Field Guide to

Lasers

Rüdiger Paschotta

SPIE.

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Rüdiger Paschotta
RP Photonics Consulting GmbH

SPIE Field Guides
Volume FG12

John E. Greivenkamp, Series Editor

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Within the nearly five decades since the invention of the laser, a wide range of laser devices has been developed. The primary objectives of this *Field Guide* are to provide an overview of all essential lasers types and their key properties and to give an introduction into the most important physical and technological aspects of lasers. In addition to the basic principles, such as stimulated emission and the properties of optical resonators, this *Field Guide* discusses many practical issues, including the variety of important laser crystal properties, the impact of thermal effects on laser performance, the methods of wavelength tuning and pulse generation, and laser noise. Practitioners may also gain valuable insight from remarks on laser safety (emphasizing real-life issues rather than formal rules and classifications) and obtain new ideas about how to make the laser development process more efficient. Therefore, this *Field Guide* can be useful for researchers as well as engineers using or developing laser sources.

I am greatly indebted to my wife, who strongly supported the creation of this *Field Guide*, mainly by improving the majority of the figures.

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Zürich, Switzerland

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Glossary of Symbols

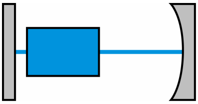
A	area (e.g., the cross section of a laser beam)
B	brightness (radiance) of a laser beam
c	velocity of light in a vacuum
E	electric field strength
E_{sat}	saturation energy (e.g., of a laser medium)
f	focal length (e.g., of a thermal lens)
f_{ro}	relaxation oscillation frequency
F_{p}	fluence (energy per area) of a pulse
F_{sat}	saturation fluence (e.g., of a laser medium)
g	gain coefficient
g_0	small-signal gain coefficient or initial gain
G	power amplification factor (= $\exp(g)$)
h	Planck's constant
I	optical intensity (power per unit area)
I_{sat}	saturation intensity (e.g., of a laser medium)
k	wave number (= $2\pi / \lambda$)
l	loss coefficient (e.g., for round-trip losses of a resonator)
L	length (e.g., of a laser medium)
M^2	beam quality factor
n	refractive index
N_2	number density of ions in energy level 2
NA	numerical aperture
P	optical power (e.g., of a laser beam)
r	radial position (= distance from beam axis)
R	radius of curvature (e.g., of wavefronts)
T_{rt}	round-trip time of a resonator
T_{oc}	output coupler transmission
w	beam radius
w_0	beam radius at the beam waist
z	position coordinate along a laser beam
z_{R}	Rayleigh length of a laser beam

α	linewidth enhancement factor
φ	optical phase or azimuthal angle
θ	divergence angle
κ	thermal conductivity
λ	wavelength
ν	optical frequency
$\Delta\nu$	optical bandwidth
σ_{abs}	absorption cross section
σ_{em}	emission cross section
τ_2	upper-state lifetime

Principle of a Laser

In order to understand the basic principle of a laser, it is instructive to first consider a passive resonator ("cavity"), such as an arrangement of mirrors that creates a closed path for a light beam. The simplest configuration is made with only two mirrors, one being flat and one being curved. Due to that curvature, a light beam with a suitable beam radius can circulate around the resonator without getting wider and wider each time. However, its optical power will decay, as some energy is lost in every resonator round trip.

A so-called **gain medium** can now be inserted that, when supplied with energy ("pumped") in some way, amplifies the light in each round trip. If the gain g is lower than the resonator losses l, the power decay is only slowed down. For $g = l$, the optical power stays constant; and for $g > l$, the power rises with each round trip. The latter condition can not be maintained forever; sooner or later, the high intracavity intensity will **saturate the gain**. In the steady state, as reached after some time, the gain will be exactly sufficient to compensate for the resonator losses. We then have **continuous-wave laser operation** with constant optical power and $g = l$.



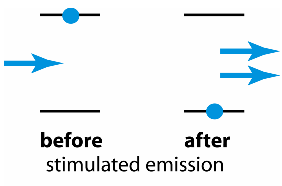
For extracting a laser beam as a useful output of the device, the left mirror, for example, acts as an **output coupler**, transmitting some percentage (say 10%) of the intracavity power. The output coupler transmission for optimum output power depends on the available gain and on other optical losses in the resonator.

As mentioned above, the gain medium needs to be pumped (i.e., supplied with energy). In most cases, a laser-gain medium is pumped either electrically (e.g., with an electric current through a semiconductor structure) or optically (e.g., with light at a typically shorter wavelength than the laser light being absorbed in the gain medium).

Spontaneous and Stimulated Emission

A laser gain medium contains some kind of laser-active atoms or ions, which have different energy levels (states), and a mechanism to put the atoms (or ions) into a certain excited state.

If an atom is in an excited state, it may spontaneously decay into a lower energy level after some time, releasing energy in the form of a photon, which is emitted in a random direction. This process is called **spontaneous emission**. It is also possible that the emission is stimulated by incoming photons, which is called **stimulated emission**. The emission then goes into the same direction as the incoming photon. In effect, the incoming radiation is amplified. This is the physical basis of light amplification in amplifiers and lasers.

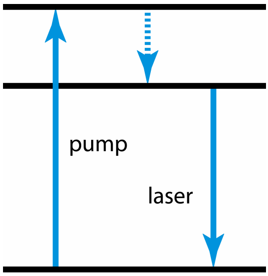


Of course, stimulated emission can only occur for incoming photons that have a photon energy close to the energy of the laser transition. Therefore, the laser gain occurs only for optical frequencies (or wavelengths) within a limited **gain bandwidth**. A laser normally operates at the optical wavelength where the gain medium provides the highest gain.

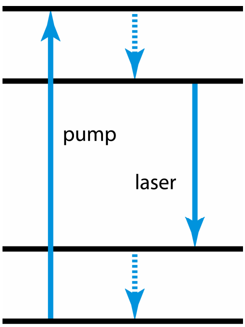
In an ensemble of atoms having only two energy levels (a ground state and an excited state), the excited atoms can amplify light, while those atoms in the ground state can absorb light, which brings them back to the excited state. Net amplification can then be achieved only when more than 50% of the atoms are in the excited state. This condition is called **population inversion**. Laser gain is more easily achieved when there is a mechanism that rapidly removes the atoms from the lower energy level after each emission event (e.g., by transfer into an even lower energy level).

Optical Pumping: Three- and Four-Level Systems

In a simple two-level system, it is not possible to obtain a population inversion with optical pumping because the system can absorb pump light (i.e., gain energy) only as long as population inversion, and thus light amplification, is not achieved. Essentially, the problem is stimulated emission caused by the pump light itself.



Inversion by optical pumping becomes possible when using a **three-level system**. Pump light with a shorter wavelength (higher photon energy) can transfer atoms from the ground state to the highest level. From there, spontaneous emission or a nonradiative process (e.g., involving phonons in a laser crystal) transfers atoms to an intermediate level, called the upper laser level. From that level down to the ground state, the laser transition with stimulated emission can occur. With sufficiently high pump intensity, population inversion for the laser transition can be reached as stimulated emission by the pump radiation is prevented by the transfer to the intermediate level. Also see p. 52 for **quasi-three-level gain media**.



Laser gain with a much lower excitation level is possible in a **four-level system**, such as Nd:YAG. Here, the lower level of the laser transition is somewhat above the ground state, and a rapid (most often nonradiative) transfer from there to the ground state keeps the population of the lower laser level very small. Therefore, a moderate population in the third level (the upper laser level), as achieved with a moderate pump intensity, is sufficient for laser amplification.

Cross Sections and Level Lifetimes

The rate of stimulated emission processes for an excited atom can be calculated as

$$R_{se} = \sigma_{em} \frac{I}{h\nu},$$

which is the product of the so-called **emission cross section** σ_{em} (with the dimension of an area) and the photon flux (the number of photons per unit area and time interval). I is the optical intensity, and $h\nu$ is the photon energy. Similarly, absorption cross sections describe the rates of absorption events. Cross sections are wavelength-dependent, and for ions in solid-state media they are significantly influenced by the surrounding medium.

The strength of *spontaneous* emission is governed by emission cross sections and the optical frequency and bandwidth of the radiative transitions.

All energy levels except the lowest state (ground state) of an atom have a finite lifetime because, sooner or later, there will be a transition to a lower level. If only spontaneous emission causes such transitions, the inverse lifetime is given by the Füchtbauer-Ladenburg equation,

$$\frac{1}{\tau_{rad}} = \frac{8\pi n^2}{c^2} \int \nu^2 \sigma_{em}(\nu)\, d\nu ,$$

where τ_{rad} is the so-called **radiative lifetime**, n is the refractive index, and ν is the optical frequency. The integral spans the optical frequencies of all transitions to lower levels.

Level lifetimes in solid-state media can be further reduced by nonradiative processes, such as multiphonon emission or energy transfer to other ions or crystal defects. For a laser medium, one ideally has a purely radiative **upper-state lifetime** combined with a much shorter lower-level lifetime.

Transition Bandwidths

Optical transitions all have a finite **bandwidth**, such as a finite range of frequencies or wavelengths where the corresponding cross sections are large. Different physical phenomena influence the transition bandwidth.

The term **homogeneous broadening** refers to cases where all involved atoms or ions have the same spectral width and position of the considered optical transition. In many cases, the transition linewidth is determined by the finite lifetime of involved energy levels. In the case of Stark level manifolds in solid-state media, the relevant lifetime can be that of a single sublevel of a manifold, which can be rather short if the interaction with crystal lattice phonons leads to fast transitions between different sublevels. This effect increases the linewidth of transitions in laser crystals by orders of magnitude above the linewidth that would be calculated from the lifetime of the whole Stark level manifolds.

Additional **inhomogeneous broadening** means that different atoms or ions differ in the spectral positions or widths of their optical transitions, so that the overall cross-section spectrum, which is a kind of average over many contributions, becomes broader. Inhomogeneous broadening occurs, for example, when laser-active ions can occupy different lattice positions in a laser crystal (e.g., in a disordered crystal), and similar effects occur in glasses. In a gas laser, atoms move with different velocities, so that inhomogeneous broadening results from the Doppler effect.

A certain transition is often called (in)homogeneously broadened when (in)homogeneous broadening is dominant. The type of broadening also affects the saturation characteristics (see p. 9) and thus the performance details of many laser systems.

Calculating Laser Gain

In the simplest case, we only have ions (or atoms) in the upper laser level with a number density N_2. We then obtain a **gain** coefficient of

$$g(\lambda) = N_2 \sigma_{\text{em}}(\lambda) L \,,$$

where L is the length of the medium. This translates into a power amplification factor of

$$G = \exp(g) = \exp\left[N_2 \sigma_{\text{em}}(\lambda) L\right]$$

for the incident light.

If there is also absorption from the lower laser level with a population density N_1, for example, we must take this into account and obtain

$$g(\lambda) = \left[N_2 \sigma_{\text{em}}(\lambda) - N_1 \sigma_{\text{abs}}(\lambda)\right] L \,.$$

If the population densities are varying with the position z along the beam, we have to integrate

$$g(\lambda) = \int \left[N_2(z) \sigma_{\text{em}}(\lambda) - N_1(z) \sigma_{\text{abs}}(\lambda)\right] \mathrm{d}z \,.$$

The z-dependent population densities can be calculated with coupled rate equations (i.e., with differential equations for the temporal evolution). Alternatively, the steady-state population densities as calculated from the local optical intensities of pump and laser radiations can be used. These intensities themselves then depend on population densities, as those determine the gain or absorption. Numerical models can handle such issues. They are particularly complicated when transverse dimensions are also of interest.

Fortunately, simpler models can be used in many cases. For example, the transverse dimension can often be neglected so that the overall gain or absorption in a laser crystal depends only on the spatially integrated population densities, not on their detailed distribution. Also, it is often sufficient to calculate steady-state values, not considering the dynamical aspects.

Gain Saturation

Stimulated emission not only amplifies light, it also removes laser-active ions from the upper state. Even if the gain medium is constantly pumped, a high rate of stimulated emission (resulting from a large amplified intensity) will reduce the population of the upper laser level and therefore "saturate" (reduce) the laser gain.

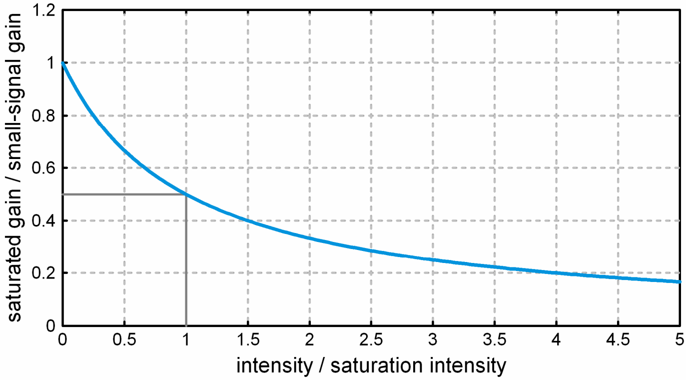
In many cases, the **steady-state** value of the gain is of interest. Rate equations for an optically pumped gain medium, combined with a few (often valid) assumptions, lead to the simple equation

$$g(I_p, I_L) = \frac{g_0(I_p)}{1 + I_L / I_{L,sat}},$$

where I_p and I_L are the pump and laser intensity, respectively, g_0 is the so-called small-signal gain (achieved for $I_L = 0$), and $I_{L,sat}$ is the **saturation intensity** according to

$$I_{L,sat} = \frac{h\nu_L}{\sigma_{em}\tau_2},$$

where $h\nu_L$ is the photon energy of the amplified laser light, σ_{em} is the emission cross section, and τ_2 is the upper-state lifetime.



Gain Saturation (cont.)

If the intensity of the laser light equals the saturation intensity, the gain is reduced to one-half the small-signal gain. The latter depends on the pump power applied to the gain medium. This dependence may or may not be linear, depending on the circumstances. When constant pump and signal power is applied, the gain usually requires a few times the upper-state lifetime until it reaches the steady-state value as given by the formula.

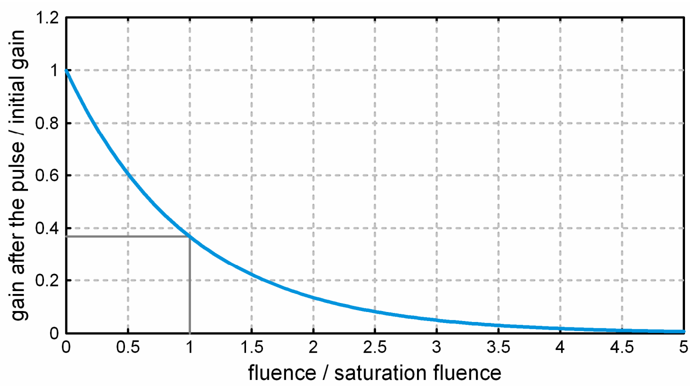
Another important case is that of a **short laser pulse** with the fluence (energy per unit area) F_p. After amplification of that pulse, the gain is reduced from an initial value g_0 to

$$g_{\text{end}} = g_0 \exp\left(-\frac{F_p}{F_{\text{L,sat}}}\right)$$

with the **saturation fluence**

$$F_{\text{L,sat}} = \frac{h\nu_L}{\sigma_{\text{em}}} .$$

The upper-state lifetime does not occur here because the pulse duration is assumed to be much shorter than the upper-state lifetime, so that spontaneous emission within that time is not relevant.

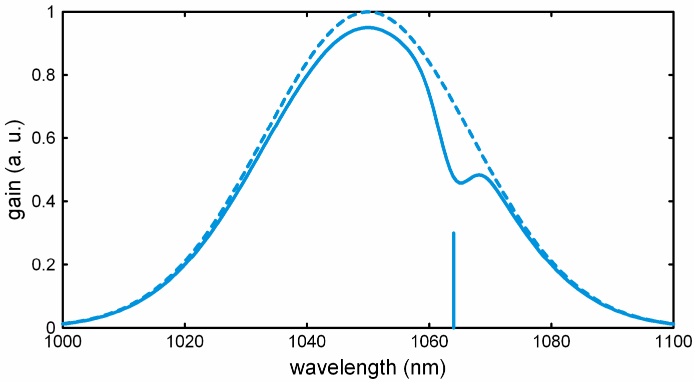


Inhomogeneous saturation (see the following page) leads to a more complicated situation.

Homogeneous vs. Inhomogeneous Saturation

If all laser-active ions (or atoms) have the same emission spectra, and absorption (e.g., in a quasi-three-level medium, see p. 52) can be neglected, gain saturation will simply reduce the magnitude of the gain but not affect its spectral shape. This **homogeneous gain saturation** occurs, for example, in laser crystals where all laser-active ions occupy equivalent positions of the crystal lattice.

Inhomogeneous saturation can occur when different ions have different emission spectra (e.g., as a result of different lattice positions in a solid medium) or different particle velocities in a gas. In that case, a narrow-band laser beam may primarily saturate those ions (or atoms) that emit most strongly at the given wavelength. As a result, the balance of different contributions to the gain, and thus the gain spectrum, is modified. The figure below illustrates this effect for a narrow-band laser beam at 1064 nm: The gain is most strongly reduced for wavelengths around that of the saturating beam.

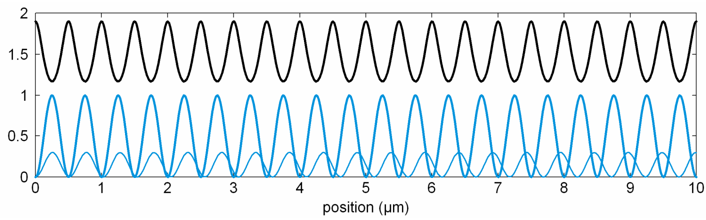


Obviously, saturation effects are significantly more complicated to calculate in the case of inhomogeneous saturation. They can have a significant impact on the operation of wavelength-tunable and single-frequency lasers.

Spatial Hole Burning

In many lasers, particularly those with linear resonators, the gain medium is subject to counterpropagating laser beams, which form a so-called "standing wave" via interference, leading to strong, location-dependent laser intensity. This has essentially two effects:

- Gain saturation is stronger at locations with higher laser intensities, leading to a spatial pattern of excitation density. This effect is called **spatial hole burning**.
- The excitation density in regions with higher optical intensity is more important for the resulting laser gain.

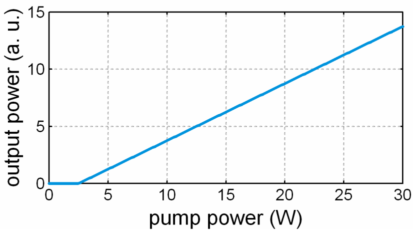


The figure shows how the intensity of a single-frequency laser beam saturates the laser gain (black curve). The reduction of gain for that beam itself is stronger than that for a second beam with a lower intensity and a slightly different wavelength: the antinodes of the latter beam do not fully overlap with the strongly saturated regions of the gain medium. Effectively, we have a kind of inhomogeneous saturation (see p. 9).

The possible consequences on laser operation are manifold. Single-frequency operation becomes more difficult to achieve because the lasing mode experiences more gain saturation than any weak competing modes. The laser efficiency can be reduced if the excitation in the field nodes (dark regions) can not be utilized. Spatial hole burning also has consequences for wavelength tuning and for ultrashort pulse generation with mode locking.

Threshold and Slope Efficiency

Laser operation requires an optical gain that at least compensates for the optical losses in the laser resonator. For a pump power that is too low, this is not achieved; the laser is said to be below **threshold**. It then emits only some amplified fluorescence, which is normally much weaker than the regular laser emission for pumping above the **threshold pump power**.



Above the laser threshold, the output power often increases linearly with the pump power, assuming optical pumping. The slope of the curve for output versus input power is called **slope efficiency**. The figure shows a case with a threshold power of 2.5 W and a slope efficiency of 50%.

Both threshold pump power and slope efficiency of an optically pumped laser can be defined with respect to either incident or absorbed pump power.

A lower output coupler transmission leads to lower threshold pump power, but this can also reduce the slope efficiency because a larger fraction of the circulating power may be lost via parasitic losses. The value of the output coupler transmission for optimum output power depends on the pump power. Most lasers are designed so that the pump power is several times that of the threshold pump power.

Low threshold pump powers can be achieved by keeping the resonator losses small, by using an efficient gain medium with a large product of emission cross section and upper-state lifetime (σ-τ product), by using a resonator with a small mode area, and by pumping only the region of the resonator mode within the gain medium.

Threshold and Slope Efficiency (cont.)

For example, the threshold pump power of a simple, optically pumped ring laser (see p. 56) can be calculated, assuming a four-level gain medium (e.g., a Nd:YAG crystal) with length L, a top-hat mode profile with area A in the crystal, and total round-trip resonator losses l. At threshold, we have $g = l$, thus

$$N_2 \sigma_{em} L = l \, ,$$

with the average density N_2 of excited laser-active ions in the crystal (within the mode volume), and the emission cross section σ_{em} at the laser wavelength. This degree of excitation causes the emission of fluorescence with the total power of

$$P_{fl} = \frac{N_2 A L \, h\nu_L}{\tau_2} \, ,$$

where $h\nu_L$ is the laser photon energy, and τ_2 is the upper-state lifetime. To compensate for that loss of energy, we need an absorbed pump power of

$$P_{p,abs} = \frac{N_2 A L \, h\nu_p}{\tau_2}$$

at threshold and a somewhat higher incident pump power for incomplete pump absorption. (Note also that some of the pump light may be absorbed outside the mode volume, where it is useless.) Using the first equation to substitute N_2, we obtain

$$P_{p,abs} = \frac{A \, l \, h\nu_p}{\sigma_{em} \tau_2} \, ,$$

which shows that for low-threshold pump power a resonator with a small mode area and low round-trip losses is needed in addition to a gain medium with a high σ-τ product.

In simple cases, the slope efficiency can be calculated as a product of various factors, such as the pump absorption efficiency (for a slope efficiency with respect to *incident* pump power), the quantum efficiency, the ratio of pump and laser wavelength, and the output coupling efficiency (the fraction of generated photons that is extracted via the output coupler rather than lost via parasitic losses).

