Laser Safety

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To Ruth (RH) and Gabi (KS)

Contents

Preface

Laser safety, for some, can be a tedious business that gets in the way of the 'real' work of using lasers. While in many cases it is straightforward, at other times the need to evaluate laser hazards and determine the necessary precautions can seem to involve quite difficult concepts that the safety standards do not really manage to explain very clearly. For others, laser safety can be a fascinating subject, a challenging combination of optical physics, biological phenomena, engineering design and human behaviour. New issues constantly occur, as technology advances and applications spread.

Our aim in writing this book has been to provide the reader, at whatever level of involvement in the manufacture or use of laser equipment, with a comprehensive handbook that explains in detail both the background to laser safety and its practical implementation. It discusses the safety of laser equipment for manufacturers and the establishment of safe working practices for laser users. It explains the biophysical basis for emission and exposure limits, and describes in detail the revised system of laser product classification.

The book is heavily based on the international standard for laser safety, IEC 60825-1 (Edition 1.2), adopted in Europe as EN 60825-1 and increasingly relevant to laser safety in the United States as well. We also discuss the application of the IEC standard to LEDs, which are included within its scope but can lead to the necessity for quite complex evaluations. In addition, we include discussion of other relevant standards, such as the European laser eye protection standards EN 207 and EN 208. Where requirements in the US differ, under ANSI user standards or the CDRH product standard, we explain what these differences are. Our intention throughout is to give guidance to the reader on the application of the various safety standards, and this book should therefore be seen as supplementary to those standards, not a replacement for them.

We discuss terminology and the misuse of terminology, and point out common pitfalls and misunderstandings. A large section of the book is devoted to the evaluation of laser emission and laser exposure. It is our experience, as practitioners in laser safety, that misunderstandings can be widespread and sometimes lead to significant underestimation or overestimation of the level of hazard, resulting in the adoption of safety measures that are either inadequate (and thus potentially hazardous) or overprotective (and therefore unduly restrictive).

While we have limited the book primarily to the safety of lasers and LEDs, and discuss topics related to broadband incoherent sources only briefly, much of the book also has relevance to the safety of broadband sources, especially the chapter on units and radiometry, and that on the interaction of laser radiation with human tissue.

Readers will find that our discussions extend from detailed theoretical considerations to practical issues or workplace safety; our aim of making this book as comprehensive as possible inevitably means that our coverage varies considerably in depth and content, and not every reader will find all of the book of direct relevance to their needs. Nevertheless, it is our hope that we have structured the material in such a way as to enable people to readily find the information they seek, at the level which they require. Moreover, we trust that we have given enough detail to enable people to recognize when their own particular problem may not be as straightforward as they may have originally thought.

Both authors are heavily involved in the work of the international laser safety committee, and our own understanding of laser safety has grown over the years through discussions and debate (and sometimes argument!) with numerous professional colleagues. We are indebted to them all, but in particular we would like to thank Jack Lund, David Sliney, Bruce Stuck, Steve Walker and Joe Zuclich for many helpful discussions. We would also like to thank our wives for their continued understanding and support.

The development of this book, and in particular many meetings between the authors, was in part funded by ARC Seibersdorf research on behalf of the Austrian Ministry of Transport, Innovation and Technology, which we gratefully acknowledge. We would also like to thank many of the staff at ARC Seibersdorf research, especially Thomas Auzinger for skilful artwork, Sandra Althaus for beam propagation modelling, Ulfried Grabner for work on LEDs and line lasers, Marko Weber for data plots and Georg Vees for his comments on chapter 2.

Finally, to show that the potential dangers of optical radiation have long been recognized—

> He saw; but blasted with excess of light, closed his eyes in endless night.
>
> Thomas Gray, 1716–1771 (*on Milton, written in Cambridge*)

Roy Henderson, Cambridge
Karl Schulmeister, Seibersdorf

Chapter 1

Lasers, light and safety

1.1 Lasers: stimulating light

1.1.1 Creating light

Lasers are devices that can produce intense beams of light. First developed during the 1960s, they were originally regarded as something of a technical curiosity; a new and fascinating light source but with an unknown future. While investigations began into a number of potential uses and whole new areas of research opened up, lasers were initially dubbed ‘a solution looking for a problem’. Although they captured the imagination of science-fiction writers and film makers, many early aspirations went unfulfilled, mainly due to the limited types of laser then available and the poor understanding of how such intense light beams interact with matter. Since then, however, the technology has greatly matured. New words, such as ‘optronics’ and ‘photonics’, have been coined to describe the new science of light, and lasers have found extensive application in a wide range of very different fields, ranging from manufacturing industry to medicine and from communication to creative arts.

Safety is, or should be, an integral part of using laser technology. Laser hazards can result in serious injury, even death. These hazards arise mainly, although not entirely, from the ability of lasers to produce harmful effects at a distance from the laser itself, through the intense beams of light which they generate.

The name ‘laser’ is an acronym, and is taken from a phrase that describes what lasers are and how they work. It stands for—Light Amplification by the Stimulated Emission of Radiation.

Lasers emit light, but can generate visible *or* invisible emission, and so the term ‘light’ can be misleading. It is often applied in everyday use in a more restricted sense to refer only to ‘visible light’, that is, to the light that we can see with our eyes. This kind of light—the light of which we are aware through our sense of sight—forms only part of the spectrum of what is known as *optical radiation*. Optical radiation encompasses both the ultraviolet and infrared regions

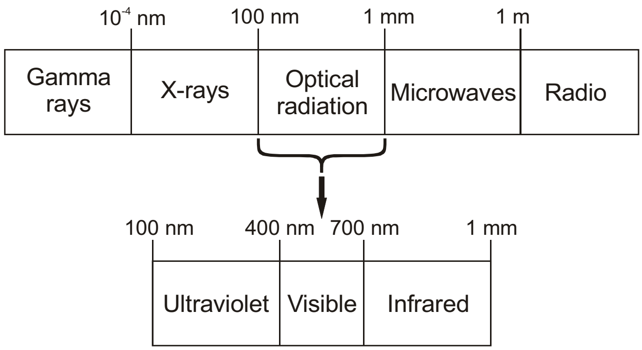

Figure 1.1. The electromagnetic (EM) radiation spectrum, indicating the wavelength boundaries of the principle wavebands.

in addition to the band of visible light. It would be more accurate, therefore, to say that lasers produce intense beams of optical radiation. This radiation may be visible (that is, visible light), but it can also be invisible ultraviolet radiation or invisible infrared radiation.

Optical radiation itself is just part of a more general kind of radiation known as *electromagnetic* (EM) radiation. EM radiation is a form of wave energy that can propagate through empty space, as well as through many material substances (in the way that visible light, for example, can pass through water or glass). Being a wave motion (consisting of oscillating electric and magnetic fields), EM radiation can be characterized by its wavelength. The EM radiation spectrum, extending from gamma rays at very short wavelengths to radio waves at very long wavelengths, is illustrated in figure 1.1. Radiation in different parts of the EM spectrum can have very different properties. Not all of this radiation can pass through the atmosphere, however, and we are therefore protected from a large part of the more harmful short-wavelength EM radiation that is emitted quite naturally by the Sun.

The wavelength of EM radiation within the optical band is usually specified in units of nanometres. One nanometre (abbreviated to nm) is one thousand-millionth, or 10^{-9}, of a metre. In the infrared region, however, micrometres (also known as microns) are also commonly used. One micrometre (abbreviated to μm) is one millionth (10^{-6}) of a metre, i.e. it is equal to one thousand nanometres.

The band of visible radiation, visible light, extends from a wavelength of 380 nm at the blue end of the visible spectrum to 780 nm at the red end. This defines the limits over which the human eye can see, and is the definition of visible light that is used by the Commission Internationale de I'Eclairage (CIE—the International Commission on Illumination). The eye's visual sensitivity to light is illustrated in figure 1.2. As can be seen, it is very non-uniform, and reaches its maximum sensitivity in the middle of the visible spectrum, in the green

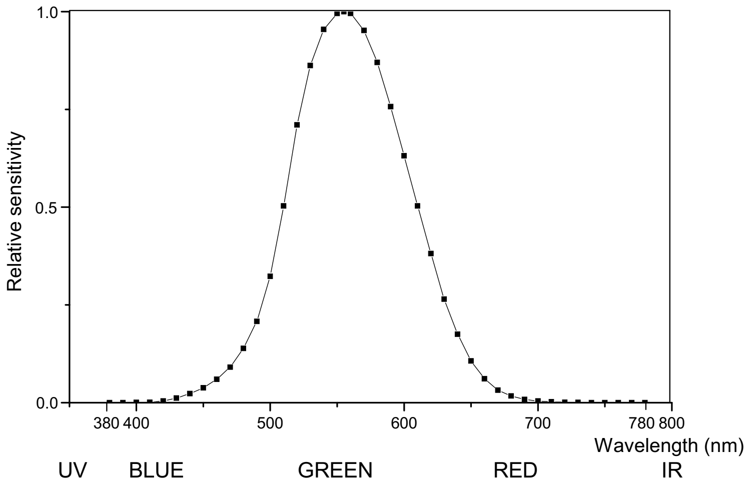

Figure 1.2. The visual sensitivity curve of the human eye.

region at a wavelength of around 555 nm. (This corresponds quite closely to the peak emission of the Sun.) At the extreme ends of the visible spectrum the eye's sensitivity is very low. For this reason, in laser safety, where a distinction often has to be made between visible and invisible laser beams, the visible band is defined as the more limited region between 400 and 700 nm, as shown in figure 1.1. Under the definition used in the majority of laser safety standards, therefore, the ultraviolet region lies below 400 nm, extending down to 100 nm (although the lowest wavelength for which safety limits are currently specified is 180 nm, the start of which is termed the vacuum ultraviolet where absorption in air is very high), while the infrared region lies above 700 nm, extending out as far as 10^6 nm, or 1 mm.

