PHOTOMETRIC LIGHT SOURCES

Any emitter of electromagnetic radiation is a photometric light source. Electromagnetic radiation is produced whenever a charged particle, such as an electron, is accelerated (synchotron radiation) or decelerated (bremsstrahlung radiation). This occurs in a number of ways. For instance, heat is the irregular motion of electrons, atoms, and molecules. The higher the temperature, the more rapid the motion. Such thermal motion produces irregular oscillatory charge motion, and each oscillation at a particular frequency acts as a tiny "antenna" that emits and receives electromagnetic radiation. Other prevalent physical processes that produce electromagnetic radiation are the quantum energy transitions within materials by electron orbital energy transitions within atoms, recombination of free electrons with atoms, or transitions from excited bonding states of atoms within molecules. Absorbed energy raises a system to an excited state, and electromagnetic radiation is released upon transition to a lower energy state. The frequency of the radiation is related directly to the energy transition. As energy transitions are quantized characteristics of the material makeup, so is the frequency of the electromagnetic radiation produced.

Almost all photometric light sources used in practice result from one of two categories of physical phenomena: (1) incandescence and (2) luminescence. Light from incandescent bodies, such as burning wood or coal, molten iron, and filament wire heated by an electric current, results from thermal motion. Luminescence observed in fluorescent lamps, X-ray fluoroscope screens, organic substances found in fireflies and glowworms, lightning, high intensity discharge lamps, light-emitting diodes, lasers, and, electroluminescent phosphors results from light emission after energy has been absorbed by a material raising its energy state and then subsequently transiting to a lower energy state. Luminescence is sometimes called "cold light" because a number of photometric light sources based on this phenomenon operate in the vicinity of room temperature. In some cases the distinction between incandescent and luminescent phenomena becomes blurred, such as in shock tubes at very high temperatures, where the collisions of atoms are so violent that electrons dissociate from the atoms and then recombine.

The functionality of a light source is largely determined from the wavelength (frequency) distribution of electromagnetic radiation that it produces. The top diagram of Fig. 1 shows the wavelength range (log scale) and standard nomenclature used for various spectra of electromagnetic radiation. The three diagrams below in Fig. 1 show further subdivisions of specific wavelength spectra. The term *photometric light sources* is applied to sources of electromagnetic radiation emitting at any of the wavelengths in Fig. 1, although the term "light" is usually only applied to electromagnetic radiation visible to the human eye.

The visible spectrum with a wavelength from roughly 400 to 700 nm produces different color perceptions which are chromatically completely saturated for single wavelength distributions. Multiple wavelength distributions in this range produce less saturated colors, white light, and other colors, such as earth tones. Longer wavelength infrared electromagnetic radiation comprises much of the thermal emission from materials at room temperature to well above 5000 K. The subdivision of infrared radiation into near, intermediate and far is standard terminology that has grown out of various measurement applications, although the divisions are arbitrary. Ultraviolet electromagnetic radiation has a wavelength shorter than visible light and the main difference of this type of radiation from that at longer wavelengths is its ability to ionize atoms by removing electrons. This gives ultraviolet radiation the ability to influence chemical reactions, such as in plant life, and it also makes this type of radiation potentially harmful to human and animal life. Photobiologists have as-

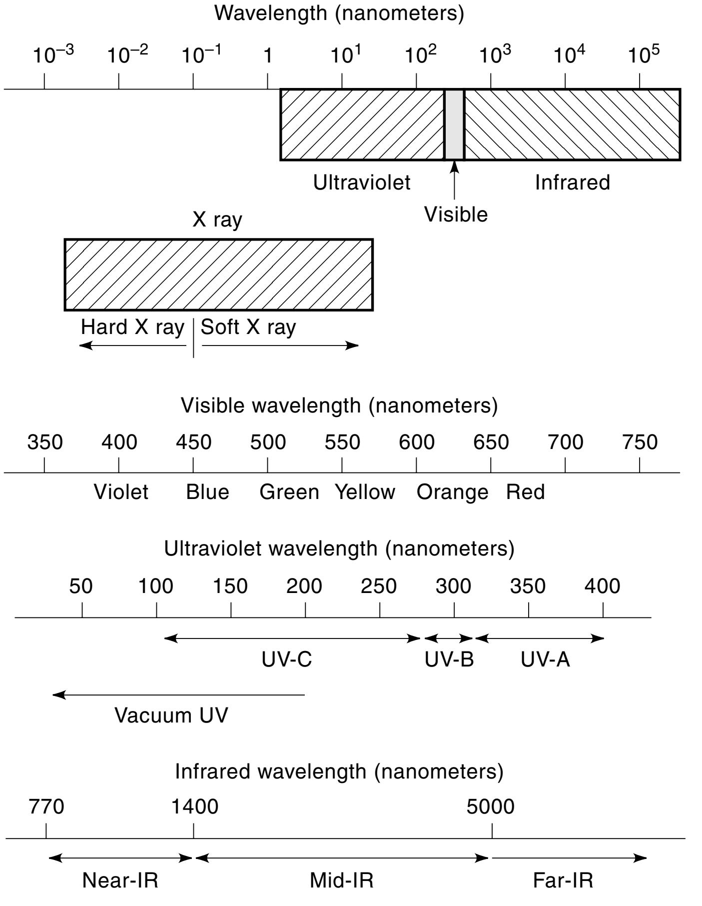

Figure 1. Nomenclature for important divisions and subdivisions of part of the electromagnetic spectrum.

signed significance to the UV-A, UV-B, and UV-C subregions of the ultraviolet spectrum according to their interaction with biochemical phenomena. Of great importance to ultraviolet spectroscopy is the spectral region below 200 nm in which ultraviolet radiation is absorbed by air. Hence the term *vacuum* ultraviolet requiring the almost complete evacuation of air from instrumentation measuring or producing such radiation. At still shorter wavelengths (higher frequency) is X-ray electromagnetic radiation. Infrared, visible, and ultraviolet radiation are produced by ionization/recombination in the outer valence electrons of atoms. The X-ray region occurs at the higher ionization/recombination energies involving the inner electron orbitals of atoms. X rays are energetic enough to ionize and also to penetrate many materials. "Hard" and "soft" X rays are differentiated by their penetrating power. The top diagram of Fig. 1 shows other important forms of electromagnetic radiation, longer wavelength millimeter and still longer radio waves to the right and high-frequency energetic gamma rays from cosmic sources to the left.