Power Efficiency

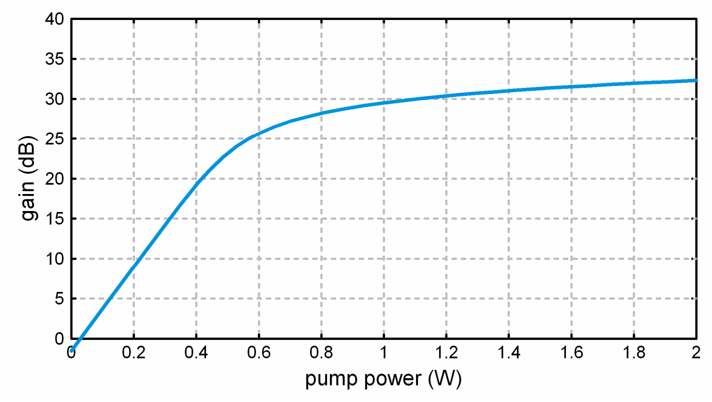
Various issues are important for achieving a **high power conversion efficiency**, particularly for optically pumped solid-state lasers:

- The gain medium should be long enough and sufficiently doped for efficient absorption of pump light.
- For (quasi-)three-level gain media (see p. 3 and p. 52), the length must also not be too long, even if this somewhat compromises the pump absorption. Otherwise, reabsorption effects become too strong.
- The threshold pump power should be kept low by minimizing the resonator losses. Also, the resonator losses should be dominated by the output coupler transmission (high output coupling efficiency), so that most of the generated photons are transferred into the output beam rather than lost through parasitic losses. The latter should be minimized, for example, by using high-quality mirrors (with high reflectivity) and materials with low scattering and absorption losses, and by minimizing the number of optical surfaces.
- The resonator should have modes with suitable effecttive areas, and pumping should only occur within the volume of the resonator mode(s).
- The gain medium should not exhibit detrimental processes, such as parasitic absorption (including excited-state absorption) or quenching of the upper-state population via unwanted cross-relaxation or upconversion. It should also have a small quantum defect (i.e., a high ratio of laser and pump radiation photon energies).

This shows that optimizing the power efficiency requires a balance of many factors, sometimes involving subtle trade-offs.

Amplified Spontaneous Emission

Even for pump powers below the laser threshold, a laser emits some light, usually at a low power level. This light originates from spontaneous emission in the gain medium and is further amplified. While this **amplified spontaneous emission** (ASE) can be very weak in lasers with small resonator losses, it often limits the achievable gain in a laser amplifier because it extracts a significant amount of power as soon as the gain reaches a level of several tens of decibels. The figure below shows this effect for a fiber amplifier, where ASE saturates the gain for pump powers above ≈0.6 W.



While fluorescence goes in all spatial directions, ASE can be strongly directional for gain media with a large aspect ratio (e.g., fibers or long laser rods), providing a longer path with amplification for some spatial direction.

Amplified spontaneous emission is not always unwanted. It can be used in cases where a broad and smooth optical spectrum, combined with significant output power and high spatial coherence, is required (e.g., for optical coherence tomography, gyroscopes, and some fiber-optic sensors). Such ASE sources (also called **superluminescent sources**) are essentially lasers (often laser diodes) where the optical feedback from resonator mirrors has been removed.

Characteristics of Laser Light

Laser light has a number of special properties:

- Lasers normally emit light in the form of laser beams. Their high degree of **spatial coherence** (the phase relationship over the whole beam profile) allows for a small beam divergence of a moderately sized beam (a high directionality), and also makes it possible to focus laser radiation on very small spots.

- In many cases, laser light also exhibits a high degree of **temporal coherence** (see p. 16), which means a long **coherence length** and a narrow optical spectrum (quasi-monochromatic emission). Some carefully stabilized lasers can emit monochromatic light with an extremely well-defined optical frequency. In extreme cases, the optical bandwidth is less than 10^{-15} times the optical mean frequency.

- Most lasers emit **infrared** (invisible) **light**, while only a few can emit visible or even ultraviolet light. However, methods of nonlinear frequency conversion can be used to generate other wavelengths (see p. 110-115).

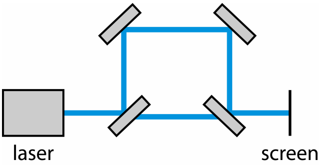
- In most cases, laser radiation is **linearly polarized**; for example, the electric field oscillates only in one direction, which is perpendicular to the laser beam.

An additional interesting feature is that some lasers can emit light in the form of short pulses, with pulse durations of nanoseconds, picoseconds, or even down to a few femtoseconds. Even moderate pulse energies (e.g., a few millijoules) lead to enormous peak powers when combined with ultrashort pulse durations.

Some of these characteristics, in particular the possible high optical intensities, can make laser light quite hazardous (see p. 121). Diligent laser safety measures are then required, particularly for avoiding eye injuries.

Temporal Coherence of Laser Radiation

Perfectly monochromatic emission of a laser would imply that the electric field's phase evolution is predictable over arbitrarily long times. Any real oscillator, however, is subject to noise that makes the oscillation phase drift away with time. A measure for the degree of **temporal coherence** is the **coherence time** τ_c, which is the length of time over which the phase coherence is significantly degraded. In simple cases with exponential decay of the coherence function, the **optical bandwidth** (or **linewidth**) is $\Delta\nu = 1 / (\pi\, \tau_c)$.



The **coherence length** is another measure for temporal (not spatial) coherence. It is simply the coherence time multiplied with the velocity of light. It determines how large, for example, the path length difference in an interferometer can be until interference effects fade away. (In the figure to the right, the path length difference is the sum of the vertical distances.)

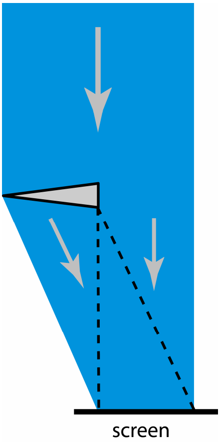
Interferometry often requires a long coherence length. On the other hand, high temporal coherence can be a nuisance when, for example, taking images with a camera; even weak reflections (e.g., from the surfaces of a cover glass), which would have no noticeable effect with sunlight, can then cause disturbing interference patterns. Similarly, laser projection displays can suffer from speckle effects on the screen.

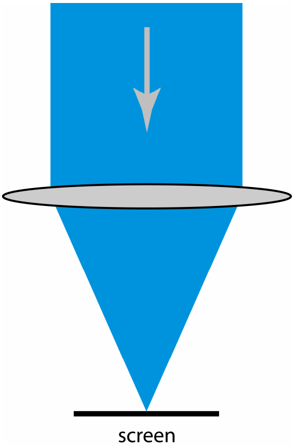
A laser operating on a single resonator mode (see p. 23) can easily have a coherence time of, for example, 1 ms, which may seem small, but it corresponds to a coherence length of 300 km and to hundreds of billions of oscillation cycles. Correspondingly, the optical frequency or wavelength is then precise to a very tiny fraction of its mean value.

Spatial Coherence

Spatial coherence is a fixed phase relationship between electric fields at different locations. For example, the electric fields at different positions within a spatially coherent laser beam oscillate in a totally correlated way, even if the temporal coherence is poor. On the other hand, different points on the filament of an incandescent bulb emit without any correlation.

As an example, consider an interference experiment (like in the figure), where a prism is inserted into a spatially coherent laser beam. On the screen, the overlapping portions of the beam generate an interference pattern. This effect would not occur without a strong correlation of electric field oscillations on both sides of the incoming beam.





A high degree of spatial coherence is also the essential prerequisite of the strong **directionality of laser beams** and of their ability to be **focused** to very small spots. A tight focus results from constructive inter-ference from every amplitude contribution at this point and destructive interference any-where else on the screen. If the wavefronts are randomly scrambled (e.g., by sending a laser beam through a milky glass), a strongly divergent beam is obtained, which cannot be properly focused.

Gaussian Beams

Lasers often generate so-called **Gaussian beams**, where the transverse profile of the beam's electric field distribution can be described with a Gaussian function:

$$E(r,z) \propto \exp\left(-\frac{r^2}{w(z)^2}\right)\exp\left[i\varphi(z,r)\right].$$

Here, r is the distance from the beam axis, z is the coordinate along the propagation direction, $w(z)$ is the so-called Gaussian beam radius, and $\varphi(z,r)$ is a term describing the phase evolution along the beam as well as the curvature of the wavefronts:

$$\varphi(z,r) = kz - \arctan\frac{z}{z_R} + \frac{kr^2}{2R(z)}.$$

Here, $k = 2\pi / \lambda$ is the wave number, $R(z)$ is the curvature of the wavefronts, and

$$z_R = \frac{\pi w_0^2}{\lambda}$$

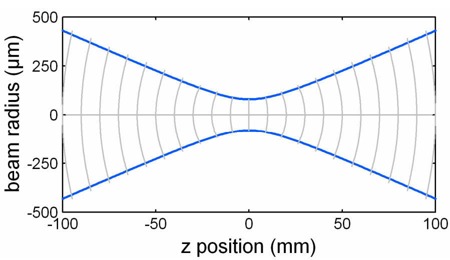
is the **Rayleigh length** (or Rayleigh range) calculated from the beam radius w_0 at the beam focus. The beam radius evolves according to

$$w(z) = w_0\sqrt{1+\left(\frac{z}{z_R}\right)^2}$$

and the curvature radius as

$$R(z) = z\left[1+\left(\frac{z_R}{z}\right)^2\right].$$

The figure shows the evolution of the beam radius around the focus and also the curvature of the wavefronts, which is weak near and very far from the beam focus.



Gaussian Beams (cont.)

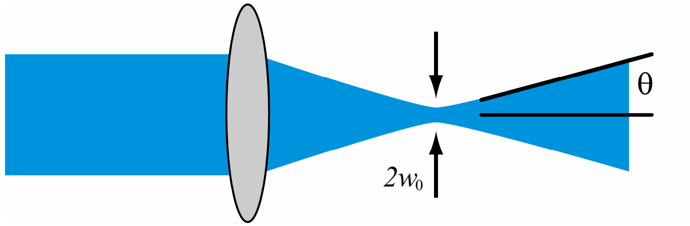
The beam intensity is

$$I(r,z) = \frac{P}{\pi w(z)^2/2} \exp\left[-2\frac{r^2}{w(z)^2}\right];$$

for $r = w$, it reaches ≈13.5% of its value on the axis.

For $z >> z_R$, the beam radius evolves in a nearly linear fashion, and the divergence angle is defined as

$$\theta = \frac{\partial w}{\partial z} = \frac{\lambda}{\pi w_0}.$$



The equation shows that the **beam parameter product** (BPP), defined as the product of beam waist radius w_0 and the divergence angle, is λ / π and thus independent of w_0. In fact, a Gaussian beam has the smallest possible (diffraction limited) BPP, which can be interpreted as the highest possible **beam quality** (see the next page).

During propagation in a homogenous medium, a Gaussian beam stays Gaussian, only its parameters (beam radius, wavefront curvature radius, etc.) change. The same holds for propagation through thin lenses or for reflection at weakly curved mirrors. These properties give Gaussian beams an important role in optics, including the physics of optical resonators. Even for distinctly non-Gaussian beams, there is a generalization of Gaussian beam propagation (involving the so-called M^2 factor) that can be widely used. However, Gaussian beam propagation breaks down for very strongly divergent beams (thus also for very tightly focused beams), as the analysis is based on the so-called **paraxial approximation**, which is then violated.

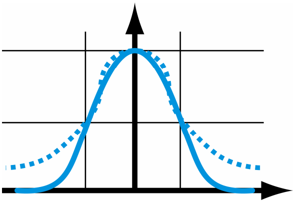
Laser Beam Quality

The **beam quality** of a laser beam determines how well it can be focused to a small spot or over which distance it can be sent with moderate beam divergence. Essentially, beam quality is a matter of spatial coherence.

As a quantitative measure for beam quality, the **BPP** can be used, which is the product of the **beam radius** (at the focus) and the beam divergence. The BPP is not changed when the beam is sent, for example, through a lens (without aberrations), so a focus of convenient size to measure the BPP of a beam may be generated.

Another common measure is the **M^2 factor**, defined as the BPP divided by the ideal BPP for the given wavelength. This means that the beam divergence is M^2 times larger than diffraction limited for the given beam waist size. A high beam quality means a low BPP and M^2 value; it allows focusing to a small spot without excessive beam divergence.

ISO standard 11146 defines in detail how the BPP and M^2 factor must be measured. One of several important factors is the definition of beam radius for non-Gaussian intensity profiles. The figure shows that the often-used full width at half maximum (FWHM) cannot be sensible because the two profiles shown have the same FWHM but clearly shouldn't be considered as having equal width. Instead, the definition



$$w_x \equiv 2\sqrt{\frac{\int x^2 I(x,y)\,\mathrm{d}x\,\mathrm{d}y}{\int I(x,y)\,\mathrm{d}x\,\mathrm{d}y}}$$

is used, for example, for the x direction, based on the intensity profile $I(x,y)$. For a Gaussian beam, this results simply in the Gaussian beam radius w.

Brightness or Radiance of Laser Beams

A laser beam's **radiance** or **brightness** is its optical power divided by the product of the mode area in the focus and the solid angle in the far-field, with units of watts per square centimeter and steradian ($W / cm^2\ sr$):

$$B = \frac{P}{\pi w_0^2\ \pi\theta^2},$$

with the beam radius w_0 in the focus and the divergence angle θ. It is proportional to the inverse square of the beam parameter product (or M^2 factor). The brightness is a measure for the intensity that can be produced in a beam focus with a limited beam divergence.

For a Gaussian beam, the brightness is the optical power divided by the square of the wavelength.

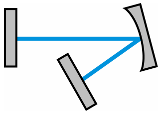
Some high-power lasers have a rather low beam quality and thus only a moderate brightness. For example, laser diode stacks can produce kilowatt powers but have a much lower brightness than a diffraction-limited 100-mW laser. Some lasers (e.g., some solid-state bulk lasers and fiber lasers) generate an output with a much higher brightness than their pump source; they are then sometimes called **brightness converters**. The design of a laser often becomes more difficult when the available pump brightness is low or when the output brightness must be high.

The term brightness is more common in laser technology, although radiance would actually be more appropriate in the context of the terminology of photometry; strictly speaking, brightness should be used only for non-quantitative quantities related to subjective perception.

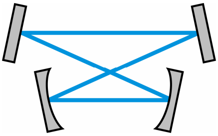
Basic Structure of an Optical Resonator

An **optical resonator**, often also called an optical **cavity**, is an arrangement that allows a beam of light to circulate in a closed path. The two basic types of optical resonators are

- Standing-wave (or linear) resonators, where the light bounces back and forth between two end mirrors (although additional folding mirrors can be used); and

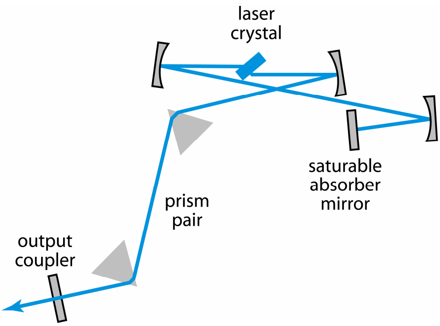


- Ring resonators (e.g., with a bow-tie shape as shown here), where the light can circulate in two different directions.



Laser resonators and other optical resonators are usually formed with some kind of **laser mirrors**, which are in most cases dielectric mirrors. Some mirrors may be partially transmissive, coupling light into or out of the resonator. A resonator may contain additional optical elements, such as a laser crystal, an optical modulator, or a nonlinear device. Some resonators are monolithic, consisting of, for example, a single crystal with total internal reflection at all or most surfaces (see p. 63), or a spherical piece of glass, or a microtorus.

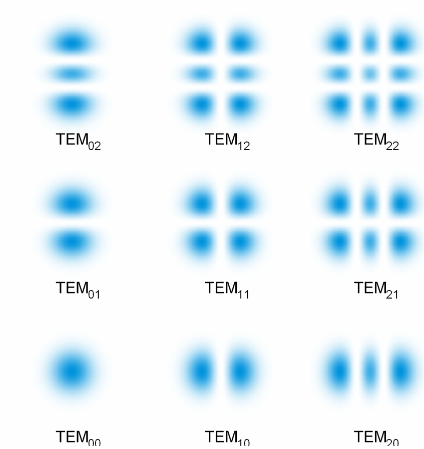
The figure to the right shows a more complicated laser resonator, as used for a mode-locked laser, containing a prism pair for dispersion compensation.



Resonator Modes

Resonator modes are electric field distributions that maintain their complex amplitude distribution after a complete resonator round trip, apart from a possible loss of optical power.

For example, consider the simple linear resonator shown on the right. If the right mirror's radius of curvature is larger than the distance to the flat left mirror, this resonator is stable, and the simplest resonator mode corresponds to a Gaussian beam with a focus on the left mirror, where the beam radius of the focus is such that the wavefront curvature on the right side exactly matches that of the mirror. (Unstable resonators are discussed on p. 27)

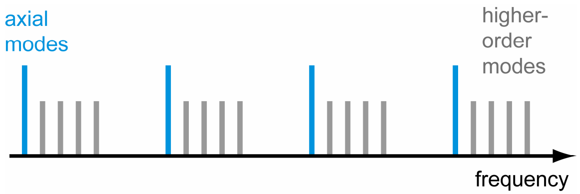


In addition, a stable resonator has so-called **higher-order transverse modes** with more structured intensity distributions. In simple cases (without intracavity aberrations), we have Hermite-Gaussian modes, where the electric field strength is proportional to the product of a Gaussian function and a Hermite polynomial. The lowest-order function of that type is Gaussian, while the intensity profiles of the higher-order modes are more complicated patterns (see the figure).

Resonance Frequencies

So far, the requirement for a mode to maintain the shape of its amplitude distribution after a resonator round trip has only been addressed. In addition, the acquired optical phase shift has to be an integer multiple of 2π, so that the field after one round trip oscillates in phase with the original field. This condition is fulfilled for certain optical frequencies—the **resonance frequencies**.

Addressing the fundamental (Gaussian) modes first, the resonance frequencies of these are approximately equidistant, with a spacing (called **free spectral range**) equal to the inverse round-trip time. (A slight departure from equidistance results from chromatic dispersion.) Any other type of mode, such as TEM_{32}, has resonance frequencies with the same spacing but some offset relative to those of the fundamental modes. This offset results from the Gouy phase shift.



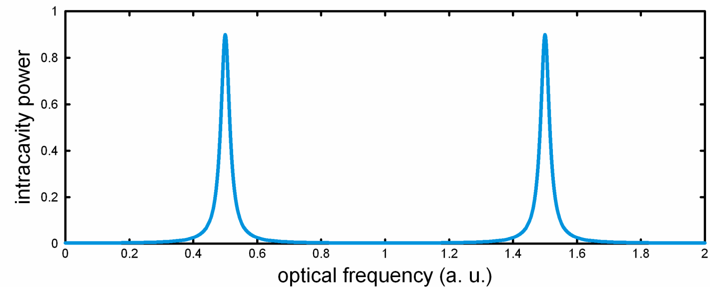
For TEM modes, the mode frequencies can be calculated as

$$\nu_{nmq} = \nu_0 + q\,\Delta\nu + (n+m)\,\delta\nu\ ,$$

where q is the axial mode index, $\Delta\nu$ is the free spectral range, and $\delta\nu$ is the transverse mode spacing. The latter is proportional to the Gouy phase shift per round trip. The figure above shows the axial modes with spacing $\Delta\nu$ and four low-order modes with spacing $\delta\nu$.

Bandwidth and Finesse of a Resonator

A resonance of an optical resonator can be excited, for example, by injecting light from outside onto a partially transmissive mirror of the resonator. Resonant enhancement is possible if (a) the incident light has good spatial overlap with a resonator mode, and (b) the frequency of incident light approximately matches a mode frequency.



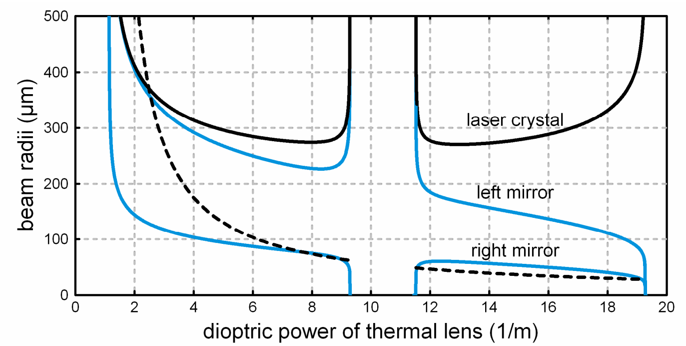
The figure shows the power in a resonator when the optical frequency is scanned through two subsequent axial resonances, and the profile of the input beam matches that of the fundamental modes. The full width at half maximum of such resonances is called the resonator **bandwidth**. It is proportional to the corresponding mode's rate of power losses (without incident light). A small bandwidth can result from low losses per round trip and/or from a long resonator length, such as long round-trip time.

The **finesse** of a resonator is the axial mode spacing divided by the resonance bandwidth. The finesse is determined only by the power losses per round trip. (In confocal Fabry-Pérot resonators, multiple modes can be involved in the resonances, and the overall resonance width can then also depend on the alignment.)

The bandwidth of a laser resonator (measured with the pump source turned off) is important for laser noise but also, for example, in the context of injection locking.

Stability Zones of a Resonator

When a resonator parameter such as the focusing power of a lens or some resonator arm length is varied, the resonator may go through one (for ring resonators) or two (for linear resonators) **stability zones**. Within these stability zones, the mode radii at all locations in the resonator change.



For example, the figure shows the fundamental mode radii at the two end mirrors and in the laser crystal of a laser resonator as functions of the dioptric power of the **thermal lens** (see p. 57) in the crystal. At the edges of the stability regions, these mode radii either go toward zero or diverge. The width of the stability zones in terms of focusing power is always inversely proportional to the minimum mode area in the crystal. The alignment sensitivity (dashed curve) is more critical in one of the stability zones (in this case, in the left one), where it diverges at one stability edge.

