

# Chapter 2

## Basics of Lasers and Laser Optics

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**Abstract** The purpose of this chapter is to introduce the entering professional or graduate student to the basics of laser physics and optics. I start with the various types of lasers, some rather exotic, and the ever-increasing span of wavelengths that has resulted since the laser's invention in 1960. I then discuss typical techniques as well as the "rules of thumb" used to transport and manipulate the laser output so it can be used for materials processing. The chapter concludes with a discussion of laser damage, as these physical processes limit the ability to transport and manipulate high intensity beams.

### 2.1 Introduction

When this book is published, the laser will be just months from the 50th anniversary of its first demonstration on May 16, 1960. That first laser operated in millisecond long bursts at 694 nm [1]. Since then, lasers have operated with wavelengths spanning mm to angstroms, and were found to occur naturally in the atmospheres of Mars and other planets [2]. In this section, we touch briefly on the optical arrangement that makes laser action possible, then discuss how this enables lasers to span such an enormous spectral range. While some spectral ranges may seem less amenable to use in a laser processing application than others, one never knows what future opportunities might yet arise.

### 2.2 Optical Processes

Quantum mechanics has been quite successful in explaining the absorption and emission of light in atomic systems, no matter what state of matter they find themselves in. Bound states exist due to the behavior of electrons moving in the central

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potential of the nucleus, *modulo* perturbations due to the bonding of atoms to one another, as in the case of liquids and solids [3–5]. Electrons transitioning between states do so through several processes, namely through stimulated absorption from one state to a more energetic state, followed by spontaneous emission, and, as will be explained shortly, stimulated emission from this higher state to the same, or another, lower state. Absorption and spontaneous emission occur around us all the time, because these are processes that occur in systems in thermal equilibrium, e.g., the emission of photons from an incandescent light. Stimulated emission requires that more electrons be in the upper, or excited state than the state they will transition to. This is known as population inversion. Population inversion requires energy in excess of that provided by thermal equilibrium, e.g., a laser diode pumping an energy level in a laser crystal. It is the EM field from the photons whose energy matches the transition energy of the excited electrons in the vicinity that stimulates them to emit coherently. As the field propagates through the excited ensemble of electrons, the field grows exponentially stronger. For laser action to occur, the gain per pass through the system must be greater than the loss. The population inversion process has been diagrammed in many publications, the reader is referred to Figs. 1.21, 1.27, and 1.28 in [3].

In many cases, particularly in systems where the gain for each pass through the medium is low, mirrors are used. One mirror is as completely reflective as practical, with the value  $R_{HR}$ , the other is a partially transmissive (typical reflectivities are in the range 70–99%), with the value  $R_{OC}$  and is known as the outcoupler. This is the configuration one generally conjurs up when thinking of a laser; and this configuration is shown in Fig. 2.1.

The threshold condition for laser oscillation occurs when the gain per unit length  $g$  for each pass just equals the loss (absorption, scattering, etc.) per unit length  $\alpha$ :

$$R_{HR}R_{OC} = \exp(g - \alpha)2l = 1 \quad (2.1)$$

Where  $l$  is the length of the gain region. Different arrangements of these mirrors are used to create a resonant EM field that selects and provides positive feedback to the stimulating field. On the early passes through the gain medium, the number of photons increases exponentially, as expressed in (2.1). This is called the small signal regime. However, the stimulating field increases the stimulated emission rate to the point that the upper level population becomes depleted at exactly the excitation rate. At this point, the gain and loss become equivalent, and the gain is said to be saturated and in most cases is equal to the transmission of the outcoupling mirror. A discussion of optical resonators is given in [3, 5, 6].



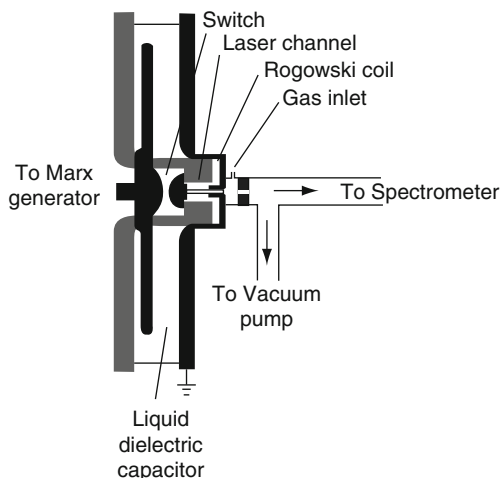
**Fig. 2.1** The laser resonator configuration

