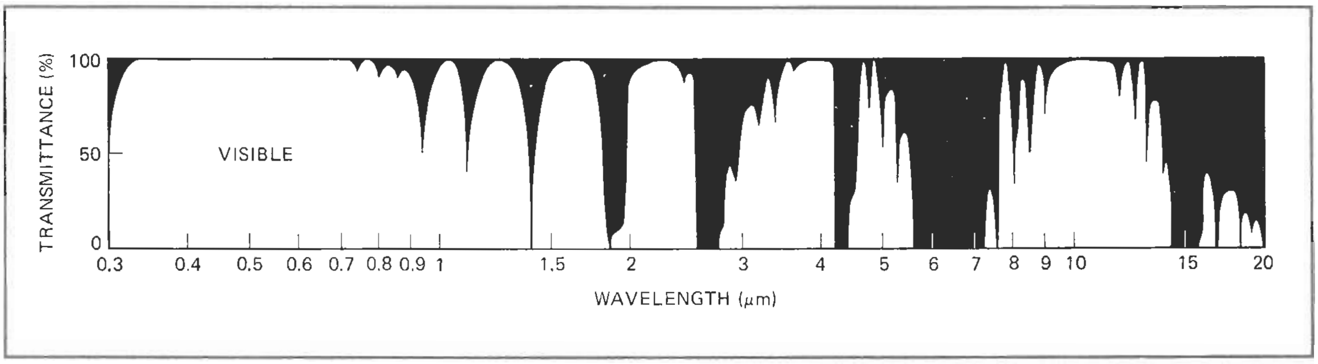
Light travels between a source and a detector through a transmission medium which may substantially alter the light's properties and usually passes only a portion of the optical spectrum. Transmission materials include glass, plastics and other transparent compounds, and function as protective windows, lenses, or optical filters.

In the visible portion of the spectrum, common soda-lime glass is used extensively as a window material. Its transmittance is very nearly 100% over the entire visible range, but falls off quite rapidly on each end (30% transmittance cutoff points are approximately 350 and 3,000 nm).

Injection-molded plastics, however, are ousting glass in many applications in the visible spectrum [*Electronics*, July 3, 1972, p. 77]. While plastic is more susceptible to temperature and abrasion than glass, its low cost of

7. Plastic optics. For an increasing number of production applications, the low cost of molded plastic lenses and windows more than offsets their high-performance limitations when compared to glass or other optical transmission materials.





8. Atmospheric windows. Transmittance through 1,000 feet of atmosphere is high throughout the visible spectrum, but periodically falls to zero in the infrared region between 1 and 20 micrometers. Window from about 8 to 13 μm is region of special interest to equipment designers; it peaks at about 10.6 micrometers, which is also the wavelength of the CO_2 laser.

production more than compensates for these limitations in many commercial and industrial electro-optic systems. The most popular plastics—acrylic, polystyrene, and polycarbonate—transmit over the entire visible spectrum, and some plastics become transparent again at the very long infrared wavelengths past 50 to 100 μm.

Widening the window

Since glass and plastic are opaque to ultraviolet wavelengths below about 350 nm, more exotic window materials must be found for equipment operating in the ultraviolet region. For this purpose, fused quartz, sapphire, and lithium or magnesium fluoride are commonly used.

Fused quartz passes ultraviolet wavelengths as low as 180 nm, besides being transparent at all visible wavelengths. It is relatively inexpensive and is commercially available from several manufacturers. Sapphire (Al_2O_3) and lithium fluoride (LiF) are more expensive. Sapphire is the most abrasion-resistant of all windows and has good ultraviolet transmitting properties to 180 nm, and lithium fluoride is most attractive for applications requiring transmittance at wavelengths down to about 104 nm.

As for far-infrared wavelengths beyond about 4 μm, one optically good material is sodium chloride, NaCl. Windows or lenses made of NaCl transmit IR wavelengths to a little beyond 20 μm, but because they absorb moisture from the air, must be frequently replaced or stored in dessicators to keep them dry.

A more durable group of IR transmission materials is the commercially available line called Irtran, developed by Eastman Kodak Co. The spectral transmittance of these materials is approximated on the foldout chart, and they are made of MgF_2, ZnS, CaF_2, ZnSe, MgO, and CdTe respectively for Irtran-1 through Irtran-6.

Other infrared-transmitting materials include barium fluoride, cesium iodide, and thallium bromide. Barium fluoride is often used in systems operating at 10.6 μm, the wavelength of frequently used CO_2 lasers. Cesium iodide and thallium bromide both transmit at wavelengths to about 50 μm.

Atmospheric properties

Depending on its wavelength, light energy is selectively scattered, absorbed, or refracted as it passes through the earth's atmosphere. These effects can be severe in optical communications, infrared radiometry, and, in fact, viewing by the human eye, whenever the atmospheric path extends more than just a short distance.

For gas molecules and particles that are extremely small in relation to the light wavelength, the degrading process is known as Rayleigh scattering. Such scattering is the cause of the blue of the midday sky and the red of sunsets. Rayleigh scattering is wavelength-dependent, increasing with shorter wavelengths, and it has a negligible effect on infrared wavelengths longer than about 1 μm.

For larger aerosol particles, the process is called Mie scattering and is relatively independent of wavelength. The nonselective nature of Mie scattering is what makes fog and clouds appear white. Its effect on visibility is to reduce contrast to the point where an object's outline can no longer be resolved. Visibility in haze, then, is commonly defined as the distance at which contrast is reduced below 2%.

Attenuation through the atmosphere is never constant. It depends on such parameters as temperature, pressure, and amount to water vapor and other impurities. However, a typical attenuation as a function of wavelength is shown in Fig. 9. The attenuations shown are for a 1,000-foot atmospheric path, at sea level, containing relatively little moisture and impurities. The curve identifies the important atmospheric window in the visible region from 400 to 700 nm. It also shows the 6-μm-wide window centered at about 11 μm, which is of much current interest to infrared systems designers.

Tight fit

In conclusion, it's interesting to note the relationship between the (humanly speaking) most important source, detector, and transmission medium found in nature. The peak spectral output of the sun (about 555 nm) coincides with the center of a major optical window in the earth's atmosphere. The peak response of the human eye is conveniently adapted to this wavelength. □

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Copies of the optical spectrum chart following this page are available at $2.00 each. Write to Electronics Reprint Department, P.O. Box 669, Hightstown, N.J. 08520.