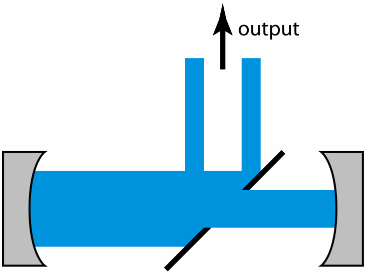
The whole diagram will change, for example, if any arm length or mirror curvature of the resonator is changed. The stability zones can move and change their widths according to changes of the minimum mode size in the crystal.

In resonators with noncircular beams, there is one such diagram for each transverse direction. The stability zones for both directions may or may not overlap.

Unstable Resonators

Most lasers have a stable resonator. In a purely geometrical analysis, stability means that a ray injected into the optical system will stay at a finite distance from the axis even after many round trips, while instability implies that a ray would sooner or later leave the resonator in the transverse direction. Although in the latter case the resonator modes have a much more complicated structure than for a stable resonator (essentially because they reach out to the edges of some resonator mirrors), **unstable resonators** are utilized in some high-power lasers, particularly those with high laser gain.

A common type of unstable resonator consists of two mirrors, where a significant part of the radiation escapes outside the edges of the smaller mirrors (see the figure above). Although the output beam has an annular shape in the near field, the beam quality can (under certain circumstances) be better than achievable with a stable resonator.



Another type of resonator uses a **scraper mirror** that sends some of the circulating light to the output. Variations of that scheme are applied to certain slab lasers, where the scraping is done on one side only.

There are also unstable resonators containing a partially transmissive output coupler mirror with a transverse variation of reflectivity (e.g., a Gaussian reflectivity mirror).

Resonator Design

The **design of a resonator**, such as the **laser resonator** of a solid-state bulk laser, strongly influences many properties of the laser, such as the threshold power and efficiency, beam quality, sensitivity to changes of the thermal lens or misalignment, etc., apart from the compactness and required parts. Therefore, resonator design is a very important part of laser development (see p. 126).

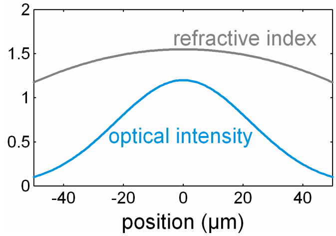
While a so-called **ABCD matrix algorithm** can be used to calculate the mode properties (e.g., beam radii in optical components) of a given design and (with some mathematical extension) the alignment sensitivity as well, the difficult task is to find a resonator design possessing the targeted properties. These usually have a complicated dependence on inputs like resonator arm lengths and mirror curvatures.

Good resonator designs require a combination of physical understanding, practical experience, and flexible software. A powerful numerical method for resonator design is to define a **figure of merit** (FOM), calculated as the sum of "penalties" for all nonideal properties, and to minimize that FOM with numerical techniques by varying resonator arm lengths and possibly mirror curvatures. Because the FOM often has a huge number of local extrema, a Monte Carlo method is often required to find the global optimum or at least a good solution. Note that the procedure starts with some basic resonator structure, which may have to be varied as long as no good solution is found. Such a numerical strategy may often lead to designs that cannot be fully "understood" but have a performance close to the absolute optimum.

Particularly challenging resonator design tasks arise in the context of Q-switched, mode-locked, and intracavity frequency-doubled lasers that require combinations of various mode sizes, cavity length constraints, and other complications. Also, resonators with large mode volumes involve difficult trade-offs.

Principle of Waveguiding

When propagating in an optically homogeneous medium, a laser beam will sooner or later start to diverge. This can be interpreted as the phenomenon of diffraction, which is common to all kinds of waves. The divergence is accompanied by a curvature of the wavefronts.



A constant beam radius can be obtained for arbitrarily long propagation distances if the effect of diffraction is balanced (e.g., by an optically inhomogeneous structure). A simple case is that of a medium with a radially decreasing refractive index, as shown in the figure. The beam then experiences a focusing effect, which can exactly balance diffraction for certain beam profiles. The wavefronts then stay planar everywhere.

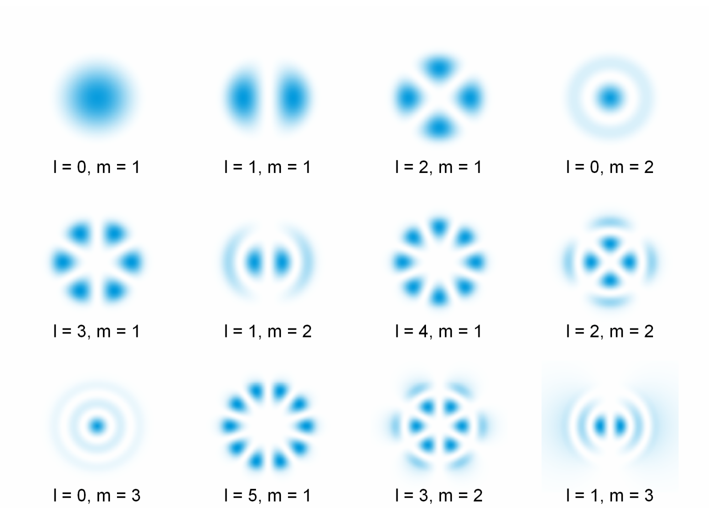
Waveguiding may occur in two dimensions (e.g., in an optical fiber), or in one direction only, with free (unguided) propagation in the other direction. The latter occurs, for example, in a planar waveguide structure in the form of a thin film with an increased refractive index on some crystal or glass material (see p. 32).

To some limited extent, waveguiding may also be understood by considering the passes of light rays experiencing total internal reflection. However, this picture is not precise and totally breaks down for small waveguide dimensions.

There are **waveguide lasers**, where the light circulating in the laser resonator is at least partially propagating in a waveguide structure. Fiber lasers and most diode lasers constitute important examples for waveguide lasers. Also, laser light can be transported from the light source to some application, using a waveguide. In most cases, optical fibers are used for that purpose.

Waveguide Modes

Waveguides have certain optical field distributions that stay constant during propagation, except for a change in the overall phase and possibly the optical power. Such field distributions, which depend on the refractive index profile, correspond to so-called **waveguide modes**. For a given optical frequency, a waveguide may support multiple modes, a single mode, or no mode at all.

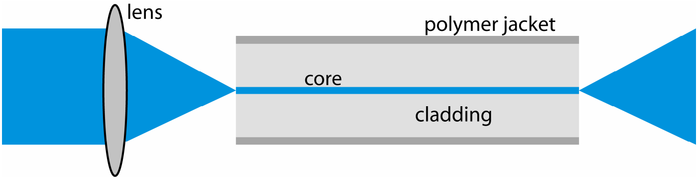


The figure shows the intensity profiles for every mode of an optical fiber (for a given design and wavelength). The lowest-order mode has a nearly Gaussian intensity profile, while the profiles of higher-order modes are more complicated. Generally, the number of waveguide modes increases with decreasing wavelength.

Each mode has a certain **propagation constant** β, specifying the phase change per unit length. The lowest-order mode has the smallest β value. If a superposition of modes is excited, the total intensity profile will vary during propagation, since (in general) the different β values of different modes lead to varying relative optical phases.

Optical Fibers

Optical fibers constitute a particularly important type of waveguide. The most common type is the glass fiber, which has a **fiber core** with a slightly increased refractive index surrounded by the **cladding** and usually a polymer jacket.



When light is properly injected into the fiber core, it propagates along the fiber core (even if the fiber is somewhat bent) until it leaves the fiber at the other end.

Fibers can transport light as well as manipulate it in various ways:

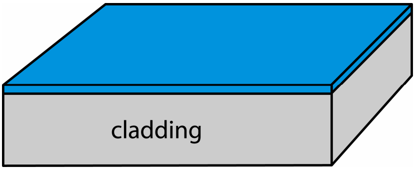
- By using a **single-mode fiber** (supporting only one fiber mode per polarization direction), a stable output beam profile is ensured, independent of the detailed launching conditions. However, efficient launching requires good input beam quality and precise alignment.

- When a fiber is doped with some rare-earth ions (e.g., Er^{3+}, Yb^{3+}, or Nd^{3+}), it can be used to amplify light within a **fiber laser** or **fiber amplifier** if additional pump light is injected.

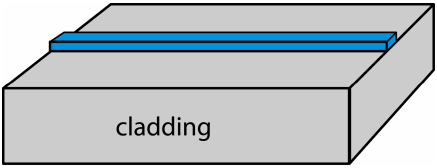
- Optical nonlinearities and chromatic dispersion in the fiber can give rise to a wide range of phenomena, such as Raman amplification, four-wave mixing, spectral or temporal pulse broadening or compression, super-continuum generation, soliton pulse formation and break-up, etc.

Planar and Channel Waveguides

When a thin layer with a slightly increased refractive index is fabricated on top of some crystal or glass, it functions as a **planar waveguide**. Light injected into the waveguide layer with a small enough divergence will be guided perpendicular to the layer and unguided in the other direction. The waveguide layer may also be embedded between two cladding layers.



A **channel waveguide** (with guidance in both directions) has a guiding structure in the form of a stripe with a finite width. This may be a ridge on top of the cladding structure or an embedded channel. The latter has more symmetric waveguide modes.



Channel waveguides are extensively used, for example, within various laser diodes (LDs; see p. 35-39). Small, low-power LDs have a single-mode channel waveguide with transverse dimensions of, for example, 1 µm. Broad-area LDs have a wider channel that supports multiple modes in the horizontal direction. Diode bars (diode arrays) contain an array of broad-stripe diode structures.

Larger channel and planar waveguides made from rare-earth doped dielectric materials are used for high-power **waveguide lasers** and amplifiers (see p. 76). Pump light may be injected along the amplified beam, from the side, or from the top. Even in situations with strong heating, the waveguide may help to stabilize a single-mode laser beam with high beam quality.

Semiconductor Lasers

Semiconductor lasers utilize a semiconductor as the gain medium. Most of them are electrically pumped **laser diodes**, where electron-hole pairs are generated by an electrical current in a region where n-doped and p-doped semiconductor materials meet. However, there are also optically pumped semiconductor lasers, where carriers are generated by absorbed pump light.

Laser devices are fabricated on polished semiconductor wafers with lithographic techniques. Common semiconductor materials for the active regions are GaAs, AlGaAs, GaP, InGaP, GaN, InGaAs, InP, and GaInP. These are all **direct bandgap** materials, because indirect bandgap materials, such as silicon, do not exhibit significant light emission.

Although semiconductor lasers occur in a great variety of forms, some typical aspects of importance include:

- **Electrical pumping** with moderate voltages and high efficiency is possible particularly for high-power diode lasers and allows for their use as, for example, pump sources for highly efficient solid-state lasers.

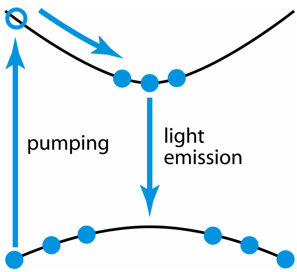
- A **wide range of wavelengths** is accessible with different devices, covering much of the visible, near-infrared, and midinfrared spectral region. Some devices also allow for wavelength tuning.

- Small laser diodes allow **fast switching** and **optical power modulation**, allowing their use, for example, in optical data link transmitters.

Such characteristics make semiconductor lasers the most important type of lasers, technologically speaking. Their applications are extremely widespread and include optical telecommunications, optical data storage, metrology, spectroscopy, material processing, pumping of other lasers, and medical treatments.

Light Amplification in Semiconductors

Light emission in semiconductors is usually associated with electronic transitions from the conduction band to the valence band. Optical amplification via stimulated emission is possible for a sufficiently high carrier density in the conduction band. In this situation, electrons near the bottom of the **conduction band** make transitions to the highest (and depleted) energy levels of the **valence band**, which can also be described as recombination with holes in the valence band. The photon energy is at or somewhat above the bandgap energy, and this determines the emission wavelength. Optical pumping is possible at a somewhat shorter wavelength and involves the fast relaxation of carriers in both bands. Pumping is also possible with an electrical current sent through a p-n junction; carrier recombination occurs where the p and n materials meet.

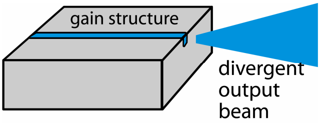


Optical gain and efficient laser operation is more difficult to achieve at high temperatures, where the carrier distributions in the two bands are more "smeared out" in thermal equilibrium. Temperature changes also somewhat affect the wavelength of maximum gain—often by roughly 0.3 nm per kelvin.

The achievable optical gain can be quite high (easily 10% in a millimeter) and in some cases even significantly more. However, the required high power density can be applied only to small volumes. Therefore, the light is often tightly confined in a waveguide structure, which also confines the carriers generating the gain. This is called a **double heterostructure**.

Low-Power Edge-Emitting Laser Diodes

Small laser diodes are often based on a short (e.g., 1-mm long) single-mode waveguide along the wafer surface, with emission out of a cleaved edge. Multiple laser chips (dies) are cut from a single wafer, processed further (e.g., obtaining electrical contacts and optical coatings), and then packaged. The figure illustrates a laser chip without the electrical contacts. There are many variations of such edge-emitting laser diodes (LDs):



- **Index-guided LDs** have a waveguide structure for both directions, while **gain-guided LDs** confine the light in the horizontal direction by gain guiding, such as by a higher gain in the central region.

- The end reflectors can be based on the Fresnel reflection (for an output coupler), on optical coatings, or on semiconductor distributed Bragg reflectors.

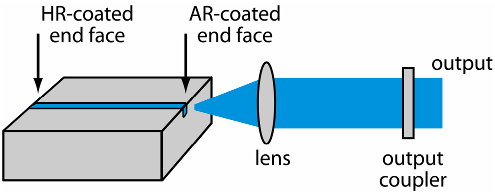
- In a **distributed feedback laser** (DFB laser), the whole resonator consists of a periodic structure that acts as a distributed reflector in the wavelength range of laser action and ensures stable operation on a single axial resonator mode. Such lasers can have a rather narrow linewidth of typically a few hundred megahertz.

- Different materials are used for emission wavelengths in the visible spectral region (e.g., red or blue) or in the near infrared.

The output power can be up to ≈0.5 W, and the output beam is strongly diverging. It may be collimated with a suitable high-NA lens or coupled into a single-mode optical fiber. Fiber coupling may already be done within the LD package.

External-Cavity Diode Lasers

Some diode lasers have an **extended laser resonator**, which contains external optical elements. The figure shows a simple case with a collimating lens and an external end mirror. One facet of the laser chip is antireflection (AR) coated.



The increased resonator length can help to reduce the emission linewidth to below 1 MHz. Besides, this approach allows for the insertion of additional optical elements for implementing other functions:

- **Wavelength tuning** is possible by including some adjustable optical filter as a tuning element. This can be, for example, a diffraction grating arranged in the Littrow or in the Littman/Metcalf configuration. By tilting the grating or a mirror, the laser wavelength can be tuned.

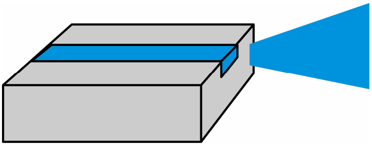
- A **saturable absorber** for passive mode locking (see p. 107) can be inserted, such as for generating ultrashort optical pulses. Mode locking may also be achieved with an absorber section integrated into the gain chip or by modulation of the drive current, but the long resonator is nevertheless important for achieving the desired pulse repetition rate.

- A special type of external-cavity laser uses a resonator based on an optical fiber rather than on free-space optics. Narrowband optical feedback can then come from a **fiber Bragg grating**.

Typically, external cavity–diode laser applications appear in optical communications and spectroscopy. They are often rivaled by distributed Bragg reflectors or distributed feedback laser diodes.

Broad-Area Laser Diodes

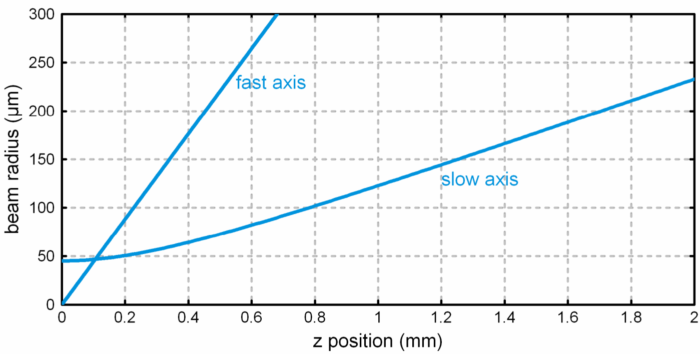
For higher output powers, the width of the emitting region can be increased from a few microns (as in typical low-power diodes) to 50 µm, 100 µm, or 200 µm. Several watts of output power can be obtained from a 100-µm stripe diode.



The beam properties are very different between the horizontal and vertical direction:

- In the vertical direction ("fast-axis direction"), the emission is still single-mode, with a relatively high divergence according to the small mode size in that direction. The beam quality is close to diffraction limited; M^2 is not much larger than 1.

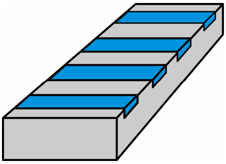
- For the horizontal direction ("slow-axis direction"), there is no single-mode waveguide. As a result, the beam divergence is much larger than for a diffraction-limited beam of that size, although it is still significantly smaller than for the vertical direction. The beam quality is reduced; M^2 might, for example, be around 20 for a 100-µm stripe.



Beam collimation has to take care of the asymmetric beam profile; two cylindrical lenses are often used.

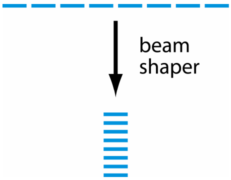
Diode Bars

A still higher output power can be obtained by combining multiple broad-area emitters in a single device, called a **diode bar** or **diode array**. For example, 20 emitters could be combined to obtain several tens of watts, which is sufficient to pump a multiwatt solid-state laser.



While the beam quality in the vertical direction can still be close to diffraction limited (if it is not spoiled, for example, by a "smile" of the bar), it is further reduced in the horizontal direction. The brightness (radiance) is even lower than that of a broad-area single-emitter laser, particularly for devices with a low fill factor (large spacing of emitters). Still, this approach is better than making a single broad-area emitter with a very large width because that would lead to the formation of filaments and lateral-mode instabilities.

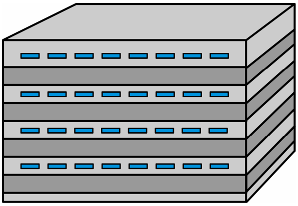
Beam collimation often starts with a **fast-axis collimator** in close proximity to the diode facet, followed by a **slow-axis collimator**. For fiber coupling and other applications, it can be advantageous not only to generate a roughly circular beam profile but also to somewhat symmetrize the beam quality in the two directions, using a suitable kind of **beam shaping optics**.



Diode bars are often watercooled (e.g., with a micro-channel cooler), allowing for a high fill factor (the ratio of emitter width to the total width of the emitting region) of, for example, 80% and thus for a high brightness. Conduction-cooled bars (often used with a thermoelectric cooler) tend to have a lower fill factor of, for example, 30% because the heat can be extracted less efficiently.

Diode Stacks

Diode stacks, consisting of multiple diode bars and having a two-dimensional array of emitters, are used for multikilowatt output power. Such stacks are assembled from diode bar chips, with thin heat sinks in between. For example, combining 20 diode bars with 100 W each, a total output power of 2 kW is obtained. Even higher powers are often possible in **quasi-continuous-wave operation**, such as with current pulses of a few hundred microseconds. However, the brightness of a diode stack is still lower than that of a diode bar. To some extent, the brightness can be improved by, for example, spatial interleaving of the outputs of different diode stacks, by polarization coupling, or by wavelength multiplexing.

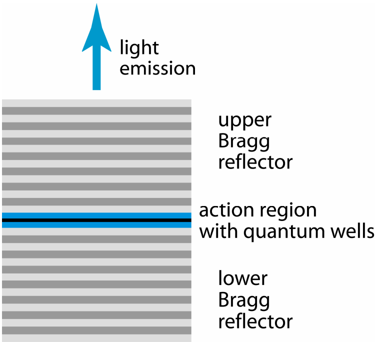


Using a suitable **beam shaper**, the radiation of a diode stack can be coupled into a multimode fiber with a rather large core diameter. For example, several kilowatts in a 600-μm core can be obtained. Fiber coupling (see p. 42) often makes it easier to deliver the light to the application.

Diode stacks can be used for pumping very high-power solid-state bulk or fiber lasers. Direct material processing with the output of a diode stack is another option for cases where the higher brightness of a solid-state bulk or fiber laser is not required, while the lower complexity and higher wall-plug efficiency of a diode laser is advantageous. Examples for direct diode applications are hardening, alloying, and cladding of metallic surfaces.

Vertical-Cavity Surface-Emitting Lasers

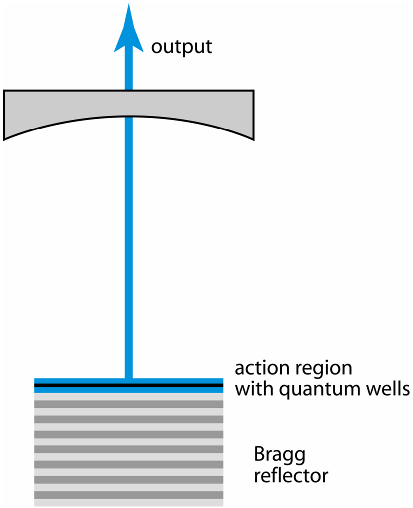
A **vertical-cavity surface-emitting laser** (VCSEL) emits light that is perpendicular to the semiconductor wafer surface. The laser resonator consists of a thin active region with one or several very thin (quantum well) amplifying layers sandwiched between two **distributed Bragg reflectors** (DBRs), where one has a very high reflectivity and the other (the output coupler) has a slightly lower reflectivity of ≈99%. For example, electrical pumping is possible by making the DBRs from doped (electrically conducting) material and connecting them to metallic electrodes, where the top electrode has a ring form to couple out the light. A low pump threshold can be achieved with additional structures for confining the electrical current to a small area. Thousands of such VCSEL chips can be fabricated on a single wafer, and they may be packaged separately or as laser arrays.