The generation of electromagnetic radiation by photometric light sources is classified into two categories: (1) systems and processes that produce electromagnetic radiation covering a broad continuous spectrum of frequencies and (2) those that emit electromagnetic radiation of discrete frequencies characteristic of the materials making up the light source. For most photometric light sources, the production of continuous and discrete spectra are concurrent. A classic example of a continuous spectrum-emitting source is an ideal blackbody radiator, which is used as a fundamental reference standard. The term blackbody refers to an object that absorbs all frequencies of electromagnetic radiation, and hence appears black when emitting little radiation at cooler temperatures. The rule of reciprocity states that a body radiates strongly at those frequencies it absorbs. Analogous to the oscillation of charges from thermal motion as "tiny antennas," an antenna is part of an electric resonance circuit that transmits and receives at the same frequency. A piece of black coal is a good example of a blackbody. When heated to increasingly high temperatures, it first glows red, then yellow, and finally white. The continuous distribution of frequencies depends solely on its absolute temperature and the frequency at which the maximum radiative energy increases in proportion to absolute temperature. When glowing red, a blackbody emits a large portion of infrared radiation. When glowing white, a significant amount of ultraviolet radiation is emitted.

Because of the inhibition of certain oscillatory modes of electric charges, in practice all materials are *selective* radiators with respect to emission at a particular wavelength compared with the emission from an ideal blackbody at exactly the same temperature. The ratio of the emission energy of a material to the emission energy of a blackbody at the same temperature and at a particular wavelength is called the wavelength *emissivity* of the material. Emissivity also depends on the direction in which radiation is emitted relative to the body. The closer the emissivity of a material to 1.0, the better the approximation to a blackbody at that wavelength. For instance, tungsten in incandescent filaments has high emissivity in the visible spectrum, but lower emissivity in the infrared. As a visible photometric light source, heated tungsten filaments closely approximate the output of a blackbody. Glass is transparent because it transmits (i.e., lacks absorption) visible light radiation and as a result has low emissivity in the visible spectrum. Heated glass looks relatively colorless compared with heated opaque materials. However glass has even higher emissivity than tungsten in the mid-infrared. References 1–3 provide thorough background on the topics discussed thus far.

Other sources of continuous frequency spectra of electromagnetic radiation are high-energy electron accelerators, appropriately called synchotrons because they use magnets to accelerate free electrons in circular orbits. The first experimental investigation was conducted in 1947 on the 70 MeV General Electric synchotron to produce visible light radiation. Subsequently higher energy synchotrons were developed which produce broad continuous spectrums at higher frequencies into the ultraviolet and X-ray spectral regions.

Sources of discrete frequencies or line spectra are produced from energy transitions characteristic of the atomic and/or molecular structure of the material comprising the light source. Some important examples include the five principal visible spectral lines of mercury gas from a high-intensity mercury discharge lamp and the 589nm strong spectral line from a high-pressure sodium lamp. The intense line spectra for these lamps occur against a lower grade background of a radiative frequency continuum. Laser light is produced by light amplication by stimulated emission of radiation and is coherent (i.e., all emitted light is in the exact same phase), monochromatic or containing only a few monochromatic lines, and is intensely focused within a narrow aperture beam. Atoms of a material are stimulated to an excited state by using a noncoherent light source or with electricity, and synchronous radiative emission occurs from the corresponding synchronously generated energy transitions. An example is the red HeNe laser with its characteristic 632nm radiation.

BLACKBODY RADIATION

In the 1890s the German physicist Wilhelm Wien came up with the idea of constructing a good approximation to an ideal blackbody photometric light source by using an enclosed oven to create a cavity with a small hole through which the cavity can be viewed. The radiation coming out of this hole is very close to the equilibrium blackbody electromagnetic radiation corresponding to the oven temperature. Any external radiation that enters the hole is internally scattered and reflected within the cavity so that almost all of it is ultimately absorbed, and extremely little finds its way back outside the hole. Wien carefully measured the radiative energy dW per wavelength interval $d\lambda$ for the blackbody radiative distribution.

The theory to accurately explain the shape of this empirically observed blackbody radiative distribution came shortly later in 1900 when Planck used the radically new idea that internal electric charge oscillators within the blackbody emit only electromagnetic radiation in finite quantized amounts of energy of size $E = h\nu$, where ν is the frequency of the radiation. With $c = \lambda\nu$, the Planck radiation law accurately predicts that the radiative energy per unit wavelength for a blackbody is given by

$$\frac{dW}{d\lambda} = \frac{8\pi ch\lambda^{-5}}{e\dfrac{hc}{\lambda kT} - 1}$$

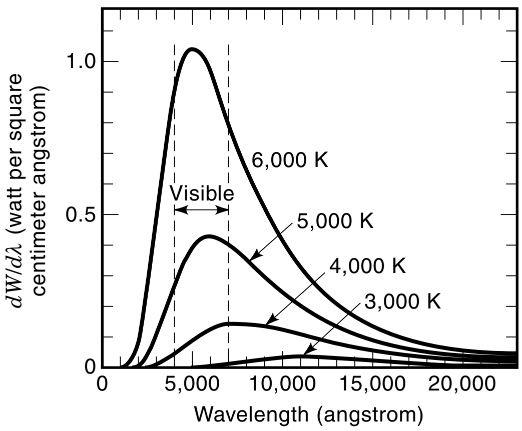

Figure 2. Spectral power distribution for a blackbody at various absolute temperatures, predicted by Planck's radiation law.

where $k = 1.38 \times 10^{-23}$ J/K is Boltzmann's constant from thermodynamics. The value of Planck's constant $h = 6.626 \times 10^{-34}$ J · s is determined from the best fit with empirical data. The properties of this distribution are consistent with Wien's law which states that the product of the wavelength with maximum radiative energy and the absolute temperature is an absolute constant $\lambda_m T = 0.2898$ cm · K and are consistent with the Stefan-Boltzmann law that the total radiant energy emitted per second and per unit area W of a blackbody is proportional to the fourth power of the absolute temperature, $W = \sigma T^4$, where $\sigma = 5.67 \times 10^{-12}$ $W/(\text{cm}^2 \cdot \text{K}^4)$. Figure 2 shows wavelength distribution plots for a blackbody at various absolute temperatures.