A pumped gain medium without mirrors still undergoes stimulated and spontaneous emission. Without further intervention, such a system would emit in all directions, at a rate sufficient to bring the populations in the lower and upper states to equilibrium. But, if one unidirectionally introduces light in resonance with the energy difference, stimulated emission amplifies the light as it traverses the medium. The pumped gain medium is termed a laser amplifier. For decades, systems composed of the exciting laser oscillator pumping the laser amplifiers have been used to achieve output powers unachievable using just an oscillator. Systems as small as erbium doped fiber amplifiers (EDFA) are used in fiber optic communications systems to extend the distance between repeater stations [7, 8]. On the other end of the scale, the National Ignition Facility (NIF) starts with an injected energy of 0.75 nJ and amplifies it to over 1 MJ [9].

However, in systems with sufficient gain, it is possible to obtain laser emission without the use of an optical cavity. This phenomena, termed self-amplified stimulated emission (SASE) makes lasers possible at wavelengths where laser resonators can not easily be constructed, such as the soft X-ray spectral region (sub 5 nm). Table-top realizations of such systems were demonstrated in 1994 by J.J. Rocca and a coworkers [12], who demonstrated lasing at 46.9 nm by creating a long capillary discharge in Ne gas. A schematic of this system is shown in Fig. 2.2.

The region termed the laser channel in the figure contains a region of highly excited Ar ions in a highly inverted population. Spontaneous emission from the region near the switch is amplified by the confined region of the discharge, and amplified as they traverse it. Using the same principles, but with a different gas, the same group has produced a laser emitting at 13.9 nm.

Other techniques for achieving laser emission in the soft X-ray region include laser ablation and high harmonic generation (HHG) in gases. These are discussed in more detail in Chap. 4. While one might consider such wavelengths irrelevant for laser processing applications, consider the fact that the shorter the wavelength, the smaller the spot at focus, and, as discussed in later chapters, processing need



**Fig. 2.2** Schematic diagram of the capillary discharge setup used to obtain saturated amplification of the 46.9 nm line of Ne-like Ar from Rocca et al. [10–12]

not be ablative, it can also be physicochemical. Thus, these soft X-ray lasers open possibilities for lithography and even ablative processes [13].

## 2.3 Time Dependence

So far we have concentrated on the interplay of the three electronic processes, absorption, spontaneous emission, and stimulated emission, to explain the lasing process, without regard to the time dependence of the laser output. So long as there is a population inversion that provides sufficient gain to overcome losses laser action will occur. But it is possible to introduce a time dependence on the laser output, and this greatly expands laser's increasingly important role in both the sciences and technology, so they deserve a brief mention. More lengthy (and excellent) discussions are found in [3, 6].

### 2.3.1 *Q-Switching*

In atomic systems where the lifetime of the upper state (the inverse of the spontaneous emission rate) is relatively long, of order  $100\ \mu\text{s}$  or more, it is then possible to let the population build by suppressing stimulated emission until the population saturates. At that time, the suppressant is removed and stimulated emission begins. Since the upper state population is so much larger than it would have been otherwise, the rate is much higher and a larger percentage of the population suddenly transitions to the lower state. The output, rather than being continuous, becomes a brief burst, the duration of the burst being dependent on the technology used to create, then remove the stimulated emission suppressant. Resonant cavities have a quality factor  $Q$  rigorously defined as the ratio of energy stored to power dissipated per unit angular frequency. However, we will take the more common approach of defining the laser cavity  $Q$  as the ratio of the mirror reflectivities:

$$Q = \frac{R_{\text{HR}}}{R_{\text{OC}}} \approx \frac{1}{R_{\text{OC}}} \quad (2.2)$$

Since the reflectivity of the HR mirror is so close to 1, the approximation to unity is quite good. So, the cavity  $Q$  typically ranges from 3 to 100. When the suppressor is active, the  $Q$  is essentially infinite. The device that changes the cavity is called a  $Q$  switch, and the phenomena, once called *giant pulsing*, is now called Q-switching. A schematic representation of the phenomena is shown in Fig. 26.1 from [3].

Typically, the pulselength of Q-switched pulses is of the order 10 ns. As much of the upper level population is depleted in a very short time, peak power can be several orders of magnitude greater than the average power.