The ability to produce both visible and invisible emission is common to many ordinary light sources. A filament lamp, for example, not only generates broadband visible radiation (that is, emission right across the visible spectrum at all wavelengths between 400 and 700 nm which combines to produce the effect of white light), but in addition generates considerable quantities of infrared emission and a very small amount of ultraviolet emission. Indeed, most of the output of a conventional filament lamp is in the infrared region which, for purposes of illumination, represents wasted energy.

However, while most lamps produce broadband emission, lasers concentrate their output over an extremely narrow portion of the spectrum that may, for most practical purposes, be considered as a single wavelength. Lasers, therefore, are often referred to simply by the wavelength of their emission. Some lasers do have the ability to generate outputs at more than one wavelength, but these remain discrete, separate wavelengths that do not merge into a continuum.

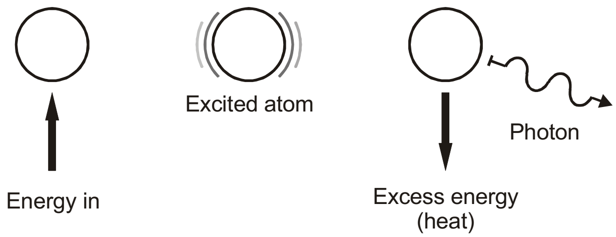

Figure 1.3. In the process of spontaneous emission an atom is first excited (energized) and then releases some of this absorbed energy in the form of a single photon. The excess energy (the difference between the absorbed energy and the photon energy) is dissipated as heat. Once the atom has returned to its initial or 'ground' state, the process can be repeated.

What distinguishes lasers from lamps, however, is not simply the spectral characteristics of the output but the fundamentally different process by which the radiation is generated. This process in turn gives rise to very special properties that make lasers unique.

Optical radiation is generated by energy transitions that occur within individual atoms or molecules. Any material that emits light must first absorb energy, and the energy that it absorbs is then contained in the atoms or molecules that make up the material. Some of this energy can then be released from these atoms or molecules in the form of photons. A photon is the smallest possible 'packet' of light energy, and can be considered as a short burst of waves or a 'light particle' having no mass (and is therefore 'light' in both senses of the word). Considering packages of light in this way can be a useful though far from perfect analogy. The energy of an individual photon is inversely proportional to the associated wavelength. Thus, ultraviolet photons (normally generated by processes involving the inner electrons of atoms), are far more energetic than infrared photons (which largely arise through changes in the energy levels that bind atoms together in molecules). At intermediate wavelengths, and consequently at intermediate photon-energy levels (that is, within or close to the visible band), the process is one involving energy exchanges of the outer electrons of the individual atoms.

In conventional light sources the photons are emitted 'spontaneously' in a process known as spontaneous emission. This means that the atom or molecule, having first absorbed energy and therefore being in an energized or 'excited' state, releases this energy quite spontaneously after a random (but very small) interval of time. Any single photon that is produced during this release of energy is emitted in a random direction (figure 1.3). In consequence, therefore, as this process is repeated, radiation is emitted in all directions away from the source, and the individual photons or 'wave packets' of which this radiation is comprised have a quite random or 'incoherent' relationship to each other.

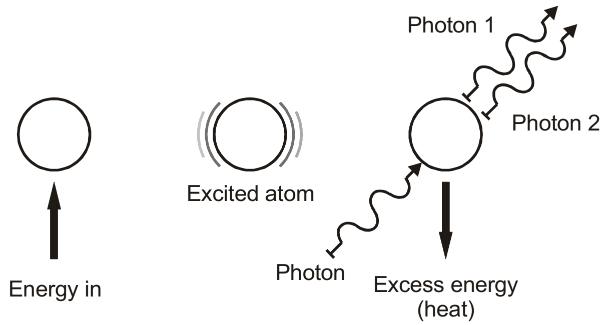

Figure 1.4. In stimulated emission, an excited atom is stimulated to emit a photon (before it would have done so by spontaneous emission) by a photon colliding with the atom. Two photons are then emitted in the same direction (the one that has caused the stimulation and one generated by the atom), and are both in phase with each other. These photons can then collide with other excited atoms to cause further stimulated emission.

In a laser, on the other hand, having first been energized, the individual atoms or molecules can be 'stimulated' to release their energy before they would have done so spontaneously. This is achieved by arranging for a photon, having the same energy as the photon that would have been released spontaneously, to collide with the atom or molecule. The result of this process of 'stimulated emission' is that two photons now exist; the original one that caused the stimulation and a second one, due to the release of energy arising from this process of stimulation. Furthermore, both these photons now travel in exactly the same direction, and the waves of which they are comprised are exactly in phase, or in step. This process of stimulated emission is illustrated in figure 1.4.

Stimulated emission by itself would be of little practical value unless it were possible to exploit this process to create gain, that is to 'amplify' the coherent emission that is generated. This is done in two ways. First, by ensuring that an efficient energizing process is utilized, such that there is a high probability of the individual atoms or molecules being in an excited state. This will allow stimulated emission to occur on a significant scale, and is known as 'population inversion', since it is the reverse of the normal or stable state in which, at any given time, most of the atoms or molecules will be in the ground or 'unexcited' state. Secondly, in order to ensure that a large number of photons pass through the material to cause stimulated emission, some form of 'feedback' is required. Feedback is needed so that a high proportion of the photons that are generated are fed back into the material. This is achieved by creating a 'resonator', formed by a pair of mirrors at each end of the material within which stimulated emission, or 'laser action', can occur (figure 1.5). One of these two mirrors is designed to have a very high reflectivity (at the laser wavelength), so directing back into the resonator the majority of photons produced along the resonator axis. The other

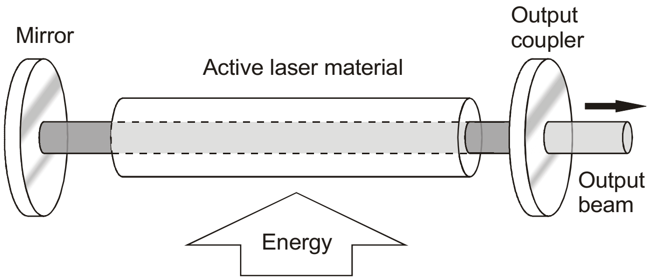

Figure 1.5. The principal components of a laser resonator. The laser material or 'medium' (which may be a solid, a gas or a liquid) is often in a cylindrical form and located between two mirrors to create a 'resonant cavity'. An energy source couples energy into the laser medium, in which the build-up of stimulated emission between the mirrors generates the laser beam.

mirror, known as the 'output coupler', also has a reasonably-high reflectivity but this is combined with some transmission, such that while the majority of incident photons are reflected by this mirror back into the laser resonator, a small fraction of them are allowed to pass through the mirror so forming the output beam of the laser.

Initially, of course, at the start of this process (when the laser is switched on and the laser material is first energized), only spontaneous emission can occur, and this emission will be in all directions. A sufficient number of photons will, however, be emitted by chance parallel to the axis of the laser resonator to initiate the process of stimulated emission. Through a cascading effect, as more and more photons are produced along the laser axis, stimulated emission rapidly grows to become the dominant mechanism of photon generation.

Many lasers generate, through this process, well-collimated and essentially parallel beams. Others, such as laser diodes, produce divergent emission. This latter effect arises because of the very small cross-sectional area of the resonator in such lasers. Optical radiation, being a wave motion, is subject to diffraction. This is the unavoidable bending of light caused by structures that are small on an optical scale (that is, with respect to the emission wavelength). Because of the very small size of laser diodes, diffraction effects produce this characteristic divergent emission. This is usually not a problem, however, because it is possible, if desired, to employ a lens system to collimate this output and thereby form a beam identical to that of other kinds of lasers. Indeed, both types of output are equivalent. A laser diode produces divergent emission from a very small, effectively point-source of emission, which can be readily formed into a collimated beam. A collimated (parallel) beam, on the other hand, appears to originate from a point-source located an infinite distance away. Both types of laser are, therefore, often and quite justifiably called *point sources*. This is very different from the majority of conventional lamps, which are *extended sources*, by virtue of the extended nature of the emitting surface.

The fact that a point source of light (whether it is a laser or not) can produce a parallel beam having a finite diameter may not be immediately obvious. Consider, however, the three illustrations shown in figure 1.6. These show a point source, radiating in all directions, where the emission passes through a circular aperture to form a beam. In figure 1.6(*a*), the source is close to the aperture and so the divergence or angular spread of the beam beyond the aperture is quite large. As the distance between the source and the aperture increases, as shown in figure 1.6(*b*), the divergence of the beam formed by the aperture decreases. At very great distances, the divergence of the beam becomes very small; in the limit, at an infinite distance, the beam that is produced by the aperture is essentially parallel, as shown in figure 1.6(*c*). This is a simplified description of a collimated laser beam; the *apparent* source (from which the radiation *appears* to originate) is a single point located, effectively, at infinity. The apparent source of a well-collimated laser beam is *not* the emission aperture of the laser, or even the inside of the laser resonator. It lies a long way *behind* the laser.

A common example of a point source producing parallel emission is that of a star. Although we know that stars are very large, they appear from Earth, even through the most powerful telescopes, to be no more than points of light because of their vast distances from us. A star approximates very well to a point source at an infinite distance. Because of this, even though stars radiate in all directions, the rays of light that reach us from a star are all parallel. (Indeed, it is only with the closest stars that there is any detectable difference in the direction from which the rays originate when observed from one side of the Earth's orbit around the Sun compared to those arriving at the opposite side; a baseline—corresponding to the aperture diameter in figure 1.6—of over 260 million kilometres!)