A typical VCSEL emits a few milliwatts of output power in a circular, moderately divergent, and nearly diffraction-limited beam, which is easier to collimate (or couple into a single-mode fiber) than the output of an edge-emitting laser. Output wavelengths can vary from between 650 nm and 1300 nm for GaAs-based VCSELs or 1300 nm to 2000 nm using InP. The optical spectrum is narrow due to emission on a single resonator mode, and the output can be rapidly modulated (e.g., for data transmission with 10 Gbit/s). The active area and thus the output power are limited by the difficulty of achieving single transverse mode operation with a very short laser resonator and homogeneously pumping a large area with a ring electrode.

Vertical-External-Cavity Surface-Emitting Lasers

A **vertical-external-cavity surface-emitting laser** (VECSEL) is similar to a VCSEL, but the laser resonator is completed with an external mirror and may contain additional optical elements. The **external resonator** allows for single transverse mode operation with larger active areas. With electrical pumping, ≈1 W of output power is possible in a diffraction-limited beam, with tens of watts possible from optical pumping, where it is easier to homogeneously pump a large region. In any case, high-power operation requires additional features for efficient cooling (not shown in the figure), such as a heat sink soldered to the back side of the thinned gain chip or a transparent heat sink bonded to the top surface.



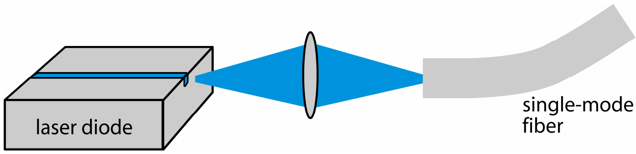
The external resonator may contain additional optical elements, such as an optical filter for wavelength tuning or a saturable absorber for passive mode locking, which generates picosecond or femtosecond pulses, typically with multigigahertz repetition rates. Alternatively, a nonlinear crystal inside the resonator allows for efficient frequency doubling, leading to devices with red, green, or blue output, for example.

The most powerful VECSELs are based on InGaAs quantum wells operating between 950 nm and 1050 nm, but longer wavelengths are also possible (e.g., around 1.3 μm with GaInNAs or 1.5 μm with InP).

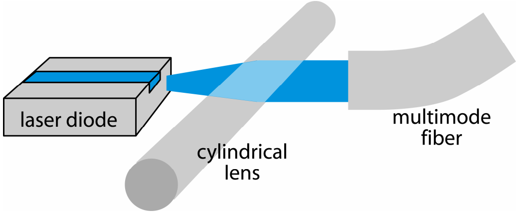
Fiber-Coupled Diode Lasers

In many cases, it is convenient to couple the output of one or several diode lasers into an optical fiber in order to deliver it to the application. The circular shape of the fiber output can be useful, and defective laser diodes can be easily replaced. Also, device construction can benefit by removing space constraints and the generated heat from other optical elements (e.g., a solid-state laser head). Many diode lasers are thus sold in fiber-coupled form, with the **fiber coupling** built into the laser package. The fibers and techniques vary greatly depending on the type of diode laser:

- Small, **edge-emitting laser diodes**, as well as most VCSELs, emit in a single spatial mode, allowing efficient coupling to a single-mode fiber with a lens (imaging the diode facet to the fiber core) or sometimes with butt coupling (direct coupling).



- **Broad-area laser diodes** are multimode in one direc-tion. If a circular beam is shaped with a cylindrical lens in order to launch the light into a multimode fiber, a lot of the brightness is lost because the good beam quality in the fast-axis direction cannot be exploited. For example, 1 W may be obtained in a multimode fiber with a 50-μm core diameter and an NA of 0.12.



Fiber-Coupled Diode Lasers (cont.)

- An improved technique is based on reshaping the beam for a symmetrized beam quality (and not only beam radius) before launching. This can be done, for example, with micro-optical elements.

- For **diode bars**, the problem of asymmetric beam quality is even more severe. Here, the individual emitter outputs may be coupled into separate fibers of a fiber bundle. The fibers are arranged in a linear array on the side of the diode bar, but as a circular array on the output end. Alternatively, some kind of beam shaper for symmetrizing the beam quality may be used before launching into a single multimode fiber. For example, 30 W can be coupled into a fiber with a 200-μm core diameter and an NA of 0.22.

- For **diode stacks**, fibers with even larger core diameters are required. For example, hundreds of watts or several kilowatts of optical power could be coupled into a fiber with a 600-μm core diameter and an NA of 0.22.

Some potential disadvantages of fiber-coupled diode lasers, compared with free-space emitting lasers, include:

- The cost is higher; this may, however, be offset by the savings from simpler beam processing and delivery.

- The output power and (more importantly) brightness are somewhat reduced. The loss of brightness can be substantial (more than an order of magnitude), depending on the technique of fiber coupling.

- In most cases, the fiber is not polarization maintaining. Normally, the fiber output is partially polarized, and the polarization state can change when the fiber is moved or the temperature changes. This can cause substantial stability problems for diode-pumped solid-state lasers when the pump absorption is polarization dependent (e.g., in $Nd:YVO_4$).

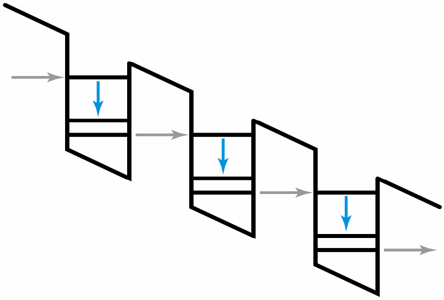
Properties of Diode Lasers

Aspect	Properties
important types	low-power, single-mode laser diodes; broad-area laser diodes; diode bars; diode stacks
applications	laser pointers; optical data storage; transmitters for telecommunications; pumping of bulk lasers; direct diode material processing
pump source	electrical current
power efficiency	order of 50%
accessible wavelengths	mostly near infrared but also mid-infrared, visible, or ultraviolet
wavelength tuning	over a few nanometers via temperature; over tens of nanometers with frequency-selective optical feedback
average output power	typically between 1 mW (small, low-power diodes) and 5 kW (diode stacks)
beam quality	diffraction-limited for very low-power devices, poor for high-power devices
continuous-wave operation	yes
nanosecond pulse generation	yes, with gain switching but low pulse energies
picosecond & femtosecond pulse generation	picosecond pulses with gain switching

Quantum Cascade Lasers

While most semiconductor lasers emit in the near-infrared region, **quantum cascade lasers** (QCLs) emit in the midinfrared, with wavelengths between a few microns up to more than 10 µm, sometimes even many tens of microns (for optical frequencies in the terahertz region).

Instead of interband transitions (conduction band to valence band), QCLs rely on **intersubband transitions** between the sublevels of quantum wells with a much smaller photon energy. In order to more efficiently utilize the electric power and generate a higher gain, a cascade of such transitions is used, where electrons can tunnel from the lowest level of one quantum well to the upper laser level of the next quantum well. The figure shows the electron energy versus position in a region with three quantum wells, where one electron going through the structure can contribute three laser photons.

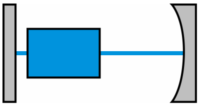


While continuously operating, room-temperature devices are normally limited to output power levels in the lower milliwatt region (although hundreds of milliwatts can be generated in exceptional cases), hundreds of milliwatts are easily possible with liquid-nitrogen cooling. Even at room temperature, watt-level peak powers can be achieved by using short pump pulses.

Perhaps the most important applications for quantum cascade lasers will be spectroscopy of trace gases (e.g., the detection of air pollution). Besides the suitable wavelength range, QCLs usually feature a relatively narrow linewidth and good wavelength tunability, making them very suitable for such applications.

Solid-State Bulk Lasers

A **solid-state bulk laser** is based on a bulk piece of doped crystal or glass as the laser gain medium. In most cases, the gain medium is doped either with rare-earth ions or transition metal ions.



With no waveguide structure in the gain medium, the laser beam radius in the gain medium is essentially determined not by the gain medium, but by the resonator design. Important consequences are:

- The laser resonator may be designed for a large effective mode area in the crystal so as to enable, for example, Q-switched operation with very high pulse energy.
- Alternatively, a small mode area for low-threshold pump power may be preferred. However, a small mode area implies strong beam divergence and thus cannot be maintained over a large length of material.
- The beam radius can be influenced by thermal lensing and thus may change, for example, when the pump power is changed.

A **bulk laser resonator** is often formed with laser mirrors placed around the crystal. However, there are also laser crystals with a highly reflective dielectric mirror coating on one side, which serves as a resonator end mirror. Also, there are monolithic solid-state lasers (see p. 63) where the beam path is entirely inside the crystal.

As a rule of thumb, bulk lasers and amplifiers are preferable for devices operating with high peak power, while low-threshold and high-gain operation is more easily achieved with waveguide devices, particularly with fiber lasers and amplifiers.

Rare-Earth-Doped Gain Media

Most laser crystals and glasses, and most laser-active optical fibers, are doped with **rare-earth ions**. Typically, these ions replace a small percentage of other ions of similar size in the host medium; for example, Nd^{3+} ions in **Nd:YAG** substitute a few percent of the yttrium (Y) ions. The laser-active ions have suitable optical transitions for pumping and laser emission at wavelengths where the host medium is transparent. Many laser transitions have a quasi-three-level nature (see p. 52).

The most important laser-active rare-earth ions are listed in the following table. Nd- and Yb-doped gain media for lasers and Er-doped fibers for erbium-doped fiber amplifiers are technologically most important.

Ion	Common host media	Important emission wavelengths
neodymium (Nd^{3+})	YAG, YVO_4, YLF, silica	1.03-1.1 μm, 0.9-0.95 μm, 1.32-1.35 μm
ytterbium (Yb^{3+})	YAG, tungstates, silica	1.0-1.1 μm
erbium (Er^{3+})	YAG, silica	1.5-1.6 μm, 2.94 μm, 0.55 μm
thulium (Tm^{3+})	YAG, silica, fluoride glasses	1.7-2.1 μm, 1.45-1.53 μm, 0.48 μm, 0.8 μm
holmium (Ho^{3+})	YAG, YLF, silica	2.1 μm, 2.8-2.9 μm
praseodymium (Pr^{3+})	silica, fluoride glasses	1.3 μm, 0.635 μm, 0.6 μm, 0.52 μm, 0.49 μm
cerium (Ce^{3+})	YLF, LiCAF, LiLuF, LiSAF	0.28-0.33 μm

A characteristic property of the trivalent rare-earth ions is that their electronic transitions occur within the 4f shell, which is somewhat shielded from the host lattice by the optically passive outer electronic shells. This reduces the influence of the host lattice on the transitions.

Transition-Metal-Doped Gain Media

A number of solid-state laser gain media are doped with **transition-metal ions**, exhibiting optical transitions that involve electrons of the 3D shell. The following table gives an overview of common transition-metal ions and their host media:

Ion	Common host media	Important emission wavelengths
titanium (Ti^{3+})	sapphire	0.65-1.1 µm
divalent chromium (Cr^{2+})	zinc chalcogenides, such as ZnS, ZnSe, and ZnS_xSe_{1-x}	3.0-3.4 µm
trivalent chromium (Cr^{3+})	ruby (Al_2O_3) and alexandrite ($BeAl_2O_4$); LiSAF, LiCAF, and LiSAF	0.8-0.9 µm
tetravalent chromium (Cr^{4+})	YAG, $MgSiO_4$ (forsterite), and other silicates	1.1-1.65 µm

While the first laser on earth was a ruby (Cr^{3+}:Al_2O_3) laser, **Ti3+:sapphire** is now frequently used for wavelength-tunable and/or ultrashort-pulse lasers. Some Cr^{3+}-doped lasers rival Ti^{3+}:sapphire lasers; they can be diode-pumped but have a smaller gain bandwidth and are more limited in terms of output power. The relatively new Cr^{2+}-doped lasers have very broad wavelength tuning ranges in the midinfrared region.

More exotic ions for lasers are cobalt (Co^{2+}), nickel (Ni^{2+}), and iron (Fe^{2+}).

Compared with rare-earth-doped media, transition-metal-doped laser media typically have a larger gain bandwidth. This results from the stronger interaction between the laser-active electron shells and the vibrations of the host lattice. For that reason, such lasers are sometimes called **vibronic lasers**.

Properties of Host Crystals

Even though the laser process is essentially done by the laser-active-dopant ions (e.g., Nd^{3+} ions in a Nd:YAG crystal), the **host crystal** is much more than just a means to fix the laser-active ions at some places. Some of its most important properties include:

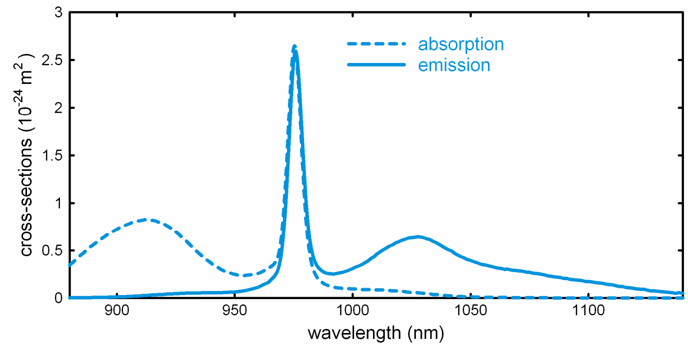
- A high transparency for pump and laser radiation;
- Optical isotropy or anisotropy (birefringence);
- A possible tendency toward laser-active ion clustering;
- An influence on the wavelength, bandwidth, and cross sections of pump and laser transitions;
- The tendency for various processes that allow for nonradiative transitions (e.g., via multiphonon emission);
- Mechanical properties influencing the ease of fabricating surfaces with a high optical quality;
- Chemical stability (e.g., resistance to water vapor);
- The thermal conductivity, thermal-optic coefficients (important for thermal lensing), and stress resistance;
- The optical damage threshold (particularly for pulse amplifiers).

Depending on the particular application, the demands on the host medium can be very different. Therefore, a wide range of different host crystals is in use, and new crystal materials are still being developed decades after the realization of the first rare-earth-doped lasers.

Effective Cross Sections

Optical transitions in solid-state gain media involve Stark level manifolds consisting of several sublevels, rather than isolated energy levels. The transitions between these sublevels are usually spectrally overlapping, so that they are hard to distinguish (except sometimes at very low temperatures). Depending on the exact wavelength, transitions between different Stark levels contribute to the total transition rate. Since it is neither possible nor necessary to resolve the contributions of every sublevel, it is convenient to use so-called **effective cross sections**, which are essentially averaging the cross sections of all the different sublevel transitions, with weight factors depending on population densities in thermal equilibrium.

Effective cross sections can be obtained directly from spectroscopic measurements. Absorption cross sections can be calculated from absorption spectra, taking into account the density of the absorbing ions. Emission spectra reveal at least the spectral shapes of emission cross sections, provided they are not distorted, for example, by additional absorption effects. The absolute scaling of emission cross sections can be more difficult to evaluate.



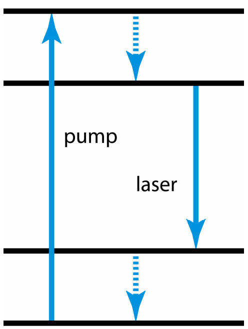
For example, the figure shows effective absorption and emission cross sections of ytterbium (Yb^{3+}) ions in germanosilicate glass, as used in the cores of ytterbium-doped fibers.

Phonon Effects in Solid-State Gain Media

In solid-state laser gain media (including crystals, glasses, and ceramics) there are lattice vibrations. According to quantum mechanics, these vibrations are quantized, with the energy quanta called **phonons**. Depending on the lattice structure, phonon energies can vary within a wide range. Phonons can influence the lasing properties in various ways:

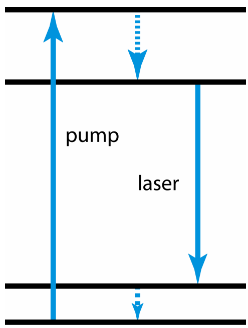
- They initiate transitions within the previously mentioned Stark level manifolds, reducing the lifetime of a single sublevel to picoseconds and causing significant lifetime broadening, which also affects the pump absorption and gain bandwidth.

- Transitions between different Stark level manifolds are possible by the emission of multiple phonons. The rate of such processes rapidly decreases for larger energy spacings between the Stark level manifolds because this increases the number of involved phonons. As a rule of thumb, **multiphonon transitions** are strong when the energy difference is no more than roughly three times the maximum phonon energy of the lattice. This effect is extremely useful in many solid-state lasers: multiphonon processes (the dotted lines in the figure) can assist in populating the upper laser level and depopulating the lower laser level, while not bypassing the laser transition itself, if the laser transition has a larger energy difference. (For long-wavelength laser transitions, a laser crystal with low phonon energies is required to avoid this bypassing.)



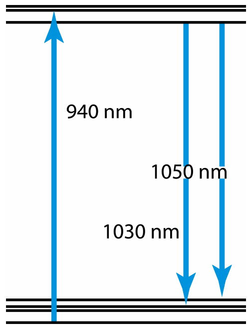
- Phonons can also facilitate **energy transfers** between different ions by removing any excess energy.

Quasi-Three-Level Laser Transitions



Four-level and three-level laser transitions have already been discussed on p. 3. As a kind of intermediate case, there are also so-called **quasi-three-level transitions**, where the lower laser level is only slightly above the ground state, so that it has a significant population in thermal equilibrium. (Phonons usually establish that equilibrium within picoseconds.) As a consequence, the threshold pump power can be significantly increased, although not as strongly as in a true three-level system.

An important example of a quasi-three-level gain medium is the laser crystal material Yb:YAG. Here, only two Stark level manifolds are involved in laser operation. The laser transition (e.g., at 1030 nm) starts on the lowest sublevel of the upper manifold and ends at a higher sublevel of the lower (ground state) manifold. The pump wavelength has to be shorter than the laser wavelength; otherwise, absorption at the pump wavelength could not occur while there is gain at the laser wavelength. Note also that without pumping there is significant absorption on the laser transition; positive gain is achieved only for pump intensities above the so-called **transparency intensity**.

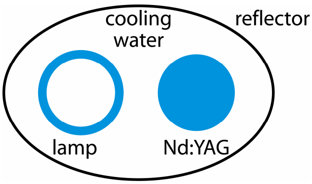


One benefit of quasi-three-level lasers is that they can have a rather low quantum defect (the difference between pump and laser photon energy) and thus a potentially high power efficiency. However, it is often not easy to realize this potential. Certainly, laser designs that are specifically adapted to such gain media are required.

Lamp Pumping vs. Diode Pumping

The first laser was pumped with a **flash lamp**, and **lamp pumping** is still widely used, even though pumping with laser diodes is an attractive alternative in many cases.

There are various types of discharge lamps, all being based on an electric discharge in some gas (excluding the very rarely used tungsten-halogen lamps). Some of these lamps (**arc lamps**) can be operated continuously with moderate current density; others are flash lamps generating short and very intense flashes of light. For a lamp-pumped YAG laser, a **krypton lamp** with an electrode distance of 5–15 cm is placed in a pump chamber that also contains the laser rod and has a reflecting surface that increases the percentage of absorbed pump light. Excess heat is removed by cooling water, and an additional filter glass may be used to protect the laser rod from ultraviolet light emitted by the lamp.



For diode pumping, one may use a small laser diode with <0.5 W for the smallest of devices, broad-area laser diodes for a few watts of output, diode bars for dozens of watts, or diode stacks for multikilowatt lasers.

Lamp pumping and diode pumping differ in many respects:

- Particularly for pulsed pumping, lamps are much cheaper than laser diodes. This makes them preferable for Q-switched laser systems with very high pulse energy and peak power.

- Lamps emit broadband radiation, while laser diodes emit with narrow spectra, so that their radiation can be much more strongly and efficiently absorbed in a laser crystal.

Lamp Pumping vs. Diode Pumping (cont.)

- The strongly directional emission of laser diodes allows for end pumping or side pumping, while lamps are suitable only with side pumping (see p. 55). End pumping is usually more efficient, although side pumping has advantages for high power levels.

- Overall, the power efficiency of a diode-pumped system can be much higher, which reduces the power consumption and the generation of heat, which eliminates the need for cooling. The beam quality can also be better because thermal effects are weaker.

- Lamps need high-voltage power supplies, introducing safety hazards as well as electromagnetic interference, while diodes are operated with relatively low voltages but high currents.

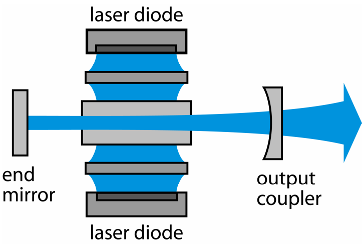
- Laser diodes have to be carefully protected against static discharges or excessive currents (even for short times), while lamps are relatively robust. However, suitably operated laser diodes can reach lifetimes of tens of thousands of hours, while lamps have much shorter lifetimes.

- Diode pumping allows the use of a wider range of laser gain media, while lamp pumping requires gain media with broadband pump absorption in spectral regions accessible with lamps. Diode-pumped lasers can also be built with much smaller crystals, at least for low power levels, and can span a much wider range of output powers.

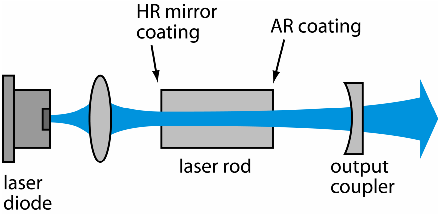
Lamps are still widely used, for example, in pulsed lasers, particularly in those with low pulse repetition rates and high peak power, while diode pumping has become very common for continuous-wave operation and for high pulse repetition rates.

Side Pumping vs. End Pumping

Side pumping means that pump light is injected in directions roughly perpen-dicular to the laser beam. This can be done with laser diodes or with lamps.



End pumping (also called **longitudinal pumping**) means that pump light is injected along the laser beam. The figure to the right shows a low-power device pumped with a small laser diode.