### 2.3.2 Mode-Locking

In any laser system in a resonator configuration, as opposed to one that operates via SASE, there are a number of longitudinal modes, analogous to the tones on a plucked string, that satisfy the round trip condition. As the resonator length is short, relative to the distance traveled by light in a second, a great number of closely-spaced longitudinal modes exist in a laser resonator. Mode selection occurs to some extent by the spectral width, and hence the frequency span over which there is sufficient gain. If one sets the cavity length of the resonator very accurately (to within microns) of that required to support the longitudinal mode so it precisely fulfills the requirement that:

$$f = \frac{c}{2L} \quad (2.3)$$

Then this one mode predominates. The resonator, instead of producing a cw (time independent) output, produces a continuous train of short pulses. Pulse widths ranging from a few ps to 100 ps have been demonstrated, with repetition rates ranging from 10's of MHz to GHz. While these lasers have generally been used in scientific applications, there are material processing applications as well.

### 2.3.3 Ultrashort Pulse Generation

The quest to understand the details of electronic excitation and de-excitation has driven the laser technology for producing ultrashort (less than 1 ps) pulse lengths. This is due to the fact that the timescales for these processes can be as short as some 10's of femtoseconds. In order to create laser pulses of such short duration, modulation of the cavity population is sometimes done using mode-locking. In addition, ultrashort pulses can only be generated by materials that have a sufficiently wide spectral (and thus frequency) bandwidth. This is because the time-bandwidth product satisfies the equation:

$$\Delta\tau\Delta\nu = \text{const} \quad (2.4)$$

The value for the constant depends on the lineshape, for most ultrafast solid state lasers it is 0.33. The original technique for producing ultrashort pulses, colliding pulse amplification (CPA) has been largely replaced by Kerr lens mode-locking (KLM), and the reader should consult [14] for more information.

### 2.3.4 Harmonic Generation

When short (fs-ns) laser pulses are focused sufficiently to create high intensities (typically  $>10^8$  W/cm<sup>2</sup>) in materials, the electric field strengths (in V/m) become so great that nonlinearities in material properties emerge. Chief among them is the

index of refraction,  $n$ . Though a constant of the material, and a manifestation its bonding, at high intensity, nonlinear terms become evident. One that is exploited is that of harmonic generation, where light of some frequency (expressed as  $\omega$ ) is focused into a material and some of this light is converted to higher frequencies, either  $2\omega$  or  $3\omega$ , depending on the material. These can then be focused into other materials to generate  $4\omega$ ,  $5\omega$ , etc., although the efficiency drops rapidly, so typically only these harmonics are generated. While these nonlinearities can be created in the appropriate gases, liquids, or solids, from a practical, and sustainable point of view, solids are preferable and the norm. A good review of the processes and applications may be found in [6].

## 2.4 Free-Electron Lasers

So far we have discussed lasers based on bound electron systems. It is possible to have laser action using an ensemble of free electrons. At first blush, elementary quantum mechanics would lead one to think that since a free electron has a continuous set of energy levels to choose from, there is no upper or lower energy level to transition between. As we will see below, it is possible to create such a pair of states. What is notionally correct, based on elementary quantum theory is that one can set the transition energy over an enormous range. Laser action has been demonstrated at millimeter wavelengths to as short as 6.5 nm (at this time), with plans to operate at a scientific user facility at 0.15 nm in the next couple of years. Since these lasers use free electrons, they are called free-electron lasers (FEL).

The first FEL was operated at 3.4  $\mu\text{m}$  in 1976 [15]. A recent review of FELs is found in [16]. A schematic view of an FEL, using superconducting linear accelerator technology to achieve high average power, is shown in Fig. 2.3.

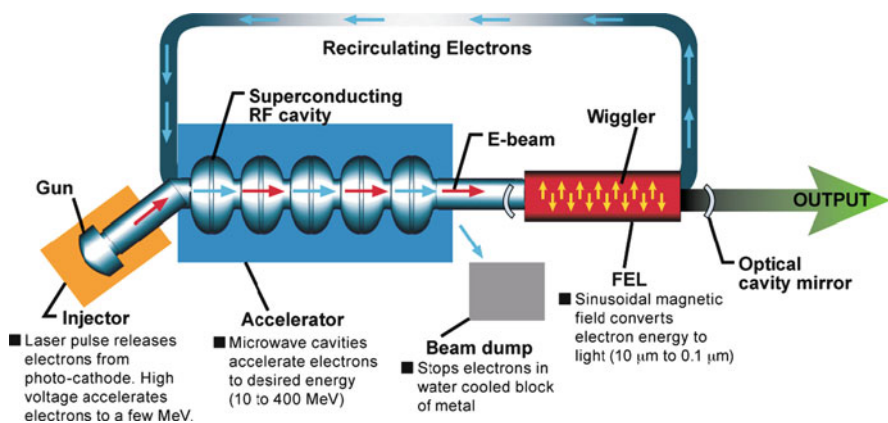


Fig. 2.3 Schematic diagram of a free-electron lasers (FEL) (courtesy Jefferson Lab)