The size of a source can, of course, be defined in terms of its actual dimensions. The globe of a frosted filament lamp (the *apparent* source from which the light produced by such a lamp appears to originate) might be 60 mm in diameter. The diameter of the Sun, on the other hand, is almost 700 000 km. What is often more useful, however, is to express source-size in terms of the angular diameter of the source, the *angular subtense*, measured at the position from which the source is being viewed. Thus, when seen from a distance of one metre, the 60 mm lamp subtends an angle of 3.5 degrees, while the Sun, observed from the Earth, subtends an angle of 0.5 degrees. The lamp, one metre away, therefore *appears* to be seven times larger than the Sun.

The angular size of a source determines the size of its optical image, that is the image created by a focusing system (such as in a camera or by the eye). In the previous example, the image of the lamp (produced at the film in a camera or on the retina at the back of the eye) is seven times larger than the image of the Sun. A star, on the other hand, produces only a tiny spot as its image. It is, in fact, unresolvable (meaning that its angular size is less than the smallest image that can be created by the optics); the size of the focused spot is in this case governed by

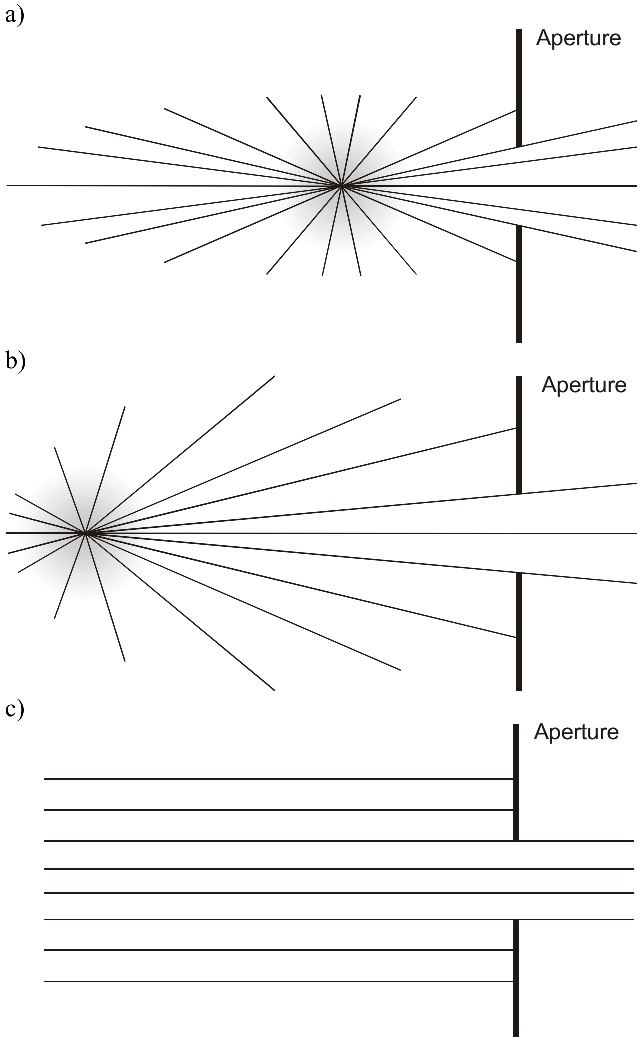

Figure 1.6. A point source (such as a distant star) produces divergent emission in all directions, and a circular aperture can be positioned some distance from the source to produce a beam of light beyond the aperture. (*a*) When the aperture is close to the source the beam is very divergent. (*b*) As the distance from the source to the aperture increases, the beam becomes less divergent. (*c*) Where the distance is very large (in comparison to the size of the aperture), the beam is effectively parallel or 'collimated'.

the fundamental limitations of the optical system, not by the angular size of the source.

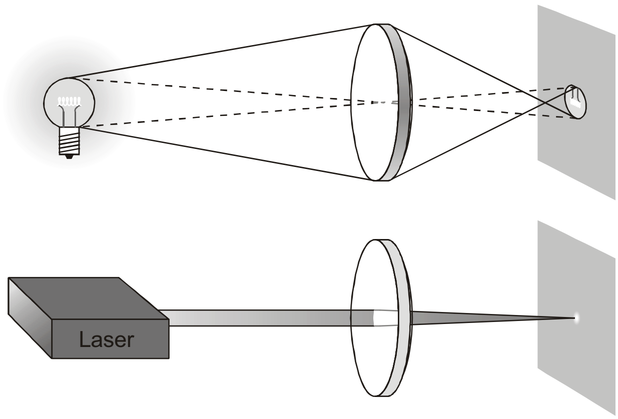

Figure 1.7. Comparison between an extended source and a point source. A conventional lamp (upper picture) is an extended source (because it has a finite emitting area), and the smallest patch of light that can be created by focusing the output of the lamp with a lens is the geometric image of the source. A laser, however, (lower picture) is effectively a point source, and so its output can be focused by a lens to create a point image. Furthermore, while only a small proportion of the output of the lamp can be collected and focused by the lens (because the lamp emits in all directions), the entire output of the laser, which is contained in a narrow collimated beam, can be focused to a small spot. Even if the total light output of the lamp and the laser were the same, the concentration of power produced by the lens would be very much higher in the case of the laser.

Lasers, like stars, are point sources because they produce point images (focused points of light), even though the laser beam, as it emerges from the laser, may have a diameter of several millimetres or more. In contrast, the light from a conventional lamp, when imaged by an optical system, cannot be focused down to produce anything smaller than the geometrical image of its emitting area. (This is the filament itself in the case of a clear-glass filament lamp, or the glass globe in the case of the frosted or ‘pearl’ lamp previously discussed.) This difference in the source size between a laser (a point source) and a conventional lamp (an extended source) that is apparent from their corresponding images produced by a lens is shown in figure 1.7.

If, instead of using a focusing lens to produce an image on a screen, the laser beam were to be viewed directly by the eye, then the image produced on the retina would be as shown in figure 1.8. The laser beam, if it were visible, would appear to the eye as a small spot inside the emission aperture, even though the emerging beam might have almost the same diameter as the aperture. (This obviously ignores the serious injury that could be caused to the eye through the direct viewing of a laser beam!) In fact, the image of the emission aperture and of the focused beam may not be simultaneously in focus on the retina, since the

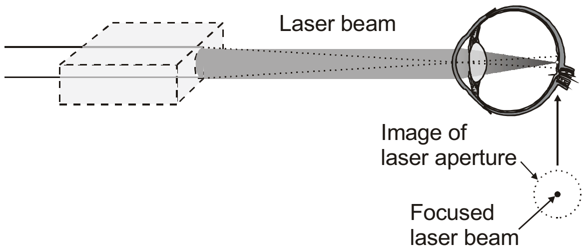

Figure 1.8. Direct viewing of a laser beam. Just as in the case of the laser in figure 1.7, a laser beam entering the eye can be focused to produce a very small spot on the retina. The image of the laser's emission aperture, however, can be very much larger. The fact that a laser beam may have an appreciable diameter as it leaves the laser does not limit its ability to form a point image.

position of the apparent source (for a collimated beam) is not at the emission aperture but at infinity, off the left-hand side of the diagram. The eye can focus on the emission aperture, in which case there will be an out-of-focus image of the laser source (appearing as a larger blurred spot), or it can focus at infinity, to produce a sharp focused spot from the laser beam surrounded by an out-of-focus image of the emission aperture.

In the case of a highly-divergent laser source, such as a bare laser diode, the apparent source position and the exit aperture can be co-located. Nevertheless, the laser can still be a point source because of the very small emitting area. As with a collimated beam, the emission can be focused by the eye to produce a very small spot on the retina, unlike a conventional lamp.

1.1.2 Quantifying light

When light is used for illumination purposes (which, after all, remains the principal application of light), light quantities are normally expressed in photometric units. These units (having names such as lumen, lux and candela) are spectrally-weighted quantities that are based on the visual response of the human eye (figure 1.2). Under the photometric system, measurements are made by using a combination of optical detector and filter (a light meter or 'photometer') that has the same spectral sensitivity as a normal human eye. This gives more 'weight' to green light, for example, than it does to blue or red light where the visual response of the eye is much lower. Ultraviolet and infrared radiation, of course, have a zero value in photometric units, regardless of the actual quantity of radiation that may be present. This is because it is invisible to the eye, and any photometric light-meter should be insensitive to it.

The usefulness of light for purposes other than illumination, and the ability of light to cause damage, are both unrelated to the process of vision: what matters is the total magnitude of the optical radiation that is present. For the majority of laser applications, therefore, and in all light-safety assessments, absolute, radiometric units are used. These are fundamental quantities of power and energy. While radiometric measurements are discussed in more detail in the next chapter, we give here an overview of the principle quantities and units that are relevant in laser safety.

The watt (W) is used as the unit of radiant power and the joule (J) as the unit of radiant energy. Power is defined as the rate of flow of energy. An emitted power of one watt is equivalent to an energy rate of one joule per second. Quantities expressed in terms of energy (in J) can thus be readily converted to power (in W) by dividing the energy by the emission duration in seconds. Similarly, quantities expressed in terms of power may be converted into corresponding energy units by multiplying the power by the emission duration (provided that the level of power remains constant throughout the emission duration). A laser beam of three watts that is emitted for ten seconds will therefore generate a total energy during this time of thirty joules.

Quantities of power or energy that are very much smaller or larger than the base units of joules and watts can be used as shown below:

- 1 milliwatt (mW) and 1 millijoule (mJ) are equal to 1/1000 W and 1/1000 J, respectively;
- 1 kilowatt (kW) and 1 kilojoule (kJ) are equal to 1000 W and 1000 J, respectively;
- 1 megawatt (MW) and 1 megajoule (MJ) are equal to 1000 000 W and 1000 000 J, respectively.