LUMINESCENCE

In contrast to incandescence, radiative emission from luminescent phenomena occurs at relatively cool temperatures. The process by which an appropriate material absorbs energy and then subsequently releases electromagnetic radiation upon an electronic transition to a lower energy state or its original ground state occurs in a variety of ways depending on (1) how the electronic transitions occur and (2) in what form energy is initially absorbed by the material. In all cases the energy transitions involve the outer valence electrons of atoms comprising the material. The field of luminescence is very broad, so discussion here is limited to that most practically relevant to photometric light sources.

For luminescence there is an important distinction between two different types of electronic transitions upon absorbing energy, *fluorescence* and *phosphorescence.* The process of radiative emission from fluorescence occurs very quickly, on the order of 10 ns after initial excitation. The high-energy excited state upon absorption is unstable and therefore rapidly transits back to a lower state. Sometimes there are metastable excited states in fluorescent materials that are much longer-lived before transiting to a lower state. Radiative emission from such a phenomenon is called phosphorescence and, from the time of initial excitation, transition back to a lower energy state takes anywhere from milliseconds to several days.

The predominant sources of energy initiating luminescence in photometric light sources are ultraviolet or visible electromagnetic radiation and electricity. The former is called *photoluminescence* and the latter is called *electroluminescence.* In photoluminescence the wavelength of emitted light typically has a wavelength longer (i.e., lower frequency and therefore lower energy) than the incident radiation. Other sources of energy for luminescence are electron guns, such as in television tubes, and particles emitted by radioactive materials which is called *radioluminescence.*

MEASUREMENT OF LIGHT SOURCES

The terms "intensity" and "color" of a light source are often used loosely, but each of these has a formal International Standard (SI) definition that is universal in practical application. Units of radiosity apply to energy of light radiation whereas units of luminosity apply to the perception of the energy of light radiation by the human eye. For instance radiant intensity from a light source refers to the radiant flux per unit solid angle, usually expressed in watts per steradian. The SI unit for luminous intensity is the candela. One candela is the perceived luminous intensity of monochromatic radiation at 540×10^{12} Hz (approximately 555 nm) at the radiant intensity of 1/683 watt per steradian. The *lumen* is the SI unit of luminous flux. One candela is equal to one lumen per steradian. The human spectral photopic response curve is approximately a bell shape which is maximal at 555 nm (yellow–green light) and falls to zero near 400 nm on one side and near 700 nm on the other side. Because the spectral response of the human eye is variable from 400 to 700 nm, the relationship between watts and lumens, therefore, is wavelength-dependent. The ratio of lumens to watts is termed *luminous efficacy.* Maximum efficacy of 683 lm/W is achieved at a wavelength of 555 nm and falls off in proportion to the spectral response to blue and to red. Many visible light sources are rated in terms of the luminous efficacy of their spectral outputs. See reference (7) for more details.

Instruments called *radiometers* are used to measure radiant power (watts) of light sources that is cumulative over wide ranges of wavelengths including the ultraviolet, visible, or infrared spectral regions. Radiometers employ a variety of detectors, such as thermocouples, thermopiles, and pyroelectric detectors. Visible radiometers use a filter transmitting light according to the human spectral photopic response for measuring luminous power (lumens). By incorporating a device called a *monochromator* which separates or disperses the various wavelengths of the spectrum through prisms or gratings, one can determine the radiant power in a very small range of wavelengths. Such an instrument called a *spectroradiometer* measures the spectral power distribution for a light source, which is the radiant power per unit wavelength, as a function of wavelength. From the spectral power distribution, one determines all radiometric, photometric, and colorimetric properties of a light source in the absolute sense.

Radiometers are limited to measuring light power within a small aperture. An instrument called an *integrating sphere photometer* measures the total radiant power emitted by a light source over the entire 4π steradian spherical solid angle. The most common is called the Ulbricht sphere which is about 3 m in diameter and whose inner coated surface, ideally, is coated by a perfectly diffusing substance with uniformly nonselective reflectance. White magnesium oxide and barium sulphate are coating materials that come close to these properties. The light source is placed at the center of the sphere, and every point on the inner surface then reflects to every other point so that the flux incident on each unit area along the inner wall is uniform regardless of the angular distribution of the emitted power from the source. The total flux E received per unit area of the sphere from reflection and multiple interreflections is related to the total flux F emitted by the source inside the sphere, according to the following expression:

$$E = \frac{\rho F}{4\pi r^2(1-\rho)}$$

where r is the radius of the sphere and ρ is the total energy reflectance coefficient of the material (4). In practice this formula requires a number of photometric corrections due to nonuniform reflectance in wavelength and nonuniformity across the interior surface of the sphere. Another way of computing total luminous flux is by comparing the measurement of flux incident on a unit area of the inner surface of the sphere for two light sources. If the total emitted power of one of the light sources is known, then the total power of the other light source can be determined.