As shown in the figure, bunches of free electrons (the charge per bunch is in the range of 10's of pC to about a nC) are accelerated to relativistic speeds and enter a structure known as a “wiggler”, a periodically-spaced arrangement of magnets. As the electron's trajectory oscillates, they radiate through the well-known phenomenon of synchrotron radiation [17]. This radiation interacts with the magnetic field of the wiggler to form a ponderomotive wave, which appears at rest with respect to the electrons. The electrons bunch in the troughs of this wave, and form energy levels. There is a natural population inversion, as the electrons have a lot of kinetic energy. The photons that are present from spontaneous emission serve as the seed for stimulating emission from the electrons. Each bunch is separated by one wavelength from the adjacent bunch, so the light adds coherently.

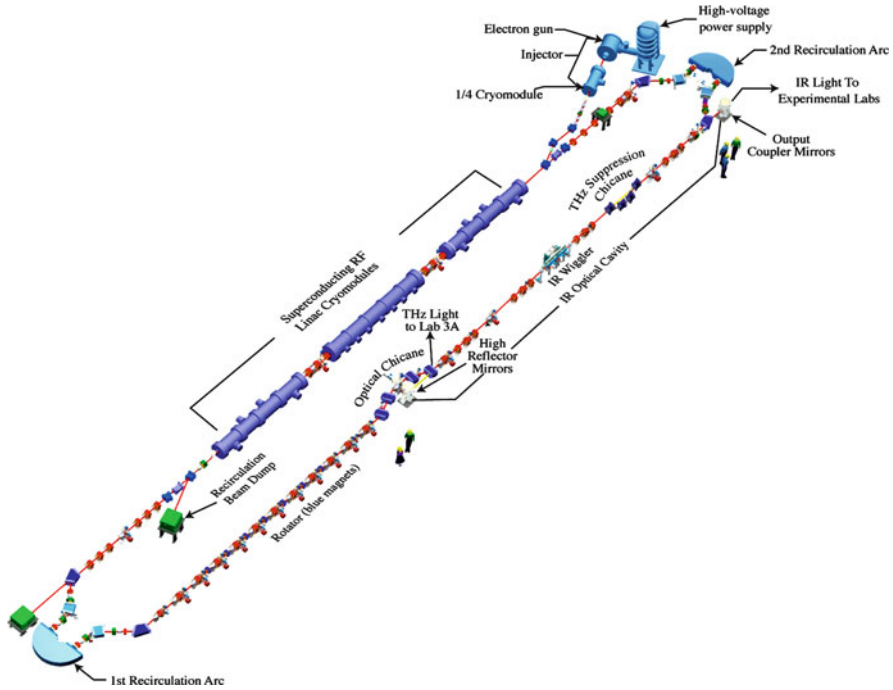
As described, this arrangement has gain. In most cases, the gain is low for each pass through the wiggler, so mirrors are used to form a resonator, as shown in Fig. 2.3. This raises the stimulating field, or thinking in terms of photons, the flux, which increases the gain. However, the gain enhancement only occurs if the photons produced by a previous electron bunch arrive in time to stimulate a fresh electron bunch in the wiggler. Thus, the optical cavity length must be precisely set, to within a few microns, so the following equation is satisfied:

$$L = \frac{nc}{2f} \quad (2.5)$$

Where  $f$  is the electron bunch frequency, and  $n = 1, 2, 3, \dots$  to allow for longer cavity lengths that are also in synchronism [18].

With the enhancement provided by the resonant cavity, small signal gains of the order of 10's to over 100% per pass can be achieved with short wigglers of a couple of meters length, or less. With a superconducting radiofrequency (SRF) linac, it is possible to continuously produce fresh bunches of electrons, so the output power can be quite high. At the Thomas Jefferson National Accelerator Facility, we have produced over 14 kW of average power at 1.61  $\mu\text{m}$ , and kilowatt levels of power through the near-IR to mid-IR spectral range [18]. A schematic depiction of this machine is shown in Fig. 2.4. These machines are always big, typically many 10's of meters in length, so they tend to be installed as part of multiuser facilities. At present, there are over a dozen of such facilities around the world. Given the wavelength flexibility of FELs, there has been a growing trend to build them to produce X-rays. The proper electron bunch parameters and the use of longer wigglers allow the gain through the wiggler to reach many orders of magnitude, typically  $10^3$ – $10^7$ . In these cases, lasing of the SASE type occurs. This is how the 6.5 nm laser was produced [19].

