Chapter 1
Introduction

For many years, lasers had been considered by engineers to be a problem in search of a solution—not the other way ‘round, as is often repeated in the scientific literature. The problem was getting the laser to work properly, reliably, cost-effectively, etc.—and then getting it to “play” well with the other components in the system. This historical difficulty in obtaining working hardware with these unique sources of photons led to the many Immutable Laws of Lasers:

- The optimum number of lasers in any system is zero.
- The only likely result of a laser development program is that all available funds will be expended.
- The performance of any given laser cannot be predicted based on the measurements of the performance of any other laser.
- Lasers are the wave of the future—and always will be!

Fortunately, these laws have mutated over the years to the point where they are now mostly obsolete, and lasers are used in a number of difficult environments ranging from the manufacturing floor to the ceiling of outer space. Examples vary from the obvious to the obscure, including:

- Driverless cars and autonomous vehicles\(^1\)
- Biomedical microscopes with sub-diffraction-limited resolving power, resulting in a Nobel prize for its inventors\(^2\)
- The Internet and laser communications\(^3\)
- Manufacturing applications requiring material heating, removal, or addition\(^4\)
- Laser projection systems and displays\(^5\)
- Directed energy (aka “Star Wars”) for planetary defense against asteroids\(^6\)

Despite their many applications—and the prominence of lasers in popular culture as well\(^7\)—there is still a surprising lack of information available on how to design and engineer a laser system. The development
of lasers themselves has for years dominated academic research, yet the money has not flowed to the broader issues and intricacies involved in using these high-tech "flashlights" in industrial, commercial, biomedical, or defense applications. The purpose of this book is to take an initial step in filling this gap.

A laser is a source of both light and heat. Light is an electromagnetic wave with a wavelength \( \lambda \) and frequency \( \nu \) with energy propagating at the speed of light \( c \) in vacuum:

\[
\nu = \frac{c}{\lambda} \quad \text{[Hz]} \tag{1.1}
\]

The wavelengths that correspond specifically to "light" are shown in Fig. 1.1 as ultraviolet (UV), visible (VIS), and infrared (IR). The different types of lasers reviewed in this book can emit in any or all of these wavelength bands. Table 1.1 divides these bands into smaller units such as vacuum UV (VUV), midwave IR (MWIR), and so on.

In this chapter, we give an overview of the book by first looking in more detail at some laser systems that illustrate important laser properties (Section 1.1). As these properties depend on the design of the lasers themselves,
we then review in Section 1.2 the principles of laser engineering. Finally, we preview the book contents in Section 1.3 with an overview of the components used in typical laser systems, and some of the design trades required for optimizing overall laser system performance.

1.1 Laser Systems

As illustrated in Fig. 1.2, a generic laser system consists of lasers, optics, scanners, detectors, and a propagation medium such as air. As a result, the required tasks for laser system development may include laser selection, beam propagation, optical design, beam scanning, radiometry, detector selection, and possibly atmospheric compensation.

The heart of the laser system is, of course, the laser—of which there are nearly an infinite number of types and wavelengths (Fig. 1.3). One of the goals of this book is to narrow down the number of options to those that will cover 90% or so of the possible systems, with the more-obscure 10% not included. Some common laser systems—and the critical laser properties that make them useful—are reviewed in the rest of this section.

Figure 1.2  Typical laser system components include lasers, optics, scanners, and detectors. [Reprinted with permission from: A. Cheng et al., “Simultaneous two-photon calcium imaging at different depths with spatiotemporal multiplexing,” Nature Methods 8, 139–142 (2011).] (See color plate.)
The first system is that of optical data storage (Fig. 1.4) such as CD, DVD, and HD-DVD players, and holographic data storage. In this case, low-power semiconductor diode lasers are commonly used because a property known as beam quality (Chapter 3) allows focusing to the smallest possible, diffraction-limited spot size ($\frac{\lambda}{2D}$ for an objective lens with an aperture diameter $D$). This ensures the highest possible storage capacity on the limited surface area of a disk; a shorter wavelength also increases capacity, with wavelengths evolving from $\lambda = 780$ nm for CD systems down to 405 nm for HD-DVDs such as Blu-ray™. Additional benefits of diode lasers—critical for the consumer market—include their low cost, size, and electrical power consumption.

Another common laser application is that of testing the irregularity of optical surfaces. Such testing requires a laser with a large coherence length, i.e., the distance over which its phase is approximately unchanged (Section 1.2.1). For example, the laser’s coherence length must exceed twice the distance between the reference surface and the test surface in Fig. 1.5, as any difference in phase will interfere and appear incorrectly as an error in the surface of the test mirror. Helium-neon (HeNe) gas lasers are often used for interferometers because they have both a long coherence length and good

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Figure 1.3 The large number of laser types and wavelengths makes laser selection for system development a complex task. (© 2009 Laurin Publishing; reprinted with permission.) (See color plate.)
spatial coherence across the wavefront. Helium-neon wavelengths of 633 nm (VIS) and 3.39 μm (MWIR) are common, as are carbon dioxide (CO\textsubscript{2}) gas lasers with a wavelength of 10.6 μm for testing LWIR optics.

A third laser application is that of directed energy (DE), where it is necessary to deposit the highest amount of power in the smallest area at a large distance. This places a requirement on the laser brightness; distinct from simply output power, laser brightness is a measure of how spatially efficient a source is at emitting power. For example, if the output power of two lasers is the same, the laser emitting with fewer atoms (a smaller area) into a smaller divergence angle has a higher brightness (Chapter 6). Solid-state and fiber lasers can deliver more than 10 kW of average power from a small, near-diffraction-limited beam and are thus an option for DE applications requiring high irradiance (W/cm\textsuperscript{2}) or fluence (J/cm\textsuperscript{2}) on a target.

Finally, a fourth common laser application is that of confocal microscopy. As illustrated in Fig. 1.6, these microscopes obtain high-resolution 3D images...
by blocking out-of-focus photons with a detector pinhole (confocal aperture). Using a technique known as multiphoton excitation (MPE), image contrast can be improved by using a low-average-power laser that creates one short-\(\lambda\) photon from two (or more) longer-\(\lambda\) photons. The key laser properties that allow MPE are a high peak power (to efficiently generate long-\(\lambda\) photons) and low average power (to minimize heat absorption by the specimen). This requires ultrashort-pulse (USP) lasers that can release energy in a short pulse or “shot” on the order of 1–10 psec (Section 2.1.5). Fiber lasers allow the generation of such pulses in a product size appropriate for clinical use.

Summarizing, we see that various laser properties—beam quality, coherence length, brightness, pulse width, and so on—may or may not be important depending on the application. There are, of course, many other laser systems besides the four discussed in this section (see Table 1.2), and we will look at a number of these throughout the course of the book. As well, the different types of lasers—semiconductor, gas, solid-state, and fiber—and their properties will be reviewed in more detail in Chapter 2.

1.2 Laser Engineering

While the intent of this book is to go into detail on the development of laser systems, a brief introduction to the design of lasers themselves makes their use in a system a more-intelligent endeavor. Many references are available for details on laser design; Ref. 9 is recommended.

One of the primary goals of laser engineering is to meet system requirements by controlling the unique features of lasers that determine the properties of coherence length and beam quality, namely, the degree of
phase coherence. That is, the wavefronts must be in phase along the propagation direction (temporal coherence, Fig. 1.7); in addition, the wavefronts must also be in phase across the beam diameter (spatial coherence, Fig. 1.8). There are also variations on these themes, where specialized lasers have low temporal coherence but good spatial coherence (white-light or super-continuum lasers), or high temporal coherence but poor spatial coherence (“random” lasers).

As shown in Fig. 1.9, what’s needed for a laser’s temporal and spatial coherence is:

- A gain medium (and associated pump energy $h\nu_p$) to create a population inversion (or gain) of the medium’s electron energy states [Fig. 1.9(a)], allowing photon amplification.
• A resonant cavity—two mirrors, for example—to control the number, direction, and phase coherence of the amplified photons [Fig. 1.9(b)].

The amplification of photons is in phase with the incident wavefront and is known as stimulated emission, while atoms that spontaneously emit photons before they interact with the laser beam have a random phase relationship (i.e., are not coherent) with the wavefront (Fig. 1.10). As a result, higher gain has a larger fraction of amplified in-phase photons in comparison with the incoherent photons.

If the energy of the incident electromagnetic field more-or-less matches that of the electron’s excited state energy $E_2$ compared with some lower-energy state.

Figure 1.8 Atoms emitting independently across an incoherent source such as a tungsten-filament lamp results in a phase difference $\Delta \phi$ and poor spatial coherence of the wavefronts. (Permission to reprint granted by Newport Corporation; all rights reserved.)

Figure 1.9 (a) Changes in the gain medium’s electron energy states result in the emission of a photon with energy $h\nu$. (b) The back-and-forth reflections in a two-mirror resonant cavity increase the number of stimulated photons. (Reprinted from Ref. 10.)
$E_1$, then there is a high probability the electron will give up its energy in the form of a stimulated photon whose energy $E_p$ in Fig. 1.9(a) is

$$E_p = E_2 - E_1 = h\nu = \frac{hc}{\lambda} \quad [\text{J}]$$

(1.2)

where $h = 6.626 \times 10^{-34}$ J-sec is Planck’s constant. Physically, a higher-frequency, shorter-wavelength photon has more energy, as would be expected for an electromagnetic wave that changes at a faster rate.

The population inversion—defined as $N_2 - N_1$ in Fig. 1.9(a), with more electrons in the gain medium in an excited energy state $E_2$ than a lower state $E_1$—has a distribution of excited-state energies and thus amplifies more than a single wavelength. In its simplest form, this distribution is a result of the inevitable Heisenberg uncertainty fluctuations of the excited-state lifetime, resulting in a spread of photon energy $\Delta E_p = h\Delta\nu$ that is known as the gain bandwidth (in units of energy).

Building on these principles, laser engineering entails a large number of complexities, some of which are reviewed in the next subsections under the categories of temporal coherence, spatial coherence, pulse generation, and wavelength conversion.

### 1.2.1 Temporal coherence

We have seen in Section 1.1 how the coherence length affects the performance of an interferometer; in this section, we take another look at this idea from the laser designer’s perspective.

Even though it is common to talk of a pure “red” or 633-nm wavelength, no laser emits at a single (monochromatic) wavelength. Instead, there are unavoidable gain medium, quantum-mechanical, and optomechanical
broadenings of any laser’s wavelength, and the degree of broadening—or *linewidth* $\Delta \lambda$—determines the laser’s temporal coherence and coherence length.

Temporal coherence can be understood by using a physical picture of two wavelengths propagating along the laser’s longitudinal axis. Even if the speed of light is the same for both wavelengths, Fig. 1.11 shows that they will eventually get completely out of phase. The distance over which this occurs is known as the coherence length $d_c$.

The coherence time $\tau_c$ over which the emitted wavelengths are considered to be in phase—that is, are temporally coherent—thus depends inversely on the absolute value of the wavelength difference $|\Delta \lambda|$ or frequency difference $\Delta \nu = c|\Delta \lambda/\lambda|^2$ [from differentiating Eq. (1.1)]:

$$\tau_c \approx \frac{1}{2|\Delta \nu|} = \frac{1}{2c|\Delta \lambda|} \quad \text{[sec]}$$  (1.3)

This clearly shows that a narrow-spectrum laser with small $\Delta \nu$ has a longer time over which different frequencies propagate before they are no longer considered to be in phase. Typical numbers for a HeNe laser used for interferometric optical testing are a coherence time $\tau_c = 0.33$ nsec and a coherence length $d_c = c\tau_c = 100$ mm for a linewidth $\Delta \lambda = 2$ pm (see Table 1.3). Note that the results shown in Fig. 1.11(b)—where the different wavelengths

### Table 1.3 Coherence length $d_c = c\tau_c$ of commonly used lasers; see Chapter 2 for more detail on each of these laser types.

<table>
<thead>
<tr>
<th>Laser Type</th>
<th>Center Wavelength, $\lambda_o$</th>
<th>Linewidth, $\Delta \lambda$ or $\Delta \nu$</th>
<th>Coherence Length, $d_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-Power Diode</td>
<td>808 nm</td>
<td>3 nm</td>
<td>100 $\mu$m</td>
</tr>
<tr>
<td>Nd:YAG</td>
<td>1064 nm</td>
<td>50 pm</td>
<td>10 mm</td>
</tr>
<tr>
<td>He-Ne</td>
<td>633 nm</td>
<td>2 pm</td>
<td>100 mm</td>
</tr>
<tr>
<td>Low-Power Fiber</td>
<td>1070 nm</td>
<td>10 kHz</td>
<td>15 km</td>
</tr>
</tbody>
</table>
are out of phase at a time $t \approx 10^{-8}$ sec—are not consistent with the estimates from Eq. (1.3), as the equation assumes that $\Delta \lambda$ is small in comparison with the center wavelength $\lambda_0$.

What determines the lasing wavelength $\lambda_0$ and linewidth $\Delta \lambda$? Ideally, three factors: the axial modes based on the length of the laser cavity, the bandwidth of the gain medium, and the type of gain medium (homogeneous versus inhomogeneous).