COLORIMETRY

Perception of the color of light radiation by the human eye was first internationally standardized by the Commission Internationale de l'Eclairage (CIE) in 1931. A system for the CIE standard observer was defined in terms of color matching functions used to convert a spectral power distribution into tristimulus color values. A set of three color matching functions $\overline{X}(\lambda)$, $\overline{Y}(\lambda)$, and $\overline{Z}(\lambda)$ convert a spectral power distribution $P(\lambda)$ into tristimulus values X, Y, and Z according to the following equations

$$X = \int_\lambda P(\lambda)\overline{X}(\lambda)$$
$$Y = \int_\lambda P(\lambda)\overline{Y}(\lambda)$$

and

$$Z = \int_\lambda P(\lambda)\overline{Z}(\lambda)$$

where integration is from 400 to 700 nm. For a given fixed set of color matching functions $\overline{X}(\lambda)$, $\overline{Y}(\lambda)$, and, $\overline{Z}(\lambda)$ there is an infinity of spectral distributions $P(\lambda)$ that produce exactly the same tristimulus values X, Y, and Z. Therefore each tristimulus set of values corresponds to an equivalence class of spectral distribution functions called *metamers* with respect to the color matching functions. The chromatic coordinates x,

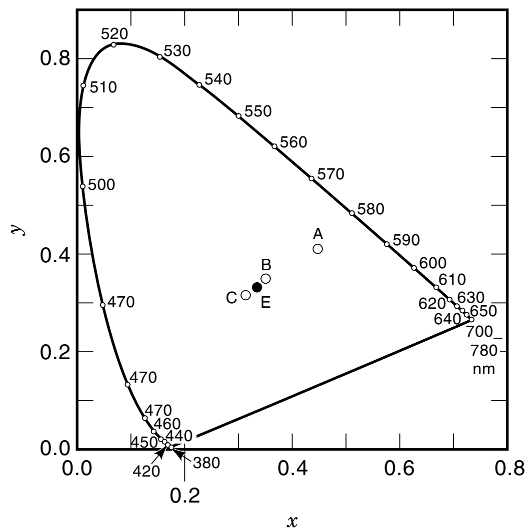

Figure 3. 1931 CIE chromaticity diagram showing chromatic coordinates for the pure spectral colors, CIE standard light sources A, B, and C, and the equal-energy source E (4).

y, z for a color are defined as the ratio of each tristimulus value of the color to their sum:

$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z}$$

and

$$z = \frac{Z}{X+Y+Z}$$

Chromatic coordinates have two degrees of freedom because specifying x and y automatically determines z on the plane $x + y + z = 1$.

The color matching functions developed for the 1931 CIE standard observer are based on earlier work on color matching for chromatic coordinates of the pure spectral colors. Details of the derivation for these color matching functions along with tabulated and graphed values are in (4). Two important criteria are (1) that the middle color matching function $\overline{Y}(\lambda)$ is the photopic spectral response function for the human eye and (2) all three color matching functions are nonnegative for all wavelengths in the visible spectrum. The first criterion implies that the tristimulus value Y represents the photopic intensity. Figure 3 shows a plot of the pure monochromatic spectral colors in the x–y CIE chromatic space together with the plot of the CIE standard light source A at $x = 0.448$, $y = 0.407$, the CIE standard light source B at $x = 0.348$, $y = 0.352$, and the CIE standard light source C at $x = 0.310$, $y = 0.316$. The definitions and constructions of these CIE standard light sources are discussed in the subsection "Incandescent Sources." The "equal-energy" source at point E where $x = y = 1/3$ appears as an achromatic gray tone. In 1964 color matching functions were developed to improve performance for a CIE standard observer viewing colors over a wider field of view of 10°, compared with the 1931 CIE standard observer which performs well over a narrow field of view of 2°.

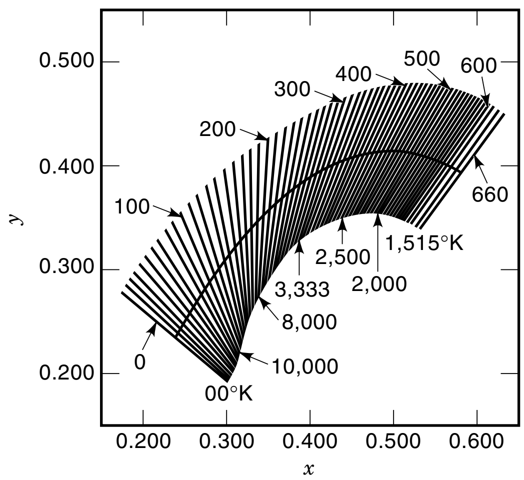

Figure 4. 1931 CIE chromaticity diagram showing the Planckian locus and isotemperature lines (4).

The trace of points in CIE chromatic space that represent x–y values for spectra produced by blackbodies is known as the *Planckian locus* depicted as a solid curve in Fig. 4 for absolute temperatures ranging from 1515 K up to infinity. An important parameter for a visible photometric light source, particularly an incandescent filament source, or a high-intensity discharge lamp is its correlated color temperature or simply its color temperature. The idea is that, given a spectral output for a light source, what is the absolute temperature of a blackbody producing the most similar spectral output sensed by a standard observer. For lamps emitting a spectrum with CIE x–y coordinates in the vicinity of the Planckian locus, the color temperature is the "nearest" point on the Planckian locus to this CIE point. This was formalized by Judd (6) using isothermal lines which were recomputed by Kelly (5) in the 1931 CIE chromatic space shown in Fig. 4. Most often the color temperature of a visible light source is not the same as the actual operating temperature of the source. Even for incandescent tungsten filament lamps heated to different temperatures which lie quite close to the Planckian locus, the filament temperature is always lower than the color temperature (e.g., by about 40 K at color temperatures around 2850 K) because of the wavelength-dependent emissivity of tungsten. Visible light sources producing CIE x–y coordinates far from the Planckian locus, such as some fluorescent lamps, are still assigned a color temperature although this is more for convenience in interior lighting design than for physical meaning.

VISIBLE LIGHT SOURCES

A diverse variety of designs are available today as sources of visible light radiation. These include incandescent filament lamps, high-intensity discharge lamps, short-arc lamps, fluorescent lamps, light-emitting diodes, electroluminescent phosphor lamps and even nuclear light sources. A number of these designs simultaneously produce a significant amount of electromagnetic radiation at wavelengths longer and shorter than visible light also making some of them good infrared and ultraviolet sources. The choice of design of a visible light source for a particular application depends on a number of factors including spectral output, radiant intensity requirements, power consumption, luminous efficacy, temperature conditions, and durability.