It is usual to express the emission of continuous wave (cw) or 'steady state' lasers in terms of power (P), but to measure the output of pulsed lasers in terms of the energy (Q) of each pulse. A pulsed laser will thus have a pulse energy of Q joules. If the pulse duration is t seconds (where t is normally much less than one second) and the pulse repetition rate is f hertz (f pulses per second), then the peak power of the laser, for each pulse, will be Q/t watts. The average power of the laser, however, (the average rate of energy emission) will be Qf watts, since this is the average rate of energy emission per second. The values for *peak* power and *average* power of a pulsed laser can be very different.

Typical laser output powers may vary from below one milliwatt to several kilowatts. The peak power of some pulsed lasers, given the extremely short pulse durations that are possible, can reach several megawatts.

It is interesting to examine the way in which we can view a laser beam, and to relate the emission power of the laser with the optical power levels necessary for vision. Consider a one milliwatt laser pointer. This produces a narrow, (typically red) almost parallel laser beam of about two millimetres in diameter. If it is directed at a projection screen, a small bright red spot is seen. Although we refer to the laser beam as being red, it only becomes visible when some of the beam enters our eye and is focused on the retina. This will occur when the beam strikes the reflecting matt surface of the screen. We cannot actually see the beam as it passes through the air between the laser and the screen. (Note, however, that more powerful beams can be visible. This is because of the small amount of scattering that arises from the dust and other particles floating in the air. Scattering, the redirection of light out of the beam caused by such particles, is always present, but with higher power beams the scattering can be sufficient to become visible.)

However, how do we actually see the beam where it strikes the screen? It becomes visible because not only is a white screen highly reflective (reflecting most of the light that is incident upon it) but, unlike a mirror, it reflects *diffusely*, redirecting the reflected radiation, not in a narrow beam as a flat mirror would, but in all directions away from the surface. The spot on the screen thus forms the apparent source, radiating in all directions. Wherever we sit around the screen, therefore, our eyes can intercept some of this reflected radiation, allowing us to see the red spot.

If the power striking the surface of the screen is one milliwatt, and it is all reflected (neglecting the very small absorption loss that will inevitably occur at the screen), then the re-radiated beam also has a power of one milliwatt. But this is radiated into a hemisphere centred on the laser spot on the screen. What we pick up with our eyes will only be a very small fraction of this. In fact, at a distance of two metres from the screen, the power entering the pupil of each eye will be about one nanowatt (10^{-9} W). Yet this is sufficient for the laser spot to be readily seen. Were the laser beam to be directed not at the screen but straight into our eye, the entire beam would pass through the pupil and could be focused to a small spot on the retina. The power entering the pupil would then be *one million times greater* (one milliwatt rather than one nanowatt) than in the case of indirect viewing. Even with a laser pointer, therefore, which is usually considered to be reasonably harmless, the effect of accidental direct exposure of the eye to the beam can be, literally, dazzling!

It is often necessary in laser safety to define the *concentration* of radiant power or energy that is incident at a surface, as shown in figure 1.9. This is expressed in terms of either the irradiance E, which is the power per unit area (normally specified in units of watts per square metre), or the radiant exposure H, the energy per unit area (specified in units of joules per square metre). These parameters are sometimes referred to as power density and energy density respectively. Strictly, however, this terminology is incorrect, since *density* properly relates to volume, not area.

Radiant power, radiant energy, irradiance and radiant exposure are all very important parameters in quantitative laser safety assessments. They are discussed in more detail in chapter 2.

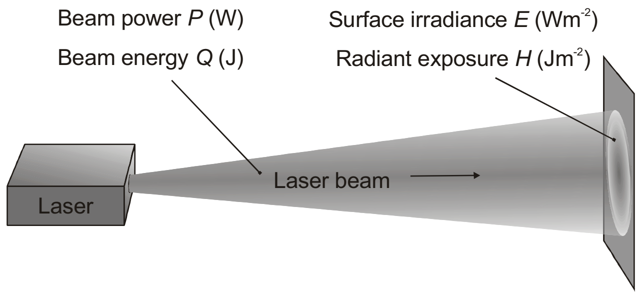

Figure 1.9. The concentration of laser power or energy at a surface. For many assessments in laser safety we need to quantify the power or energy per unit area that is incident at a surface. For radiant power, the surface concentration is called *irradiance* and is measured in units of watts per square metre; for pulse energy it is called *radiant exposure* and is measured in units of joules per square metre.

1.2 The properties of laser radiation

The term 'laser radiation' refers to the optical radiation, or 'light', that is emitted by a laser. But if lasers produce optical radiation, what are the distinctive features of this radiation that differentiate it from that produced by conventional light sources? Why is laser safety such a concern when ordinary lamp safety is much less so? Interestingly, it is not necessarily the most obvious characteristics of lasers that are the most hazardous.

It has already been noted that laser emission is monochromatic, that is, it is effectively concentrated at a single wavelength (or, sometimes, at several discrete, individual wavelengths). Most lamps, in contrast, emit broadband radiation. While this is an obvious distinction it is not, from the safety perspective, the most significant one.

Lasers are often considered to be powerful emitters of optical radiation. They can produce effects not possible using ordinary light sources. This is mainly because of the high *concentration* of the emitted power. The total emission generated by the majority of lasers (certainly in terms of average power), though hazardous, is less than that emitted by an ordinary household lamp.

Rather than monochromaticity and power, the two most important properties of lasers insofar as their hazard potential is concerned are those of *directionality* and *source-size*.

Directionality is the property that enables lasers to produce high levels of concentrated power at considerable distances from the source. Even though the output from a one-milliwatt laser pointer is much less than that produced by a pocket torch (flashlight), the concentration of this output into a narrow beam that is only a millimetre or so in diameter will produce a level of irradiance (power per unit area) much higher than that produced by the torch. Even lasers of moderate power, therefore, are capable of causing high levels of surface exposure (at the eyes or the skin) that may exceed safe limits.

This property of directionality can be characterized in terms of the angular *divergence* of the emitted beam; the angle at which the beam spreads out from the source. Though many laser beams can appear to be very collimated and therefore parallel, diffraction effects mean that no beam can be perfectly parallel and must diverge to a certain extent. (In other words, the diameter of the beam gets larger at increasing distances from the source.) For many lasers, the divergence angle is very low, only a fraction of a degree, but for other lasers (e.g. bare laser diodes) the beam divergence can be large. Special optics can be used to produce other beam geometries, such as fan-shaped beams which have a large divergence in, say, the vertical plane but a very low divergence in the horizontal plane.

Beam divergence angles can be expressed in degrees, but for small divergences are more usually quoted in milliradians (one thousandth of a radian), where one radian is the angle subtended at the centre of a circle by a an arc around the circumference equal in length to the radius of the circle. There are thus 2π radians in a complete circle, and one radian is therefore equal to about 57 degrees.

The ability of an optical source to produce given levels of exposure at a distant surface can be expressed in terms of the source *intensity*. Intensity is a measure of the emitted power per unit solid-angle, and can be expressed in units of watts per steradian (W sr^{-1}). One steradian is the solid-angle subtended at the centre of a sphere by an area on the surface of the sphere equal to the square of the sphere's radius. There are therefore 4π steradians in a complete sphere. A 65 degree cone has a solid angle at its apex of about one steradian. (Solid angular measure is defined more fully in chapter 2.) Because of their generally high levels of directionality (low levels of divergence), lasers have high levels of emitted *radiant intensity*.

The very small **source size** of most lasers enables their emission to be focused down to concentrate this power over an even smaller area, and so create much higher levels of surface exposure. This is how lasers are often used, of course, by focusing the beam to produce the required effect, whether it is an industrial laser being used for welding, or a semiconductor laser-diode whose output is being focused down into an optical fibre. Unfortunately, this can also happen, at certain wavelengths, inside the eye, creating extremely high and seriously damaging levels of exposure on the retina at the back of the eye.

For these reasons lasers can produce harmful effects, even though their output power may be well below that of considerably less harmful conventional optical sources. One useful way in which these properties can be quantified is that of brightness or *radiance*. Radiance (discussed further in chapter 2) is a measure of the intensity per unit area. It represents the power emitted into a unit solid angle from a unit area of emitting surface, and is measured in units of watts per square metre per steradian (W m^{-2} sr^{-1}). Because of their very small effective emitting areas (apparent source size) combined with their high levels of radiant intensity, lasers have extremely high values of radiance, greater than that of all other artificial sources and even exceeding the radiance of the surface of the Sun.

The importance of radiance is that, where a given optical system (of given f-number or focal ratio) is used to image or focus the light emitted by a source, it is the *radiance* of the source that determines the maximum value of *irradiance* that can be produced at the image plane of the system. In the case of the eye, therefore, the huge values of radiance that are possible with lasers of even low output power mean that lasers can produce higher levels of exposure (irradiance) at the retina of the eye than is possible from any conventional source, including the Sun.

Directionality and source size, which are related although separate aspects of the spatial distribution of the emitted radiation, therefore represent the most important safety-related properties of a laser beam. They govern the maximum level of exposure (the degree of light concentration at the surface of the body or inside the eye) that can be produced from an optical source of given power. Much is often made of the emission power of lasers, but it is actually their high levels of radiant intensity (arising from their low divergence) and radiance (arising from their small apparent source size) that in reality make them both extremely useful and potentially hazardous.

The uniqueness of lasers is often related to their *coherence*. Coherence is a measure of the degree to which the emitted waves remain in phase. Conventional light sources are extremely incoherent; the process of spontaneous emission results in the phase relationship between the photons that are generated being totally random. Lasers, on the other hand, can produce highly coherent emission. High levels of coherence are a very useful property for certain applications involving interference between separate paths of light that have travelled different distances, such as in holography. But while laser emission needs to be reasonably coherent in order that it has the important spatial properties that it possesses, coherence itself has no direct bearing on the resultant hazard. All that matters insofar as most laser injuries are concerned is the level of the incident exposure—the irradiance or radiant exposure at the surface of the particular body tissue. The incident exposure is primarily a function of the source intensity or, for retinal exposure, the source radiance. Since lasers have higher values of both of these parameters than other sources, lasers are capable of inflicting more serious harm than is possible from other sources of optical radiation.