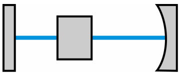


Both pumping techniques have their advantages, depending on the situation:

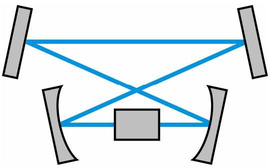
- End pumping requires a sufficiently high pump beam quality, while side pumping allows the injection of pump light from a wide area and in a wide range of angles. Consequently, side pumping is the only option for lamp pumping and can also be advantageous for diode-pumped, multikilowatt lasers.
- End pumping is usually more efficient because the pumped volume in the laser crystal can be restricted to that covered by the resonator mode(s).
- End pumping allows for a higher laser gain, which can, for example, allow the generation of shorter pulses with Q switching (see p. 103).
- Often (but not always), end-pumped lasers achieve a better beam quality.

Linear vs. Ring Laser Resonators

Most lasers are built with a **linear laser resonator**, where light bounces back and forth between two end mirrors. The beam path may be folded with additional mirrors.



In other cases, a **ring laser resonator** is used, where every mirror reflects the beam with nonnormal incidence. A bow-tie configuration (in contrast to a rectangular layout) keeps the reflection angles on the curved mirrors smaller, thus avoiding excessive astigmatism.



Some important differences between linear and ring laser resonators include:

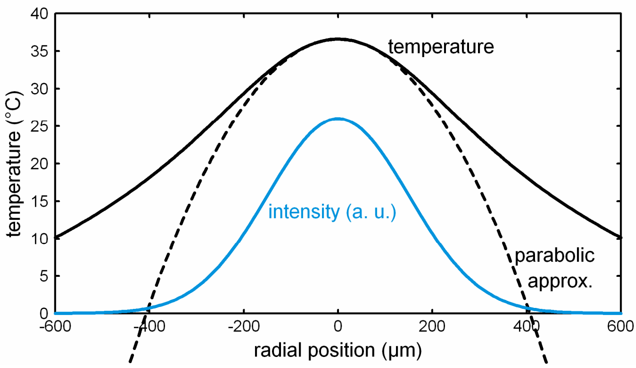
- A ring resonator supports two different propagation directions. Stable unidirectional laser operation can be achieved, for example, with a Faraday isolator (optical diode) in the resonator. Without special measures, the laser power may fluctuate between both directions.
- Output coupling via the folding mirror of a linear resonator leads to two output beams, with each one carrying about half of the power. This does not happen in a unidirectional ring laser.
- In a linear resonator, there are counterpropagating waves in the gain medium (unless ultrashort pulses are involved). The resulting interference pattern leads to spatial hole burning (see p. 10), which can make it more difficult to achieve single-frequency operation (see p. 92).

Thermal Effects in Laser Crystals and Glasses

Laser action in a gain medium involves the dissipation of some energy as heat, which can have various effects:

- The temperature rise may reduce the gain efficiency, for example, by modifying the thermal population distributions within the Stark level manifolds. This can decrease the power efficiency of a laser.

- The temperature rise is typically highest on the beam axis. This temperature inhomogeneity can introduce a focusing (lensing) effect in various ways: via the temperature dependence of the refractive index, via thermally induced mechanical stress that can also modify the refractive index, and via bulging of the end faces. The focusing power of the **thermal lens** is often proportional to the optical power throughput, but it can also depend on the excitation level.



The temperature profile is often not quite parabolic, which means that the thermal lens has aberrations.

- The temperature gradient can also cause birefringence with position-dependent orientation. This can lead to depolarization of the laser beam and thus to **depolarization loss** in lasers with enforced linear polarization.

Thermal Effects in Laser Crystals and Glasses (cont.)

- For sufficiently strong thermally induced stress, fracture of the gain medium can occur.

The strength of such effects depends not only on the optical power throughput but also on the power efficiency of the gain medium, its thermal conductivity, the thermo-optic and elasto-optic coefficients, the doping density and excitation level, and the geometry of the gain medium and cooling arrangement. For example, **thermal lensing** is strongest for heat extraction in directions transverse to the laser beam, as occurs in rod lasers.

For simple cases, the dioptric power (inverse focal length) can be calculated as

$$f^{-1} = \frac{\mathrm{d}n/\mathrm{d}T}{2\kappa A} P_{\mathrm{heat}} ,$$

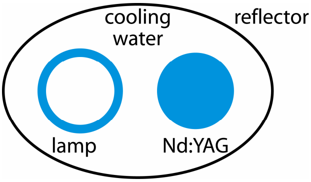
where κ is the thermal conductivity, A is the pump beam cross section, and P_{heat} is the dissipated power. The underlying assumptions are a top-hat intensity distribution, a purely transverse heat flow, and thermal lensing only via the direct temperature effect on the refractive index (i.e., no stress effects). In that simple case, the thermal lens has no aberrations, while a Gaussian-shaped pump beam does cause aberrations, as shown in the figure on the previous page.

The design of the **laser resonator** (see p. 28) has to take into account the variable (and often not precisely known) dioptric power of the thermal lens. Particularly for lasers with diffraction-limited output, the resonator should provide a slightly varying mode radius in the gain medium over the full range of thermal lens dioptric powers. Also, the laser resonator should not have an alignment sensitivity that is too high, as the asymmetry introduced by a misaligned pump beam acts in a similar way as a tilted resonator mirror. At high power levels, thermal lensing can make it difficult in various ways to obtain diffraction-limited beam quality.

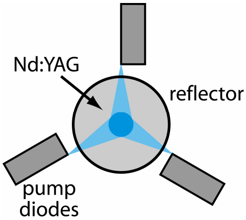
Rod Lasers

Many solid-state lasers have a laser crystal with a cylindrical (**rod**) shape, where the laser beam propagates along the rod axis, and the heat is extracted dominantly through the outer surface.

Cooling is simplest for **end-pumped rods**, where the rod can be fully surrounded by a water-cooled heat sink. However, there are also various options for side pumping. For example, the rod may be cooled with water, which transmits the pump radiation from a lamp. The used rods are normally several centimeters long, corresponding to the length of the lamp, and have a low doping concentration.



Another possibility is to inject pump light from laser diodes through slits in a reflector coating around the rod and cool the outer surface of that reflector. A diffuse reflector may be used to obtain a smoother pump intensity profile. By imaging the fluorescence from the pumped rod, the pump intensity profile can be monitored.



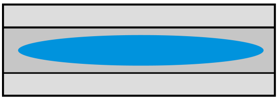
Due to heat extraction in the transverse dimension, thermal lensing inevitably gets stronger for higher powers. Diffraction-limited beam quality is usually limited to output powers of a few hundred watts.

One or several rods can be used in a laser resonator. With multiple rods, higher laser gain is obtained, allowing for a higher degree of output coupling; the intracavity intensity can be similar to that of a single-rod laser. The effects of thermally induced aberrations from the different rods do not necessarily add up; this is a matter of resonator design.

Slab Lasers

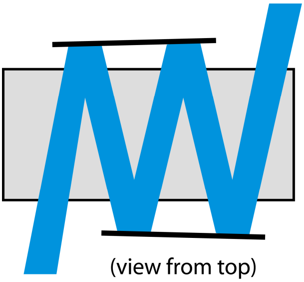
Although slab lasers all use some kind of slab-shaped gain medium, there are different types:

- Some **slab lasers** are side pumped (or less frequently end pumped) so that only a thin sheet within the laser crystal is excited, while others have the whole crystal volume pumped, with the pump beam(s) coming either from the sides (edge pumping) or from the top and bottom (face pumping).



(view from front side)

- There are slab waveguide lasers, where the thin pumped sheet is within a planar waveguide, guiding the laser light in the vertical direction.



(view from top)

- Some slab lasers use a strongly elliptical laser beam (see above) to extract the power, while others have optics to arrange for multiple passes with some lateral offset.

- There is also the zig-zag slab approach, where the beam bounces between the top and bottom surface, typically with total internal reflection at the surfaces. In this way, the thermal lensing effect in the vertical direction is, to some extent, averaged out, while it can be weak in the other direction if the pump intensity profile is smooth.

(view from the side)

Slab Lasers (cont.)

All of these slab laser concepts are used at power levels of at least some tens of watts or even multiple kilowatts. Some typical characteristics include:

- Slab lasers with folded beam geometries tend to have a high laser gain, which is beneficial not only for use as a power amplifier but also for generating short Q-switched pulses.

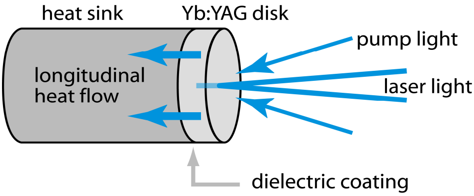
- The power throughput can, in principle, be scaled up by increasing the area (in a top view) of the slab. However, efficient power extraction with high beam quality is not necessarily an easy task. Unstable resonators (see p. 27) are often used.

- Amplified spontaneous emission (ASE) and parasitic lasing in a transverse direction can be hard to suppress in large slabs.

The architecture of slab lasers is most attractive for use at very high power levels of many kilowatts. The beam quality is normally not very close to diffraction limited, but in this regime it is hard to improve with other laser technologies.

Thin-Disk Lasers

The gain medium of a **thin-disk laser** (or **disc laser**, **active mirror laser**) is a laser crystal (often Yb:YAG) in the form of a disk with a thickness of 100–200 µm, which is fixed on a water-cooled heat sink. The cooled end face has a dielectric coating that reflects both the laser radiation and the pump radiation.



The heat is extracted dominantly through the cooled end face, and because the disk thickness is considerably smaller than the laser beam diameter, the heat flow is largely in the direction of the beam, rather than in a transverse direction, as for a laser rod. As a consequence, thermal lensing is weak.

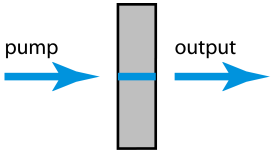
The small disk thickness, as required to limit the heating, leads to incomplete pump absorption in a double pass. Therefore, one usually uses some multipass pumping scheme, which can be realized with very compact optics.

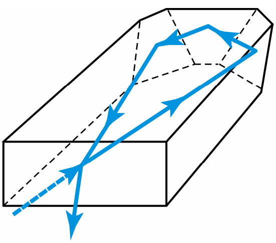
Thermal lensing is not only weak, but it also scales in a benign way: when increasing the pumped area in proportion to the power throughput, the dioptric power of the thermal lens gets even smaller. As long as stress effects are negligible, this just compensates for the higher sensitivity of a larger resonator mode. Furthermore, the temperature rise in the disk is hardly increased, as the cooled area is also enlarged. Due to this power scaling behavior, thin-disk lasers with diffraction-limited beam quality can be built for output powers between tens of watts and many kilowatts, essentially by adjusting the diameter of the pumped spot.

Q switching is possible with high pulse energies but not with very short pulses because the laser gain is quite limited.

Monolithic Lasers and Microchip Lasers

Low-power solid-state lasers can be made very compact, using **monolithic laser resonators**. There are, for example, **microchip lasers**, where the laser resonator is formed by mirror coatings on opposite sides of the laser crystal. In a resonator with two plane mirrors, stable resonator modes are established due to thermal lensing (and possibly gain guiding). By attaching, for example, a semiconductor saturable absorber mirror (SESAM), passive Q switching (see p. 104) with extremely short pulse durations (well below 1 ns) is possible due to the short resonator round-trip time.





There are also monolithic ring resonators, such as the so-called **nonplanar ring oscillator** (NPRO), where the ring encompasses three points with total internal reflection and one reflection at the front face with a dielectric mirror coating. Pump light is also injected into this front face. Due to the nonplanar geometry, there is a slight rotation of the polarization direction in each round trip. If a small magnet is attached to the laser crystal, its magnetic field can cause an additional polarization rotation via the Faraday effect. The two polarization rotations partly cancel for only one of the two oscillation directions. With that loss difference, stable unidirectional lasing can be obtained. Typical NPROs based on Nd:YAG can reach up to several watts of output power in a single mode.

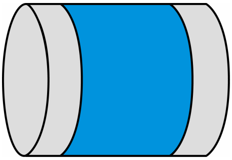
Monolithic lasers are usually not only compact but also very stable mechanically. This and the large free spectral range of the laser resonator allows for stable single-frequency operation (i.e., lasing on a single longitudinal resonator mode) with a very narrow linewidth.

Composite Laser Gain Media

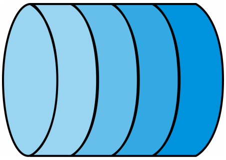
Although laser crystals usually consist of a single material throughout, there are various methods of fabricating composite crystals, consisting of parts with different dopants or doping concentrations, for example. For glasses and ceramics, there is an even wider range of methods to make composite structures.

Some examples for composite gain media are:

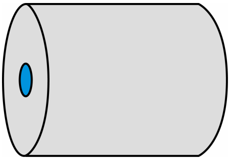
- **Undoped end caps** on a short laser rod can reduce thermal effects by extracting some of the heat through the end faces of the doped part. The tendency toward thermal fracture is also reduced. Such crystals improve, for example, the performance of quasi-three-level neodymium and ytterbium lasers.



- An end-pumped **multisegmented rod** made of stacks with increasing doping concentrations smoothly distributes the generated heat, making possible a higher optical power with a higher beam quality.



- A rod with a doped inner part and undoped cladding can concentrate the laser gain on the region within the fundamental resonator mode, which improves the beam quality.



- The crystal of a thin-disk laser may be mechanically stabilized by attaching a thicker undoped disk, which also helps to suppress ASE in the radial direction.
- A saturable absorber crystal bonded to a laser crystal can be used for a compact, passively Q-switched laser.

Cryogenic Lasers

Most high-power lasers have to be cooled to some extent. A more radical approach is to cool the laser crystal to rather low temperatures, such as 77 K (the temperature of liquid nitrogen) or even 4 K (liquid helium). This can have a number of beneficial effects:

- The thermal conductivity of the gain medium is strongly increased (e.g., by a factor of seven for YAG at 77 K, compared with room temperature), so that temperature gradients also get much weaker.
- The thermal expansion coefficient is also strongly reduced. This reduces thermal lensing by bulging and stress and, of course, the tendency for stress fracture.
- The thermo-optic coefficient (dn/dT) is also reduced, further reducing thermal lensing.
- The cooling can also increase cross sections by narrowing the optical transitions; in quasi-three-level media, cooling can reduce the population in the lower laser level. For example, Yb:YAG effectively becomes a four-level laser medium. This can make the laser transition more efficient. However, some media exhibit a reduction in pump absorption bandwidth, which can be detrimental.
- Depending on the gain medium, the strength of certain quenching processes may be reduced.

In effect, **cryogenic operation** can greatly enhance the laser's output power, efficiency, and beam quality.

The laser crystal must be kept in an evacuated dewar, with the cryogen coming from some finite supply, which is refilled from time to time or recycled in a closed loop containing, for example, a Stirling engine. This effort is sometimes justified by the obtained performance improvements and the possible simplification of other aspects of the laser device.

Beam Quality of Solid-State Lasers

Most low-power solid-state lasers generate output beams with nearly Gaussian intensity profiles and nearly diffraction-limited **beam quality**. This normally requires that the pumped region in the laser crystal approximately matches the volume of the fundamental (Gaussian) resonator modes. For high-power operation, however, there are various challenges:

- High-power lasers require large resonator modes, and these are more sensitive to **thermal lensing**. Therefore, the width of the resonator stability zones (e.g., in terms of pump power) can become inconveniently small. The resonator may then need to be designed for modes with significantly smaller beam radii. This, however, leads to the excitation of higher-order modes and thus to a degraded beam quality.

- **Aberrations**, mainly resulting from the nonideal phase profile of the thermal lens (particularly for pump intensity profiles with "hot spots"), can couple energy into higher-order modes.

Possible measures to tackle these challenges are manifold:

- The gain medium should have a high power efficiency (i.e., low quantum defect, no quenching processes, etc.), a high thermal conductivity, low thermo-optic and elasto-optic coefficients, and a suitable pump absorption coefficient (adjusted via the doping concentration).

- An optimized pump and cooling geometry, possibly with a composite laser crystal, and a smooth pump intensity distribution can be very helpful. A high-brightness pump source may allow for adjustments to the overall design, providing reduced thermal effects (e.g., if a longer end-pumped laser rod with lower doping density can be used).

Beam Quality of Solid-State Lasers (cont.)

- An optimized **laser resonator** design is essential. The design must have suitable mode sizes, a suitably located stability region, an alignment sensitivity that is not too high (which would also increase the sensitivity to thermal effects), etc. Such a design task requires extensive knowledge and experience.

- The knowledge of thermal lensing strength, pump intensity distribution, and similar factors are a prerequisite for an optimized design. Well-designed preparatory experiments allow for quicker development compared to a trial-and-error approach.

- Beam apertures can, in some situations, improve the beam quality by attenuating higher-order modes, but they may also cause mode coupling, making this approach only moderately successful in many cases.

- There are a number of additional, more sophisticated techniques, such as using adaptive optical elements to compensate for aberrations, laser resonators containing Faraday rotators, and phase-conjugation cells based on Brillouin scattering.

High beam quality is essential for many applications, such as laser material processing. For example, it allows for **remote cutting and welding**, where the focusing optics can be kept at a safe distance from the workpiece, and a beam scanner rapidly processes a large area without significantly moving the optics or workpiece.

Properties of Solid-State Bulk Lasers

Aspect	Properties
important types	high-power Nd:YAG lasers; broadly tunable Ti:sapphire lasers; Q-switched Nd:YAG and Nd:YVO_4 lasers; miniature Nd:YVO_4 lasers; various mode-locked bulk lasers
applications	material processing; optical metrology; laser displays; pumping of parametric oscillators; various scientific applications
pump sources	discharge lamps or other lasers, particularly laser diodes
power efficiency	typically 10-50%
accessible wavelengths	mostly near infrared, but also mid infrared, visible, or ultraviolet
wavelength tuning	wide tuning range possible with broadband laser crystals or glasses
average output power	typically between 10 mW and 10 kW
beam quality	often diffraction-limited, somewhat worse for high power devices
continuous-wave operation	yes
nanosecond pulse generation	yes, with Q switching; good energy storage and large mode areas allow for high pulse energies
picosecond & femtosecond pulse generation	yes; pulse duration limited by emission bandwidth

Fiber and Waveguide Lasers

Waveguide lasers contain a waveguide as the gain medium. The most important type of waveguide lasers are **fiber lasers** (apart from diode lasers). Waveguide lasers come in many varieties:

- Small **DBR** and **DFB fiber lasers**, with a resonator length of few centimeters, can serve as narrow-linewidth laser sources.
- There are **upconversion fiber lasers** (see p. 77), which generate visible light from infrared pump light.
- Some **tunable fiber lasers** adjust the emission wavelength over many tens of nanometers.
- Fiber lasers and amplifiers based on **double-clad fiber** can generate multiple kilowatts of output power with high beam quality.
- There are **Q-switched fiber lasers** generating nanosecond pulses, and **mode-locked devices** for picosecond and femtosecond pulse generation.
- **Raman fiber lasers** provide additional opportunities for wavelength conversion.
- **Fiber amplifiers** provide high-gain amplification of, for example, ultrashort pulses to higher power levels. Even if the actual laser is not a fiber laser, the resulting laser device can have some characteristics of a fiber laser.

Depending on the case, such devices utilize the various special properties of fibers, such as the large amplification bandwidth, the high gain efficiency, the geometry and waveguiding that allow for high output powers combined with good beam quality, and the potentially low cost.

Rare-Earth-Doped Fibers

Fiber lasers and amplifiers are nearly always based on a **rare-earth-doped fiber**. The most important types are listed in the following table:

Ion	Common host glasses	Important emission wavelengths
neodymium (Nd^{3+})	silicates and phosphates	1.03-1.1 µm, 0.9-0.95 µm, 1.32-1.35 µm
ytterbium (Yb^{3+})	silicates	1.0-1.1 µm
erbium (Er^{3+})	silicates, phosphates, fluorides	1.5-1.6 µm, 2.7 µm, 0.55 µm
thulium (Tm^{3+})	silicates, germanates, fluorides	1.7-2.1 µm, 1.45-1.53 µm, 0.48 µm, 0.8 µm
holmium (Ho^{3+})	silicates, fluorides	2.1 µm, 2.8-2.9 µm
praseodymium (Pr^{3+})	silicates, fluorides	1.3 µm, 0.635 µm, 0.6 µm, 0.52 µm, 0.49 µm

The most technologically important rare-earth-doped fibers are erbium-doped silica fibers, which are used for telecom fiber amplifiers, and ytterbium-doped silica fibers for high-power devices.

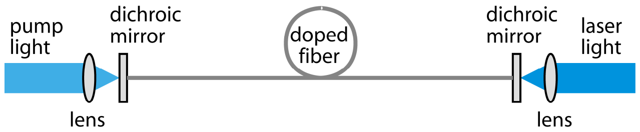
As pure silica is not ideal for rare-earth doping, silicates that are based on silica but have various additional dopants are used. For example, there are aluminosilicate, germanosilicate, and phosphosilicate glasses.

Fluoride fibers are totally different in many respects and usually contain heavy-metal ions; fluorozirconates (i.e., ZBLAN) are the most important due to their good mid-infrared transparency and low phonon energies.

Types of Fiber Laser Resonators

There are various methods for building **fiber laser resonators**:

- In simple laboratory setups, ordinary dielectric laser mirrors can be butted to the perpendicularly cleaved fiber ends. This approach, however, is not very practical for mass fabrication and not very durable.

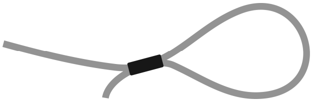


- It is also possible to deposit dielectric coatings directly on the fiber ends, usually with some evaporation method. The 4% Fresnel reflection from an uncoated bare fiber end is often sufficient for output coupling.

- For better power handling, the light exiting the fiber can be collimated with a lens and reflected back with a dielectric mirror. The intensities on the mirror are then greatly reduced due to the much larger beam area. The effect of the additional Fresnel reflection at the fiber end can be suppressed by using angle-cleaved fiber ends.

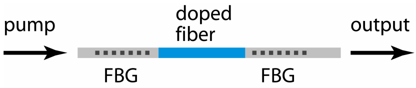
- Fiber Bragg gratings are often used for commercial products and are made either directly in the doped fiber or in an undoped fiber that is spliced to the active fiber.