With high repetition rates (MHz), ultrashort pulse lengths, and tunable wavelength output, FELs are being used in science and technology to answer questions in the fields of medicine, materials research, and as a tool for materials processing. It is not clear whether stand alone facilities for materials processing will be built solely for materials processing, but clearly it has the ability to map out a parameter space in order to optimize a process [20, 21].

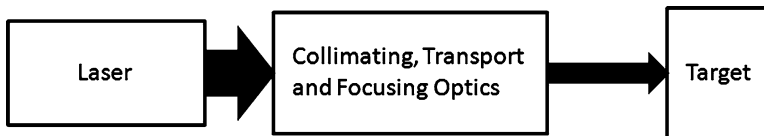


**Fig. 2.4** Schematic layout of the FEL at the Thomas Jefferson National Accelerator Facility (USA)

## 2.5 Laser Optics

A laser without optics to transport and condition the beam to meet the goals of the experiment or process is like having an automobile engine without the transmission and tires necessary to use it; it may deliver impressive performance, but not be too useful. The light emitted from the laser naturally has a divergence set by the radius of the source, the properties of the outcoupler mirror, and the wavelength. Left to freely propagate to the plane of interest, the irradiance (in  $\text{W}/\text{cm}^2$ ) or fluence (in  $\text{J}/\text{cm}^2$ ) will probably not be sufficient. Hence, the user must place intervening optics to correct for the divergence and any pathlength requirements imposed by the space available, then condition the beam to achieve the desired beam conditions at the surface being irradiated, as diagramed in Fig. 2.6. This section discusses the basic optics required to achieve simple beam propagation and conditioning, subsequent sections treat more recent and complicated means for beam conditioning. This has been well-covered elsewhere, so in my treatment, I will tend to emphasize the tricks of the trade (Fig. 2.5).





**Fig. 2.5** Generic diagram of a laser and its optical system

### 2.5.1 Optical Propagation

When thinking about how to design an optical transport system or to optimize one you have acquired, there are two ways to come to an answer; using geometrical optics, or by using physical optics. Geometrical optics treats light as traveling in rays and as these rays propagate, they are manipulated by optical elements such as lenses in precise ways, and from a starting point, known as the object, one propagates to an image, which can be either at a particular point or plane in space. Geometrical optics works well when thinking how to first set up an optical system as it directly addresses the spacing of optical elements. It does not handle the very real (and obvious when using a laser source) ramifications of the wave nature of light, such as diffraction and interference. To properly treat these cases, one moves into physical optics, which treats light as being composed of electromagnetic waves. The mathematical treatment of light propagation is more complicated than that employed for geometrical optics, but it has great validity when considering the size of optical elements, and on the diameter of the final image, as I will discuss later.

While there are a number of formulae relating to geometrical optics, only a few are needed for most applications. For an optical system with a net focal length  $f$ , a distance from the source to the focal plane  $o$  (object distance), and a distance from the focal plane to the target  $i$  (image distance)

$$\frac{1}{f} = \frac{1}{o} + \frac{1}{i} \quad (2.6)$$

There is a sign convention for focal lengths and the object and images distances. These are covered in detail in elementary physics and optics textbooks [22–24]. These references also explain and have examples on how to solve for the image position when using a combination of lenses and mirrors. Or, one can use optical modeling software, which will be discussed later in this chapter.

The laser manufacturer typically specifies the output diameter, which we will define as  $2\omega$ , where  $\omega$  is the beam radius measured at the  $1/e^2$  point (in either irradiance or fluence) as well as the divergence  $\theta$ . It is important to note whether the divergence is the full angle or half-angle, there is no standard. This is the source point in the calculations done either analytically, or by using optical modeling software. From this information, one can calculate the beam diameter at the first optical element, and on through the system. This brings us to an important consequence of physical optics, the size of the optical elements.