Incandescent Sources

Incandescent filaments are the most commonly used source of visible light radiation. An electric current is passed through a filament which glows because of thermal motion. The filament is encased in a glass envelope evacuated to prevent oxidation of the filament. The criteria for a filament material are high melting point, low vapor pressure, high strength, high ductility, and suitable radiative and electrical resistance characteristics. Earlier designs for incandescent filaments used carbon, osmium, and tantalum, but tungsten with its high melting point of 3655 K and good adherence to the other desirable properties for a filament is now the most widely used material. Subsequent designs have alloyed tungsten with metals, such as rhenium, for desired spectral characteristics, and thorium is used in tungsten filaments for rough service applications.

More recently the tungsten-halogen lamp prolongs lifetime and operates at a higher filament temperature up to 3500 K. Metal halides are added inside the glass envelope at low pressures creating a cycle of dissociation and recombination that reduces gradual blackening of the envelope by tungsten evaporated from the filament. The filament heats the metal halide gas disassociating it into metal and halogen. Tungsten evaporated from the filament combines with the halogen. When tungsten halide contacts the hot filament, the tungsten recombines with the filament, disassociating it from the halogen and completing the cycle. Tungsten-halogen bulbs are available with power up to 1000 W using a power supply between 8 and 13 V at high current. Because the output varies roughly as the eighth power of the current, the stability of the power supply is quite stringent.

Standard sources for colorimetry use incandescence from tungsten filaments with added features. Standard source A is a tungsten filament operated so that the correlated color temperature is at 2856 K. Standard source B approximates noon sunlight with a correlated color temperature of approximately 4874 K. Standard source B uses the standard source A in conjunction with a special filter one centimeter thick consisting of layers which include compounds of copper and cobalt. Standard source C approximates daylight provided by a combination of direct sunlight and clear blue sky with a correlated color temperature of approximately 6774 K. Standard source C is of construction similar to standard source B except that the special filter has different concentrations of copper and cobalt compounds. In addition there are D-type standard illuminants D_{55}, D_{65}, and D_{75} which approximate different phases of natural daylight with respective correlated color temperatures of 5500 K, 6500 K, and 7500 K.

High-Intensity-Discharge Sources

When an electric arc is struck within a gas, some of the atoms and molecules of the gas ionize producing free electrons whereas others are excited to high energy states. Subsequent quantum electronic energy transitions within excited atoms and molecules to lower energy states causes the emission of various line spectra characteristic of the gas. A broad continuous spectrum of light radiation is also produced by a number

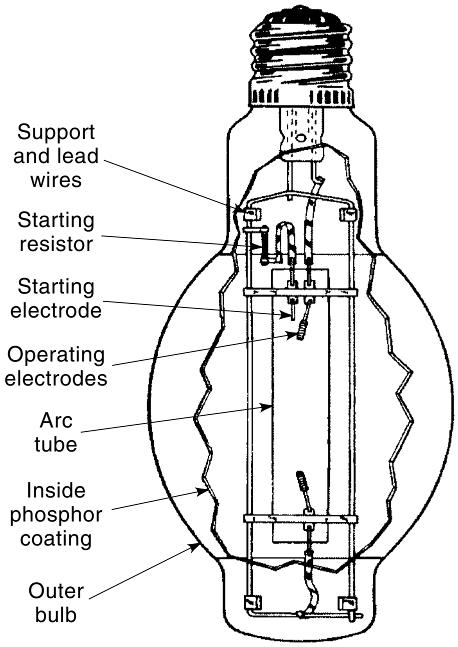

Figure 5. A 400 W phosphor-coated mercury lamp (7).

of phenomena including (1) energy transitions from stable excited electronic states of a molecule to lower repulsive states, (2) the recombination of free electrons with ions, and, (3) the acceleration and deceleration of free electrons within the electric arc. Except for (3), all of these phenomena that produce light radiation are examples of electroluminescence. For light production in the visible spectrum, the most common high-intensity-discharge lamps are mercury, metal halide, and high-pressure sodium.

The basic construction of a high-intensity-discharge lamp consists of a starting electrode and a pair of operating electrodes contained in an evacuated glass tube. The tube contains the principal gas or gases responsible for light emission and a rare gas, such as argon or xenon, which is easily ionized, to help initiate the electric arc. The principal gas or gases have very low vapor pressure at room temperature and require very high voltage to create an electric arc between the operating electrodes. Instead, an arc is initially struck by ionizing the rare gas with the starting electrode heated up. This produces heat which in turn raises the vapor pressure of the principal gas or gases facilitating the creation of an electric arc between the operating electrodes at lower voltages. Adding rare gases also reduces the warm-up time to full operational output.

Figure 5 shows the standard construction of a mercury lamp. The mercury lamp uses mercury gas and approximately 10 to 30 torr pressure of argon gas to initiate the electric arc. When in full operation, the vapor pressure of the mercury gas is usually between two and four atmospheres. The characteristic mercury spectrum consists of five visible principal lines at 404.7, 435.8, 546.1, 577, and 579 nm. This occurs against a continuous broad spectrum which extends well into the ultraviolet. Altogether a mercury lamp appears bluish-white. Increasing the operating vapor pressure of the mercury pushes the continuous spectrum to longer wavelengths (i.e., more red is added). Figure 5 shows the mercury lamp constructed with two glass envelopes. The inner envelope (arc tube) contains the electric arc and the outer envelope shields the arc tube from convection drafts and is usually filled with an inert gas, such as nitrogen, to prevent oxidation of internal parts. The outer envelope also provides an inner surface for a phosphor coating which converts the high amount of emitted UV radiation to visible light by photoluminescence (fluorescence), thereby increasing the efficiency of light power output.