A more detailed discussion of these exposure conditions and of the effects that lasers can cause is given in chapter 3.

1.3 The safety of laser technology

The concerns that arise over laser hazards and the need for having a formal and systematic approach to risk analysis and safety control really stem from three unique aspects of laser technology. First, laser hazards are not at all obvious. The appearance of the laser equipment or even a knowledge of its output power may give little indication to an untrained person of its ability to cause injury. Second, a person who is accidentally exposed to laser radiation may be unaware of this until a serious injury has been caused. Third, lasers can cause harm at a distance, sometimes at a considerable distance, from the laser equipment itself. There need be no direct physical contact with the laser itself.

Laser safety, as a discipline, is the task of controlling the risk of laser technology through the appropriate design and use of laser equipment. It therefore impacts on both manufacturers and users, and requires an understanding of legal requirements, laser safety standards and established principles of best practice. While the main focus of laser safety is, inevitably, on the harm that could arise from accidental human exposure to hazardous levels of laser radiation, there are other safety issues that may also need to be considered. These are often termed ancillary or associated hazards, and result from aspects of laser operation that include the interaction of the laser beam with materials, especially of concern with high-power lasers (which can ignite inflammable materials or generate fume by vaporization), or other hazards associated with the laser (such as electrical hazards or toxic materials). These additional hazards are discussed further in chapter 6.

Laser safety requires that all potential hazards are evaluated, that the impact of these hazards is assessed, and that appropriate safety precautions are adopted. Safety precautions are more usually referred to as control measures or protective measures, or sometimes simply as ‘controls’. They include such aspects as physical enclosures to limit access to the hazard, written procedures that have to be followed and protective equipment (such as safety eyewear) that has to be worn.

The level of detail that safety evaluation requires, and the depth of knowledge needed to complete it, can vary widely, depending on the type of laser in use, the purpose for which it is being used, and the circumstances under which it is operated. There are, however, two broad categories into which most laser safety activities can be divided. These cover *qualitative* aspects and *quantitative* aspects of laser safety.

Qualitative aspects include overall management and policy issues, the identification of possible hazards, the use of beam enclosures and procedural methods of hazard control. In other words they require a recognition that hazards exist, but not necessarily a detailed evaluation of the magnitude of those hazards. For many of those involved with laser safety it is these aspects with which they are mainly concerned.

Quantitative aspects, however, involve numerical assessments of the levels of laser radiation and the application of the various emission and exposure limits specified in laser safety standards. Such assessments may be necessary, for example, whenever classifying a laser product, or when evaluating the exposure conditions that might exist in order to determine the distance over which the hazard extends or to specify the level of eye-protection that is needed. These assessments can require a reasonable familiarity with optical principles and radiometric parameters, a confidence in undertaking arithmetic calculations, and an understanding of the detailed measurement specifications defined in the safety standards.

Laser safety should not be seen in isolation, however, but considered as part of an overall approach to health and safety, both in the workplace and amongst the public at large. It may at times require specialist knowledge and appear to be highly technical in nature. Nevertheless, the aim is simply stated; to ensure that laser equipment is designed to be safe and that it is used in a safe manner.

The process of identifying what needs to be done in order to ensure the safe use of laser equipment is accomplished, in essence, by finding answers to the following questions.

- What can go wrong? (The hazards that might exist and the conditions under which they can arise.)
- How likely is this to happen? (The likelihood that harm will occur.)
- What are the consequences? (The severity of the injury that could be caused.)
- How can this injury be prevented? (The control measures that need to be set in place.)

This assessment process should be undertaken within the framework of general health and safety requirements using the detailed standards on laser safety that have been developed. It is the aim of this book to help with this process, and to provide much of the background understanding that is necessary in order that these questions can be successfully answered.

1.4 Safety standards

Maximum limits of safe exposure to laser radiation for both eyes and skin are issued by the International Commission for Non-ionizing Radiation (ICNIRP) [1]. These limits, called exposure limits (ELs), are incorporated into international laser safety standards and also form the basis for product classification.

The main international standard for laser safety is IEC 60825-1, published in Geneva by the International Electrotechnical Commission [2]. This standard defines the accessible emission limit (AEL) for each of several laser product classes and specifies requirements for laser products, including labelling, according to the product class. It also provides guidance to users on the safe operation of laser equipment, and defines safe limits of laser exposure, given in terms of the maximum permissible exposure (MPE), which is based on ICNIRP's ELs. The IEC standard is adopted in Europe as EN 60825-1, and is mandated to be applied to laser equipment under a number of European Product Directives, including the Low Voltage Directive, the Machinery Directive, and the Medical Devices Directive.

While the AELs define the emission limits of the various laser product classes, the MPEs are used to assess whether a given level of exposure to laser

Table 1.1. International laser safety standards published by the International Electrotechnical Commission (IEC).

Reference	Title
IEC 60825-1	Equipment classification, requirements and user's guide
IEC 60825-2	Safety of optical fibre communication systems
IEC 60825-3	TR Guidance for laser displays and shows
IEC 60825-4	Laser guards
IEC 60825-5	TR Manufacturer's checklist for IEC 60825-1
IEC 60825-6	TS Safety of products with optical sources, exclusively used for visible information transmission to the human eye
IEC 60825-7	TS Safety of products emitting 'infrared' optical radiation, exclusively used for wireless 'free air' transmission and surveillance (NOHD < 2.5 m)
IEC 60825-8	TR Guidelines for the safe use of medical laser equipment
IEC 60825-9	TR Compilation of maximum permissible exposure to incoherent optical radiation
IEC 60825-10	Laser safety application guidelines and explanatory notes

TR signifies a Technical Report and TS a Technical Specification, otherwise the document is a full standard. Users of these documents should ensure that the most recently published version or amendment is used.

radiation is safe. They can also be used to determine the hazard distance, i.e. the distance from the laser within which an exposure hazard can exist. This can be a very important factor in evaluating the risk.

IEC 60825-1 is one of a series of related laser safety standards and guidance documents. It is, however, the generic standard that defines the basic manufacturing requirements that laser products have to satisfy, and it establishes an overall framework under which laser products should be used. Other documents in the 60825 series either define additional requirements (as normative standards) or provide more detailed guidance (in the form of technical reports or specifications) on the use of lasers in specific applications, for example in optical telecommunication, in industrial processing, and in medicine. A full listing of these documents is given in table 1.1. Further documents in the IEC 60825 series are under development, and existing ones do undergo revision from time to time, and so users of these standards should always ensure that they remain up to date with the latest requirements and recommendations given in these documents. (Readers may refer to the IEC website, www.iec.ch, for up-to-date information on IEC standards.)

In the United States, all laser products sold or offered for sale must satisfy the requirements of the Federal Performance Standard for Laser Products

Table 1.2. US laser safety standards published by the Laser Institute of America (LIA) on behalf of the American National Standards Institute (ANSI).

Reference	Title
ANSI Z136.1	American National Standard for the Safe Use of Lasers
ANSI Z136.2	American National Standard for the Safe Use of Optical Fiber Communication Systems Utilizing Laser Diode and LED Sources
ANSI Z136.3	American National Standard for the Safe Use of Lasers in Health Care Facilities
ANSI Z136.5	American National Standard for the Safe Use of Lasers in Educational Institutions
ANSI Z136.6	American National Standard for the Safe Use of Lasers Outdoors

Users of these standards should ensure that the most recently published version is used. The Laser Institute of America also publish a number of practical guides on various aspects of laser safety.

(21 CFR 1040) [3]. Such products have to be registered with CDRH (the Center for Devices and Radiological Health, a division of the Food & Drug Administration), and a report submitted confirming compliance of the product with the Federal Performance Standard. The classification procedures and manufacturing requirements defined in the US laser product standard differ, in certain respects, from those of IEC, but CDRH is adopting the IEC classification scheme in changes to the Federal standard. In addition, for laser users, ANSI (the American National Standards Institute) issues a number of safety standards covering different laser applications (see table 1.2), and has adopted the ICNIRP MPEs in its latest standard for laser users (ANSI Z136.1) [4]. This standard also defines a classification scheme, differing from that of CDRH, which is intended for non-commercial lasers such as research equipment. A full listing of ANSI laser safety standards is given in table 1.2.

One important difference between IEC and US safety requirements is that both CDRH and ANSI laser safety standards generally *exclude* LEDs. The exception is ANSI Z136.2 (see table 1.2), which covers the use of lasers and LEDs in telecommunication applications.

References

[1] ICNIRP Guidelines 2000 *Health Phys.* **79** 431–40

[2] IEC 60825-1 2001 *Safety of Laser Products—Part 1: Equipment Classification, Requirements and User's Guide* (Geneva: IEC)

[3] 21 CFR 1040 1994 *Performance Standards for Light-Emitting Products: Section 1040.10 Laser Products* and *Section 1040.11 Specific Purpose Laser Products* (Maryland: FDA)

[4] ANSI Z136.1 2000 *American National Standard for Safe Use of Lasers* (Florida: LIA)

Chapter 2

Quantifying levels of laser radiation

In order to evaluate the potential hazard of exposure to laser radiation, the level of human exposure needs to be characterized (by measurement or calculation). Similarly, when the manufacturer has to classify his laser product, the level of radiation emitted from the product needs to be assessed. These measured or calculated values are then compared to appropriate exposure or emission limits. The basic concepts of quantifying light were introduced in chapter 1, here we explain the principles of units and optical measurements, generally referred to as radiometry, in more detail. Besides reviewing general radiometric terms we also discuss particular issues pertinent to laser safety where the *biologically effective* levels of exposure have to be determined in order to be compared to exposure limits. In some cases, these biologically effective quantities can differ significantly from the actual physical radiometric quantities. At the end of the chapter, relevant properties of equipment used to measure the level of laser radiation are discussed, and practical information for performing measurements is given.