Axial (or longitudinal) modes are determined by the geometrical fit (or resonance) of a given wavelength in the laser cavity. That is, if the two mirrors that define a laser cavity are nearly planar and perfectly reflecting—an ideal assumption, given that one mirror will be designed not to be so that light can escape the cavity as output power—then Fig. 1.12 shows that an integer number $m = 1, 2, 3,$ etc., of half-wavelengths of the electric field fit in the cavity length $L$:

$$m \frac{\lambda}{2n} = L \quad [m] \quad (1.4)$$

where the refractive index $n$ of the gain medium is included to account for the reduction in wavelength in comparison with its free-space ($n = 1$) value. With the exception of a specific type of semiconductor laser known as a vertical-cavity surface-emitting laser (VCSEL) with a cavity length $L \approx \lambda$, the number of half-wavelengths is large in practice. For example, for a HeNe laser emitting at $\lambda = 633$ nm with $L = 100$ mm and $n \approx 1$, $m = 2L/\lambda = 2 \times 0.1$ m/633 nm = 315,955 half-wavelengths.

Unless they are specifically “locked” together in phase (as in Section 1.2.3), these axial modes are emitting independently of one another, and are thus all potential wavelengths at which the laser can oscillate. Solid-state lasers using titanium-doped sapphire as a gain medium, for example, may emit hundreds of thousands of axial-mode wavelengths (Section 2.2.2). These lasers are commonly specified by the frequency difference between each axial mode,
where each frequency $v_m$ for a planar cavity is obtained by combining Eqs. (1.1) and (1.4),

$$v_m = \frac{c}{\lambda_m} = \frac{mc}{2nL} \quad [\text{Hz}]$$

and the frequency difference $\Delta v_a$ between adjacent axial modes—also known as the free spectral range (FSR) of the laser cavity—is given by

$$\Delta v_a = v_{m+1} - v_m = \frac{c}{2nL} \quad [\text{Hz}]$$

For example, a HeNe laser with $L = 100$ mm has an axial mode spacing $\Delta v_a = (3 \times 10^8 \, \text{m/sec})/(2 \times 1 \times 0.1 \, \text{m}) = 1.5$ GHz, while a short-cavity semiconductor laser with $L = 100 \, \mu\text{m}$ and $n = 3$ gives $\Delta v_a = (3 \times 10^8 \, \text{m/sec})/(2 \times 3 \times 100 \times 10^{-6} \, \text{m}) = 500$ GHz.

Whether or not multiple axial modes will lase depends, in part, on the cavity-mode spacing $\Delta v_a$ in comparison with the frequency spectrum (or gain bandwidth) $\Delta v_g$ of the gain medium. This is shown in Fig. 1.13, where the gain curve is superimposed over the longitudinal modes of an ion laser. The gain bandwidth is determined by a number of possible gain-medium mechanisms: natural broadening due to spontaneous decay of excited-state energies, Doppler broadening due to atomic or molecular motion, collision broadening due to intermolecular impacts of gas molecules that change the phase of the emitted wavefront (Fig. 1.7), or phonon broadening due to imperfections and variations in lattice spacings in semiconductor, solid-state and fiber lasers. Independent of mechanism, a gain bandwidth wider than the axial mode spacing—as shown in Fig. 1.13—has the potential to lase at more than one axial-mode wavelength.

**Figure 1.13** The gain bandwidth $\Delta v_g$ of many lasers exceeds the longitudinal-mode spacing $\Delta v_a$. (Permission to reprint granted by Newport Corporation; all rights reserved.)
Whether or not this occurs depends on the third contributor to the emission wavelength and linewidth, namely, how the gain medium responds (saturates) to power levels inside the cavity. There are two possibilities: (1) the gain decreases equally across the entire gain bandwidth as excited-state population levels are used up to increase the output power (homogeneous saturation), or (2) the gain decreases only at specific wavelengths depending on the gain-broadening mechanism (inhomogeneous saturation).

For homogeneous gain saturation—as is found with natural, collision, and homogeneous phonon broadening—the peak of the gain at steady state will drop to equal the cavity losses, and this will occur at or near one axial mode. This mode will thus lase, and homogeneous saturation typically leads to single-longitudinal-mode (SLM) lasing at one axial mode (aka single-frequency), rather than over the entire gain curve. Stimulated emission thus results in a narrowing of the output spectrum from its spontaneous width $\Delta v_{sp}$, a principal reason for the narrow linewidth of a laser; as a result, semiconductor lasers have a smaller $D_l$ than spontaneously emitting LEDs made from the same material.

For inhomogeneous saturation, on the other hand, the gain saturates only at those axial-mode wavelengths preferred by the gain medium—with Doppler and inhomogeneous (strained lattice) phonon broadening being typical examples. This can lead to lasing at more than one axial mode, and such multi-longitudinal-mode lasers emit at discrete frequency spacings given by Eq. (1.6).

For a long coherence length, then, the first option for the laser systems engineer is a frequency-stable SLM laser, as is required for interferometry, coherent sensing, and holography. Because the drop-off of the gain curve might not be sufficient to prevent small cavity and refractive-index fluctuations from causing the axial mode to “hop” to an adjacent wavelength, laser designers might also use an additional frequency-stabilization component in the cavity.

The most commonly used component is a Fabry–Pérot (FP) etalon. In its simplest form, this is a flat piece of glass whose thickness $d_{FP}$ is much smaller than the laser cavity’s, and its axial mode spacing is thus much larger [Eq. (1.6)]. As seen in Fig. 1.13—where only one axial mode of the etalon is shown—the wavelengths that can lase are now based on the superposition of the etalon transmission and the longitudinal modes of the laser. The full-width at half-maximum (FWHM) bandwidth $\Delta v_R$ of the etalon transmission is based on its finesse $F_R$ and axial mode spacing $\Delta v_{FP} = c/2nd_{FP}$:

$$\Delta v_R = \frac{\Delta v_{FP}}{F_R} \approx \frac{c}{2nd_{FP}} \cdot \frac{1 - \sqrt{R_{p1}R_{p2}}}{\pi(R_{p1}R_{p2})^{1/4}} = \frac{c}{2nd_{FP}} \cdot \frac{1 - R}{\pi\sqrt{R}}$$  \[\text{Hz}\]  \(1.7\)

for surface power reflectivities $R_{p1}$ and $R_{p2}$, valid for $R \equiv (R_{p1}R_{p2})^{1/2} \geq 0.4$ or so. The etalon’s transmission bandwidth is usually much smaller than its mode spacing; e.g., using an etalon with $R = 0.9$ gives $F_R = \pi R^{1/2}/(1 - R) \approx 30$. 

\[\text{Introduction}\]
Because the mode spacing of the etalon is so much larger than that of the laser, however, even a relatively wide $\Delta \nu_R$ may drop off faster with laser frequency than the gain curve (Fig. 1.13); as a result, the laser is less sensitive to small fluctuations in power, cavity length, or refractive index, and mode hops are less likely to occur. In practice, the etalon bandwidth also depends on the parallelism and flatness of its surfaces—effects that can be controlled to such a degree with the fabrication of the etalon as to still make the etalon a useful frequency-stabilization component.

Even a frequency-stabilized SLM laser has a linewidth—an unavoidable consequence of random spontaneous-emission phase variations resulting from quantum fluctuations in excited-state energy levels. For such lasers, the ideal single-mode (Schawlow–Townes) linewidth $\Delta \nu_{ST}$ for a laser cavity $\Delta \nu_R$ (not its etalon) is given by Refs 9 and 12 as

$$
\Delta \nu_{ST} = \frac{\pi h \nu \cdot (2\pi \Delta \nu_R)^2}{P} \quad [\text{Hz}]
$$

(1.8)

where $P$ is the output power of the given axial mode. Physically, the higher power has a larger fraction of amplified in-phase photons in comparison with the incoherent, out-of-phase photons from spontaneous emission, reducing $\Delta \nu_{ST}$ to something smaller than the cold-cavity FWHM bandwidth $\Delta \nu_R$ of the laser’s axial modes [also Eq. (1.7)] given the laser-cavity reflectivity $R$.

Equation (1.8) represents the ultimate lower limit on linewidth, with no commercial products able to achieve this level of frequency stability (< 1 Hz). In practice, some SLM fiber lasers have a linewidth smaller than 10 kHz—limited by “technical noise” (fluctuations in optical and optomechanical parameters, e.g.), and resulting in a coherence length $d_c \geq 15 \text{ km}$.

There are, of course, many applications where coherence length is either unimportant or a hindrance to system performance. One example is that of speckle, where the reflections from a rough surface coherently interfere to produce a spotted image—a huge disadvantage for laser-based displays. In such cases, the system might still be limited by a different property of importance to both laser designers and systems engineers, namely, spatial coherence.

### 1.2.2 Spatial coherence

We have mentioned in Section 1.1 how the concept of beam quality affects focused spot size for optical data storage; in this section, we take a closer look at this idea from the laser designer’s perspective. We have also seen in Section 1.2.1 how the laser wavelength is determined by three factors, but in practice additional factors such as mode hopping play a role. In this section we will see that yet another factor—the spatial coherence—also affects the lasing wavelength.
As discussed by Siegman (Ref. 9, pp. 55–58), the concepts of spatial coherence and beam quality arise because there may be phase variations $\pm \lambda/4$ across the diameter of each mirror in any laser cavity. These variations can result from manufacturing imperfections in each mirror, refractive-index non-uniformities of the gain medium, or misalignments of the mirrors.\textsuperscript{13}

A typical laser cavity for solid-state and gas lasers\textsuperscript{14,15} is shown in Fig. 1.14. Known as a confocal resonator, this particular type of cavity is designed with the radius of curvature of each mirror ($R_1$ and $R_2$) centered on the surface of the opposing mirror one cavity length $L$ away. In the absence of manufacturing imperfections and index non-uniformities, this cavity is relatively stable against misalignments and produces a beam with a Gaussian irradiance profile and has no phase variations across it. In addition, the electric and magnetic fields are transverse to the longitudinal axis, and the combined irradiance and phase profiles are known as a Gaussian beam, i.e., a spatially coherent transverse electro-magnetic (TEM$_{00}$) mode of order (0, 0).

In practice, unavoidable misalignments between mirrors are one of the most common causes of excessive phase variations across the beam (Fig. 1.15)—and resulting loss of beam quality. For a small misalignment angle $\Delta \theta$, which keeps the on-axis length $L$ the same by pivoting around the mirror surface at the longitudinal (or $z$) axis, there is still an optical axis determined by the line connecting the center of curvature of each mirror. However, there is also the potential for an asymmetry in the phase of the wavefront if the optical axis propagates through a solid-state crystal or Brewster window at an angle (see Section 2.1.12). Such asymmetries—astigmatism and coma, for example—can also result from manufacturing imperfections in each mirror or refractive-index non-uniformities in the gain medium.

**Figure 1.14** A symmetric confocal laser cavity with the radius of curvature of each mirror ($R_1$ and $R_2$) equal to the cavity length $L$. The minimum beam radius (or waist) $w_0$ is at the center of the cavity where the focal length $f = R/2 = L/2$ of each mirror coincides. [Adapted from R. Scheps, Introduction to Laser Diode-Pumped Solid State Lasers, SPIE Press, Bellingham, Washington (2002).]
To first order, the asymmetries result in an approximate phase difference \( \Delta \phi \) across the beam proportional to the change in cavity length \( \Delta L \) at the edges of the mirrors:

\[
\Delta \phi \propto \frac{2\pi n}{\lambda} \Delta L \quad [\text{rad}]
\]  

where the type of mirror determines the actual phase difference. Two flat mirrors, for example, give \( \Delta L = D \Delta \theta \), while curved mirrors will modify the phase with an additional quadratic term \( \Delta L = D^2 / 2R_i \) that depends on the diameter \( D \) and radius of curvature \( R_i \) of the mirrors.

As a Gaussian beam starts to develop from spontaneous emission within the cavity, there are additional phase terms—Gaussian wavefront propagation (see Chapter 3), Guoy phase shift, and so on—that become important with misaligned mirrors. Independent of these details, the phase variations across the mirrors modify the Gaussian beam in three ways: (1) an increase in the divergence angle at which the beam exits the laser; (2) an increase in spot size if the beam is focused with a lens; and (3) a small shift in the emission wavelength, and a possible linewidth broadening as well.

The beams that result can be either aberrated Gaussians (for small misalignments) or are no longer circularly symmetric, with the asymmetric profile of the misalignment direction [Fig. 1.15(b)] and one (or more) zero-irradiance lines (or nodes). The mode shown in Fig. 1.15(b), for example, is a TEM\(_{01}\) mode because there are no nodes in the horizontal direction and one node in the vertical. Depending on the degree of phase shift across the mirror, there might be higher-order modes as well, specified as TEM\(_{pq}\) for the integers \( p > 0 \) and \( q > 0 \) defining the number of nodes in the profile.
It sometimes happens that the transverse irradiance profile from a misaligned cavity is circularly symmetric, even though the profile shown in Fig. 1.15(b) is not. This occurs when the misalignments in both directions combine to produce a symmetric beam. A common example is the “donut” mode—a combination of TEM$_{01}$ and TEM$_{10}$ profiles—which is circularly symmetric. This is perhaps the most common multi-transverse-mode profile, as it is likely that there will be a slight angular misalignment of the cavity mirrors about both the $x$ and $y$ axes. In practice, it is unusual to obtain a pure higher-order mode such as TEM$_{31}$, as other contributors such as contamination or manufacturing imperfections of each mirror and refractive-index non-uniformities contribute to the phase profile, leading to combinations of modes.