Metal halide lamps are constructed similarly to mercury lamps. Combinations of metal halide gases are added with mercury and argon to produce the spectra of metallic elements. This improves color balance and increases luminous efficacy. Three typical combinations of halides used in metal halide lamps are (1) sodium, thallium, and indium iodides; (2) sodium and scandium iodides; and (3) dysprosium and thallium iodides. Because strong characteristic lines of sodium (589 nm) and thallium (535 nm) are so close to the maximum efficacy wavelength of 555 nm, these particular halides are added to increase efficacy. The use of metal halides in discharge lamps is to combine spectral lines of metals providing two desirable advantages. First, although fused silica comprising the inner arc tube chemically reacts with some metals by themselves, it does not react with the metal halides when they are at the cooler wall temperature. The second advantage is that whereas some metals cannot be vaporized at temperatures which fused silica withstands, they are vaporized when they approach the high temperature central core of the arc tube.

High-pressure sodium lamps are produced by passing an electric current through sodium vapor above 200 torr pressure. Xenon is used as a starting gas. Because of the small diameter of the tube used for sodium lamps, no starting electrode is present, and an arc is initialized by a high-voltage, high-frequency pulse. A high-pressure sodium lamp is golden-white with all frequencies present and the strong 589 nm line characteristic of sodium. Low-pressure sodium lamps principally radiate the 589 nm spectral line and appear as an almost monochromatic yellow. For best efficacy, the vapor pressure for a low-pressure sodium lamp is about 0.005 torr. Although the low-pressure sodium lamp has very high efficacy, it requires much more power than the high-pressure sodium lamp per watt of output.

Short-Arc Sources

Short-arc lamps are basically high-intensity-discharge lamps with very high gas vapor pressure and a small interelectrode distance compared with the diameter of the enveloping tube. Depending upon rated wattage, the length of the electrode-stabilized arc varies from about 0.3 up to 12 mm. The output of these arcs has the highest luminance and radiance of any continuously operating visible light source (i.e., up to well above 30,000 W) and are the closest to a true "point" source. These lamps are used primarily in searchlights, projectors, display systems, and optical instrumentation, such as spectrophotometers.

Mercury and mercury–xenon short-arc lamps are available from 30 to 5000 W operating under the same principle as the mercury high-intensity-discharge lamp. With the same pressure of argon as a starting gas as the standard mercury lamp, the mercury short-arc lamp requires several minutes to achieve full operation. Adding over one atmosphere of xenon gas, the resulting mercury–xenon lamp reduces warm-up time to full operation by about half. The spectral power distribution for both the mercury and the mercury-xenon lamps are essentially the same in the visible spectrum.

Xenon short-arc lamps are filled with approximately five atmospheres of xenon gas and are available from 5 W up to 32,000 W output. Their appearance closely resembles a phase of daylight similar to the visible range of the blackbody spectral distribution at 6000 K. The time to full operational output is quite short, reaching 80% immediately after the initial start.

Fluorescent Sources

The most commonly used fluorescent sources combine light production from electroluminescence and photoluminescence to create a low-temperature discharge lamp. As with the mercury lamp, both mercury and argon gas fills a tube except at much lower pressure. At the operational temperature of 40°C, the vapor pressure of the mercury gas is maintained at about 0.008 torr, and argon gas used to initiate the electric arc is maintained at from one to three torr depending on energy-saving measures. At this low operating pressure, the mercury gas primarily emits a strong characteristic line in the UV at 253.7 nm which is invisible to the human eye. The inside of the tube for the fluorescent source is coated with phosphors designed particularly to fluoresce when stimulated at this wavelength in the UV and reradiate visible light with desirable color properties. Two common phosphors are zinc silicate and magnesium tungstate. In addition to flourescence, these phosphors exhibit the longer-lived phenomenon of phosphorescence which helps to reduce the stroboscopic effect of ac current operation.

Like most gas-discharge lamps, the electric arc of fluorescent sources must be carefully regulated with a current limiting device called a ballast. The two electrodes hermetically sealed at opposite ends of the tube are designed for either "cold" or "hot" cathode operation, more correctly, respectively, called *glow* and *arc modes* of discharge operation. The tradeoff for these modes of operation is voltage versus current. Electrodes for glow (cold cathode) operation are coated with an electron emissive material, and the standard operating current is on the order of a few hundred milliamperes at 50 V. Electrodes for arc mode (hot cathode) operation are constructed from tungsten wire and, in operation, the current is on the order of 1.5 A at about 10 to 12 V. The lower voltage for the arc mode makes lamp operation more efficient and this is used most frequently.

Light Emitting Diodes

The light emitting diode (LED) is a p–n junction semiconductor device which emits radiation when a forward applied voltage yields a flow of current (see Figs. 6(a) and 6(b)). The material comprising an LED is a specially prepared semiconductor of high purity to which small amounts of other elements are added as controlled "impurities." One type of impurity creates an excess of electrons to produce n-type material, and another impurity has a shortage of electrons (i.e., "holes") which act as positive charges to produce a p-type material. When a dc voltage is applied to a p–n junction with polarity such that the n-type is negative and the p-type is positive, electrons are forced to meet at the junction and recombine with holes. Light radiation is produced by electroluminescence caused by the recombination of electrons in the conduction band with holes in the valence band. The energy gap crossed during this recombination determines the wavelength of the emitted radiation. Changing the energy gap and, therefore, the wavelength of emitted radiation is achieved by changing the composition of the added impurities. The ratio of the number of emitted