### 2.5.2 *Sizing Optical Elements and Other Tricks of the Trade*

A premise of physical optics is that the waves traveling away from the source are smoothly-varying functions in both space and time. Hence, if the beam is “too big” when it intercepts an optical element, the wavefront will be truncated (clipped is the vernacular term). While the effects of this truncation are subtle while the beam is relatively large in extent, when brought to a focus, one will see intensity fringes within and surrounding the central spot. It is surprising just how little of the clear aperture of the optic can be filled before these effects become apparent. As discussed in detail in [3], to be assured of minimum fringing it is best to have the clear aperture of the optic be about four times the beam radius. This “ $4\omega$ ” criterion will transmit 99.96% of the incident power and have about 1.1% of the power in the fringes when brought to focus. As tempting as it might be to let the beam fill more of the aperture (especially when trying to save money), consider what happens if you use a  $\pi\omega$  criterion. While the transmission remains high, 99%, now 17% of the power has been moved into the diffraction fringes. This can be a serious problem if you are trying to remove material in the smallest area, as the diffraction ripple causes uneven ablation and prevents the laser from focusing to the smallest spot, as “Airy rings” around the central lobe can also induce ablation. Another factor impacting final image quality is the orientation of lenses in the beam path. One learns in an optics class that the “principle of reversibility” states that rays of light will trace the same path through an optic independent of direction. However, with optics made to some wavefront tolerance (e.g.,  $\lambda/10$ ), there is a difference. In general, it is best to place the curved surface of the optic toward the beam path, if the beam is collimated (object at infinity). An exception to this rule is when a high power; especially high peak power laser beam is incident on a concave surface. The concave surface forms a virtual image before it, and the intensity can become high enough that you get breakdown of the air at the focal point. If that focal point happens to lie on or within another optical element, you can damage that element.

Finally, always check the optics you buy, at least for focal length. Vendors state a precision in their specs, but production parts are checked at the level of a percent or so, and parts with 5% error can easily pass inspection. If one is tightly tolerancing their optical beam train, some care to confirm the optical elements meet specifications will ensure that the desired performance is obtained.

### 2.5.3 *Fiber Optics*

No discussion of laser transmission is complete without at least a passing reference to fiber optics. As the name implies, rather than propagating a laser through free space, the beam is propagated down a thin (about  $5\text{ }\mu\text{m}$  to  $1\text{ mm}$ ) fiber, usually made of fused silica glass. The size of the fiber is chosen for the application – a bundle of fibers will carry more power than a single fiber, but the divergence of the output will suffer due to the fact that without some effort, the individual

beams are not coherently locked in phase to one another. For cw laser systems in the kW class, transmission with fiber optics is the norm, particularly in industrial installations, as there are fewer surfaces to become contaminated or misaligned. For pulsed systems, particularly when the pulselength is in the 100's of femtoseconds and shorter, fiber optics need to be carefully chosen or avoided entirely. The dimensionally-constrained environment in the fiber raises the electric field (and hence, the intensity) within it, and short pulses can easily push this field to the damage limit (see the following section on this phenomena). For femtosecond pulses, the fiber's dispersion (index variation with wavelength) can result in undesirable pulse lengthening. For more detail, the reader should consult [25].

### ***2.5.4 Managing Diffraction***

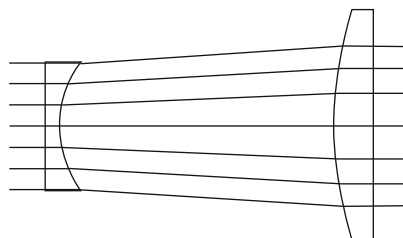
The previous discussion on the deleterious role that aperturing of laser beams has on beam properties might lead one to believe that diffraction is to be avoided at all cost. However, diffraction can be tailored to shape the beam's intensity profile to enhance the processing effectiveness. Consider the fact that the low order transverse mode output of a laser usually results in a Gaussian output. If the laser is multimode, the output is at least smoothly-varying, with the maximum intensity at the center. In most cases, this is not the most efficient beam profile to ablatively remove material, because the wings of the beam profile do not deposit enough power into the material to heat it to vaporization. At best, it has wasted power, at worst, it creates a heat-affected zone around the region being processed. The best way to avoid this is to reshape the beam profile from a gaussian to a flat-top, where the power is constant with respect to the beam radius to a certain diameter, then falls quickly to zero. There are several ways to obtain this profile, one is with aspheric lenses, the other way is with holographic optical elements (HOE) sometimes called diffractive optical elements (DOE). We will examine both.

### ***2.5.5 The Aspheric Lens Beamshaper***

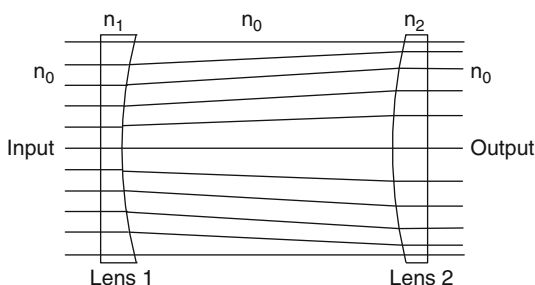
A common arrangement of two spherical optical elements, planoconvex and planoconcave lenses, can be arranged to form a Galilean telescope. This arrangement is shown in Fig. 2.6. The Galilean telescope takes a collimated beam (object distance at infinity) and either expands or condenses it by an amount equal to the ratio of the focal distances.