Whether single- or multiple-spatial mode, the paraxial transverse irradiance distribution in free-space lasers is described mathematically by the product of the circularly symmetric Gaussian distribution and the Cartesian-coordinate Hermite polynomials. Experimentally, the spatial-mode “content” is determined by a quantity known as $M^2$ which, as we will see in detail in Chapter 3, can be used to determine the increase in divergence angle and/or focused spot size. An ideal, diffraction-limited beam has an $M^2 = 1$; lasers with $M^2 \leq 1.5$ or so are said to have good beam quality.

The third modification of a Gaussian beam that results from transverse spatial modes is a small shift in the emission wavelength, in addition to a possible linewidth broadening. This is shown in Fig. 1.16, where each longitudinal-mode frequency $v_m$ has transverse-mode frequencies associated with it. That is, the transverse modes—TEM$_{01}$, TEM$_{11}$, TEM$_{12}$, TEM$_{22}$, and so on—each have a slightly different frequency, given by

$$v_{pqm} = \frac{c}{2nL} \left[ m + \frac{1}{\pi} (1 + p + q) \cos^{-1} \sqrt{(1 - L/R_1)(1 - L/R_2)} \right] \text{ [Hz]}$$ (1.10)

where the $1 - L/R_1$ term is also referred to in the literature as a cavity stability parameter $g_i$. In addition, the terms inside the square brackets in Eq. (1.10)
show that each Gaussian TEM\(_{00}\) mode may or may not have the same optical frequency as that given in Eq. (1.5) for a planar cavity.

As an example of the transverse-mode frequencies for a confocal cavity with \( L = R_i \), we have \( \cos^{-1}(0) = \pi/2 \), giving
\[
\nu_{00m} = \left( c/2nL \right) \times (m + \frac{1}{2})
\]
and
\[
\nu_{01m} = \left( c/2nL \right) \times (m + 1).
\]
The transverse mode spacing \( \Delta \nu_{tr} \) is then
\[
\nu_{01m} - \nu_{00m} = c/4nL,
\]
or one-half of the axial mode spacing \( \Delta \nu_a \). Also note that the absolute value of the axial-mode frequency \( \nu_{00m} \) has shifted to a higher frequency by the same amount, given the factor of \( m + 1/2 \) in comparison with the factor of \( m \) in Eq. (1.5) for a near-planar cavity [for which the \( \cos^{-1}(1) \) term for \( R_i \approx \infty \) is zero, reducing Eq. (1.10) to Eq. (1.5) for TEM\(_{00}\) modes].

There are other cavity designs—semi-confocal, spherical, hemispherical, etc.—where the transverse mode spacing is much smaller than that for the confocal cavity. For designs that are relatively insensitive to misalignments—confocal and the widely used near-hemispherical (or half-concentric)—it is feasible to control the misalignments, fabrication errors, index non-uniformities, and mirror cleanliness to such a degree that single-spatial-mode lasers with near-TEM\(_{00}\) beam quality are common and inexpensive. These lasers will be reviewed in detail in Chapter 2.

In summary, beam quality is a measure of the phase variations across a beam. The resulting transverse spatial mode properties—the systems-level consequences of which will be reviewed in Chapters 2 and 3—are an increase in beam divergence angle and focused spot size, as well as the possibility of a shift in wavelength in comparison with an ideal near-planar cavity. Also note that the term “multimode laser” can be ambiguous, as we have seen in this section that in addition to multi-longitudinal-mode lasers, there are also multi-transverse-modes that must be considered in system design. More typically, “multimode” refers to spatial modes, while “multifrequency” refers to axial modes.

### 1.2.3 Pulse generation

The lasers considered up to this point have been continuous wave (CW), with no obvious change in power level over time. In many applications, however, there is a need to concentrate the lasing energy into a shorter period of time—a pulse of width \( \Delta t_p \)—to increase the peak output power
\[
P_{\text{peak}} = Q_p / \Delta t_p
\]
for a pulse energy \( Q_p \) (Section 2.1.4). As we will see, applications for which this is important include nonlinear wavelength conversion (Section 1.2.4), “cold” laser machining (Section 2.1.5), multiphoton microscopy, as well as laser ranging and active imaging where the detector responds to reflected peak power (Chapter 7).

The first and most obvious approach to generating pulses is to switch the pump (and thus the gain) on-and-off—resulting in pulse widths shorter than the pump pulse, but with low peak power. This is a result of the dynamic interaction between excited-state electrons and photons leading to relaxation oscillations as the excited-state energies “relax” (and are stimulated) to a lower-energy state; reducing these oscillations limits the degree of
above-threshold pumping and thus the peak powers obtained. Despite its limitations, such gain switching is necessary for some types of CO\textsubscript{2} and excimer lasers for which other types of switching are not practical.

To avoid the relaxation oscillations and generate much higher peak power than is possible with gain switching, two methods are used for pulse generation: Q-switching and mode locking.

The concept of Q-switching refers to changing the quality $Q_c$ of the laser cavity. “Quality” in this case is not the transverse beam quality, but the cavity’s ability to store laser energy:

$$Q_c = 2\pi n_{pqm} \frac{Q_{\text{store}}}{P_{\text{loss}}} = \frac{n_{pqm}}{\Delta n_{pqm}}$$

(1.11)

where the stored photon energy $Q_{\text{store}} = n_p h\nu$ for $n_p$ photons, each with energy $h\nu$, and the power loss $P_{\text{loss}} = Q_{\text{store}}/\tau_p$ for a photon lifetime $\tau_p$ in the cavity. This gives a cavity quality $Q_c = 2\pi n_{p} \tau_p$ with a photon lifetime that depends on the internal cavity losses $\alpha_{\text{int}}$ (due to internal absorption and diffraction) and coupling losses $\alpha_{\text{m}}$ (i.e., output power through the cavity mirrors). The photon lifetime is given as

$$\tau_p = \frac{1}{v_g} \cdot \frac{1}{\alpha_{\text{int}} + \alpha_{\text{m}}} \quad [\text{sec}]$$

(1.12)

for a pulse traveling with a group velocity $v_g$. If the power reflectivity of each mirror is $R_{p1}$ and the internal losses are small, then the round-trip power-conservation condition [i.e., $R_{p1}R_{p2}\exp(2gL) = 1$] shows that the mirror loss that must be compensated by the gain $g$ at threshold is

$$\alpha_{\text{m}} = -\frac{1}{2L} \ln(R_{p1} R_{p2}) \quad [1/\text{cm}]$$

(1.13)

For example, if the laser cavity length $L = 100$ mm and the power reflectivity $R_{p1} = R_{p2} = 0.98$ for each mirror, then $\alpha_{\text{m}} \approx 0.002/cm$. Increasing the cavity length allows photons more time to travel around the cavity before being “expelled” by the mirror as output power, thus decreasing the mirror loss on a per-centimeter basis.

Physically, a low-loss cavity with high-reflectivity mirrors has a long photon lifetime and thus efficiently stores energy (i.e., has a large $Q_c$), while a high-loss cavity with low-reflectivity mirrors has a short photon lifetime and thus dissipates (or damps) energy (i.e., has a small $Q_c$). A typical gas-laser cavity has a $Q_c$ value of $\approx 10^8$–$10^9$, indicating an extremely long photon lifetime: $\tau_p = Q_c/2\pi n \approx 0.025$–$0.250$ μsec for visible-wavelength light.
Q-switching, then, changes the laser cavity’s losses to create shorter pulses than can be obtained with gain switching. By initially keeping the loss high (low $Q_c$) while the pump is activated, the population inversion and gain build up (Fig. 1.17); lasing is not possible, however, as the cavity loss from the switch is kept too high for the gain to overcome.

When the switch is turned off, the losses decrease (high $Q_c$) and the gain is then much higher than the total cavity loss; after a slight delay $t_d$, this gain is quickly utilized to create photons in the form of a short pulse with a FWHM width $\Delta t_p$. The Q-switch is then turned back on to increase the cavity loss again; if this did not happen, no additional pulses would be generated, and lasing would start at a steady-state power where gain balances losses.

Both active and passive technologies are available for Q-switching. Active switching typically uses an acousto-optic (AO) modulator to reduce the laser’s internal losses in synchronization with the pulse’s round-trip through the laser cavity, producing pulse widths on the order of 1–10 nsec. Unfortunately, the AO modulator, while allowing large pulse energies and a variable switching rate, has a number of size, weight, and speed disadvantages in comparison with passive Q-switching.

Passive Q-switching with a saturable absorber generally produces lower-energy pulses but at a higher rate than an AO modulator. That is, just as the population inversion $N_2 - N_1$ in Fig. 1.9 can saturate to zero at a sufficiently high power, so can the absorption that is proportional to its negative (or $N_1 - N_2$). A saturable absorber thus has less loss—i.e., is “bleached”—as the incident power increases; the absorption at high power decreases as the number of atoms in a higher energy state approaches that in the lower, and the absorption (low-to-high energy transitions) approaches the emission
In this way, even a slight increase in peak pulse power reduces the loss of a saturable absorber, with the pulse Q-switching itself into narrower pulses in a self-reinforcing feedback loop with multiple round-trips through the laser cavity.

Typical materials with large saturable absorption include Cr$^{4+}$:YAG crystals for use at $\lambda \approx 1064$ nm,$^{19}$ semiconductor saturable-absorber mirrors (SESAMs) such as GaAs-InGaAs multilayers for $\lambda = 1064$ nm, and the recent development of low-loss graphene for broadband Q-switching.$^{20}$ Passive Q-switching—with its lower size, weight, complexity, and cost—is preferred over active switching unless large pulse energies are required. For either type of switching, peak power on the order of $10^4 \times$ larger than the average power ($P_{\text{peak}} \approx 10–100$ MW) is common—though only for 1–10 nsec, so not nearly enough kilowatt hours to bring down the power grid (in most cases).

In practice, a number of non-ideal characteristics limit the laser systems engineer’s use of Q-switching. For example, the fast change in gain can lead to multi-axial-mode lasing; the time between pulses (or timing jitter) for saturable absorbers changing due to the high spontaneous emission rate from the large gain; and the lifetime of the saturable absorber being limited due to the high power densities.

For shorter pulses than are possible with Q-switching, a method known as mode locking is widely used.$^{21}$ That is, the axial modes determined by the combination of cavity length and gain bandwidth (Fig. 1.13)—which normally lase independently of each other—are coherently added in time (in phase, or constructively interfere) to produce short pulses on the order of 10 psec or less. This can occur for both inhomogeneous and homogeneous broadening of the gain, as an inhomogeneous gain medium normally supports multiple axial modes, and the homogeneous medium does so as well under non-steady-state (i.e., pulsed) conditions.

The modes must be shifted in phase by exactly the right amount to ensure that they all have the same phase at the same time somewhere in the cavity [for example, at the output mirror where the mode peaks line up on the right-hand side (RHS) of Fig. 1.12]. Even though the relative phase of any mode with respect to another is not initially known, we can modulate the beam—either actively or passively—so that the relative phase “locks” into a fixed value.

To understand how this can be achieved, an oscillating sinewave that is amplitude-modulated (AM) has frequency sidebands—a well-known result from Fourier analysis.$^{22}$ The frequency shift from the sinewave frequency $\omega = 2\pi \nu$ (in units of radians/sec) is simply the modulation frequency $\Omega$, giving AM frequencies of $\omega - \Omega$, $\omega$, and $\omega + \Omega$.

If the sinewave frequency corresponds to a laser mode frequency $\omega_m = 2\pi \nu_m$, and the modulation frequency $\Omega = 2\pi \Delta \nu = \pi c / n L$ equals the axial mode spacing $\Delta \omega_m$, then the AM sideband frequencies of $\omega - \Omega$ and $\omega + \Omega$ are superimposed on the neighboring axial modes $\omega_{m-1}$ and $\omega_{m+1}$. If all

Introduction
of the axial modes that are lasing are modulated at $\Omega$, then all modes will be coupled to their neighbors, to their neighbor’s neighbors, and so on. To the degree that $\Omega$ is constant, the modes are thus locked together—in frequency difference and in phase.\(^{23}\)

Once locked, the modes coherently add together to produce pulses that are much shorter than implied by the amplitude-modulation frequency $\Omega$ (Fig. 1.18). With the peaks of $N$ modes coinciding, for example, the sum from all modes increases the peak power by a factor of $N$ if the power from each mode is the same, which is not the case given the dropoff in the gain curve, but is useful for understanding the concept of axial-mode addition.

In addition, Fig. 1.18 shows that the sum of in-phase axial modes also narrows the FWHM pulse width by a factor of $N$. This is analogous to a diffraction grating, where the beam reflected from the grating lines constructively interfere at a particular direction in space, with the width of the interference pattern decreasing as more lines are illuminated. The net effect of more modes, then, is to increase the peak power by a factor of $N^2$—one factor of $N$ from power addition and one factor of $N$ from pulse narrowing.