2.1 Power and energy

The basic quantity to characterize the potential of optical radiation to affect a given material or tissue in terms of heating it up or inducing chemical reactions is *energy*. The physicist's definition of energy is the ability to perform work, where work has to be understood in a broad sense which includes affecting chemical changes or increasing the temperature in matter. For some effects on tissue, such as photochemical changes (discussed in detail in chapter 3), the *energy* delivered to tissue is the relevant quantity and the effect does not depend on the time taken to deliver that energy. For interactions where an increase of temperature is necessary, the *rate of energy delivery* to a given volume is important, as it has to compete against thermal conduction which drains thermal energy into surrounding matter. The rate of energy flow has its dedicated name, it is referred to as *power*, sometimes also as *radiant flux*. The exact term for power and energy

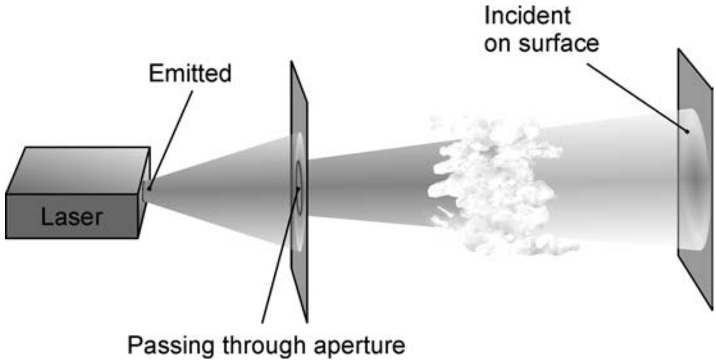

Figure 2.1. When one refers to radiant energy or power, for completeness one should also specify the geometrical reference, i.e. one might have to distinguish between levels of radiation *emitted* from a radiation source, passing through an aperture or *incident* on a surface, as there might be losses of energy or power.

when used for laser and optical radiation (and not for instance for electrical power of the equipment), is 'radiant power' and 'radiant energy'. For brevity, in this book, 'radiant' is often omitted.

Since power is the rate of energy flow, i.e. energy flow per unit of time, the two quantities *power* and *energy* are closely linked via the period of time over which they are being considered. The mathematical representation of the interdependence is, therefore,

$$\text{Power} = \frac{\text{Energy}}{\text{Period of Time}} \tag{2.1}$$

The internationally standardized units with which power and energy are measured are watts (W) and joules (J), respectively, and the relationship of the units, following equation (2.1), is

$$1 \text{ watt} = \frac{1 \text{ joule}}{1 \text{ second}} \tag{2.2}$$

Depending on the problem at hand, one might have to differentiate between power or energy that is *emitted* by a laser and the power or energy that arrives at a target, i.e. is *incident* on a target. Some losses may have occurred between the point of emission and the point of incidence. For instance there could be an aperture which physically obstructs part of the beam, or there could be other losses (see figure 2.1).

The concept of power being equivalent to energy flow can be visualized by recalling that a laser beam, or optical radiation in general, can be seen as consisting of a stream of light particles, or 'photons'. Each photon carries a certain energy, and the more photons that are emitted in a given time, the more powerful the laser beam is. For instance, for a wavelength of 620 nm, the energy of one photon is 3.6×10^{-19} J so that a beam with a radiant power of 1mW corresponds to about 3×10^{15} emitted photons per second (3 million billion photons per second). Although it might seem that one photon carries very little energy, especially when one considers thermal interaction (i.e. heating up of material), one should also bear in mind that the energy of one visible photon and especially of an ultraviolet photon is sufficient to induce chemical changes or even to break biomolecular bonds.

The definition of *radiant power* as *flow rate of energy* (equation (2.1)) is equivalent to saying that energy equals emitted (or incident) power multiplied by time, i.e. expressed as the formula

$$\text{Energy} = \text{Power} \times \text{Time} \tag{2.3}$$

Strictly speaking, equations (2.1) and (2.3) are only correct for levels of power which do not change during the time under consideration. The general mathematical definition of power P (which may vary with time t) is

$$P = \frac{\mathrm{d}Q}{\mathrm{d}t} \tag{2.4}$$

where Q is the symbol for energy and the ratio is defined for the momentary energy flow $\mathrm{d}Q$ during an (infinitesimally) small time interval $\mathrm{d}t$, i.e. equation (2.4) is the exact definition for the momentary value of P.

The generally valid expression for equation (2.3) is an integral

$$Q = \int_{t_1}^{t_2} P(t)\,\mathrm{d}t \tag{2.5}$$

where the time t_1 is for instance the beginning of a pulse and t_2 the end of the pulse to determine the pulse energy, but there could be also several pulses between t_1 and t_2, when one considers the total energy over a longer time domain.

The relationship between energy and power can be best visualized when one plots the power as function of time, as is shown in figure 2.2. This shows laser radiation where emission of radiation commences at 1 s, and radiation is consequently emitted with a constant power of 10 mW up to 3 s, i.e. laser radiation is emitted for a duration of 2 s. Since in this example, the level of power is constant during the period of emission, the emitted energy can be calculated by multiplying the power by the emission duration to obtain the energy value of 20 mJ. Graphically, the temporal behaviour of the emission makes up a rectangle, where the power is represented by the height and the duration of the emission is represented by the width of the rectangle; the energy is therefore equivalent to the *area* of the rectangle. Pulses and emission patterns with the same graphical area have the same energy, as is also shown in figure 2.2, where the emission on the right hand side has half the power but double the duration of the emission on the left.

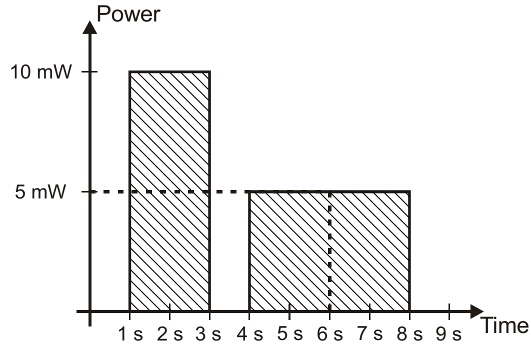

Figure 2.2. Emitted radiant power plotted as function of time. Two emissions with different peak power and duration but equal energy.

As an everyday example of the temporal relationship between power and energy, we can think of a household electricity bill, which characterizes the energy consumption in a given period of time. The energy is given in units of kilowatt-hours, kWh, where 'kW' is the unit of power, and 'h' the unit of time. If one has a 1000 W water heater on for 1 h, it has delivered an energy of 1 kWh to the water. The energy of 1 kWh could also be converted into joules: $1000 \text{ W} \times 3600 \text{ s} = 3.6 \times 10^6$ J. The 'electricity bill units' (used energy) of kilowatt-hours can be a mnemonic help for the relationship between energy and power (equation (2.3)).

When we refer to energy, it is important to specify which 'entity' contains that energy, such as the electrical energy consumption for the last month, the energy contained in a litre of milk or, when referring to laser radiation, the energy per photon, the energy per laser pulse, or the energy emitted or incident over a certain period of time. For instance, one often hears people say 'the laser emits one joule', when they actually should refer to 1 joule *per pulse*—after all, a laser pointer with a radiant power of 1 mW can also emit 1 J, but it takes 1000 s of emission. The concept of energy only makes sense when it is associated with a certain event, an entity or a period of time. In photobiology, the incident energy is often referred to as *dose*. To be precise, dose in photobiology is usually equivalent to energy per unit area, not simply energy (see section 2.2).

When laser radiation is continuously emitted for longer than about a second (with a power level which is reasonably constant), we refer to a *continuous wave* laser, abbreviated to *cw*. To characterize pulsed laser radiation, the parameters listed in table 2.1 are usually used (see also figure 2.3).

Table 2.1. Parameters usually used to characterize pulsed laser radiation.

Quantity	Symbol	Unit
Energy per pulse	Q_{pulse}	joule (J)
Peak power	P_{peak}	watt (W)
Pulse duration	t_{pulse}	second (s)
Average power	P_{aver}	watt (W)
Pulse repetition frequency, also called repetition rate	f	hertz (Hz)
Period	t_{period}	second (s)

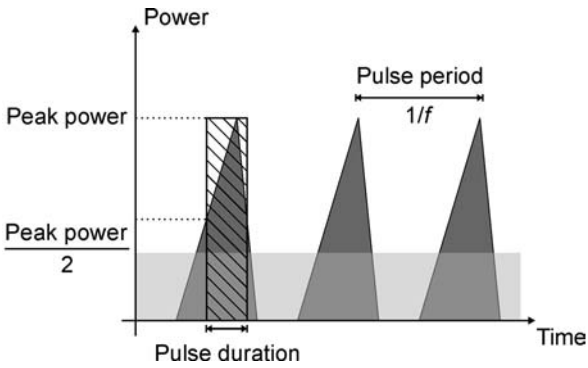

Figure 2.3. A pulse train consisting of three triangular laser pulses with a given pulse duration t_{pulse} and peak power, spaced by the period of the pulse train. Also shown is the average power level, which is the average rate of energy emission, resulting from a redistribution of the energy contained in the pulses over time.

Pulse duration and peak power

The pulse duration is usually defined as the FWHM, the Full Width of the pulse at Half the Maximum power level, which is also the applicable definition in laser safety (see figure 2.3). For rectangular and triangular pulse shapes, the peak power can easily be calculated by dividing the pulse energy with the pulse duration:

$$P_{peak} = \frac{Q}{t_{pulse}}. \tag{2.6}$$

For pulse shapes other than triangular or rectangular, there will be a varying degree of over- or underestimation of the peak power when using equation (2.6). However, since emission limits for product classification and exposure limits for eye and skin hazard evaluation of pulses are generally specified in terms of energy rather than peak power (with the exception of pulse durations shorter than 1 ns for wavelengths outside the retinal hazard area), it is usually not necessary to calculate peak power for safety purposes. In addition, the emission of pulsed lasers is normally specified by the manufacturer in terms of pulse energy, and radiometers intended for measuring pulses are also usually calibrated in terms of energy values.