However, this leaves the beam's intensity profile unchanged, a Gaussian profile remains Gaussian. If one uses aspheric lenses, the telescope becomes a beam shaper as well, either expanding or condensing the beam and converting the Gaussian profile to a flat top. First published by B. Frieden in 1965 [26], it was little noticed until

**Fig. 2.6** A Galilean telescope. Collimated light entering from the *left* leaves the telescope on the *right* magnified by the ratio of the focal lengths



**Fig. 2.7** Design of a two-element beam shaper (from [28])



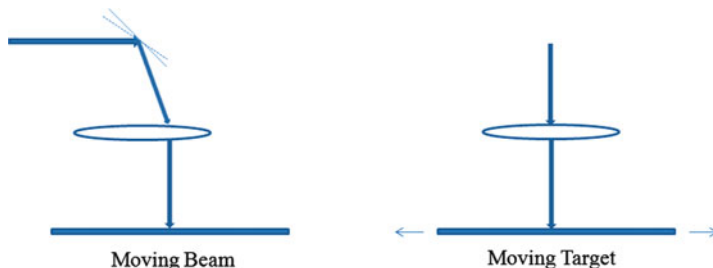
the early years of this century [27] and can now be purchased from several optics manufacturers in the USA and Europe.

These designs (Fig. 2.7) require careful alignment of the beam shaper with respect to the input beam, e.g., about 100 rad angular and  $<50\text{ }\mu\text{m}$  in linear misalignment, necessitating the use of lasers able to deliver a very stable input – these include fiber lasers and laser diode-pumped laser systems.

### 2.5.6 Holographic Optical Elements

Another way to shape a beam so as to give the user a far larger set of patterns to choose from is to use (or have fabricated) a HOE. As the name implies, these elements are computer designed for a particular laser wavelength and set of beam parameters, then holographically patterned. An advantage of a HOE over a beam shaper is the relatively small size; an HOE usually looks like a rather thin substrate with a characteristic spectrum of colors when a light source is viewed in reflection. A disadvantage (partially shared by the beam shaper) is the sensitivity to beam parameters and angle.

Having covered how to shape and transmit a laser's output to the target, we now turn to the final optics used to adjust the irradiance to the desired value. Since the irradiance through the transport must be low enough to not damage the transport optics, it is the final optics that have the task to bring the irradiance to the desired high value. The choice of the final optics is dictated by the geometry of the processing site. Two geometries are common, as shown in Fig. 2.8, either a moving beam or a moving target.



**Fig. 2.8** Two common laser processing target geometries

In the moving beam geometry, the f-theta lens is used. This optical system produces a focus at the target plane even though the angle of incidence of the beam is changing. In the case of the moving target, the lens system may be as simple as a planoconvex lens, or as complicated as the lenses used in UV lithography, which may number as many as 20 elements. These lenses are now augmented with a fluid placed between the lens and the target – the nonunity index of refraction effectively makes the wavelength shorter by 30–40%, thus creating a tighter focus.

### 2.5.7 *Laser Damage*

Since this text treats the latest aspects of laser material processing, it is given that lasers, used properly, will damage and ablate material. But what about those cases when apparently transparent media, the optical elements the beam traverses, suddenly fails? What are the causes? Since it was first observed in the 1960s, laser damage, the irreversible change in the optical properties (be they reflectance, transmission, etc.) has been studied, and over the years both measurements and models have advanced our understanding of the mechanisms that cause it. An annual conference devoted to the topic has been held in Boulder, Colorado, since 1969 and the proceedings of these conferences are available [29,30]. There is a good summary on the subject in [5]. The underlying mechanisms for laser damage depend on whether the source is pulsed or cw (or quasi-cw) and whether the duration of the pulse is less than about 10 ps or not. In general, laser damage occurs because either an absorbing defect raised its temperature above the melting point, or a flaw, be it a pit, scratch, embedded nodule of the coating or polishing material results in a local increase of the E-field intensity to the level that a few free electrons are accelerated to the point that they impact and free other electrons. The free electron population increases to a level that the region becomes absorbing enough to melt and/or vaporize the immediate defect and its surroundings. This is known as the electron avalanche process. Ultrashort pulses cause laser damage in a slightly different manner. The E-field is sufficiently high that multiphoton absorption occurs, promoting electrons to the conduction band so they are free to move and collisionally promote other electrons to