Given that the locking of more modes decreases the pulse width $\Delta t_p$, and a wider gain bandwidth $\Delta v_g$ allows more modes to have enough gain to lase, the pulse width is approximately

$$\Delta t_p = \frac{1}{N} \cdot \frac{2nL}{c} \approx \frac{1}{\Delta v_g} \quad [\text{sec}] \quad (1.14)$$

for $N \approx \Delta v_g/\Delta v_a$ and $\Delta v_a = c/2nL$. Titanium-doped sapphire (or Ti:Al\(_2\)O\(_3\)) lasers, for example, have an extremely large gain bandwidth ($\Delta\lambda_g \approx 300 \text{ nm}$) and are thus commonly used for generating pulses as short as 10 fsec.

![Figure 1.18](image_url)  
*Figure 1.18*  
Mode-locked period $T_p$ and FWHM pulse width $\Delta t_p$ for $N = 10$ and $N = 20$ axial modes with equal power in each mode.
Finally, the pulse period $T_p = 2nL/c$ equals the round-trip time of a pulse as it circulates around the laser cavity. While the axial-mode picture in Fig. 1.12 appears to be static, the dynamic picture is that each mode reflects from the output mirror and coherently combines as an in-phase pulse after each round-trip transit $2L$ through the cavity, after which it is partially transmitted through the output mirror. Long fiber lasers, for example, have a long pulse period and relatively low pulse repetition frequency $PRF = 1/T_p$, while much-shorter semiconductor lasers can in principle produce pulses at gigahertz rates.

As with Q-switching, both active and passive technologies are available for mode locking. Active mode locking typically uses a Pockels-cell electro-optic (EO) modulator\textsuperscript{24} to create AM (or possibly frequency-modulated) sideband frequencies such that all of the axial modes that are lasing are modulated at $\Omega$. Alternatively, we can think of the modulator as reducing the laser’s internal losses in synchronization with the pulse’s round-trip through the laser cavity, producing pulse widths on the order of 10 psec.\textsuperscript{17}

Passive mode locking with a saturable absorber—using materials such as SESAMs—produces even shorter pulses. The power-dependent absorption modulates the beam power, creating frequency sidebands for each mode that are locked to the other modes. Alternatively, by transmitting the peak power while absorbing the leading and trailing edges of the pulse, saturable absorption narrows the pulse width; the process is ultimately limited by the gain bandwidth and, with much more hardware complexity than is described here, leads to pulses on the order of 10 fsec to 10 psec. As with Q-switching, passive mode locking is generally preferred to active mode locking with its increase in size, weight, complexity, and cost.

Typical examples of mode-locked USP applications include Ti:Al$_2$O$_3$ (also known as Ti:sapphire) lasers for research into molecular dynamics, and fiber lasers for “cold” laser machining to reduce thermal damage. This is an active area of product development and there are, of course, many engineering details required to implement mode locking. Practical limitations include variations in EO modulation frequency $\Omega$, refractive-index variations across the gain bandwidth that modify the mode spacing, thermal expansion causing changes in cavity length and mode spacing, etc. For more details, see Paschotta\textsuperscript{18} and Chapter 2.

1.2.4 Wavelength conversion

It sometimes happens that the inherent laser wavelength—1064 nm for a neodymium (Nd)-doped yttrium-orthovanadate (YVO$_4$) crystal as a gain medium, for example—is not useful for the task. In these cases, the laser designer must provide some mechanism of wavelength conversion, where the laser wavelength based on the gain medium is converted to some other wavelength of interest to meet the system requirements.
A common example is the conversion of 1064-nm light to 532 nm—a wavelength that the human eye can detect. Such conversion has been used for many years in low-cost laser pointers (Fig. 1.19), where the green (532-nm) light is easily obtained using a potassium titanium-oxide phosphate (KTP) crystal.25 Another example is the conversion of 1064-nm light to 1570 nm; this conversion is useful because the 1570-nm photons are not as damaging to the eye as the 1064-nm photons, allowing the development of eye-“safer” laser rangefinders.

Figure 1.19 illustrates the wavelength-conversion hardware for second-harmonic generation (SHG). That is, by sending 1064-nm light of a sufficiently high peak power density (W/m²) through a KTP crystal, second-harmonic wavelengths (one-half of 1064-nm) are generated. This occurs because the crystal’s electrons cannot respond linearly to the large EM field; instead, an incident sinusoidal wave is re-emitted as a distorted waveform, which Fourier analysis tells us requires wavelengths shorter than the fundamental sinusoid—i.e., “harmonics”—to create. These harmonic wavelengths are in fact generated by the crystal, and the nonlinear conversion process of SHG is also known as frequency doubling.26

Another example of wavelength conversion is the use of an optical parametric oscillator (OPO) to create eye-“safer” photons at \( \lambda = 1570 \) nm.

![Figure 1.19 Second-harmonic generation (SHG) of 1064-nm photons from a Nd:YVO₄ laser into 532-nm photons uses a nonlinear crystal such as KTP. (Credit: Chris Chen, Wikimedia Commons.) (See color plate.)](image)
In this case, KTP (or some other nonlinear crystal) is used in a resonant cavity, thus assuring high-power density—for a nonlinear wavelength-conversion mechanism known as sum-frequency generation (SFG). This nonlinear wavelength-conversion process relies on the conservation of photon energy to convert one short-wavelength (higher-energy) photon into two longer-wavelength (lower-energy) photons. With $E_{\text{pump}} = E_{\text{signal}} + E_{\text{idler}} = h\nu_{\text{pump}} = hc/\lambda_{\text{pump}}$ [from Eq. (1.1)], we have

$$\frac{1}{\lambda_{\text{pump}}} = \frac{1}{\lambda_{\text{signal}}} + \frac{1}{\lambda_{\text{idler}}} \quad [1/\text{nm}] \quad (1.15)$$

where the sum of photon energies [or the sum of frequencies using Eq. (1.2)] gives this nonlinear mechanism its name. The labeling of a photon as a "signal" or "idler" is a bit arbitrary, as there are also applications where the MWIR 3301-nm wavelength shown in Fig. 1.20 is the desired output and is therefore the signal in that case.

In addition to SHG and SFG, there are a number of other nonlinear mechanisms used for wavelength conversion: frequency tripling or third-harmonic generation (THG), frequency quadrupling or fourth-harmonic generation (FHG), difference-frequency generation (DFG), etc.\footnote{26} To implement these technologies, the laser designer must consider wavelength range, nonlinear response, phase matching, temperature sensitivity, angular sensitivity, walk-off angle, and laser damage threshold, among other parameters.

In practice, two requirements play a key role for the laser systems engineer in the use of wavelength-conversion technologies:

- Conversion efficiency: Energy is lost in the conversion of wavelengths, and the conversion efficiency is the transmitted energy in comparison with the incident energy. The large peak power from pulsed lasers is more efficient at generating nonlinear effects than CW lasers. Up to 80% efficiency has been obtained for SHG using a KTP crystal at $\lambda = 1064$ nm, and >65% efficiency has been obtained for SHG with a lithium triborate (LBO) nonlinear crystal at $\lambda = 1064$ nm and $\Delta t_p \sim 2$ nsec.\footnote{27}

- Temperature tuning: The requirements on the laser pointer in Fig. 1.19 are not difficult to meet, while the power stability (Section 2.1.8) and

![Figure 1.20](image-url)  
A high-energy photon at $\lambda_{\text{pump}} = 1064$ nm is converted to two lower-energy (longer-wavelength) photons by a nonlinear crystal such as KTP in a resonant cavity.
frequency stability (Section 2.1.9) requirements for a complex laser radar system that uses both 1064-nm and 532-nm photons to obtain information on the Earth’s atmosphere from a low-Earth orbit may be extremely challenging. In such cases, temperature tuning of the nonlinear crystal—i.e., controlling the refractive indices $n(\nu)$ and $n(2\nu)$ to maintain phase matching—may be required; see Ref. 27 for more details.

Summarizing Section 1.2, laser designers must control a number of important parameters, including: (1) axial modes for “color” purity and temporal coherence, (2) transverse modes for directionality and spatial coherence, (3) pulse width and period, and (4) wavelength conversion. Many more engineering specifications of importance to the user of lasers—i.e., the laser systems engineer—will be reviewed in Chapter 2. A brief overview of the laser systems engineering process and the remainder of the book are first given in Section 1.3.

### 1.3 Laser Systems Engineering

An awareness of the laser designer’s options will only simplify the laser systems engineer’s job, as many of the tasks are similar. But even with this understanding, an obvious first question to ask for any system architecture is: why—or under what conditions—is a laser even necessary? While we have reviewed some of the properties of lasers, answering a question such as this requires a follow-on question: What are the properties of the alternatives?

The alternatives to lasers are incoherent sources—solar energy, arc lamps, tungsten-halogen bulbs, and so on—and the first comparison (or design trade) to make is how much power is available from each type of source. This may seem like a strange design trade; after all, if the laser and the incoherent source both emit 100 mW of power, then isn’t 100 mW available from both for material ablation, biomedical sample fluorescence, or any other application?

Figure 1.21 illustrates why this is not the case. In Fig. 1.21(a), we see that an incoherent source on the left of the lens is imaged to something resembling the source with a magnification $m_{\text{lens}} = -s_i/s_o$ for an object distance $s_o$ and an image distance $s_i$. In Fig. 1.21(b), on the other hand, a laser of the same size and placed at the same object distance $s_o$ is imaged to a focused spot whose size depends on the laser wavelength $\lambda$, the lens diameter $D$, and the beam quality $M^2$.

The reason for the difference in Fig. 1.21 is that the wavefronts from the incoherent source are emitted by each point on the source independently of the other (Fig. 1.8), and thus recombine to an image independently of each other as well. Each point on the source is in fact focused to a small spot, but
because each point emits independently of the others—i.e., incoherently—they recombine as shown on the RHS of Fig. 1.21(a).

For the laser, however, the points are to a large degree emitting in phase, and thus coherently recombine into a small, focused spot. The degree to which they are in phase depends on the spatial coherence, which as we will see in Chapter 3 determines in part the size of the spot.

In addition, essentially all of the power emitted by the laser is collected by the lens, while a large fraction of the power emitted by the incoherent source is not. That is, the laser’s full-divergence angle (or directionality) $2\theta_0 \approx \lambda/D$, while an incoherent source typically emits at least some power into a sphere encompassing the source. Sizing a lens to capture the laser’s divergence angle is thus relatively straightforward (see Chapter 6), while specialized reflectors are required to capture even a decent fraction of an incoherent source’s power.

Finally, the incoherent source emits an extremely large wavelength band, while the laser typically does not (exceptions such as super-continuum lasers will be reviewed in Section 2.2.3).

It turns out that it is possible to use an incoherent source in such a way that it has many of the properties of lasers—but at a cost. Figure 1.22 illustrates how this is possible using a small aperture size $s$ (such as a pinhole after the source itself) and a narrow bandpass filter (BPF) to transmit only a small fraction of the wavelengths emitted. In addition, if the pinhole is placed

**Figure 1.22** An incoherent source can be designed with a small aperture size $s$ to increase spatial coherence, and a bandpass filter (BPF) to control temporal coherence.
at the focal length of the lens, the lens collimates the incoherent source with a divergence angle \( \theta \approx s/f \).\(^{28}\) As the pinhole is made smaller—and the wavefront across it is thus more coherent—the divergence angle will approach the full divergence angle \( 2\theta_o \) of a laser, after which \( \theta \) is limited by wavefront diffraction and cannot be made any smaller (see Problem 1.10).

So with some additional optics, it is possible to design an incoherent source with a spatial and temporal coherence similar to a laser’s—but at the cost of a huge loss of power. The pinhole, for example, allows only a small fraction of the incoherent source’s light through it, as does the BPF. One of the unique features of a typical laser, then, is not the directionality and narrow wavelength band, but these properties combined with almost all of its output power available for useful tasks such as material ablation, fluorescence microscopy, or directed energy.

For a laser system, however, laser output power is not the whole story, and there are other requirements, components, and subsystems that must be considered as well. The perspective taken to do this—that of the laser systems engineer—is sometimes thought of as “designing the right laser” versus “designing the laser right.” Unfortunately, this is both incomplete and overly centered on the laser designer’s goal of designing the laser right. Designing the right laser—i.e., one that meets system-level requirements such as output power—is certainly key, but designing the right optical, scanning, and detector subsystems is equally critical.

Table 1.4 is a common systems-engineering tool that illustrates one way in which these other subsystems are taken into account. Known as a trade table, it compares three different design options for a laser radar system. The options evaluated in this case—and there are many other criteria that must also be used—are based on a power budget, i.e., is there enough power reflected from the target to be “useful” to the detector?

In this simple example, system performance depends on three components: the laser output power, the size of the telescope aperture collecting the reflected power, and the detector’s sensitivity (i.e., the smallest power it can detect). In Design 1, it was assumed by the laser-system architect that a laser with 1 W of output power was available, as well as a telescope aperture of 100 mm and a minimum power for the detector (or sensitivity) of 1 nW.

Table 1.4  A trade table summarizing component specifications for laser radar system design options.