Example. Excimer lasers typically have pulse durations of about 20 ns and pulse energies of about 200 mJ. The corresponding peak power for these values (assuming a triangular pulse shape) is 10 MW (megawatt). This value can seem very high, and corresponds to the electrical output of a medium sized power plant. The example shows that when a given energy, which need not be high, is emitted within such a short time, then very high peak powers result. It is these high peak powers which make such short pulses an interesting tool in medicine and technology, but also highly hazardous when they are incident on the skin or the eye.

Note: The actual pulse shape of excimer lasers is closer to a skewed Gaussian shape where the maximum value is shifted towards the beginning of the pulse. Such a shape could, for instance, be described quite well by $P(t) = t^2 \exp(-t^2/\sigma)$ where σ determines the pulse width. When this formula is used, the peak power is found to be 4.79 MW. When a Gaussian pulse shape is assumed, the peak irradiance value becomes 4.70 MW, i.e. the assumption of a triangular pulse shape slightly overestimates the peak power when calculated from the energy per pulse.

Pulse repetition frequency and period

The pulse repetition frequency (number of pulses per second) is the reciprocal value of the period of the pulse train, i.e. the time between maxima (or other characteristic points) of two consecutive pulses. It is also often called repetition rate. The concept of frequency really only applies to pulse trains that for some time exhibit a constant period.

Duty cycle

The term duty cycle (dimensionless) is sometimes used to characterize the ratio of the pulse duration to the period, i.e. it can be calculated by multiplying the pulse duration by the pulse frequency, i.e. it is a measure of how much the pulses ‘fill out’ the time; for a cw laser, the duty cycle equals 1.

Average radiant power

Radiant power can either describe a momentary power level, such as when describing the change of power as a function of time during the pulse, or it can be a value averaged over a finite period of time. The average power level is also determined by using equation (2.1), but then *energy* is the total energy emitted or incident within a given duration over which the power is averaged, and *time* is the averaging duration

$$P_{\text{aver}} = \frac{\text{Total energy within averaging duration}}{\text{averaging duration}}. \tag{2.7}$$

Equation (2.7) is the general expression for average power. For a train of pulses with constant pulse energies and with pulse repetition frequency f, the average power can be calculated by

$$P_{\text{aver}} = Q \times f. \tag{2.8}$$

This relationship can be simply inferred by considering that the number of pulses within time t is $f \times t$, so that the total energy within the time t becomes $Q \times f \times t$, which needs to be divided by time t to obtain the average power, and $Q \times f$ remains. The averaging process can be visualized as spreading out the energy contained in the pulses over the averaging time. Following this understanding, the average power does not depend on the pulse duration as long as the pulse energy remains the same. For non-constant pulse trains, i.e. when the repetition rate or the pulse energy varies, the value of the average power depends both on the duration of the averaging duration and on the section of the pulse train which is considered for averaging, i.e. over which section of the train the 'temporal frame' of averaging is laid.

Example. If the excimer laser in the previous example emits a stream of pulses at a constant pulse repetition frequency of 100 Hz, each pulse having an energy of 200 mJ, the average power equals 20 W. Obviously, when the energy of the pulses is spread over time, the average power is a lot smaller than the pulse peak power.

2.2 Irradiance and radiant exposure

The previous section has dealt with the basic quantities of energy and power, and their temporal relationship. When considering the actual laser interaction with material, however, i.e. laser radiation being incident on a surface and being absorbed at or relatively close to the surface (be it a workpiece or human tissue), then not only the power or energy contained in the incident beam is relevant, but also the surface area over which the radiation is distributed. When a given power is focused into a small spot, it is evident that the irradiated material will be affected (for instance heated) faster or more intensely than when the same power is distributed over a larger surface area. The appropriate quantity to describe this level of irradiation therefore relates the power or energy to the size of the irradiated area, and these quantities are referred to as *irradiance* and *radiant exposure*, respectively (see figure 2.4):

$$\text{Irradiance} = \frac{\text{Power incident on area}}{\text{Area}} \qquad \text{with units of W m}^{-2} \tag{2.9a}$$

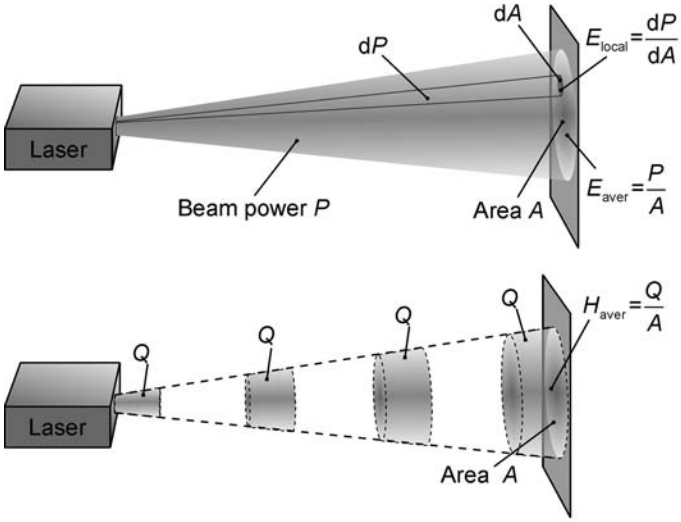

Figure 2.4. Irradiance E and radiant exposure H is derived by relating the power or energy incident on a surface to the irradiated area.

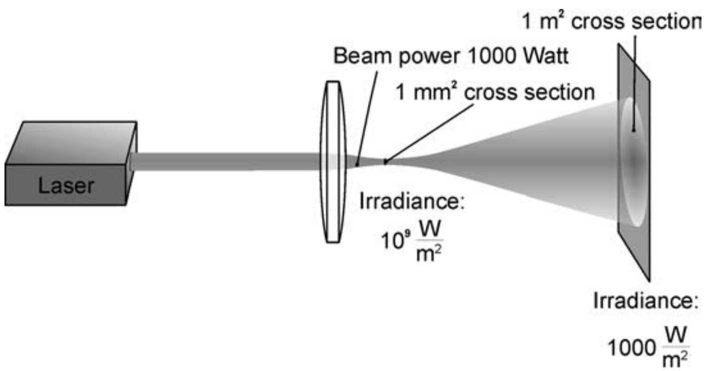

Figure 2.5. Example of a laser beam having a power of 1000 W being focused to a spot with a beam cross section of 1 mm^2 and some distance behind the focus being incident with a beam cross section of 1 m^2. The effect on a workpiece or human tissue in the two locations within the beam is quite succinct.

and

$$\text{Radiant Exposure} = \frac{\text{Energy incident on area}}{\text{Area}} \quad \text{with units of J m}^{-2}. \quad (2.9b)$$

For example, when a laser beam with 1000 W radiant power is focused to a spot having an area of 1 mm^2, the irradiance at the spot would be 1000 W per square millimetre, or 10^9 W m^{-2}, i.e. 1 gigawatt per square metre (see figure 2.5). At first glance, it might be puzzling how a one kilowatt laser could produce gigawatts per square metre, but the point is that this irradiance exists only over the irradiated area of 1 mm^2. If we wished to produce the same level of irradiance over the area of one square metre, we would need a laser beam having a power of one gigawatt. When the power of 1000 W of this laser is spread over an area of 1 m^2 (for instance at some distance behind the focus), than at this surface it would produce an irradiance of 1000 W m^{-2}. (This simple treatment assumes homogenous irradiation, i.e. a constant beam profile; the rigorous definition is given in section 5.3.) While the power of 1000 W when concentrated on 1 mm^2 produces an irradiance sufficient to melt metal and to produce deep burns in human tissue within milliseconds (lasers used for surgery have powers of about 30–50 W), the same power distributed over an area of 1 m^2 is comparable to the irradiance produced by sunlight at the Earth's surface. The power contained in the laser beam is always 1000 W, it is the cross section of the beam and hence the irradiance, which makes the difference. In practice, irradiance and radiant exposure are often related to an area of 1 cm^2, as the irradiated areas are more appropriately measured in square centimetres; 10^9 W m^{-2} would then recalculate to 100 kW cm^{-2}, and 1000 W m^{-2} would recalculate to 0.1 W cm^{-2}. However, it is recommended that parameters are always converted to the base units of m, s, W, J, W m^{-2}, J m^{-2} etc, before embarking on laser safety calculations.

2.2.1 Terminology

Irradiance and radiant exposure can be seen as quantifying the 'concentration' or 'density' of power or energy; in fact, they are often referred to as 'power density' or 'energy density', respectively. However, these terms strictly refer to power or energy per unit volume, not per unit area [1]. Following this international convention, power density would be measured in W m^{-3} and energy density would be measured in J m^{-3}. Nevertheless, the terms power density and energy density are in practice widely used (and are also easier to remember) instead of the correct terms irradiance and radiant exposure, for example in the field of low level laser therapy.

Another quantity which is often confused with radiant exposure is *fluence*, as it is also defined as energy per unit area, but it actually refers to the energy passing through a given area from both sides, which is relevant in scattering media. Radiant exposure refers to radiation that is incident on the (surface) area only from the direction of the irradiating source (see figure 2.6). For non-scattering matter, such as clear glass or metal, radiant exposure and fluence have the same value, but for scattering media, such as tissue exposed to red light, fluence can be higher than radiant exposure. In this context, fluence is used in the science of laser-tissue interaction, but in laser safety we refer only to the radiation that is incident from the 'outside' of the body, and therefore radiant exposure is used exclusively.