the conduction band. This impact ionization continues until the population is high enough that the material becomes absorbing and damages as the material vaporizes. Note the subtle difference—longer pulses require some free electrons, which may or may not be present at the location the laser strikes, whereas ultrashort pulses always make them. Consequently, while long pulse damage is stochastic in nature, ultrashort laser damage is deterministic. Moving from general comments about damage mechanisms to more specific comments on how to prevent damage, doing all that one can to minimize the introduction of contaminants on optical surfaces will raise the damage threshold of a given optical element. Handling should be done with gloved hands and speaking should be kept to a minimum (or, wear a face mask). If the surfaces are observed to be contaminated, one can attempt to remove the contaminant with “canned air” or with a solvent like isopropyl alcohol or acetone and lens tissue. A thorough discussion of cleaning techniques and their efficacy is in [31]. Depending on the irradiance (if the laser output is cw or quasi-cw) or fluence (if pulsed), surface quality is important. Surface quality is still generally defined by “scratch-dig” values, these have an advantage for the optics fabrication shop, but at best are semiquantitative. Generally, a scratch-dig value of 20-10 is sufficient for cw lasers, while 10-5 is necessary for ns pulsed lasers. Of course, in any optical transport system the optics will be coated, and one can increase the damage threshold by choosing the type of coating deposition technique that works best for the time structure of the laser system. For long-pulsed (>few ns duration), electron beam deposited films are best, for cw or quasi-cw lasers, ion beam deposited films perform better. Having touched on the “why” laser damage occurs, we turn now to the how to design an optical system that would not damage. Over time experimenters desired to have a standard for determining laser-induced damage thresholds (LIDT) values, the testing procedures are given in ISO 11254. A recent summary of current LIDT values was recently published [32], Tables 2.1 and 2.2 summarize the values presented in this paper.

LIDT values are different for other substrates. An excellent discussion and data are presented in [5].

**Table 2.1** CW laser-induced damage thresholds for high reflectors as a function of spot size and wavelength [31]

	30–50 μm	100 μm	>5 mm
0.55 μm	>1 MW/cm <sup>2</sup>	>500 kW/cm <sup>2</sup>	25 kW/cm <sup>2</sup>
1–2 μm	50–200 MW/cm <sup>2</sup>	10 MW/cm <sup>2</sup>	75 kW/cm <sup>2</sup>

**Table 2.2** Pulsed laser-induced damage thresholds for different coating applications as a function of pulse duration at 1,064 nm for IBS films on fused silica substrates [31]

	1 ps	10 ps	10 ns
AR	–	–	>18 J/cm <sup>2</sup>
Brewster angle polarizer	–	–	>20 J/cm <sup>2</sup>
HR	>2.5 J/cm <sup>2</sup>	>8.5 J/cm <sup>2</sup>	>20 J/cm <sup>2</sup>

### 2.5.8 Optical Modeling Software

Throughout this chapter, we have relied on relatively straightforward examples that are amenable to analytical solutions. For actual laser and transport system design, this is more often than not too simplistic or too tedious to contemplate. The coherence of laser sources is actually an asset when it comes to calculations, but also drives the designer to eschew the typical ray-tracing design packages, in favor of software designed for physical optics (see Sect. 2.6) which properly treat diffraction from the edges of optical elements or other physical apertures. Of the various software packages available, three that I typically use are Paraxia™ [33], GLAD™ [34], and OPC [35]. The first two software packages are commercial products while the last is offered for free, noncommercial use. Paraxia has the advantage of an easy, graphical interface, and the ability to “drop and drag” optical and free space elements into place. It does not have a way to incorporate gain regions. The other two software packages use scripting languages to construct the optical system, although one of my students has been developing a “user friendly” graphical front end to OPC, known as the Jefferson Lab Interactive Front End (JLIFE) which is under development [36]. GLAD, an acronym for General Laser Analysis and Design, has commands that incorporate atmospheric and optical aberrations, OPC, an acronym for Optical Propagation Code, both allow gain regions; the former can simulate the gain from solid state or gas lasers, the latter is particularly good at treating free-electron laser gain. For examples of the Paraxia or GLAD interfaces, consult the software creator’s websites shown in [33, 34].

## 2.6 Conclusions

In this chapter, I have attempted to acquaint the reader with both conventional and emerging laser sources. Fiber lasers and laser diodes create robust and easy-to-use sources in the near infrared, while FELs offer the opportunity to exploit material properties with power at wavelengths where conventional sources are not available. In the chapters that follow, the applications of lasers are discussed in more detail.

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