<table>
<thead>
<tr>
<th>Component</th>
<th>Design 1</th>
<th>Design 2</th>
<th>Design 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Power</td>
<td>1 W</td>
<td>0.1 W</td>
<td>0.1 W</td>
</tr>
<tr>
<td>Telescope Aperture</td>
<td>100 mm</td>
<td>316 mm</td>
<td>100 mm</td>
</tr>
<tr>
<td>Detector Sensitivity</td>
<td>1 nW</td>
<td>1 nW</td>
<td>0.1 nW</td>
</tr>
</tbody>
</table>
In reviewing the architecture with the laser designer, however, it was found that the 1-W laser would not be ready for product development for quite a while, and that a 100-mW laser was the only reliable option for now. So with a factor of $10 \times$ less power available from the laser, a factor of $10 \times$ increase in telescope area (Design 2)—or a $10^{1/2} = 3.16 \times$ increase in aperture size—was considered to compensate. At this point, the optical engineer on the project mentioned that such an aperture was much larger in terms of size and weight than the customer would consider, thus removing Design 2 as one of the options.

Fortunately, in reviewing the architecture with the detector specialist, it was found that detectors with $1/10^{th}$ the sensitivity were available as commercial off-the-shelf (COTS) parts, thus allowing Design 3 to proceed as the baseline architecture.

As we will see in Chapter 6, there are a number of additional details such as beam quality to consider when developing power budgets, and this simple example illustrates only one of the many design trades between the subsystems—laser, optics, scanning, and detector—to be reviewed in this book. Included are chapters on laser types and selection (Chapter 2), the unique requirements on using optical components in laser systems (Chapter 4), scanning technologies and system trades (Chapter 5), and detector types and selection (Chapter 7). Interspersed between these chapters are the concepts needed to understand beam propagation (Chapter 3) and radiometry (Chapter 6). The book does not include software or electrical subsystems.

The emphasis in all chapters is on real-world design problems and the first-order equations and COTS components used to solve them. As with any book, not every topic can be included; however, readers may also find my previous books useful for understanding the many differences between laser systems and conventional optical systems using incoherent sources [Optical Systems Engineering, McGraw-Hill (2011)], or obtaining additional details on the optomechanical aspects of building laser systems [Optomechanical Systems Engineering, John Wiley (2015)].

1.4 Problems

1.1 Analyze the 1950s Laser-Eyed Monster from the perspective of the laser systems engineer. For example, is there a possible eye-safety issue associated with launching a high-power beam through one’s eyes? In addition, how would such a laser be powered, how would the heat be removed, and how would the wavelength be controlled? Hint: See Chapter 2 for additional considerations.

1.2 What is the linewidth $\Delta \lambda$ for an inhomogeneously broadened laser that lases at five axial-mode frequencies based on Eq. (1.6)?
1.3 Does the transmission of an etalon drop off faster or slower with laser frequency as the etalon reflectivity $R$ is increased? Are there disadvantages to using a higher reflectivity?

1.4 What is the cold-cavity (zero gain) FWHM bandwidth $\Delta v_{\text{SLM}}$ of the individual longitudinal modes of a laser resonator based on the mirror reflectivities? (Hint: What is the finesse of the laser cavity?) And is this result consistent with that obtained from Eqs. (1.11), (1.12), and (1.13)?

1.5 What is the axial mode spacing $\Delta v_a$ for the confocal cavity? How does it compare with that of the planar-mirror cavity?

1.6 Are there any laser cavity designs that have the same absolute value of the axial-mode frequency as the planar-mirror cavity? Hint: See Ref. 9.

1.7 What is the approximate cavity length $L$ needed to obtain the mode-locked pulse period $T_p$ shown in Fig. 1.18? The gain medium’s refractive index $n \approx 1$.

1.8 In a mode-locked laser, what is the relation between the coherence length $d_c$ and the pulse width $\Delta t_p$?

1.9 If a SFG oscillator creates one 2128-nm photon from 1064-nm photons, what is the wavelength of the second long-wavelength photon that an OPO must produce to conserve energy?

1.10 Referring to Fig. 1.22, what pinhole size is required to give the same collimated-beam full-divergence angle as a laser with $2\theta_o = 4\lambda/pD$? Assume that the wavelength $\lambda = 1$ $\mu$m and the smallest relative aperture available for the lens is $f/D \equiv f/\# = 1$.

Notes and References


11. In practice, small time-varying fluctuations in cavity spacing, lattice strain, and the refractive index of the gain medium lead to mode hops; see Section 2.1.9 for more details.


14. This section does not apply to lasers that rely on total-internal-reflection (TIR) waveguiding between the mirrors, with semiconductor and fiber lasers being the most common. For those lasers that do not rely on waveguides, i.e., solid-state and gas lasers, the free-space modes in this section are applicable; see Ref. 15 for more information on waveguide modes.


16. Spatial coherence is defined by correlations across the wavefront (stationary phase). Unfortunately, this leaves open the possibility that
a wavefront with phase errors (a single TEM$_{01}$ mode, for example) is spatially coherent. As we will see in detail in Chapter 3, the concept of beam quality avoids this limitation by using a comparison of a wavefront not with itself, but with an ideal (uniphase), diffraction-limited ($M^2 = 1$) TEM$_{00}$ mode with zero phase errors across it, and which can be focused to the smallest-possible spot size.


Glossary of Symbols and Acronyms

\( A \)  area (m\(^2\)); optical absorption
\( A_b \)  beam area (mm\(^2\))
\( A_d \)  detector area (mm\(^2\))
\( A_{EP} \)  entrance pupil area (mm\(^2\))
\( A_o \)  illuminated object area (mm\(^2\))
\( A_p \)  pixel area (\(\mu\)m\(^2\))
\( AO \)  acousto-optic
\( AOI \)  angle of incidence (rads)
\( APD \)  avalanche photodiode
\( APS \)  active-pixel sensor
\( AR \)  antireflection
\( ASE \)  amplified spontaneous emission
\( A\Omega \)  \(\text{étendue} \) (m\(^2\)-sr)

\( B \)  focused blur diameter (\(\mu\)m); PSD frequency exponent
\( B_{SA} \)  focused blur diameter due to spherical aberration (\(\mu\)m)
\( BFD \)  back focal distance
\( BPF \)  bandpass filter
\( BPP \)  beam-parameter product (mm-mrad)
\( BSDF \)  bidirectional scatter distribution function

\( c \)  speed of light, \( \approx 3 \times 10^8 \) m/sec
\( C \)  wavefront or surface curvature (1/mm)
\( C_o \)  wavefront curvature incident on lens (1/mm)
\( C_i \)  wavefront curvature exiting lens (1/mm); image contrast
\( C_{sp} \)  speckle contrast
\( C_{well} \)  charge-well capacitance (pF)
\( CA \)  clear aperture
\( CCD \)  charge-coupled device
\( CDS \)  correlated double sampling
\( CMOS \)  complementary metal-oxide semiconductor
CoO  cost of ownership
COTS  commercial off-the-shelf
cps  counts per second
CRT  cathode-ray tube
CTE  charge-transfer efficiency; coefficient of thermal expansion
CTIA  capacitive transimpedance amplifier
CW  continuous wave

d
  distance (m)
dc
  coherence length (m)
dc,n
  coherence length in a medium of index n (m)
d_{FP}
  Fabry–Pérot cavity thickness (mm)
dn/dT
  change in index with temperature (1/K)
do
  pixel size (µm)
D
  lens diameter or aperture size (mm); fiber diameter (µm)
D_{1/2}
  beam diameter (1/ε²) incident on or exiting from a lens (mm)
D_{EP}
  entrance-pupil diameter (mm)
D_{o}
  waist diameter (mm)
DBR  distributed Bragg reflector
DCR  dark-count rate [e⁻/sec or counts per sec (cps)]
DE  directed energy
DFG  difference-frequency generation
DI  direct injection
DLC  diamond-like carbon
DoF  degrees of freedom
DOF  depth of focus (µm)
dpi  dots per inch
DPSS  diode-pumped solid-state
DWDM  dense wavelength-division multiplexing

E
  irradiance (W/m²); Young’s modulus (GPa)
E_g
  bandgap energy (J or eV)
E_i
  electron energy for energy level i (J or eV)
E_o
  Gaussian peak irradiance (W/m²)
E_p
  photon energy (J or eV)
EB-CCD  electron-bombarded CCD
EB-CMOS  electron-bombarded CMOS
EFL  effective focal length (mm)
EM  electromagnetic
EM-CCD  electron-multiplying CCD
EOL  end of life
EOM electro-optic modulator
ESD energy spectral density

\( f \) focal length (mm); electrical frequency (Hz)
\( f_d \) FPA cutoff frequency (lp/mm)
\( f_{RO} \) relaxation-oscillation frequency (Hz)
\( f_s \) spatial frequency (lp/mm); mirror scan frequency (Hz)
\( f/# \) relative aperture, \( \equiv f/D \)
\( F \) fluence (J/m²)
\( F(G) \) excess noise factor
\( F_R \) cavity finesse based on power reflectivity \( R_P \)
FBG fiber Bragg grating
FET field effect transistor
FF FPA fill factor
FHG fourth-harmonic generation
FOI field of illumination (rad)
FOR field of regard (rad)
FOV field of view (rad)
FP Fabry–Pérot
FPA focal plane array
FPN fixed-pattern noise
FR frame rate [Hz or frames per sec (fps)]
FSM fast-steering mirror
FSR free spectral range (Hz)
FWHM full-width at half-maximum

g laser gain (1/cm)
\( g_i \) laser-cavity stability parameter
\( G \) detector gain; thermo-optic constant (1/K)
GM-APD Geiger-mode APD
GVD group-velocity dispersion

\( h \) Planck’s constant, \( = 6.626 \times 10^{-34} \) J·sec; mirror thickness (mm)
HFOV half-FOV (rad)
HAZ heat-affected zone
HPD hybrid photodetector
HR high reflectivity
HSF high spatial frequency
HT high transmission
HWP half-wave plate

\( i \) current (A)
\( i_b \) detector background current (A)
### Glossary of Symbols and Acronyms

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i_d$</td>
<td>detector current (A)</td>
</tr>
<tr>
<td>$i_{dc}$</td>
<td>detector dark current (A)</td>
</tr>
<tr>
<td>$i_s$</td>
<td>detector signal current (A)</td>
</tr>
<tr>
<td>$i_{th}$</td>
<td>laser threshold current (A)</td>
</tr>
<tr>
<td>$I$</td>
<td>intensity (W/sr)</td>
</tr>
<tr>
<td>IAD</td>
<td>ion-assisted deposition</td>
</tr>
<tr>
<td>IBS</td>
<td>ion-beam sputtering</td>
</tr>
<tr>
<td>ICCD</td>
<td>intensified CCD</td>
</tr>
<tr>
<td>IFOV</td>
<td>instantaneous FOV (μrad)</td>
</tr>
<tr>
<td>IR</td>
<td>infrared</td>
</tr>
<tr>
<td>IRCM</td>
<td>IR countermeasure</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standards Organization</td>
</tr>
<tr>
<td>$J$</td>
<td>rotational moment of inertia (kg-m²)</td>
</tr>
<tr>
<td>$k$</td>
<td>APD ionization coefficient; thermal conductivity (W/m-K)</td>
</tr>
<tr>
<td>$K_{SA}$</td>
<td>blur size factor due to spherical aberration</td>
</tr>
<tr>
<td>$K_T$</td>
<td>truncation factor</td>
</tr>
<tr>
<td>KTP</td>
<td>potassium titanium-oxide phosphate</td>
</tr>
<tr>
<td>$L$</td>
<td>length (m); radiance or brightness (W/m²-sr)</td>
</tr>
<tr>
<td>$L_i$</td>
<td>image radiance (W/m²-sr)</td>
</tr>
<tr>
<td>$L_s$</td>
<td>source radiance (W/m²-sr)</td>
</tr>
<tr>
<td>$L_\lambda$</td>
<td>spectral radiance or brightness (W/m²-sr-nm)</td>
</tr>
<tr>
<td>LAM</td>
<td>laser additive manufacturing</td>
</tr>
<tr>
<td>LCOS</td>
<td>liquid crystal on silicon</td>
</tr>
<tr>
<td>LCPG</td>
<td>liquid crystal polarization grating</td>
</tr>
<tr>
<td>LDT</td>
<td>laser damage threshold (J/cm² or W/cm²)</td>
</tr>
<tr>
<td>LED</td>
<td>light-emitting diode</td>
</tr>
<tr>
<td>LIDT</td>
<td>laser-induced damage threshold</td>
</tr>
<tr>
<td>LLL</td>
<td>low light level</td>
</tr>
<tr>
<td>LMA</td>
<td>large mode area</td>
</tr>
<tr>
<td>LM-APD</td>
<td>linear-mode APD</td>
</tr>
<tr>
<td>lp</td>
<td>line pair</td>
</tr>
<tr>
<td>LWIR</td>
<td>longwave IR</td>
</tr>
<tr>
<td>$m$</td>
<td>integer, 1, 2, 3...; waist magnification $w_{02}/w_{01}$; mass (kg)</td>
</tr>
<tr>
<td>$m_i$</td>
<td>image modulation; image magnification</td>
</tr>
<tr>
<td>$m_{lens}$</td>
<td>lens object-image magnification</td>
</tr>
<tr>
<td>$m_p$</td>
<td>peak waist magnification $w_{02}/w_{01}$ at 1f:1f conjugates</td>
</tr>
<tr>
<td>$M$</td>
<td>square-root of $M^2$</td>
</tr>
<tr>
<td>$M^2$</td>
<td>beam quality compared with a diffraction-limited TEM₀₀ beam</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>$M_a$</td>
<td>afocal telescope magnification</td>
</tr>
<tr>
<td>MCP</td>
<td>micro-channel plate</td>
</tr>
<tr>
<td>MCT</td>
<td>mercury cadmium telluride</td>
</tr>
<tr>
<td>MEMS</td>
<td>micro-electromechanical system</td>
</tr>
<tr>
<td>MLM</td>
<td>multiple longitudinal mode</td>
</tr>
<tr>
<td>MMF</td>
<td>multimode fiber</td>
</tr>
<tr>
<td>MOPA</td>
<td>master-oscillator power amplifier</td>
</tr>
<tr>
<td>MPE</td>
<td>maximum permissible exposure; multiphoton excitation</td>
</tr>
<tr>
<td>MPN</td>
<td>mode-partition noise</td>
</tr>
<tr>
<td>MPPC</td>
<td>multipixel photon counter</td>
</tr>
<tr>
<td>MRF</td>
<td>magneto-rheological finishing</td>
</tr>
<tr>
<td>MSF</td>
<td>mid-spatial-frequency</td>
</tr>
<tr>
<td>MTF</td>
<td>modulation transfer function</td>
</tr>
<tr>
<td>MTF$_{det}$</td>
<td>detector MTF</td>
</tr>
<tr>
<td>MTF$_{opt}$</td>
<td>optical MTF</td>
</tr>
<tr>
<td>MTF$_{sys}$</td>
<td>system MTF</td>
</tr>
<tr>
<td>MTTF</td>
<td>mean time-to-failure</td>
</tr>
<tr>
<td>MWIR</td>
<td>midwave IR</td>
</tr>
</tbody>
</table>