- Another option involves forming a fiber loop mirror, based on a fiber coupler (e.g., with a 50:50 splitting ratio) and some piece of passive fiber.

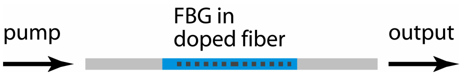


DBR and DFB Fiber Lasers

A **DBR** (distributed Bragg reflector) **fiber laser** has a resonator formed with a usually short piece of active fiber between two fiber Bragg gratings (FBGs). Such gratings can be fabricated by illuminating a photo-sensitive fiber with spatially patterned ultraviolet light. They have a high reflectivity within a narrow optical bandwidth (often <1 nm) and thus determine the emission wavelength. If the resonator is short enough (e.g., a few centimeters), single-mode operation with a linewidth in the kilohertz region may be achieved.



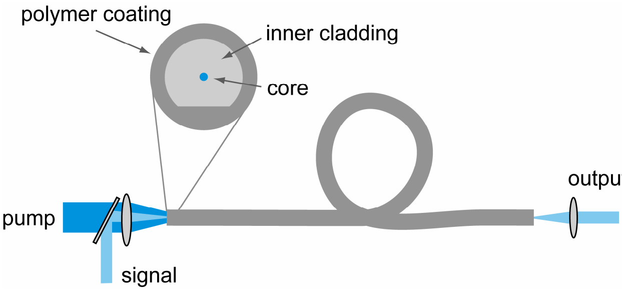
A slightly different approach involves the **DFB** (distributed feedback) **fiber laser**, which only contains a single fiber Bragg grating directly made in the doped fiber with a phase change in the middle. This kind of laser can provide very stable single-mode operation without mode hopping, even within a large temperature range. However, the output power and power efficiency are usually lower than those of a DBR laser, essentially because of the shorter resonator length.



The same principles are also applied to other kinds of waveguide lasers, in particular to semiconductor devices. Some small laser diodes use corrugated waveguide structures as distributed Bragg reflectors and also operate on a single mode. Their output powers are comparable to those of DBR fiber lasers, but the linewidth is usually in the megahertz region.

Double-Clad High-Power Fiber Devices

A **double-clad fiber** can guide signal (laser) light in a relatively small doped core and, at the same time, guide pump light in a larger undoped inner cladding, which is surrounded by an outer cladding with an even lower refractive index. This configuration maintains single-mode propagation (for diffraction-limited beam quality) of the generated laser light, while also guiding pump light from, for example, high-power diode bars with poor beam quality. The pump light still has some overlap with the doped core, where it transfers energy to the laser-active dopant.

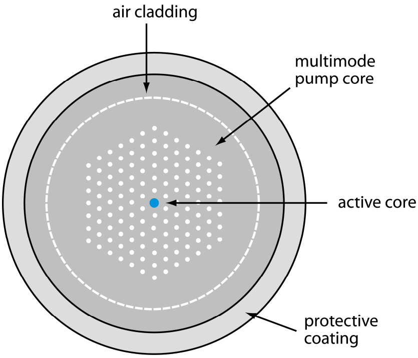


The figure shows a double-clad fiber amplifier. A laser could be formed by inserting two plane laser mirrors just outside the two lenses. However, high-power devices are more often made as "master oscillator power amplifiers," consisting of a seed laser and a power amplifier.

An important parameter of a double-clad fiber is the area ratio of inner cladding and core. A large area ratio decreases the beam quality requirements for the pump source, but it also decreases the pump absorption and possibly the gain. A longer fiber is then often required.

A larger fiber core helps to increase the pump absorption but makes it increasingly difficult to obtain robust single-mode guidance. Some of these devices use a core supporting a few modes and some means to restrict emission to a single mode.

Double-Clad High-Power Fiber Devices (cont.)



There are all-silica, air-clad fibers where the outer cladding is a structure of air holes (rather than, for example, a polymer coating). This allows for a particularly high numerical aperture and a robust all-silica design. Guiding in the active core is also achieved with tiny air holes. Such fibers are called **photonic crystal fibers**.

There are different methods for injecting pump light into a double-clad fiber. Instead of directly focusing pump light onto a bare fiber end face, certain pump coupler and combiner devices can be used, which combine the outputs of several fiber-coupled high-power diode lasers.

Ytterbium-doped double-clad fiber amplifiers allow for the highest output powers, with output wavelengths typically between 1040 nm and 1100 nm. Several kilowatts can be generated, with diffraction-limited beam quality and power efficiency on the order of 80%. However, the optical intensity in the core is then very high.

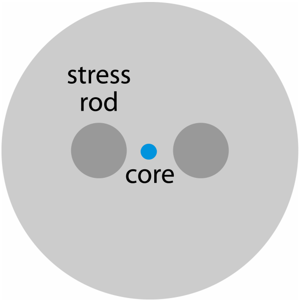
The high optical intensities in high-power fiber devices introduce not only a risk of damage, but they also cause potentially deterimental nonlinear optical effects, such as stimulated Raman and Brillouin scattering, four-wave mixing, and self-phase modulation. For pulse amplification, such effects are particularly important. Optimum performance often involves finding the ideal trade-off between various limiting effects.

Polarization Issues

Most optical fibers have, in principle, a cylindrical symmetry but with random distortions introducing some amount of birefringence. As a result, the **polarization state of light** is not preserved during propagation. Furthermore, the polarization changes can strongly depend on wavelength and temperature and be influenced by bending the fiber. Therefore, the outputs of many fiber lasers and amplifiers exhibit a rather unstable polarization state, which is bad for subsequent nonlinear frequency conversion.

This problem can be solved by using only **polarization-maintaining fibers**, which are fibers with a strong built-in birefringence ("high-birefringence fibers"). If the polarization of the input light is aligned with one of the birefringent axes, this polarization state will be preserved even if the fiber is bent. For other input polarizations, one would obtain randomly polarized outputs.

Introducing birefringence by including two **stress rods** of a modified glass in the preform on opposite sides of the core (PANDA fibers) is a common method. Another technique uses an elliptical core, causing so-called **form birefringence**. Such principles can also be applied to photonic-crystal fibers.



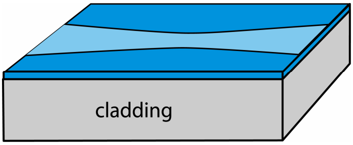
Unfortunately, many fibers are not available in polarization-maintaining form. Also, the need to align the polarization axes at every fiber joint makes polarization-maintaining devices more expensive.

There are also **single-polarization fibers**, which can only guide light with a certain linear polarization or strongly absorb light with the other polarization direction.

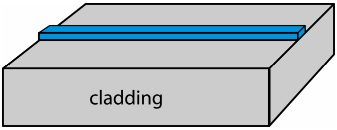
Other Waveguide Lasers

Besides fiber lasers, there are other types of waveguide lasers:

- High-power **planar waveguide lasers** exploit guidance in the vertical direction provided by a thin, rare-earth-doped film on an undoped substrate material. In the horizontal direction, the beam experiences regular diffraction and no guidance. The doped film may also be embedded between two undoped layers, making the guided mode more symmetrical and protected, for example, against dust particles.



- **Channel waveguides** can be made by fabricating thin ridges on a wafer surface. Amplification and lasing is possible with rare-earth-doped waveguides or with stimulated Raman scattering. Such devices can be made on silica, with semiconductors (e.g., silicon), or on nonlinear materials (e.g., $LiNbO_3$), and can be used in integrated photonic circuits.



- Nearly all **laser diodes** contain a waveguide structure, at least for one spatial direction and often for two directions. The refractive index contrast is usually quite high compared to that of an optical fiber, so that single-mode waveguides must have a correspondingly smaller cross section.

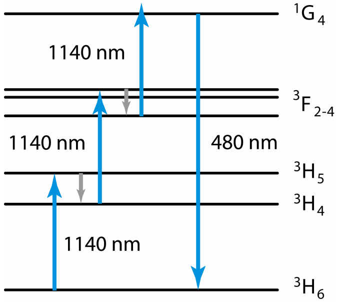
Upconversion Fiber Lasers

Most lasers emit at a wavelength that is longer than the pump wavelength. The opposite situation, where the emitted photons have a higher energy than the pump photons, occurs in **upconversion lasers**, where several pump photons are used to generate one laser photon:

- In media with suitable metastable intermediate electronic states, subsequent absorption of pump photons can be used to excite ions to a rather high energy level, from where high-energy photons can be emitted.

- Alternatively, one can exploit energy transfer processes in highly doped media, where, for example, two excited ions combine their energy to place one ion in a higher-lying level.

The figure shows the former process for a thulium-doped **fluoride fiber**. A 1140-nm pump beam can perform an efficient three-step excitation process, followed by the emission of blue light at 480 nm. Fluoride fibers have suitable phonon energies, allowing for quick non-radiative transfers (gray arrays) while not affecting the lifetimes of the metastable levels $^3H_4$ and $^3F_4$.



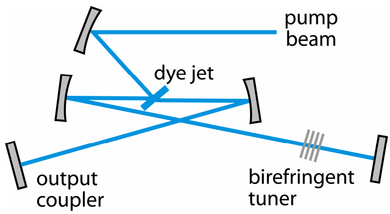
In principle, such processes are also possible in solid-state bulk lasers. However, they are normally more efficient in fiber lasers, where high pump intensity can be achieved over a long length of material. Good examples are thulium-doped blue lasers (see above) and praseodymium-doped lasers with an emission of red, orange, green, or blue light.

Properties of Fiber Lasers

Aspect	Properties
important types	high-power, ytterbium-doped fiber lasers; upconversion lasers based on thulium-doped or praseodymium-doped fluoride fibers; mode-locked, multi-GHz erbium-doped fiber lasers for telecommunications
applications	material processing; telecommunications; optical metrology; surgery
pump sources	other lasers, particularly laser diodes
power efficiency	typically 30-70%
accessible wavelengths	mostly near infrared, but also mid-infrared, visible, or ultraviolet
wavelength tuning	often possible over tens of nanometers
average output power	typically between 10 mW and 1 kW
beam quality	normally diffraction-limited
continuous-wave operation	yes
nanosecond pulse generation	yes, with Q switching; good energy storage but limited mode areas, thus pulse energies up to order of 1 mJ
picosecond & femtosecond pulse generation	yes; pulse duration limited by emission bandwidth, nonlinearities, or chromatic dispersion

Dye Lasers

A dye can selectively absorb light with certain wavelengths corresponding to certain electronic transitions. However, it may also emit fluorescence and even exhibit laser gain. A wide range of emission wavelengths—from the ultraviolet to the near-infrared region—is accessible with different **laser dyes**, most often used in a liquid solution. They offer a broad gain bandwidth and thus broad wavelength tunability as well as the potential for ultrashort pulse generation with passive mode locking (see p. 107). Upper-state lifetimes are typically a few nanoseconds, and the gain per unit length can be rather high (on the order of 10^3/cm).



Most **dye lasers** use a thin jet (with or without a thin cuvette) of dye solution. The dye molecules are exposed to the pump light only for a short time interval. From time to time, the dye solution has to be exchanged because it degrades during operation. The laser resonator may contain a birefringent tuner (or some other kind of tuner) for adjusting the emission wavelength.

There are also dye lasers that utilize a large volume of dye solution pumped with a flash lamp or a Q-switched laser. Such dye lasers can generate pulses with many millijoules.

While dye lasers have dominated the fields of tunable lasers and ultrashort pulse generation for a long time, they have been largely replaced by solid-state lasers (often based on Ti:sapphire), which avoid the disadvantages of handling poisonous dye solutions, a limited lifetime, and limited output power. However, dye lasers are still used in some areas, such as spectroscopy with wavelengths that are otherwise hard to generate.

Properties of Dye Lasers

Aspect	Properties
important types	continuous-wave or mode-locked Rhodamine 6G lasers; flashlamp-pumped lasers with various dyes
applications	spectroscopy; ultrashort pulse generation
pump sources	other lasers or flash lamps
power efficiency	a few percent to an order of 50%
accessible wavelengths	mostly visible and near infrared
wavelength tuning	possible over tens of nanometers
average output power	typically between 10 mW and 1 W, but >1 kW is possible
beam quality	normally diffraction-limited; worse for pulsed high-power devices
continuous-wave operation	yes
nanosecond pulse generation	yes, with pulsed pumping
picosecond & femtosecond pulse generation	yes, with mode locking

Gas Lasers

There are several lasers that use some gas as a laser gain medium. Even though such lasers greatly differ in terms of physical principles, emission wavelength, efficiency, and output power, they share certain aspects:

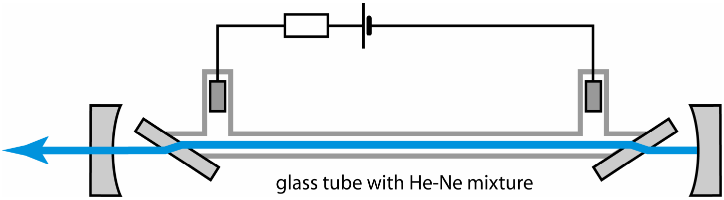
- Most **gas lasers** are pumped with an electrical discharge and thus require a high-voltage supply, often with high electrical power.
- Despite their low densities, gases can generate high optical gains due to their large emission cross sections (on "allowed" transitions). On the other hand, optical beam distortions caused by the gas are usually small.
- Gases are rather robust gain media, not prone to the problems associated with solids, such as fractures or defect creation. They may, however, be chemically modified or contaminated during laser operation, resulting in a limited lifetime, particularly for devices operating with high electrical current densities.

The most important types of gas lasers are discussed on the following pages and briefly listed here:

- Helium-neon lasers generate milliwatt powers at visible or infrared wavelengths, often with a narrow linewidth and good frequency stability.
- Argon- and krypton-ion lasers can generate multiwatt visible laser output with good beam quality but with poor power efficiency.
- Carbon-dioxide lasers are relatively efficient sources for 10.6-μm laser radiation and are widely used for material processing.
- Excimer lasers are powerful pulsed ultraviolet lasers.

Helium-Neon Lasers

A **helium-neon laser** is based on a tube filled with a mixture of helium and neon gas. An electrical glow discharge excites helium atoms, which transfer their energy to neon atoms during the collisions. Neon has several laser transitions, the most popular being in the red spectral region at 632.8 nm, with others at 1.15 μm, 543.5 nm (green), 594 nm (yellow), 612 nm (orange), and 3.39 μm. A particular wavelength is selected by using suitable resonator mirrors. Due to the low laser gain, the resonator loss has to be small, typically below 1%.



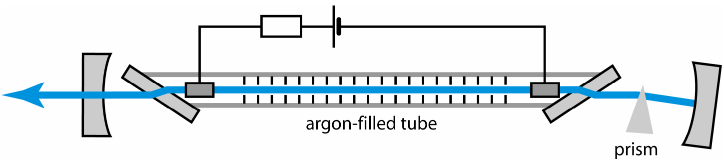
The above setup is based on a glass tube that could be used with different mirror sets and is terminated with Brewster windows. Low-cost devices often have internal mirrors that cannot be exchanged.

Typical HeNe lasers have a gas cell with a length of roughly 20 cm, and they can generate a few milliwatts of output power in continuous-wave operation at 632.8 nm, using several watts of electrical power. The beam quality is usually excellent.

Helium-neon lasers, particularly the standard devices operating at 632.8 nm, are often used for alignment purposes and are competing with laser diodes, which are more compact and efficient but have less convenient beam properties.

Argon-Ion Lasers

Argon-ion lasers are based on an argon-filled tube (often 1 m in length and made of beryllium oxide ceramics) within which an intense electrical discharge between two hollow electrodes generates a plasma with a high density of argon ions. A solenoid around the tube (not shown in the figure) can increase the power by confining the plasma.



More than 20 W of output power can be generated in the green spectral region at 514.5 nm, using more than 20 kW of electrical power. The dissipated heat must be removed by water flowing around the tube. There are smaller air-cooled devices that generate tens of milliwatts of output power from several hundred watts of electrical power.

By rotating the intracavity prism (on the right side) the laser can be switched to other wavelengths, such as 457.9 nm (blue), 488.0 nm (blue-green), or 351 nm (ultra-violet).

The argon-filled tubes are expensive and have a limited lifetime of a few thousand hours. Multiwatt argon-ion lasers can be used for pumping titanium-sapphire lasers and dye lasers, or for laser light shows. They are rivaled by frequency-doubled diode-pumped solid-state lasers, which are much more efficient, have a longer lifetime, but are more expensive.

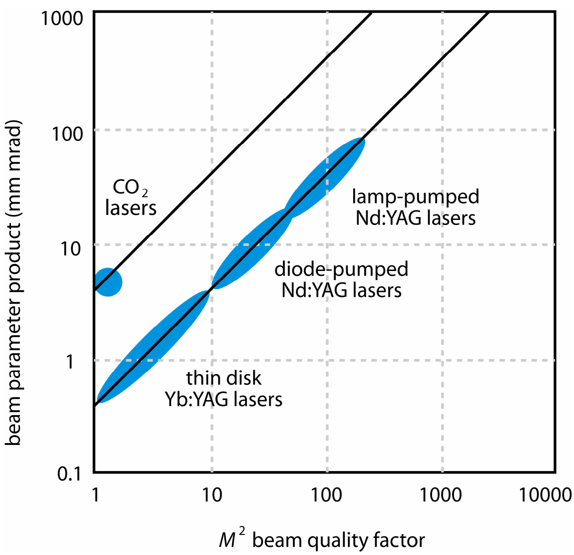
Properties of Ion Lasers

Aspect	Properties
important types	Argon- and krypton-ion lasers; helium-cadmium lasers
applications	pumping of Ti:sapphire lasers; laser shows
pump source	electrical current
power efficiency	order of 0.1%
accessible wavelengths	mostly in the visible, partly UV, and near infrared
wavelength tuning	switching between different lines
average output power	typically between 100 mW and 20 W
beam quality	normally diffraction-limited
continuous-wave operation	yes
nanosecond pulse generation	yes, with mode locking
picosecond & femtosecond pulse generation	≈100-ps pulses with mode locking

Carbon-Dioxide Lasers

Carbon-dioxide (CO_2) **lasers** are powerful and comparati-vely efficient gas lasers emitting at 10.6 µm or at other wavelengths around 9–11 µm. A gas discharge excites nitrogen molecules, which transfer their energy to the laser-active CO_2 molecules.

CO_2 lasers of different types span a wide range of powers—from tens of watts to many kilowatts or even several megawatts. While low-power versions can work with a sealed tube (no-flow lasers), high-power lasers use a fast gas flow. Continuous-wave and pulsed operation are possible.



Even at high power levels, CO_2 lasers often reach nearly diffraction-limited beam quality. Due to the longer wavelength, the beam parameter product is larger than that of diffraction-limited solid-state lasers (e.g., thin-disk lasers), but it is still smaller than that of many solid-state lasers with nonideal beam quality. The figure above gives a rough indication of the typical parameter regions.

Properties of Carbon-Dioxide Lasers

Aspect	Properties
important types	multi-kW TEA lasers; low-power, sealed-tube lasers
applications	laser cutting and welding; laser marking
pump source	electrical current
power efficiency	order of 10%
accessible wavelengths	mostly around 10.6 µm with other lines at 9-11 µm
wavelength tuning	quite limited
average output power	typically between 1 W and 50 kW
beam quality	normally diffraction-limited
continuous-wave operation	yes
nanosecond pulse generation	yes, with mode locking or Q switching
picosecond & femtosecond pulse generation	no

Excimer Lasers

Excimer lasers are pulsed gas lasers that typically emit ultraviolet light with average powers between several watts and hundreds of watts, pulse repetition rates up to a few kilohertz, and pulse energies of a few millijoules to hundreds of millijoules. The power efficiency varies between 0.2% and 2%.

In an excimer laser, a pulsed gas discharge produces excited molecules with a nonbinding electronic ground state. This means that these molecules disassociate after spontaneous or stimulated emission, so that reabsorption of the radiation is not possible. Typical molecules are shown in the table. (Most of them are asymmetric and thus, precisely speaking, not excimers = excited dimers.)

Excimer	Emission wavelength
F_2	157 nm
ArF	193 nm
KrF	248 nm
CeBr	282 nm
XeCl	308 nm
XeF	351 nm

The lifetime of an excimer laser can be limited by corrosion processes, gas contamination, and dust created by the electric discharge, apart from problems with the high-voltage electronics. However, engineering efforts over many years have substantially increased device lifetimes.

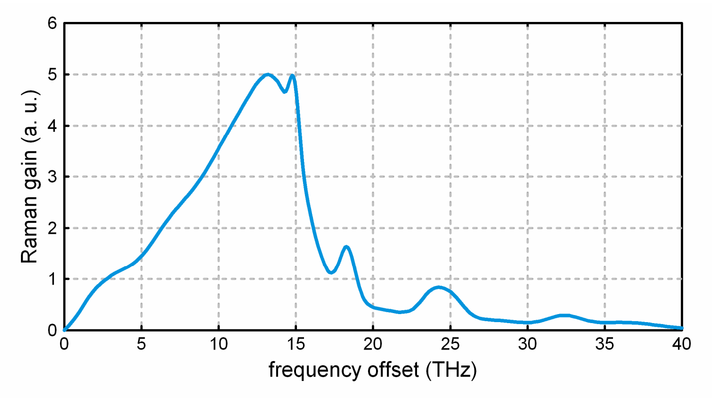
Excimer laser applications are manifold, including photolithography for semiconductor chips, laser ablation, pulsed laser deposition, laser marking, the microstructuring of transparent media, the fabrication of fiber Bragg gratings, eye surgery, psoriasis treatment, and dye-laser pumping.

Properties of Excimer Lasers

Aspect	Properties
important types	XeF lasers for 351 nm; ArF lasers for 193 nm; F_2 lasers for 157 nm
applications	UV lithography; laser ablation and pulsed laser deposition; laser marking; eye surgery; pumping dye lasers
pump source	electrical current
power efficiency	0.2% to 2%
accessible wavelengths	various lines in the ultraviolet region
wavelength tuning	quite limited
average output power	typically between 10 W and 300 W
beam quality	sometimes close to diffraction-limited; sometimes worse
continuous-wave operation	no
nanosecond pulse generation	always (pulsed pumping)
picosecond & femtosecond pulse generation	no

Raman Lasers

Raman lasers are based on amplification via stimulated Raman scattering rather than on stimulated emission from excited atoms or ions. In this nonlinear process, a pump photon is converted into a lower-energy signal photon and a quantum of lattice vibration (phonon) or molecular vibration. As this process can be stimulated by an incoming lower-energy photon, amplification of such light at a somewhat longer wavelength is possible.