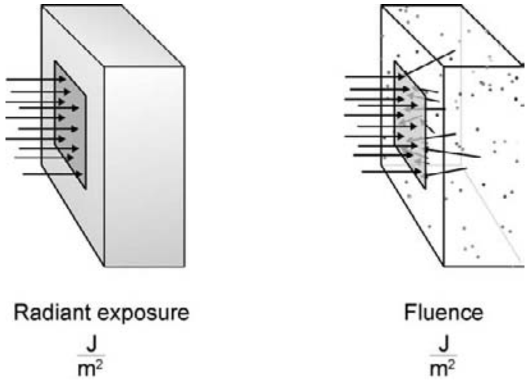

Figure 2.6. Radiant exposure is defined as energy incident or passing through an area, while fluence is defined as energy incident or passing through an area from both sides.

Intensity is another term that is frequently misused, even by optical specialists. Intensity, strictly called *radiant* intensity, is defined as the power emitted into a given solid angle of space, divided by that angle, and is measured in watts per steradian, i.e. W sr^{-1} (for a detailed definition see section 2.3.3). Often intensity is wrongly used to mean power per unit area (which properly is referred to as irradiance).

We will also introduce the quantity of *exitance* in this section, which is also defined as power per unit area, as is irradiance. Exitance, however, describes the power *emitted* per unit area from a source (using 'source' in the wider sense, for example including diffuse reflection). Exitance is a useful quantity in understanding the difference between the irradiance that is produced by a source at some distant surface and the irradiance profile that is produced in the image plane when the source is imaged. The latter is directly related to the exitance (including imaging by the eye onto the retina, or imaging by a lens for radiance measurements).

2.2.2 Averaging over area—limiting aperture

The previous example of an incident laser beam having a cross sectional area of 1 m^2 is an oversimplification, as it assumes that the irradiance profile across the reference area is uniform. For non-uniform profiles, we have to distinguish between local irradiance values and an irradiance value averaged over some finite area. The mathematically exact definition of (local) irradiance, E, and radiant exposure, H is

$$E = \frac{\mathrm{d}P}{\mathrm{d}A} \qquad \text{and} \qquad H = \frac{\mathrm{d}Q}{\mathrm{d}A} \tag{2.10}$$

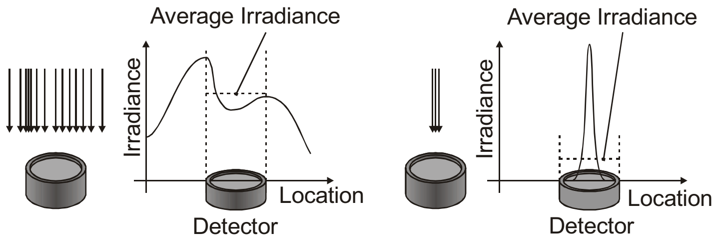

Figure 2.7. Example of irradiance profiles across a detector surface or aperture, and the corresponding averaged value. Left-hand side: inhomogeneous profile; average irradiance determined with detector, level of average irradiance depends on position of detector within beam. Right-hand side: a beam with diameter much smaller than the aperture—the averaged irradiance is much smaller than real irradiance.

which expresses that the power $\mathrm{d}P$ or the energy $\mathrm{d}Q$ (per pulse or for a certain emission or exposure duration) that is incident on the infinitesimally small area $\mathrm{d}A$ (see also figure 2.4). By relating the irradiance and radiant exposure to an infinitesimally small area $\mathrm{d}A$, the precise value of irradiance and radiant exposure at the location of $\mathrm{d}A$ is obtained. In practice, when we measure the irradiance or radiant exposure, we have to use a detector or an aperture in front of the detector with a finite area A to measure a finite power P or energy Q, and we obtain the measured irradiance or radiant exposure by dividing P or Q by the area. This practical determination of irradiance and radiant exposure represents invariably some extent of averaging over the area of the detector or the aperture, as depicted in figure 2.7. The averaging can be conceptualized as 'spreading' the total power on the detector over the detector or aperture area, as is indicated in figure 2.7.

By the nature of averaging, the averaged level of irradiance is always less than the peak irradiance within the averaging area. Only for constant irradiance profiles does the averaged value not depend on the averaging area. The aperture area, i.e. measurement area, can also be considered as the smallest spatial *resolution* with which the irradiance can be determined. Hotspots in the irradiance profile smaller than the aperture area cannot be detected.

Even a radiometer that is calibrated to measure irradiance in fact measures total radiant power incident on the sensitive area of the detector, and the division with the area of the detector is figured into the calibration factor. For such an irradiance radiometer, if we try to improve the measurement resolution for detecting hotspots in the irradiance profile by decreasing the area with an aperture, we would have to change the calibration factor correspondingly (by the ratio of the new and the original area).

It is an important principle in laser safety that an averaged value of irradiance or radiant exposure, which might be significantly smaller than the local 'true' physical irradiance, is compared to the exposure limit for the eye or the skin. In the field of laser safety and for hazard evaluation of broadband optical radiation, specific averaging apertures which are related to biological parameters such as pupil size and eye movements are defined together with the exposure limits for the eye and the skin. The specified aperture over which the irradiance or radiant exposure value needs to be averaged is referred to in laser safety guidelines and standards as the 'limiting aperture'. Because of biophysical phenomena, irradiance hot spots which are smaller than the specified apertures are not relevant for laser safety assessments. In some cases, the specified size of the aperture results in measured irradiance values that would be considered nonsense when compared to the real physical values. An example of this is when the irradiance of a laser beam having a diameter of 1 mm is averaged over an aperture of diameter 7 mm. The averaged value is about 50 times smaller than the real physical value (see example below). However, for hazard evaluations, it is this *biologically effective* value that has to be compared to the respective exposure limit for optical radiation, as will be discussed in more detail in chapter 3. When one uses an averaging area smaller than the one specified, the level of hazard to the eye or the skin would be overestimated. For practical assessments it is helpful to consider that if the beam diameter is smaller than the specified aperture diameter so that the full beam power is passing through the aperture, then there is no actual need to place an aperture in front of the detector, as the measured power will not be affected by the size of the aperture area. In this case, one just measures the power and divides the power with the area of the specified limiting aperture. It is only when the beam diameter is comparable to or larger than the specified aperture that the aperture becomes relevant, i.e. we would then need to place such an aperture in front of the detector and measure only the power (or energy) passing through the 'limiting' aperture to subsequently divide that value with the area of the aperture to obtain the irradiance value.

Example. Consider a laser pointer emitting a beam having a diameter of 1 mm (with the simplifying assumption that the beam is uniform) and having a radiant power of 1 mW. The area of the beam is therefore 7.9×10^{-7} m^2 resulting in an irradiance value of 1273 W m^{-2}. However, for ocular hazard analysis for visible wavelengths, a limiting aperture having a diameter of 7 mm is specified. With this averaging aperture, the biophysical relevant averaged irradiance equals only 26 W m^{-2}. It is this smaller value which has to be compared to the exposure limit for the eye. This example is chosen so that the averaged irradiance lies just at the exposure limit for momentary involuntary exposures. Using the actual irradiance instead of the biologically effective irradiance would overestimate the hazard by 49 times!

2.3 Angle and intensity

In laser safety, some important parameters are expressed in angular quantities, namely beam divergence, the field-of-view of a radiometer and the angular

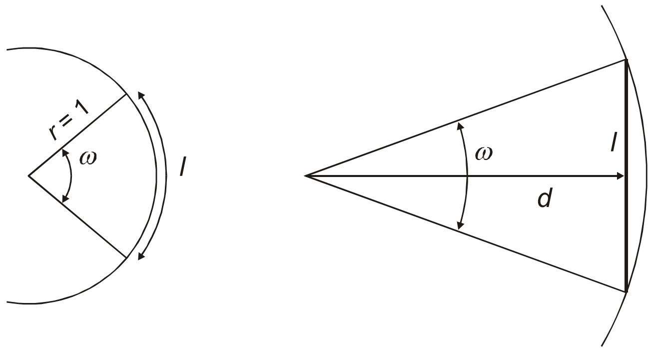

Figure 2.8. Definition of the plane angle ω (left), as well as simplified determination for small angles by dividing the extent l by the distance d.

subtense of the apparent source (which determines the irradiated area on the retina). These angles are typically measured in radians or rather milliradians (abbreviated to mrad). The field-of-view can also be measured in terms of the solid angle, in units of steradians. Beam divergence is a central parameter for beam propagation and is necessary for calculating irradiance or radiant exposure at some location in the beam, and is discussed further in chapter 6. The angular subtense of the source is one of the parameters on which the exposure limits depend and is therefore discussed in chapter 3. The measurement field-of-view is discussed in section 2.4. Here we give the basic definition of plane and solid angle, as these are also needed for the radiometric quantities radiance and intensity.

2.3.1 Plane angle

The SI unit of the plane angle is the radian, and is defined such that a full circle has an angle of 2π radians, i.e. 6.28 radians. This definition also relates the radian to the common unit of angle, the degree, as a full circle has 360°, and thus 6.28 radians $=$ 360° or 1 radian $=$ 57.3°. The plane angle in radians is numerically equivalent to the arc length of a circle having a radius of unity, as the full circle has a circumference of 2π, i.e. for a radius of 1 m, the circumference equals 6.28 m. For a circle having a radius other than unity, the angle is given by the arc length divided by the radius of the circle (see figure 2.8).

In laser safety, angles are typically small, so that the plane angle ω subtended by an object that is at distance d can be easily calculated in radians by dividing the height of the object, l, by the distance, d. The angle subtended by an object obviously changes with the distance of the reference point from the object. For instance, a person of height 1.8 m observed from a distance of 1000 m subtends an angle of 1.8 m/1000 m $=$ 1.8 mrad; at a distance of 100 m the person subtends