- $n$  | refractive index |
- $n_e$ | number of electrons |
- $n_f$ | number of polygon facets |
- $n_p$ | number of photons |
- $n_s$ | number of signal electrons |
- $n_w$ | well depth (e$^-$) |
- $n_{ramp}$ | number of amplifier noise electrons (e$^-$) |
- $n_{orb}$ | number of background noise electrons (e$^-$) |
- $n_{rdc}$ | number of dark-current noise electrons (e$^-$) |
- $n_{rFPN}$ | number of spatial noise electrons (e$^-$) |
- $n_{rread}$ | number of read noise electrons (e$^-$) |
- $n_{RIN}$ | number of RIN noise electrons (e$^-$) |
- $n_{rs}$ | number of signal noise electrons (e$^-$) |
- $n_{rsp}$ | number of speckle noise electrons (e$^-$) |
- $N$ | number of longitudinal modes; resolvable spots; detector noise (A or e$^-$) |
- $N_e$ | number of electrons per second (e$^-$/sec) |
- $N_i$ | number of electrons per unit volume in energy level $i$ (1/m$^3$) |
- $N_p$ | number of photons per second (#/sec); number of pixels |
- NBF | narrow-band filter |
- NEP | noise-equivalent power (W or W/Hz$^{1/2}$) |
- NEP$_{amp}$ | amplifier-limited NEP (W or W/Hz$^{1/2}$) |
- NEP$_s$ | signal-limited NEP (W or W/Hz$^{1/2}$) |
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEPh</td>
<td>noise-equivalent photons (# of photons)</td>
</tr>
<tr>
<td>NIR</td>
<td>near-IR</td>
</tr>
<tr>
<td>NPRO</td>
<td>nonplanar ring oscillator</td>
</tr>
<tr>
<td>NRE</td>
<td>nonrecurring engineering</td>
</tr>
<tr>
<td>NSD</td>
<td>noise spectral density (A/Hz^{1/2})</td>
</tr>
<tr>
<td>NUC</td>
<td>non-uniformity correction</td>
</tr>
<tr>
<td>NUV</td>
<td>near UV</td>
</tr>
<tr>
<td>OCS</td>
<td>optical cross-section (m^2/sr)</td>
</tr>
<tr>
<td>OCT</td>
<td>optical coherence tomography</td>
</tr>
<tr>
<td>OPA</td>
<td>optical phased array</td>
</tr>
<tr>
<td>OPL</td>
<td>optical path length (= nd, μm or waves)</td>
</tr>
<tr>
<td>OPO</td>
<td>optical parametric oscillator</td>
</tr>
<tr>
<td>OPSL</td>
<td>optically pumped semiconductor laser</td>
</tr>
<tr>
<td>OXT</td>
<td>optical crosstalk</td>
</tr>
</tbody>
</table>

- **P**  
  - CW output power (W)
  - average output power (W)
  - electrical power (W)
  - probability of detection
  - probability of false alarm
  - horizontally polarized power
  - optical power incident on a lens or surface (W)
  - peak output power (W)
  - optical power reflected by a lens or surface (W)
  - optical power transmitted by a lens or surface (W)
  - thermal heat load due to lens absorption (W)
  - vertically polarized power

- **PBS**  
  - polarizing beamsplitter

- **PCF**  
  - photonic crystal fiber

- **PDE**  
  - photon detection efficiency

- **PDH**  
  - Pound, Drever, and Hall

- **PER**  
  - polarization extinction ratio

- **PIB**  
  - power-in-bucket

- **PIN**  
  - p-i-n photodetector

- **PM**  
  - polarization-maintaining

- **PMT**  
  - photomultiplier tube

- **PRF**  
  - pulse repetition frequency (Hz)

- **PRNU**  
  - photo-response non-uniformity

- **PRR**  
  - pixel readout rate (Hz)

- **PSD**  
  - power spectral density (nm^2-m), aka energy spectral density

- **PV**  
  - peak to valley; photovoltaic

- **PZT**  
  - piezoelectric transducer
### Glossary of Symbols and Acronyms

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q$</td>
<td>electron charge, $= 1.602 \times 10^{-19}$ C/e$^-$; lens shape factor</td>
</tr>
<tr>
<td>$Q$</td>
<td>heat load (W)</td>
</tr>
<tr>
<td>$Q_c$</td>
<td>cavity quality</td>
</tr>
<tr>
<td>$Q_p$</td>
<td>pulse energy (J)</td>
</tr>
<tr>
<td>$Q_{\text{store}}$</td>
<td>cavity photon-energy storage (J)</td>
</tr>
<tr>
<td>QCL</td>
<td>quantum-cascade laser</td>
</tr>
<tr>
<td>QCW</td>
<td>quasi-continuous wave</td>
</tr>
<tr>
<td>QE</td>
<td>quantum efficiency</td>
</tr>
<tr>
<td>QWP</td>
<td>quarter-wave plate</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$</td>
<td>radial coordinate (m)</td>
</tr>
<tr>
<td>$R$</td>
<td>average power reflectivity; diffraction ripple; range (m)</td>
</tr>
<tr>
<td>$R(z)$</td>
<td>Gaussian wavefront radius of curvature (mm)</td>
</tr>
<tr>
<td>$R_{\text{f}}$</td>
<td>Fresnel surface reflectivity</td>
</tr>
<tr>
<td>$R_{\text{g}}$</td>
<td>responsivity after including detector gain $G$ (A/W)</td>
</tr>
<tr>
<td>$R_{\text{i}}$</td>
<td>wavefront radius of curvature exiting lens (mm)</td>
</tr>
<tr>
<td>$R_{\text{o}}$</td>
<td>wavefront radius of curvature incident on lens (mm); detector responsivity (A/W)</td>
</tr>
<tr>
<td>$R_p$</td>
<td>reflectance of $p$-polarized light</td>
</tr>
<tr>
<td>$R_{\text{pi}}$</td>
<td>power reflectivity of surface $i$</td>
</tr>
<tr>
<td>$R_s$</td>
<td>reflectance of $s$-polarized light</td>
</tr>
<tr>
<td>$R_t$</td>
<td>thermal resistance (K/W)</td>
</tr>
<tr>
<td>RHS</td>
<td>right-hand side</td>
</tr>
<tr>
<td>RIN</td>
<td>relative intensity noise (1/Hz or dB/Hz)</td>
</tr>
<tr>
<td>RMS</td>
<td>root mean square</td>
</tr>
<tr>
<td>ROI</td>
<td>region-of-interest</td>
</tr>
<tr>
<td>ROIC</td>
<td>readout integrated circuit</td>
</tr>
<tr>
<td>RPM</td>
<td>revolutions per minute</td>
</tr>
<tr>
<td>RSS</td>
<td>root sum square</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s$</td>
<td>incoherent source size (mm)</td>
</tr>
<tr>
<td>$s_o$</td>
<td>object distance (mm)</td>
</tr>
<tr>
<td>$s_i$</td>
<td>image distance (mm)</td>
</tr>
<tr>
<td>sCMOS</td>
<td>scientific-grade CMOS</td>
</tr>
<tr>
<td>$S$</td>
<td>Strehl ratio; mirror width (mm); detector signal (A or e$^-$)</td>
</tr>
<tr>
<td>SA</td>
<td>spherical aberration</td>
</tr>
<tr>
<td>SAM</td>
<td>saturable-absorber mirror</td>
</tr>
<tr>
<td>SESAM</td>
<td>semiconductor saturable-absorber mirror</td>
</tr>
<tr>
<td>SFE</td>
<td>surface figure error ($\mu$m or waves)</td>
</tr>
<tr>
<td>SFG</td>
<td>sum-frequency generation</td>
</tr>
<tr>
<td>SHG</td>
<td>second-harmonic generation</td>
</tr>
<tr>
<td>SiPM</td>
<td>silicon photomultiplier</td>
</tr>
<tr>
<td>SLM</td>
<td>single longitudinal mode</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>SMF</td>
<td>single-mode fiber</td>
</tr>
<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
</tr>
<tr>
<td>SPAD</td>
<td>single-photon avalanche detector</td>
</tr>
<tr>
<td>SPCM</td>
<td>single-photon counting module</td>
</tr>
<tr>
<td>SPDT</td>
<td>single-point diamond turning</td>
</tr>
<tr>
<td>SRS</td>
<td>stimulated Raman scattering</td>
</tr>
<tr>
<td>STED</td>
<td>stimulated emission depletion</td>
</tr>
<tr>
<td>SWaP</td>
<td>size, weight, and power</td>
</tr>
<tr>
<td>SWIR</td>
<td>shortwave IR</td>
</tr>
<tr>
<td>$t$</td>
<td>time (sec)</td>
</tr>
<tr>
<td>$t_f$</td>
<td>time of flight (sec)</td>
</tr>
<tr>
<td>$t_{int}$</td>
<td>detector integration time (sec)</td>
</tr>
<tr>
<td>$t_s$</td>
<td>scan time (sec)</td>
</tr>
<tr>
<td>$T$</td>
<td>truncation ratio; optical transmittance; temperature (K); torque (N-m)</td>
</tr>
<tr>
<td>$T_{atm}$</td>
<td>atmospheric transmission</td>
</tr>
<tr>
<td>$T_{ext}$</td>
<td>external transmission</td>
</tr>
<tr>
<td>$T_{int}$</td>
<td>internal transmission</td>
</tr>
<tr>
<td>$T_{opt}$</td>
<td>optical transmission</td>
</tr>
<tr>
<td>$T_p$</td>
<td>pulse period (sec)</td>
</tr>
<tr>
<td>$T_{PIB}$</td>
<td>transmitted power-in-bucket</td>
</tr>
<tr>
<td>$T_{trunc}$</td>
<td>optical transmission after truncation losses</td>
</tr>
<tr>
<td>TCK</td>
<td>transfer clock</td>
</tr>
<tr>
<td>TDL</td>
<td>times diffraction limited</td>
</tr>
<tr>
<td>TEA</td>
<td>transversely excited atmospheric</td>
</tr>
<tr>
<td>TEC</td>
<td>thermoelectric cooler</td>
</tr>
<tr>
<td>TEM$_{pq}$</td>
<td>transverse electro-magnetic mode with integer number of nodes $p$ and $q$</td>
</tr>
<tr>
<td>THG</td>
<td>third-harmonic generation</td>
</tr>
<tr>
<td>TIA</td>
<td>transimpedance amplifier</td>
</tr>
<tr>
<td>TIR</td>
<td>total internal reflection</td>
</tr>
<tr>
<td>TIS</td>
<td>total integrated scatter</td>
</tr>
<tr>
<td>ToF</td>
<td>time of flight (sec)</td>
</tr>
<tr>
<td>ULE</td>
<td>ultralow expansion</td>
</tr>
<tr>
<td>USP</td>
<td>ultrashort pulse</td>
</tr>
<tr>
<td>UV</td>
<td>ultraviolet</td>
</tr>
<tr>
<td>$v$</td>
<td>scan velocity (m/sec)</td>
</tr>
<tr>
<td>$v_g$</td>
<td>group velocity (m/sec)</td>
</tr>
<tr>
<td>$V$</td>
<td>volume (cm$^3$)</td>
</tr>
<tr>
<td>$V_b$</td>
<td>bias voltage (V)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$V_{br}$</td>
<td>breakdown voltage (V)</td>
</tr>
<tr>
<td>VAC</td>
<td>volts of alternating current</td>
</tr>
<tr>
<td>VCSEL</td>
<td>vertical-cavity surface-emitting laser</td>
</tr>
<tr>
<td>VECSEL</td>
<td>vertical-external-cavity surface-emitting laser</td>
</tr>
<tr>
<td>VIS</td>
<td>visible</td>
</tr>
<tr>
<td>VPR</td>
<td>pixel reset voltage</td>
</tr>
<tr>
<td>VUV</td>
<td>vacuum UV</td>
</tr>
<tr>
<td>$w(z)$</td>
<td>Gaussian $1/e^2$ beam radius (mm)</td>
</tr>
<tr>
<td>$w_0$</td>
<td>Gaussian $1/e^2$ waist radius (mm)</td>
</tr>
<tr>
<td>$w_{01}$</td>
<td>Gaussian $1/e^2$ object-waist radius (mm)</td>
</tr>
<tr>
<td>$w_{02}$</td>
<td>Gaussian $1/e^2$ image-waist radius (mm)</td>
</tr>
<tr>
<td>$w_{0M}$</td>
<td>laser waist radius for an embedded beam with quality $M^2$ (mm)</td>
</tr>
<tr>
<td>WD</td>
<td>working distance</td>
</tr>
<tr>
<td>WFE</td>
<td>wavefront error ($\mu$m or waves)</td>
</tr>
<tr>
<td>WP</td>
<td>wall plug</td>
</tr>
<tr>
<td>$x$</td>
<td>transverse coordinate (m)</td>
</tr>
<tr>
<td>$x_p$</td>
<td>pixel pitch ($\mu$m)</td>
</tr>
<tr>
<td>$y$</td>
<td>transverse coordinate (m)</td>
</tr>
<tr>
<td>$y'_{MSF}$</td>
<td>surface error (nm)</td>
</tr>
<tr>
<td>$z$</td>
<td>axial (or longitudinal) propagation axis (m)</td>
</tr>
<tr>
<td>$z_1$</td>
<td>object waist-to-lens distance (mm)</td>
</tr>
<tr>
<td>$z_2$</td>
<td>lens-to-image waist distance (mm)</td>
</tr>
<tr>
<td>$z_{FF}$</td>
<td>far-field distance (m)</td>
</tr>
<tr>
<td>$z_R$</td>
<td>Rayleigh range (m)</td>
</tr>
<tr>
<td>$z_{R1}$</td>
<td>Rayleigh range of the object waist (m)</td>
</tr>
<tr>
<td>$z_{R2}$</td>
<td>Rayleigh range of the image waist (m)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>angular acceleration (rad/sec$^2$)</td>
</tr>
<tr>
<td>$\alpha_{int}$</td>
<td>internal loss (1/cm)</td>
</tr>
<tr>
<td>$\alpha_m$</td>
<td>mirror loss (1/cm)</td>
</tr>
<tr>
<td>$\alpha_m(\lambda)$</td>
<td>material attenuation coefficient (1/cm)</td>
</tr>
<tr>
<td>$\alpha_t$</td>
<td>coefficient of thermal expansion (1/K)</td>
</tr>
<tr>
<td>$\beta_{SA}$</td>
<td>angular blur size due to spherical aberration ($\mu$rad)</td>
</tr>
<tr>
<td>$\delta$</td>
<td>mirror dynamic deflection ($\mu$m)</td>
</tr>
<tr>
<td>$\delta_{RMS}$</td>
<td>RMS surface finish (Å or nm)</td>
</tr>
<tr>
<td>$\delta_T$</td>
<td>mirror thermal distortion ($\mu$m)</td>
</tr>
</tbody>
</table>
Glossary of Symbols and Acronyms