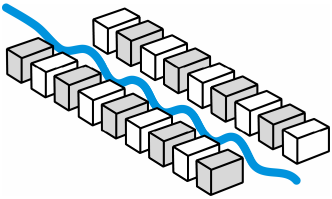


The figure above shows the Raman gain spectrum for silica, which is used, for example, in fibers. The maximum gain occurs at an optical frequency of ≈13 THz below the pump frequency (e.g., at ≈1.1-µm wavelength for a 1064-nm pump beam). By placing the pumped fiber in a laser resonator made with two fiber Bragg gratings, laser operation is achieved. It is even possible to use nested Bragg gratings for Raman wavelength conversion in multiple steps, spanning the range of 1064 nm to 1.5 µm.

Raman bulk lasers based on certain Raman-active crystals [e.g., $Ba(NO_3)_2$, $BaWO_4$, or $KY(WO_4)_2$] generate orange or red light from green pump light.

There are also Raman gas lasers, which only work with pulsed pumping because they require very high pump intensities.

Free-Electron Lasers



High-energy free electrons from a particle accelerator can emit photons when they are sent through an undulator, which generates a periodically varying magnetic field with an arrangement of permanent magnets. The photon energy depends on the electron energy, the undulator period, and (weakly) the magnetic-field strength.

The main appeal of **free-electron lasers** (FELs) is that they can be built for emission frequencies ranging from the terahertz region, through the infrared and visible spectrum, up to x rays. Also, a single device often allows wavelength tuning over a large range, and the output power can be very high.

As in many spectral regions, it is not easy to make resonator mirrors; many FELs work without such mirrors and rely on amplified spontaneous emission. This can still be relatively efficient if the gain is high enough. One then actually has a superluminescent source.

As the electron beams are usually pulsed, the FEL radiation also has a pulse structure. It is even possible to generate femtosecond pulses by letting the electron beam interact with an intense optical femtosecond pulse from an amplified mode-locked laser system.

The big disadvantage of FELs is their very large and expensive setup; they can only be used at relatively few large facilities. Typical applications are in the fundamental sciences (e.g., atomic and molecular physics, advanced material studies, chemistry, and biology) and in medicine; military applications are also considered. It might also be feasible to develop more compact FELs, which could find many more applications.

Chemically and Nuclear-Pumped Lasers

There are gas lasers that are not pumped with an electric discharge but rather convert chemical energy into laser light, typically in the mid- or near-infrared spectral region. There are, for example, hydrogen fluoride (HF) lasers (fueled with H_2 and F_2, which is converted to HF) and oxygen-iodine lasers (COIL). Although their use for material processing is possible, **chemical lasers** are studied mainly for military purposes (e.g., as antimissile weapons) onboard large airplanes. They can emit enormous optical powers in the megawatt region for a few minutes, until the fuel is exhausted.

An even more exotic type of laser is pumped by nuclear reactions. There are devices containing ^{235}U, where nuclear fission is triggered by neutrons, for example, from a pulsed nuclear reactor, and the fast fission products generate plasma suitable for laser gain. Also, there are powerful single-shot x-ray lasers pumped with radiation from a nuclear explosion. These are probably the least environmentally friendly lasers.

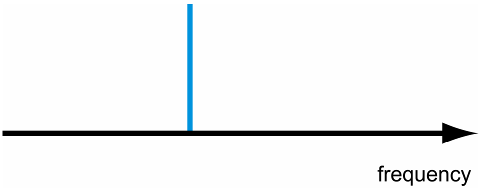
Single-Mode vs. Multimode Operation

Single-mode and multimode operation each have two different meanings:

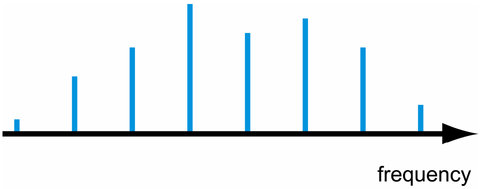
- In most cases, a single-mode laser is a device that only performs in a single resonator mode—usually an **axial mode**. This is sometimes emphasized by the term **single-axial-mode operation**.
- In some cases, it is appropriate to use **single-transverse-mode operation**, which allows for operation in multiple modes as long as they have the same transverse shape (usually close to a Gaussian shape).

The form of the optical spectrum strongly depends on the number and type of lasing resonator modes:

- In single-axial-mode operation (or single-frequency operation), the optical emission bandwidth (linewidth) is small—far below the axial mode spacing.

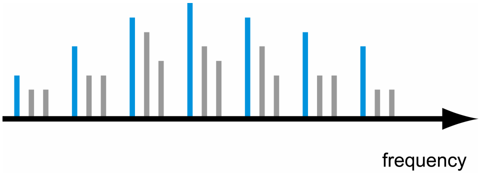


- With multiple axial modes, but no higher-order modes, the emission occurs at discrete and approximately equidistant frequencies. (Dispersion may cause a slight deviation from equidistant lines.)



Single-Mode vs. Multimode Operation (cont.)

- With higher-order modes also being excited, additional frequencies occur in the spectrum.



The number and type of oscillating modes depends on the circumstances:

- The excitation of **higher-order transverse modes** can often be avoided by pumping only the volume covered by the axial modes. This is often done, for example, in end-pumped solid-state lasers.

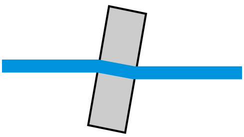
- Multiple axial modes may then still be excited if the gain bandwidth is larger than the axial mode spacing, which is the case in most solid-state lasers. This may be changed by using a medium with smaller gain bandwidth, by inserting an intracavity filter (e.g., an etalon), or by increasing the axial mode spacing (i.e., by using a very short laser resonator).

Note that there can also be various kinds of interactions between resonator modes in a laser:

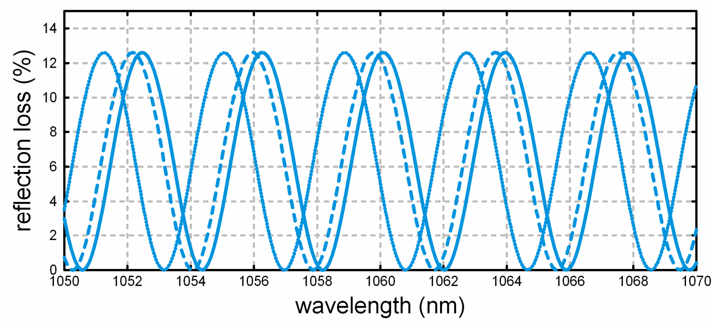
- Modes compete for gain generated by the same portions of the gain medium. If only axial modes having very similar intensity patterns are excited and no spatial hole burning occurs (e.g., in a unidirectional ring laser), mode competition is strong, and often only the mode with the highest gain will be excited.

- Parasitic reflections in the laser resonator and intracavity aberrations (e.g., of the thermal lens) can couple modes with each other.

Intracavity Etalons and Other Filters



An **etalon** is a thin transparent plate that acts as a Fabry-Pérot interferometer and is frequently used as an **intracavity frequency filter**. It is slightly tilted against the intracavity laser beam, and the tilt angle influences the frequencies of the optical resonances. This can be used for laser wavelength tuning. The figure below shows the spectrum of reflection losses for a 100-µm-thick fused-silica etalon with normal incidence (solid line) and with tilt angles of 2° (dashed line) and 4° (dotted line).

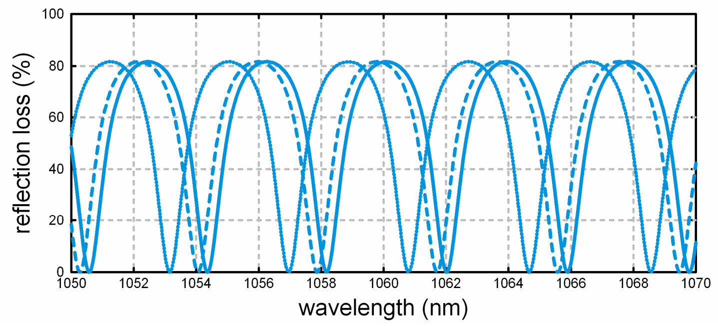


In principle, the interference effect is reduced by the tilt because it reduces the overlap of the counterpropagating beams, but this effect can be very small for thin etalons used in large-area laser beams.

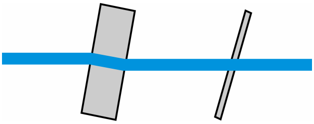
The transmission losses are lowest at the resonance frequencies. Because the thickness of the etalon is small compared to the resonator length, the free spectral range (spacing of the etalon resonances) is large compared to the resonator mode spacing. For an etalon that is too thin, lasing on multiple resonator modes close to a single etalon resonance may therefore still occur. On the other hand, an etalon that is too thick may allow lasing on modes corresponding to different etalon resonances.

Intracavity Etalons and Other Filters (cont.)

The etalon resonances may be sharpened without reducing the free spectral range by increasing the finesse with a reflective coating on both sides of the etalon. The figure below shows the transmission of the same etalon as before but with 40% reflecting surfaces.



It is also possible to combine two etalons with significantly different thicknesses; the thinner one is used for course tuning, and the thicker one is used for selecting a single resonator mode.



Other types of intracavity filters are **birefringent filters** (**Lyot filters**), which are often used in tunable bulk lasers, and fiber-pigtailed piezo-controlled resonators (with piezo-adjusted resonator length) for fiber lasers.

Examples of Single-Frequency Lasers

The following list presents an overview on the most important types of **single-frequency lasers**:

- There are various types of low-power laser diodes that often operate on a single resonator mode. Stable single-mode emission is achieved with VCSELs and distributed Bragg reflector lasers, which have a distributed Bragg reflector within the active region. Typical linewidths are in the megahertz region.

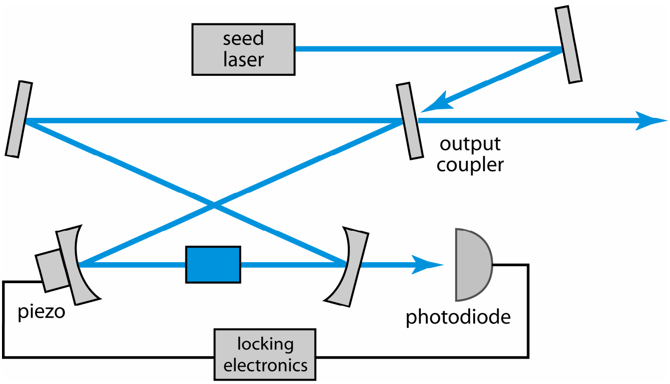
- Fiber lasers with a narrow-band output coupler (often a fiber Bragg grating) and a short resonator length (a few millimeters or centimeters) can also be stable single-frequency sources. There are also DFB fiber lasers and unidirectional fiber ring lasers with an intracavity filter selecting a single resonator mode. In any case, the linewidth can be a few kilohertz or even <1 kHz.

- Compact solid-state bulk lasers, such as nonplanar ring oscillators (NPROs; see p. 63), achieve output powers up to several watts combined with a linewidth of a few kilohertz.

Most single-frequency lasers have a very short laser resonator, which leads to large axial mode spacing, making it easier to enforce single-mode operation. If a longer resonator is used, a narrow-band intracavity filter is required; mode hops may still occur, for example, when the resonator length drifts away.

Injection Locking

High-power lasers are more difficult to stably operate in a single resonator mode because they tend to have longer resonators (with smaller axial mode spacing) and stronger fluctuations due to thermal effects or pump noise. To deal with these effects, the method of **injection locking** can be used.



Here, a single-frequency signal from a low-power seed laser is injected into the high-power laser; this “slave” laser can be forced to operate on the same frequency, provided the injected optical frequency is sufficiently close to the resonance of the slave laser resonator. That condition is usually maintained with an automatic feedback loop acting on the slave resonator length.

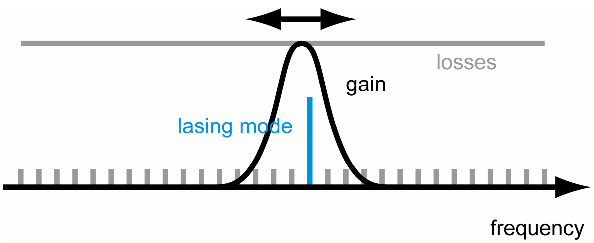
A variation of this method is called **self-injection locking**, where the seed signal is derived from the output of the laser itself with some kind of filter.

Injection locking should not be confused with **injection seeding**, as applied to some Q-switched lasers and pulsed optical parametric oscillators. Injection seeding does not necessarily imply emission in phase synchronism with the seed signal.

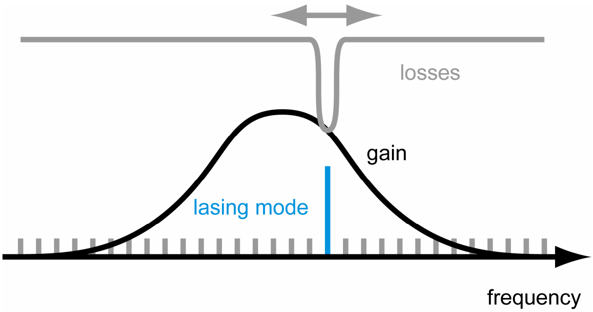
Principles of Wavelength Tuning

For some applications, the adjustability of a laser beam's wavelength (within some range) is a requirement. Different principles can be applied to accomplish that:

- The gain medium can be influenced in such a way that the wavelength of maximum gain is changed, and the output wavelength adjusts accordingly. For example, laser diodes are often tuned within a range of a few nanometers by adjusting the device temperature via the drive current or a thermoelectric cooler.



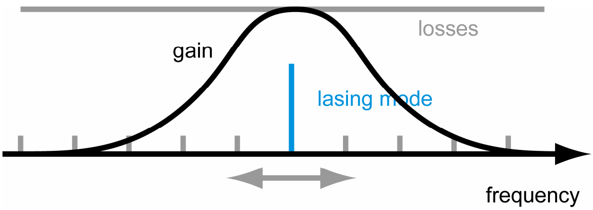
- An adjustable optical filter may be introduced into the laser resonator, which has a pronounced loss minimum at some wavelength, forcing the laser to operate close to that wavelength. This is applied to many types of lasers. For example, a birefringent (Lyot) filter may be used within a Ti:sapphire laser or an external-cavity diode laser's diffraction grating.



Principles of Wavelength Tuning (cont.)

For the figures on the previous page, it has been assumed that only a single resonator mode is oscillating. However, multimode emission is also possible, depending on the bandwidth of gains and losses and on other factors.

- A single-frequency laser can be tuned within approximately one free spectral range of its resonator by fine adjusting the resonator length, thus modifying the frequencies of the resonator modes. This method is applied, for example, to some miniature solid-state lasers.



Of course, the different techniques may be combined. For example, a larger tuning range can be achieved in the previous case by adding a tunable filter.

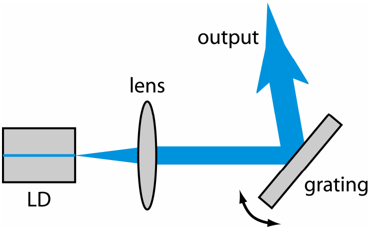
The saturation characteristics of the gain medium can be important for the tuning behavior. Ideally, the saturation is purely homogeneous. In that case, only the resonator mode with highest net gain (i.e., gain minus resonator loss) can oscillate because the gain for all other modes will be saturated to a value below their losses.

In high-gain lasers, such as fiber lasers, the **wavelength tuning range** can also be limited by ASE: if one tries to operate a laser at a wavelength that is far away from the gain maximum, ASE at wavelengths near the gain maximum may dominate the laser emission.

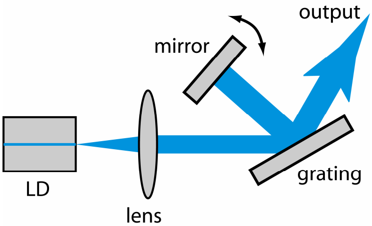
Tunable Diode Lasers

The emission wavelength of most **semiconductor lasers** can be tuned by modifying the gain maximum via the temperature of the active region (e.g., by varying the temperature of the heat sink or the drive current). The temperature coefficient is often of the order of 0.3 nm / K.

Diode lasers with a significantly larger tuning range (possibly tens of nanometers) can be realized in the form of external-cavity diode lasers with tunable wavelength-dependent resonator loss, most often obtained with a diffraction grating. The following two configurations are most often used:



In the **Littrow configuration**, a rotatable diffraction grating acts as the end mirror, and the zero-order diffracted beam is used as the output. The laser diode (LD) chip has an antireflection coating on the right side, and optical feedback is provided by the first-order diffracted beam from the grating. The wavelength can be tuned by rotating the grating, but this also rotates the direction of the output beam.



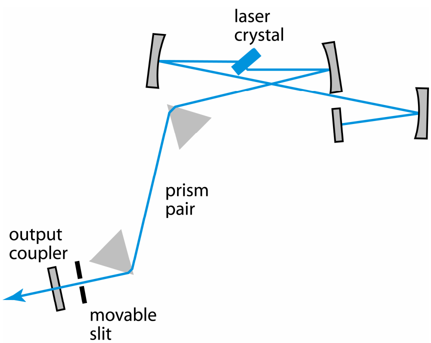
In the **Littman configuration**, the first-order diffracted beam is reflected back with a highly reflective mirror. Tuning is accomplished by rotating that mirror, while the grating and thus the output beam direction is fixed. Due to the limited diffraction efficiency, some of the light reflected by the mirror is lost, and the output power is somewhat reduced. On the other hand, the wavelength selectivity is higher, so the linewidth tends to be smaller than for a Littrow-type laser.

Tunable Solid-State Bulk and Fiber Lasers

Some solid-state bulk lasers allow for **wavelength tuning** in a large range with a width of tens (or even hundreds) of nanometers. Examples are:

- Ti^{3+}:sapphire: 0.6–1.1 μm
- Cr^{3+}:LiSAF, Cr^{3+}:LiCAF, and similar: ≈0.8–0.9 μm
- Cr^{4+}:forsterite: 1.1–1.37 μm; Cr^{4+}:YAG: 1.35–1.65 μm
- Cr^{2+}:ZnSe: 2–3.4 μm
- Er^{3+}:glass: 1.53–1.6 μm

Because such gain media only offer a limited amount of gain, an intracavity tuning element with moderate insertion loss must be used (e.g., a prism in conjunction with a movable aperture; see the figure). Lyot filters, which consist of stacked birefringent plates, are also common.



It is not always possible to cover a very broad tuning range with a single mirror set. Some lasers are therefore offered with different mirror sets for different wavelength regions.

Fiber lasers offer a higher gain and can therefore be tuned with a wider range of tuning elements, including diffraction gratings.

Other Tunable Laser Sources

There are various other types of broadband tunable laser sources:

- **Dye lasers** offer tuning ranges of tens of nanometers, often in the visible spectral region, but are no more popular because of their limited lifetime and handling issues (see p. 79).

- **Color-center lasers** use crystals with certain lattice defects (color centers), which are induced by gamma irradiation. Such crystals often have to be permanently cooled in order to prevent the thermally activated healing of the defects; therefore, they are not widely used.

- **Free-electron lasers** can be tuned in very wide ranges but are bulky and expensive.

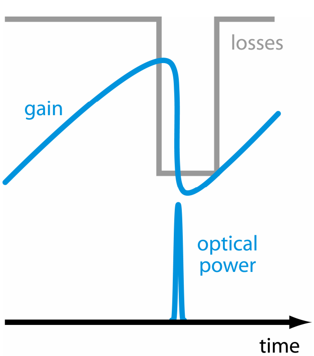
- **Optical parametric oscillators** (see p. 115) can convert laser radiation into broadly tunable radiation.

Q Switching

Q switching generates intense, short **pulses** (**giant pulses**) of laser light. The basic principle is as follows:

- In a first phase, the gain medium is pumped while energy extraction by laser light is prevented by keeping the resonator losses high. (This means that the Q factor is kept at a low value.)

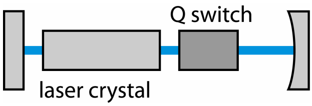
- Then, the resonator losses are suddenly reduced. Because the gain is then substantially higher than the resonator losses, the intracavity power exponentially rises (normally starting from the gain medium's weak fluorescence) until the gain is saturated and the power decreases again.



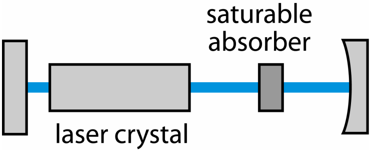
The generated light pulse can extract a large percentage of the energy that was stored in the gain medium. For high pulse energy, a gain medium with a high energy storage capability is used: desirable properties are a long upper-state lifetime, a high density of laser-active ions or atoms, and a gain efficiency that is not too high. (The latter is important because amplified spontaneous emission could otherwise limit the stored energy, and the initial loss of the Q switch required to prevent premature lasing would be very high.) Rare-earth-doped crystals and glasses are the most popular gain media. Bulk lasers (Nd:YAG, Nd:YLF, Nd:YVO_4, Yb:YAG, and Er:glass) are the most common, although fiber lasers can also be Q switched. Very compact bulk lasers can generate Q-switched pulses with multiple millijoules and durations of a few nanoseconds, leading to peak powers on the order of 1 MW.

Active vs. Passive Q Switching

Active Q switching, as described on the previous page, is based on active loss modulation. An acousto-optic modulator is often used in the resonator. While the RF power is applied to the modulator, this introduces large losses by diffraction into the first-order beam, which leaves the resonator. The pulse is triggered by suddenly switching off the RF power. For high pulse repetition rates, the crystal is continuously pumped, and the Q switch is triggered repetitively. For the highest pulse energies, pulsed pumping (e.g., with a flashlamp) and low pulse repetition rates are used.