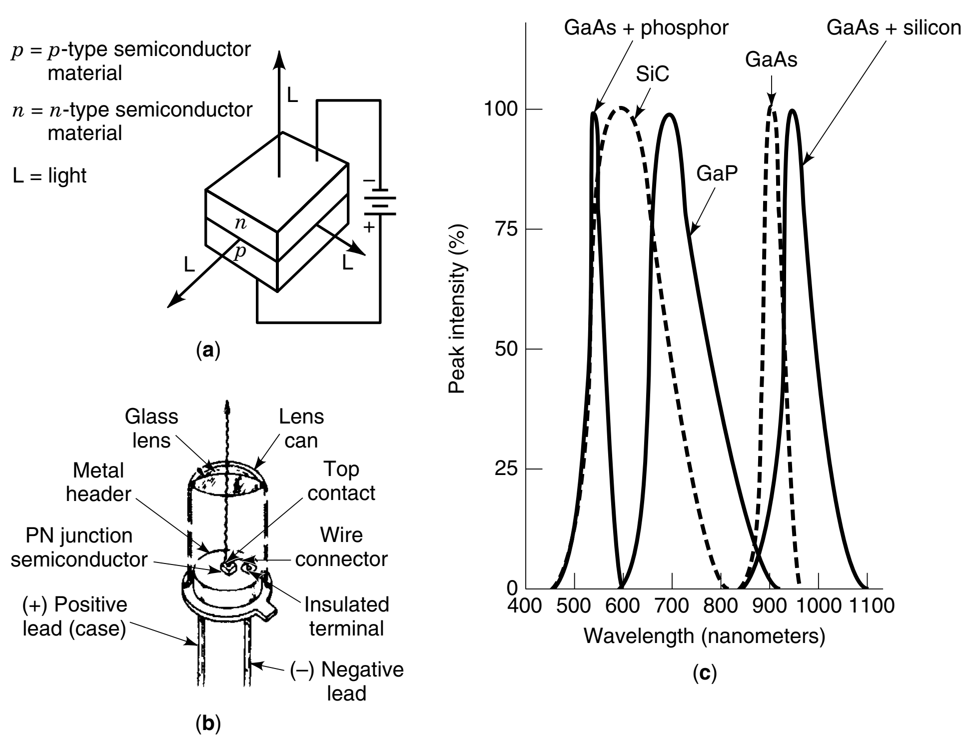

Figure 6. (a) A semiconductor junction. (b) A cross-sectional view of a typical light-emitting diode. (c) Spectral output of several light-emitting diode semiconductor materials (7).

photons to the number of electrons crossing the p–n junction is called the quantum efficiency. LEDs are made to produce electromagnetic radiation in various parts of the spectral range from 400 up to 2000 nm. Visible LEDs are used for numeric displays or for indicator lamps. Near-IR LEDs are used as opto-isolators or as sources in optical communication systems. LEDs generally operate in the range of 1 to 3 V at currents in the range of 10 to 100 mA.

The first visible LED with extensive applications and still in wide use today is based on gallium arsenide phosphide ($GaAs_{1-x}P_x$). The variable x controls the respective fractions as the elements used. One value used in practice is $x = 0.4$. For smaller values of x the spectral output is largely red light. As x is increased, the quantum efficiency is decreased but the wavelength distribution shifts lower toward 555 nm increasing efficacy. This LED can be made to emit longer wavelength radiation in the dark red and near-infrared by raising x above 0.45 and adding nitrogen. Other LED materials in use include aluminum gallium arsenide ($Al_xGa_{1-x}As$), and, gallium indium arsenide ($Ga_xIn_{1-x}As_yP_{1-y}$). Spectral output distributions are shown in Fig. 6(c) for some LEDs used in practice.

Semiconductor lasers are based on a variation of the light-emitting diode by carefully constructing structures at the p–n junction that promote stimulated emission and photomultiplication of photons which are then emitted in a single focused direction. One such laser uses ($Al_{0.3}Ga_{0.7}As$) where parallel mirrors perpendicular to the plane of the p–n junction are readily obtained by cleaving along this material's natural cleavage planes. Photons bounce back and forth between these parallel mirrors at opposite ends of the p–n junction causing electrons to recombine with holes and producing more and more photons which are partially transmitted as laser light by one of the mirrors.

Electroluminescent Phosphor Sources

Special phosphors exist that convert alternating current energy directly into visible light radiation purely by electroluminescence. This skips the intermediate step in discharge tubes of first having to create light indirectly to activate the phosphor. An electroluminescent phosphor, such as zinc sulfide or zinc sulfoselenide is placed between the two conducting layers of a plate capacitor. Standard 60 Hz alternating current at 120 V excites electrons within the phosphor that emit visible light radiation upon transition back to their ground state. The color of the visible light produced is controlled by adding different relative concentrations of activators, such as copper, lead, and, manganese. This produces low-luminance lamps for decorative lighting, night lights, switchplates, instrument panels, clock faces, telephone dials, thermometers, and signs. Colors of these lamps are blue, green, yellow, or pink. Rated wattage varies with applied voltage, frequency, and temperature.

Nuclear Sources

A nuclear light source is a self-powered device that uses a radioactive material to create light radiation. One design for such a source uses tritium gas, an isotope of hydrogen, to fill a sealed glass tube whose inner wall is coated with a phosphor. Tritium emits low-energy beta particles (i.e., electrons) which strike the phosphor causing it to fluoresce. This type of fluorescence is the same mechanism by which an electron gun creates a visible image on a television screen. Glass is impervious to the beta radiation so that it does not present a radiation hazard. The half-life of tritium is 12.3 years, although in practice half-intensity of these light sources is reached in about six to seven years, and they have a useful life of about 15 years (7).

INFRARED AND ULTRAVIOLET LIGHT SOURCES

Many of the same design concepts described for visible light sources are also employed as man-made sources of infrared and ultraviolet radiation. Incandescent tungsten filaments, in fact, radiate up to 70% of their power in the infrared region. Most of this is in the near-infrared between 800 and 1100 nm despite the lower emissivity of tungsten at these wavelengths. Tungsten–halogen lamps also have significant output in the 350 nm to 400 nm range. Figure 6(c) shows the spectral output for two types of GaAs light emitting diodes in the near-infrared. Synchotrons are ideal for producing a broad continuum of radiation throughout the entire ultraviolet region, but the engineering of high-energy electron accelerators makes this practical primarily for research in ultraviolet spectroscopy. Only some commercial applications are becoming feasible.