\( \Delta d \)  
surface figure error (SFE) or irregularity (\( \mu \text{m} \) or waves)

\( \Delta f \)  
electrical bandwidth (Hz)

\( \Delta L \)  
change in cavity length (\( \mu \text{m} \))

\( \Delta L_t \)  
change in cavity length due to thermal expansion (\( \mu \text{m} \))

\( \Delta Q \)  
gain bandwidth (J)

\( \Delta R \)  
range resolution (m)

\( \Delta t_p \)  
pulse width (sec)

\( \Delta T \)  
temperature change (C or K)

\( \Delta v \)  
velocity variation (m/sec)

\( \Delta x \)  
distance between spatial features (mm)

\( \Delta y \)  
change in beam-pointing location (\( \mu \text{m} \))

\( \Delta z_{\text{ast}} \)  
axial astigmatism (\( \mu \text{m} \))

\( \Delta \phi \)  
phase difference (rad)

\( \Delta \lambda \)  
emission linewidth (\( \mu \text{m} \) or nm)

\( \Delta \lambda_g \)  
gain bandwidth (\( \mu \text{m} \) or nm)

\( \Delta \nu \)  
emission linewidth (Hz)

\( \Delta \nu_a \)  
axial mode spacing (Hz)

\( \Delta \nu_g \)  
gain bandwidth (Hz)

\( \Delta \nu_L \)  
frequency shift or broadening due to change in cavity length (Hz)

\( \Delta \nu_{\text{MLM}} \)  
multi-longitudinal-mode emission linewidth (Hz)

\( \Delta \nu_{\text{R}} \)  
laser or etalon cold-cavity transmission bandwidth (Hz)

\( \Delta \nu_{\text{SLM}} \)  
single-longitudinal-mode cold-cavity linewidth (Hz)

\( \Delta \nu_{\text{ST}} \)  
Schawlow–Townes single-longitudinal-mode emission linewidth (Hz)

\( \Delta \theta \)  
mirror misalignment angle or change in beam pointing angle (\( \mu \text{rad} \))

\( \Delta \theta_d \)  
diffraction angle

\( \Delta \theta_m \)  
change in mirror mechanical pointing angle

\( \Delta \omega \)  
linewidth (rad/sec)

\( \Delta \omega_a \)  
axial mode spacing (rad/sec)

\( \varepsilon \)  
obscuration ratio

\( \Phi \)  
optical power collected by an optical system (W)

\( \Phi_L \)  
refractive or reflective power of a lens or mirror (1/m)

\( \gamma_{\text{obs}} \)  
obscuration loss

\( \eta \)  
polygon geometric efficiency factor

\( \eta_{\text{GM}} \)  
Geiger-mode avalanche efficiency

\( \eta_s \)  
slope efficiency (W/A)

\( \eta_{\text{QE}} \)  
quantum efficiency – also see QE

\( \eta_{\text{WP}} \)  
wall-plug efficiency (%)
\( \lambda \) wavelength (\( \mu \text{m} \) or nm)
\( \lambda_0 \) center wavelength (\( \mu \text{m} \) or nm)

\( \nu \) optical frequency (= \( c/\lambda \), Hz)
\( \nu_m \) axial mode frequency (Hz)
\( \nu_p \) pump optical frequency (Hz)
\( \nu_{\text{pqm}} \) transverse mode frequency (Hz)

\( \theta \) angular coordinate or angular scan range (rad)
\( \theta_{01} \) far-field half-divergence angle incident on lens (rad)
\( \theta_{02} \) far-field half-divergence angle exiting lens (rad)
\( \theta_d \) diffraction angle (rad)
\( \theta_{\text{DL}} \) diffraction-limited full-divergence angle (rad)
\( \theta_o \) far-field half-divergence angle (rad)
\( \theta_s \) scatter angle (rad)
\( \theta_{\text{slow}} \) slow-axis full-divergence angle (rad)
\( \dot{\theta} \) angular velocity (rad/sec)
\( \ddot{\theta} \) angular acceleration (rad/sec^2)

\( \rho \) power reflectivity; mass density (kg/m^3)

\( \sigma_{\text{amp}} \) amplifier noise (A)
\( \sigma_{\text{APD}} \) APD-detector signal noise (A)
\( \sigma_b \) detector background noise (A)
\( \sigma_{dc} \) detector dark-current noise (A)
\( \sigma_{\text{FPN}} \) detector spatial noise (A)
\( \sigma_n \) detector noise current (A)
\( \sigma_o \) second-moment beam radius (mm)
\( \sigma_p \) standard deviation of output power (W)
\( \sigma_{\text{read}} \) detector read noise (A)
\( \sigma_{\text{RIN}} \) detected RIN noise (A)
\( \sigma_s \) detector signal noise (A)
\( \sigma_{\text{sp}} \) detected speckle noise (A)

\( \tau_c \) coherence time (sec)
\( \tau_p \) photon lifetime or energy storage time (sec)

\( \omega \) optical frequency (= \( 2\pi\nu \), rad/sec)
\( \Omega \) modulation frequency (rad/sec); solid angle (sr)
\( \Omega_{\|/\#} \) solid angle of lens focusing cone (sr)
\( \Omega_{\text{IFOV}} \) solid angle of pixel IFOV (sr)
Index

1/e² radius, 102
3D printing, 33

A
AΩ product, 189
aberrated Gaussian, 108
aberrations, 131
ablation, 45, 155
absorption, 117, 149
acousto-optic modulator, 20
acousto-optic scanners, 172
active imaging, 248, 272
active quenching, 229
afocal telescope, 177
afterpulsing, 229
Airy disk, 130
along-scan jitter, 168
amplified spontaneous emission, 79
amplifier noise, 264
amplifier-limited, 274, 276
amplitude modulation, 21
amplitude stability, 50
anamorphic, 136
angle of incidence, 152
angular pointing stability, 39
antireflection coating, 152
APD gain, 224
architecture, 29
astigmatism, 135
asymmetric irradiance profile, 16
atmospheric transmission, 203
avalanche photodiode, 223
average output power, 48
average power, 44
axial mode spacing, 12
axial modes, 11
B
back-illumination, 243
back-reflections, 151
background light, 199
background noise, 261
backscattered radiance, 205
bandgap energy, 218
beam clipping, 129
beam diameter, 101
beam expander, 145
beam-parameter product, 107
beam pointing, 55
beam propagation factor, 103
beam quality, 4, 18, 32, 41, 103, 105, 131, 193
beam shapers, 148
beam size, 100, 107
beam truncation, 111
Beer’s law, 149
bending losses, 77
best-form singlet, 133
bidirectional scatter distribution function, 143, 205
birefringent crystals, 159
boresighting, 55
breakdown voltage, 227
Brewster window, 158
Brewster’s angle, 158
brightness, 5

C
carbon dioxide lasers, 85
cavity length, 11
cavity losses, 19
cavity stability parameter, 17
center wavelength, 11
charge-coupled device, 242
chromatic aberration, 136
circularization, 135
closed-loop galvos, 168
coefficient of thermal
    expansion, 118
coherence length, 4,
    10, 39, 271
coherence time, 10
coherent sensing, 76
cold ablation, 155
cold-ablation micromachining,
    72, 78
cold cavity, 14, 30
collimating lens, 135
collimator, 147
collision broadening, 12
coma, 134
confocal aperture, 6, 204
cconfocal resonator, 15
conservation of brightness, 189
conservation of étendue, 280
constructive interference, 21
continuous wave, 18, 42
conversion efficiency, 25
correlated double
    sampling, 246
cost of ownership, 90
cost per watt, 90
coupling losses, 19
critical range, 207
cross-scan wobble, 168
cutoff wavelength, 218
cylindrical lens, 136

D
dark-count rate, 230
dark counts, 229, 235
dark current, 255
dark-current limited, 263
dark-current noise, 262
dead time, 229
deep ultraviolet, 2
degrees of freedom, 270
deep of focus, 120
design trade, 26
detector current, 222
detector-limited system, 241
detector photocurrent, 217
detector selection, 277
detector sensitivity, 274
detector trades, 278
difference-frequency generation, 25
diffraction limit, 4, 17, 32
diffraction-limited blur size, 120
diffraction ripple, 130
diffuse scattering, 199
digs, 145
diode lifetime, 37
direct-injection pre-amp, 254
directed energy, 5, 164, 186
disk laser, 45
distortion, 176
distributed Bragg reflectors, 63
“donut” mode, 17, 105
Doppler broadening, 12
dose, 47, 49
double-clad fibers, 77
drift, 37, 49
dwell time, 181, 236
dynamic deflection, 173
dynamic range, 226
dynode amplification, 233

E
effective QE, 251
electrical bandwidth, 51, 222, 259
electron-bombarded CCDs, 248
electron ionization, 45
electron-multiplying CCD, 244
embedded Gaussian, 191
encircled energy, 193
encircled power, 193
end of life, 49
energy density, 47, 154
energy repeatability, 49
enhanced-silicon detector, 281
entrance pupil, 176, 182
Er:glass solid-state lasers, 71
etendue, 189, 202
excess bias, 230
excess noise, 264
excess-noise factor, 226, 264
excimer lasers, 84
excited-state lifetime, 9
exitance, 200
exposure time, 252

F
f-0 lens, 176
f/#, 120, 241, 282
fabrication errors, 137
Fabry–Pérot etalon, 13
facet-to-facet errors, 170
false positives, 229, 263
far-field divergence angle, 100, 104
fast axis, 135
fast-steering mirrors, 171
femtosecond lasers, 91
fiber lasers, 75
field curvature, 176
field of illumination, 132
field of regard, 165
field of view, 132
fill factor, 250
filters, 116
finesse, 13
fixed-pattern noise, 255, 269, 272
flash laser radar, 206, 209
flat field, 176
fluence, 5, 47, 154
fluorescence detection, 227
fluorescence microscope, 88
fluoride fibers, 75
focal length, 110
focal plane array, 237
focused spot size, 106, 128
fourth-harmonic generation, 25
frame rate, 244, 253
free space, 11, 31
free spectral range, 12
frequency, 2
frequency doubling, 24
frequency instabilities, 53
frequency quadrupling, 25
frequency sidebands, 21
frequency spectrum, 12
frequency stabilization, 13
frequency tripling, 25
Fresnel reflection, 152
Fresnel reflectivity, 157
FWHM pulse width, 46

G
gain, 7
gain bandwidth, 9, 12
gain–bandwidth product, 225
gain curve, 12
gain medium, 7
gain-multiplied responsivity, 224
galvanometer, 167
Galilean telescope, 145
gas lasers, 82
gating time, 248
gating voltage, 230
Gaussian beam, 15, 97
Gaussian-beam imaging, 109
Gaussian conjugates, 124
Gaussian to top-hat converters, 148
Geiger-mode APD, 228
geometric efficiency factor, 169
gimbal, 164
group velocity, 19
Index

H
half-concentric design, 18
harmonics, 24
head-up displays, 171
heat-affected zone, 45
HeCd lasers, 84
HeNe lasers, 83
Hermite–Gaussian modes, 103, 105
HgCdTe, 218
high spatial frequency, 143
high-power edge emitters, 62
high-power fiber lasers, 76
holdoff time, 229
homogeneous saturation, 13
homogenizer, 147
hybrid FPAs, 247
hybrid photodetector, 236

I
image contrast, 239
image distance, 109–110
image resolution, 239
Immutable Laws of Lasers, 1
impact ionization ratio, 226
incoherent imaging, 123
incoherent sources, 26
infrared, 2
InGaAs, 217
inhomogeneous saturation, 13
instantaneous FOV, 239
integration time, 252
intensified CCDs, 248
intensity noise, 50
interference, 270
interferometers, 4
internal loss, 43
International Standards
Organization (ISO), 102, 108, 213
ion-assisted deposition, 156
ion-beam sputtering, 154, 156
ion lasers, 86
irradiance, 5, 191–192
irradiance distribution, 97

J
jitter-induced misalignments, 55

K
Keplerian telescope, 145
KTP crystal, 24

L
Lambertian, 200
large mode area, 77
laser additive manufacturing, 33
laser beam, 97
laser brightness, 188
laser cavity, 11
laser damage threshold, 154
Laser-Eyed Monster, 29
laser hardening, 215
laser-induced damage threshold, 154
laser intensity, 197
laser PRF, 181
laser printer, 179
laser projection screen, 179
laser projection system, 186, 188
laser radar system, 28
laser safety officers, 215
laser system requirements, 28
laser system, 3
laser systems engineer, 28
laser types, 60
laser window, 116
lasers, 6
LASIK, 49, 84
lens bending, 133
lifecycle costs, 90
lifetime, 90
light, 2
line pairs, 239
linear-mode APD, 228
linewidth, 10
liquid crystal polarization gratings, 173
longitudinal-mode frequency, 17
Index

longitudinal mode spacing, 12
longitudinal modes, 11
longwave infrared, 2
low-power edge emitter, 60
low-power fiber lasers, 76
low spatial frequency, 142

M
$M^2$, 17, 32, 103, 108, 138–139, 190, 197
magnetorheological finishing, 139, 144
magnification, 26, 127–128, 146
maintenance, 90
marginal zones, 132
master oscillator–power amplifier, 73
maximum permissible exposure, 72
MEMS scanners, 170
micro-channel plate, 236
micro-chip laser, 69
micromachining, 85
microscopy, 5
mid-spatial-frequency, 139
midwave infrared, 2
mirror loss, 43
mirror-speed–angle–aperture trades, 177
misalignment angle, 15
mode hops, 31, 39–40
mode locking, 21
mode-partition noise, 52
mode volume, 47
modulation transfer function, 239
multifrequency, 18
multiline lens, 136
multimode laser, 18
multiphoton excitation, 6
multipixel photon counter, 232
multiple-longitudinal-mode, 52
multiple-spatial mode, 17

N
N-BK7HT, 119, 150
natural broadening, 12
Nd:YAG solid-state lasers, 68
near-eye wearables, 171
near-hemispherical design, 18
near infrared, 2
near ultraviolet, 2
nodes, 16
noise budget, 277
noise-equivalent photons, 275
noise-equivalent power, 223, 274
noise spectral density, 223, 265
nonlinear wavelength conversion, 25
nonmechanical scanning, 172
non-uniformities, 254
non-uniformity correction, 255
number of signal electrons, 252, 280

O
object distance, 109
object–image conjugates, 121, 128
obscuration losses, 194
obscuration ratio, 194, 196
open-loop resonant galvos, 168
operating infrastructure, 90
operational conditions, 93
optical coherence tomography, 81
optical cross-section, 200
optical crosstalk, 251
optical data storage, 4
optical feedback, 52, 56, 117
optical parametric oscillator, 24
optical path length, 39
optical phased arrays, 172
optical power, 218, 222
optical scan angle, 167, 169
optically pumped semiconductor lasers, 64
optimum gain, 225
optimum waist size, 111
optomechanical noise, 49
optomechanical stabilization, 53
*Optical Systems Engineering*, 29
*Optomechanical Systems Engineering*, 29
output power, 42
overbias, 230
overfill, 207
overload, 231

**P**

*p-n* junction, 60, 219
*p-polarization, 158
paraxial beam, 97
paraxial zones, 132
peak output power, 18
peak power, 44
peak responsivity, 218
phase coherence, 7
phonon broadening, 12
phosphate fibers, 75
photocathode, 233
photoelectric effect, 233
photolithography, 84
photomultiplier tube, 233
photon amplification, 7
photon counting, 234
photon detection efficiency, 230, 250
photon detector, 216
photon energy conservation, 25
photon energy, 9, 217
photon lifetime, 19
photon-number discrimination, 228
photonic crystal fiber, 81
photons per second, 217
photo-response non-uniformity, 254, 269
pico-projectors, 171
picosecond lasers, 91
piezoelectric transducer, 38
PIN photodiode, 220
pixel counts, 238
pixel pitch, 239
plane parallel plates, 116
Pockels-cell electro-optic modulator, 23
pointing instabilities, 54
Poisson's ratio, 186
polarization, 58, 157
polarization extinction ratio, 59, 159
polarizing beamsplitter, 159
polygon scanner, 169
population inversion, 7, 9
power budget, 28, 206, 277
power collection, 201, 241
power density, 154, 191
power-in-bucket, 193
power reflectivities, 13
power spectral density, 141
pre-amplifier gain, 255
probability of detection, 257
probability of false alarm, 258
programmatic requirements, 280
pulse energy, 18, 47–48, 260
pulse-height discrimination, 232, 235
pulse period, 23
pulse repetition frequency, 44, 48
pulse repetition rate, 48
pulse-to-pulse stability, 49
pulse width, 22, 45
pump diode, 36
pump noise, 51

**Q**

Q-switching, 19
quantum-cascade lasers, 66
quantum efficiency, 221
quantum wells, 66
quasi-continuous wave, 42

**R**

radius of curvature, 15
Raman self-scattering, 81
range, 206
range-gated imaging, 72
range equation, 206–208
range gating, 204
range resolution, 46, 71
rangefinders, 71
Rayleigh range, 97, 102, 107
read noise, 267
readout integrated circuit, 247
readout integrated circuits, 253
recovery time, 235
refractive index, 11
refractive power, 109
region-of-interest, 253
re-imaging, 125
relative intensity noise, 51, 260
relaxation-oscillation frequency, 52
relaxation oscillations, 18–19
relay lens, 183
reliability, 90
reset time, 229
resolution, 38
resolvable spots, 179
resonance, 11
resonant cavity, 8
responsivity, 217
retroreflection, 204
reverse bias, 221, 263
root mean square, 137
root sum square, 138, 258
rotational inertia, 170
round-trip time, 23
S
s-polarization, 158
sampling, 239
saturable absorber, 20
scan time, 179
scan velocity, 176, 181
scanned laser radar, 206
scanning confocal microscope, 182
Schawlow–Townes linewidth, 14
scientific-grade CMOS, 245
scratches, 145
screen brightness, 188
second-harmonic generation, 24
second-moment method, 102
self-driving vehicles, 206
semiconductor, 216
semiconductor lasers, 60
semiconductor saturable-absorber mirror, 21
sensitivity, 29, 223
shape factor, 133
shortwave infrared, 2
shot noise, 259
shot-noise limited, 264
signal current, 258
signal limited, 259, 264, 274
signal noise, 258
signal-noise electrons, 275
signal-to-noise ratio, 257
silicon photomultiplier, 232
silicon, 216
single frequency, 13
single-longitudinal mode, 13
single-mode telecommunications fiber, 77
single-photon avalanche diodes, 226
single-photon sensitivity, 275
single-point diamond turning, 139
slope efficiency, 42
slow axis, 135
solar background, 203, 211
solid angle, 188
solid-state lasers, 68
spatial coherence, 7, 14, 31–32, 41, 271
spatial frequency, 140, 239
spatial hole burning, 40
spatial mode, 18, 105
spatial noise, 268
spatial resolution, 239
specific stiffness, 170
specifications, 36
speckle, 14
speckle contrast, 270
speckle noise, 269
spectral brightness, 191
spectral filter, 205
speed of light, 2
spherical aberration, 131–132
spontaneous emission, 14
spot resolution, 180
stability, 49
stationary phase, 31–32
stimulated emission, 8
stimulated emission depletion microscopy, 78
stray light, 204
stress birefringence, 160
Strehl ratio, 137
subsystems, 29
subwavelength microstructures, 157
sum-frequency generation, 25
supercontinuum fiber lasers, 81
Suprasil, 119, 149
surface distortion, 142
surface error, 142
surface-figure errors, 137
surface finish, 143
surface ripple, 139
surface roughness, 143
SWaP, 279
system MTF, 240
system requirements, 282
system trades, 280
system wall-plug efficiency, 89

T
technical noise, 14
telecentric lens, 176
TEM_00 mode, 15, 32
TEM_{pq} mode, 16
temperature drift, 52
temperature gradients, 56, 175
temperature-induced drift, 53
temperature sensitivity, 64
temperature stabilization, 37, 65
temperature tuning, 25–26
temporal coherence, 7, 10, 271
temporal filtering, 262
thermal conductivity, 175
thermal damage, 45, 155
thermal diffusivity, 45, 155
thermal distortion, 175
thermal expansion coefficient, 175
thermal gradient, 118
thermal lensing, 117–119
thermal load, 44
thermal resistance, 58
thermal lensing, 70
thermoelectric coolers, 37, 230
thermo-optic constant, 119
thermo-optic effect, 117
thermopiles, 216
thin lens, 109
third-harmonic generation, 25
threshold current, 42
throughput, 90
Ti:sapphire solid-state lasers, 70
time of flight, 206
timing jitter, 21, 49
tip-tilt, 171
tolerances, 36
torque, 170
total integrated scatter, 143, 204
total internal reflection, 31, 61
trade study, 279
trade table, 28, 91
transimpedance amplifier, 253, 265
transmission bandwidth, 13
transverse mode, 18
transverse-mode frequency, 17
truncation, 129, 131
truncation ratio, 129
tuning, 38

U
ultrafast fiber lasers, 78
ultrafast lasers, 46
ultrafast scanners, 173
ultrashort pulse, 6
ultraviolet, 2
<table>
<thead>
<tr>
<th>Term</th>
<th>Page(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>underfill</td>
<td>207</td>
</tr>
<tr>
<td>uniphase</td>
<td>32</td>
</tr>
<tr>
<td>UV photodarkening</td>
<td>85</td>
</tr>
<tr>
<td>V-coating</td>
<td>153</td>
</tr>
<tr>
<td>vacuum ultraviolet</td>
<td>2</td>
</tr>
<tr>
<td>velocity linearity</td>
<td>177</td>
</tr>
<tr>
<td>vertical external-cavity</td>
<td></td>
</tr>
<tr>
<td>surface-emitting lasers</td>
<td>64</td>
</tr>
<tr>
<td>vertical-cavity surface-emitting lasers</td>
<td>63</td>
</tr>
<tr>
<td>very longwave infrared</td>
<td>2</td>
</tr>
<tr>
<td>vibration-induced jitter</td>
<td>53</td>
</tr>
<tr>
<td>visible (light)</td>
<td>2</td>
</tr>
<tr>
<td>waist, waist diameter</td>
<td>97, 101</td>
</tr>
<tr>
<td>wall-plug efficiency</td>
<td>42, 57</td>
</tr>
<tr>
<td>wavefront converter</td>
<td>110</td>
</tr>
<tr>
<td>wavefront curvature</td>
<td>109</td>
</tr>
<tr>
<td>wavefront errors</td>
<td>104</td>
</tr>
<tr>
<td>wavefront radius of curvature</td>
<td>100, 103, 107</td>
</tr>
<tr>
<td>wavefront transformation</td>
<td>128</td>
</tr>
<tr>
<td>waveguide modes</td>
<td>31</td>
</tr>
<tr>
<td>wavelength</td>
<td>2, 36</td>
</tr>
<tr>
<td>wavelength control</td>
<td>37</td>
</tr>
<tr>
<td>wavelength conversion</td>
<td>23–24</td>
</tr>
<tr>
<td>wavelength stabilization</td>
<td>61</td>
</tr>
<tr>
<td>wedge</td>
<td>116</td>
</tr>
<tr>
<td>well capacitance</td>
<td>254</td>
</tr>
<tr>
<td>well depth</td>
<td>254</td>
</tr>
<tr>
<td>Yb:YAG disk lasers</td>
<td>72</td>
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