Discharge lamps are tuned to emit different amounts of electromagnetic radiation in the ultraviolet and in the infrared depending on the type and vapor pressure of gas(es) used. Xenon has intense spectral lines in the range from 780 to 1000 nm. A xenon-discharge lamp is a good near-infrared source together with a continuous infrared emission tapering off at about 2600 nm. A xenon-discharge lamp also has good continuous emission in the 200 nm to 400 nm range. A mercury-discharge lamp is used as a good near-infrared and mid-infrared source with continuous emission up to 2600 nm. As exploited for photoluminescent stimulation in visible light fluorescent sources, mercury discharge lamps are good ultraviolet light sources. In addition to the intense 253.7 nm spectral line, mercury lamps have good continuous emission from 240 to 400 nm. The most commonly used source in absorption spectrometers is the deuterium discharge lamp which has three to five times more power output than the previously used hydrogen-discharge lamp. The deuterium-discharge lamp has good continuous emission from 180 to 400 nm in the ultraviolet. Most photometric light sources for the vacuum ultraviolet region below 200 nm are high-intensity-discharge tubes filled with rare gases including helium, neon, argon, krypton, and xenon. For more detailed information on ultraviolet light sources consult (8,9).

SOURCES OF X RAYS

X rays were first discovered by Wilhelm Conrad Roentgen in 1895 while observing the effect radiation emanating from a high-voltage vacuum tube had on a piece of barium platinocyanide. Roentgen deduced that invisible radiation was emitted from the vacuum tube causing the barium platinocyanide to fluoresce. Even placing various materials between the vacuum tube and the barium platinocyanide, such as black paper, wood, and cardboard, did not prevent the fluorescence. Roentgen then observed the bones of his own hand when placing it between the tube and a sheet of cardboard coated with barium platinocyanide producing the world's first fluoroscopic screen. He called the invisible emissions X radiation before it was soon discovered that this was yet another form of electromagnetic waves only at higher energies.

The basic designs of X-ray sources widely used today for medical imaging are variations of the original *hot cathode tube* invented by W. D. Coolidge in 1913 at the General Electric Company Laboratories. A low-voltage heating circuit operates a hot filament cathode, and the intense heat produces a source of free electrons by thermionic emission. A second circuit creates a large kilovoltage potential difference between the negatively charged cathode and a positively charged anode target. The free electrons are accelerated toward the anode target striking the anode at high velocity, typically exceeding half the speed of light. The cathode, anode and the space between them are contained in a high vacuum to prevent collisions with gas atoms and therefore prevent slowing of electrons. Two physical mechanisms produce X-ray emission, bremsstrahlung (braking) radiation from the sudden deceleration of electrons as they strike the anode target and characteristic radiation resulting from high-speed electrons which displace inner orbital electrons of the atoms composing the anode. The bremsstrahlung radiation is emitted over a continuous and broad wavelength range whereas the characteristic radiation consists of limited discrete spectra.

The broad continuous range of wavelengths for bremsstrahlung radiation is caused by the nonuniform rate at which kinetic energy is lost when each free electron strikes the anode target. The minimum wavelength emitted (i.e., maximum frequency) is given by equating the maximum energy of an electron with charge e accelerating in a potential voltage V to the energy of light at frequency ν, namely,

$$eV = h\nu_{\max}$$

With $\nu\lambda = c$,

$$\lambda_{\min}(\text{angstroms}) = \frac{12400}{V\,(\text{volts})}$$

A typical spectral distribution emitted from an X-ray tube is shown in Fig. 7 showing strong discrete lines from characteristic radiation against the broad spectrum of bremsstrahlung

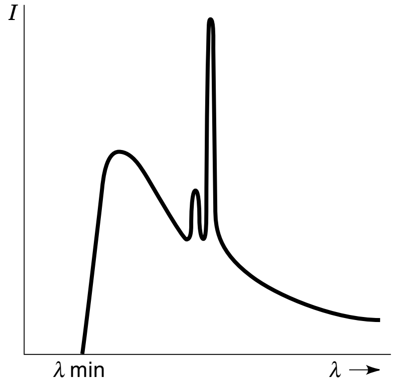

Figure 7. Typical spectrum emitted by an X-ray tube showing the continuous bremsstrahlung radiation spectrum with some characteristic radiation lines superimposed. $\lambda_{\min}$ indicates the short wavelength limit of the spectrum (8).

radiation. For potentials between the cathode and anode exceeding 2000 V, the maximum intensity over the continuous spectrum occurs at $1.5\lambda_{\min}$ and the falloff at longer wavelengths is as $1/\lambda^2$. The most useful range in many radiological applications is 0.1 to 0.5 angstroms. For characteristic radiation with a short wavelength the material composing the target anode must have a high atomic number. Tungsten with an atomic number of 74 and a high melting point of 3655 K is generally used for the target anode. If the incident-free electrons were decelerated along their direction of incidence, classical electromagnetic theory predicts that the intensity maximum of bremsstrahlung radiation occurs at 90°. However, intensity maxima have been observed for different electron energies in the range from 50° to 65°, more consistent with that predicted by quantum mechanics. Good background reading is (10).

BIBLIOGRAPHY

1. M. Born and E. Wolf, *Principles of Optics,* Oxford, UK: Pergamon, 1981.
2. F. A. Jenkins and H. E. White, *Fundamentals of Optics,* New York: McGraw-Hill, 1976.
3. R. Siegel and J. R. Howell, *Thermal Radiation Heat Transfer,* 2nd ed. New York: McGraw-Hill, 1981.
4. G. Wyszecki and W. S. Stiles, *Color Science,* 2nd ed. New York: Wiley, 1981.
5. K. L. Kelley, Lines of constant correlated color temperature based on MacAdam's (u, v) uniform chromaticity transformation of the CIE diagram, *J. Opti. Soc. Am.,* **53**: 999, 1963.
6. D. B. Judd, Estimation of chromaticity differences and nearest color temperature on the standard 1931 ICI colorimetric coordinate system, *J. Opti. Soc. Am.,* **26**: 421, 1936.
7. *IES Lighting Handbook,* New York: Illuminating Eng. Soc. North Amer., 1993.
8. J. A. R. Samson, *Techniques of Vacuum Ultraviolet Spectroscopy,* New York: Wiley, 1967.
9. A. Knowles and C. Burgess, *Practical Absorption Spectrometry,* London: Chapman and Hall, 1984.
10. J. Selman, *The Fundamentals of X-Ray and Radium Physics,* Springfield, IL: Charles C. Thomas, 1971.

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