Passive Q switching is an alternative technique, where the active modulator is replaced with a saturable absorber. For a Nd:YAG laser, for example, this can be a Cr^{4+}:YAG crystal. There are other saturable absorber crystals for other wavelengths, and SESAMs for various operation wavelengths.



The saturable absorber initially introduces a high optical loss. Once the gain reaches this loss level and the pulse begins to build up, the absorber is saturated (i.e., its loss is reduced), which further accelerates the pulse build-up.

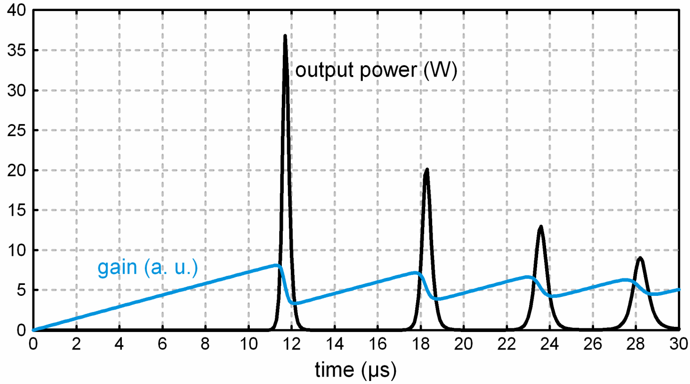
This method is simple and cost effective (eliminating the modulator and its electronics), and it is suitable for very high pulse repetition rates, but it typically leads to lower pulse energies and does not allow external triggering of the pulses.

The laser dynamics as well as damage and degradation phenomena in saturable absorbers impose certain restrictions on the pulse parameters. For example, a higher pulse repetition rate normally reduces the pulse energy and increases the pulse duration.

Gain Switching

Gain switching is another method for generating short **pulses**. It involves a modulation of the optical gain with, for example, nanosecond pump pulses or a sinusoidally modulated current to a laser diode. The obtained pulse duration can be shorter than the upper-state lifetime—for laser diodes well below 100 ps.

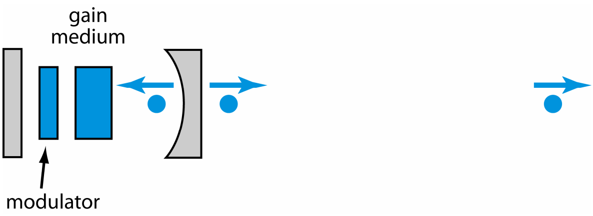
A major advantage of gain switching is its great flexibility: the pulse repetition rate and duration can be changed by simply modifying the corresponding properties of the pump pulses. However, the pulse energy and peak power are quite limited. For higher pulse energies, one may combine a gain-switched laser diode with a fiber amplifier. Such a system can have significant advantages over a Q-switched laser, particularly for high pulse repetition rates.



Gain switching can also be applied to optically pumped lasers (e.g., solid-state bulk lasers) by applying optical pump pulses from a Q-switched laser or from a diode laser in quasi-continuous-wave operation. The figure above shows a Nd:YAG laser simulation with a constant pump power turned on at $t = 0$. If the pump power were applied for only 15 μs, for example, only the first spike would be emitted, with a duration of only 0.35 μs.

Active Mode Locking

Mode locking is the most important technique for generating pulses (called **ultrashort pulses**) with picosecond and femtosecond durations. In the mode-locked state, a pulse with a duration well below the round-trip time is circulating in the laser resonator. Each time it hits the output coupler mirror, a pulse is emitted, so the laser output is a regular pulse train. The pulse repetition rate is determined by the resonator's round-trip time.



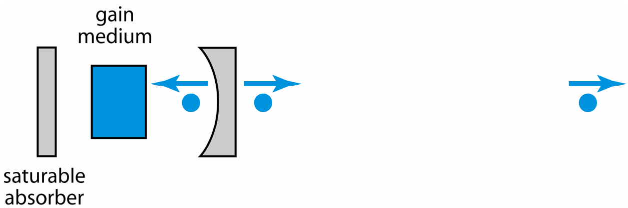
In an **actively mode-locked laser**, as shown above, mode locking is achieved with a modulator (e.g., of an electro-optic type), which modulates the resonator losses in exact synchronism with the resonator round trips. The pulse goes through the modulator at times when the losses are smallest, and the slightly higher losses in the pulse wings slightly shorten the pulse. After thousands of round trips, the pulse reaches a steady state where the shortening effect is balanced by pulse-broadening effects (e.g., the limited gain bandwidth or chromatic dispersion). The pulse duration of actively mode-locked solid-state lasers is typically some tens of picoseconds.

Synchronism of modulation and resonator round trips can be maintained with precise resonator length adjustment or with an automatic feedback system, which may adjust the modulator frequency.

By driving the modulator at an integer multiple of the resonator round-trip frequency, **harmonic mode locking** may be obtained, where multiple pulses are circulating in the laser resonator.

Passive Mode Locking

Shorter pulses can be generated with a **passively mode-locked laser**, where the loss modulation is performed by a **saturable absorber**, such as a **SESAM**. This mechanism is more effective because the shorter the pulses become, the faster is the loss modulation. The achieved pulse duration can even be an order of magnitude smaller than the recovery time of the saturable absorber. It is determined by a balance of various effects, including the pulse shaping on the saturable absorber, pulse broadening by the limited gain bandwidth and chromatic dispersion, and optical nonlinearities (i.e., the Kerr effect in the gain medium).

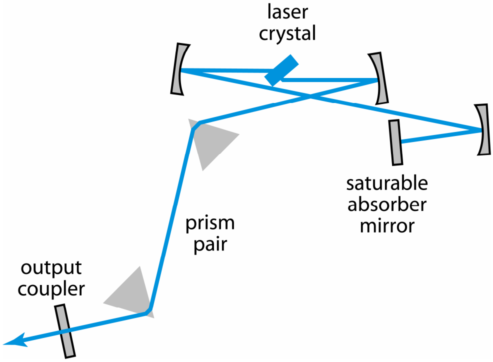


Synchronism of the loss modulation is automatically achieved, and an electronic driver is not required. However, the pulse generation can become unstable for various reasons. For example, optical nonlinearities can lead to pulse break-up, and the saturable absorber may cause Q-switching instabilities where the pulse energy undergoes strong fluctuations. A detailed understanding of various pulse shaping effects, optical nonlinearities, and laser dynamics is required for optimizing the design of a passively mode-locked laser.

The term **mode locking** resulted from an interpretation in the frequency domain: in the mode-locked state, several axial resonator modes are oscillating with a locked relative phase. However, the basic physical phenomena are more easily understood in the time domain.

Examples of Mode-Locked Solid-State Lasers

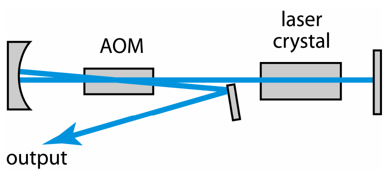
The figure below shows the setup of a typical passively mode-locked femtosecond bulk laser. Mode locking is achieved with a SESAM. A prism pair is used for dispersion compensation. Typically, the normal dispersion from the laser crystal is overcompensated, so that the overall chromatic dispersion is anomalous: the group velocity rises with increasing optical frequency. In that regime, called **soliton mode locking**, chromatic dispersion and the Kerr nonlinearity of the laser crystal work together to shape soliton-like pulses. This effect often dominates the pulse shaping, and the saturable absorber only stabilizes the pulses by preventing the build-up of competing continuous-wave radiation.



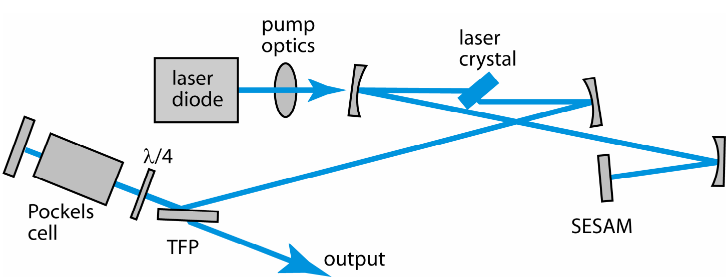
The shortest possible pulse duration (≈5 fs) can be achieved with a Ti:sapphire laser if the chromatic dispersion is very carefully controlled. Various diode-pumped mode-locked lasers are suitable for pulse durations between about 30 fs and 30 ps. Passively mode-locked thin-disk lasers have generated up to 80 W of average power in subpicosecond pulses. While typical pulse repetition rates of mode-locked solid-state lasers are between 50 MHz and 500 MHz, there are miniature lasers with high repetition rates of 10–100 GHz. High repetition rates are also achieved by harmonic mode locking, with multiple pulses circulating in the resonator.

Cavity Dumping

Cavity dumping is a technique for generating energetic **pulses**, which is quite distinct from Q switching. A pulse is built up within the laser resonator while the resonator losses are kept as small as possible (without output coupling). When the maximum pulse energy is reached, the pulse is extracted ("dumped") with an optical switch, such as an acousto-optic or electro-optic modulator. The figure shows a laser with an acousto-optic modulator (AOM), which extracts power by deflecting the beam when the RF input is switched on. The same AOM may first be used for Q switching and then for cavity dumping. Compared with simple Q switching, many shorter pulses can be obtained because the energy can be extracted within a few round trips, even if the preceding pulse build-up phase is longer.



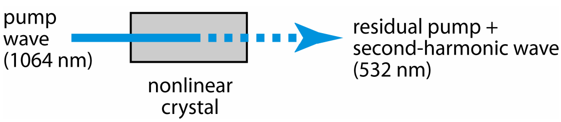
Cavity dumping is also often used with mode-locked lasers. The figure below illustrates how a Pockels cell is used to extract an ultrashort pulse as soon as it has reached its maximum energy within tens of resonator round trips. In that way, pulses with multiple microjoules and repetition rates in hundreds of kilohertz (or even a few megahertz) can be generated.



Design challenges can arise from the dispersion and Kerr nonlinearity introduced by the Pockels cell, which can affect the pulse formation process.

Frequency Doubling

Coherent visible and ultraviolet light is often generated by a laser with a longer wavelength and converting its output in a frequency doubler crystal, where the optical frequency is doubled, and thus the vacuum wavelength is reduced to one half of the original value. This is attractive because infrared lasers generally offer much higher performance than visible or UV lasers.



The principle behind **frequency doubling** (also called **second-harmonic generation**) is described as follows:

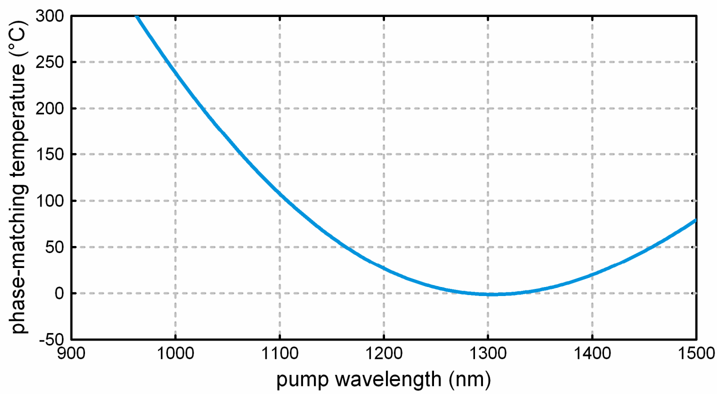
- The laser beam induces an oscillating polarization in the crystal, which (for crystals with $\chi^{(2)}$ nonlinearity) has a component with twice the pump frequency. This polarization wave always propagates with the same phase velocity as the pump beam.

- The nonlinear polarization wave radiates an optical field with the doubled frequency, propagating in the same direction.

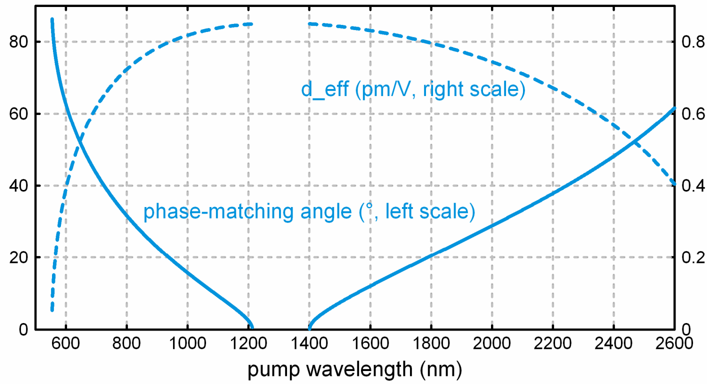
Note that the latter is a coherent process, where different portions of the crystal contribute to the overall second-harmonic amplitude (not intensity) at the crystal's exit face. In general, these portions would not be in phase with each other due to the different phase velocities of the fundamental (pump) wave and the second-harmonic wave. However, efficient power conversion is possible by **phase matching** the interaction, where one exploits, for example, the crystal's birefringence: the polarization dependence of the phase velocity may exactly compensate for the chromatic dispersion at a certain temperature or crystal orientation. Another option is quasi-phase matching in periodically poled crystals.

Frequency Doubling (cont.)

For example, the graph below shows the required phase-matching temperature for frequency doubling in lithium triborate (LBO) in the direction of the *X* axis.



In the same material, critical phase matching may also be achieved at room temperature with, for example, the beam propagating in the *XY* plane, with an angle φ against the *X* axis. The next diagram shows the phase-matching angle and the effective nonlinearity as functions of the pump wavelength.



Frequency Doubling (cont.)

Frequency doubling can be done with a power conversion efficiency of >50%, sometimes even >80%. However, this requires very high optical intensities obtained either with short or ultrashort laser pulses, with a resonant enhancement cavity, or with a nonlinear waveguide. Intracavity frequency doubling may also be done, where the crystal is placed within the laser resonator.

A common case is frequency doubling of a 1064-nm Nd:YAG or Nd:YVO_4 laser beam to obtain green light at 532 nm. This may be done with nonlinear crystal materials, such as LBO, KTP, or $LiNbO_3$. Blue light can be obtained, for example, by doubling the output of a 946-nm Nd:YAG laser in an LBO, BIBO, or $KNbO_3$ crystal. By using two subsequent frequency doublers (frequency quadrupling; see p. 114), ultraviolet light may be generated.

The choice of crystal material can depend on the available pump intensity, transparency ranges and residual absorption, phase-matching details (e.g., concerning crystal temperature or spatial and temporal walk-off), and lifetime requirements. Particularly at short wavelengths, some crystals tend to exhibit detrimental effects, such as gray tracking or photorefractive distortions, and the increased chromatic dispersion may make the phase-matching bandwidth in terms of angular orientation rather small.

The overall design of a frequency doubler—including the choice of crystal material, crystal length, phase-matching details, and possibly resonant enhancement or intracavity operation—has to meet a combination of requirements concerning conversion efficiency, various tolerances, lifetime issues, crystal availability and price, and possibly beam quality.

Sum and Difference Frequency Generation

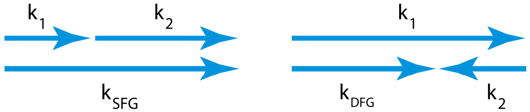
A technique somewhat less common than frequency doubling involves sending two input beams with different wavelengths into a nonlinear crystal in order to generate a beam with either the sum or the difference of the two optical frequencies. For example, beams at 1064 nm and 1535 nm may be mixed to obtain a beam with a wavelength of either

$$\frac{1}{\left(\frac{1}{1064\ \text{nm}}+\frac{1}{1535\ \text{nm}}\right)}=628\ \text{nm}$$

[**sum frequency generation** (SFG)] or

$$\frac{1}{\left(\frac{1}{1064\ \text{nm}}-\frac{1}{1535\ \text{nm}}\right)}=3468\ \text{nm}$$

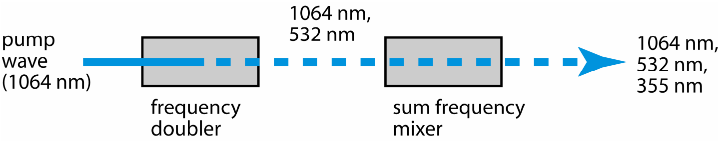
[**difference frequency generation** (DFG)]. Both processes can occur in a crystal with $\chi^{(2)}$ nonlinearity, but usually only one of them will be phase-matched, and the other one will be very weak. The phase-matching condition (for collinear beams) means that the sum of the input beams' wave numbers matches the wave number of the generated beam. Note that this does *not* require equal phase velocities for all involved waves.



Apart from phase matching, the crystal should have good transparency for all three involved waves, which often limits the achievable wavelength range, for example, of efficient midinfrared sources. It is possible, however, to reach the terahertz regime (with optical frequencies as low as a few THz or less), where transparency may be reasonable; even for good quantum efficiency, the power efficiency is then limited by the fact that the photon energy of the generated THz wave is far below that of the optical beams.

Frequency Tripling and Quadrupling

Frequency tripling is nonlinear frequency conversion where the output optical frequency is three times the pump frequency. This is usually not done directly, but by first using a frequency doubler, and thereafter a second crystal for sum frequency generation, mixing the second-harmonic light with residual (unconverted) pump light.



A common case is the generation of 355-nm ultraviolet light with a 1064-nm Nd:YAG laser (see the figure). For example, two LBO crystals may be used, each one being phase-matched for the corresponding interaction.

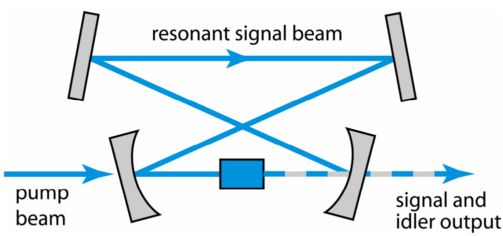
Frequency quadrupling is done with two subsequent frequency doublers. For example, it allows for the generation of 266-nm light from a Nd:YAG laser, using an LBO and a CLBO (cesium lithium borate) crystal.

Efficient frequency tripling and quadrupling are relatively easy to achieve when starting with a Q-switched laser, so that the peak intensities can be high in both nonlinear crystals. For continuous-wave beams, it is more difficult to make the second stage efficient. One possibility is to use a resonant frequency doubler or sum frequency mixer for that stage.

Challenges can also arise from the short wavelengths involved because they can introduce material issues (e.g., transparency range, lower damage threshold, and a limited lifetime under intense UV irradiation) and lead to a very small acceptance bandwidth due to strong chromatic dispersion. For conversion of ultrashort pulses, the large group velocity mismatch can limit the useful crystal length, and thus the conversion efficiency, as the optical intensities are limited by the damage threshold.

Optical Parametric Oscillators

In the process of difference frequency generation, the lower-frequency input wave is actually not depleted but amplified: each input photon of the higher-frequency wave is split into a photon of the lower-frequency input wave and one of the generated wave. This is the process of **parametric amplification**, which is the basis for laserlike devices called **optical parametric oscillators** (OPOs). Here, a higher-frequency beam serves as the pump, while a lower-frequency **signal** beam circulates in a resonator, with its losses being compensated by parametric amplification. A third beam (the **idler**) is generated, which may be resonant as well (in a doubly resonant OPO), but it is often directly extracted from the resonator (in a singly resonant OPO). By affecting the phase-matching conditions (e.g., via crystal temperature or angle) or the pump wavelength, the output wavelength can be tuned within a wide range. The primary advantages of OPOs are their wide tunability and the possibility of accessing various wavelength regions.



Ring resonators (as shown in the figure) are relatively common for OPOs, but linear resonators are also possible. It can be a disadvantage, though, to have losses in or at the crystal twice per round trip but amplification only once (for propagation in the pump direction). A ring resonator also prevents reflections from going back to the pump laser, which may destabilize that laser.

Some OPOs are suitable for continuous-wave operation, many others for pulsed pumping with Q-switched lasers, and others for synchronous pumping with ultrashort pulses from a mode-locked laser.

Forms and Origins of Laser Noise

The term **laser noise** refers to random fluctuations of laser light's various parameters. Such fluctuations occur in many different forms:

- A single-frequency laser can exhibit **amplitude** (intensity) **noise** and **phase noise**, apart from beam pointing and polarization fluctuations.

- A multimode laser can also have a fluctuating distribution of optical power on the oscillating resonator modes as well as **mode-beating noise**.

- For transverse multimode emission, the beam profile can exhibit significant fluctuations.

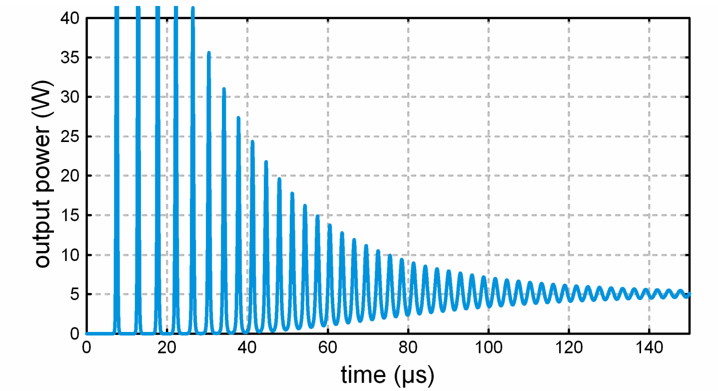
- In mode-locked lasers, noise can occur as **timing jitter** of the generated pulses but also as fluctuations of mean frequency, pulse duration, chirp, and other parameters.

Perhaps the simplest form of noise is **intensity noise** (fluctuations of the output power), as recorded, for example, with a photodiode. **Phase noise** is related to the temporal coherence and to the optical bandwidth of a single-frequency laser, and it is very important in optical frequency metrology.

Laser noise partly results from **quantum noise** (in particular, the noise associated with spontaneous emission in the gain medium) and partly from **technical noise** arising, for example, from excess noise introduced by the pump source, vibrations of the laser resonator, or temperature fluctuations. Technical noise is usually stronger at low noise frequencies, while quantum noise can dominate at high frequencies. Noises influences at frequencies around the relaxation oscillation frequency (see p. 117) can have a particularly strong impact.

Relaxation Oscillations and Spiking

In the steady state of continuous-wave operation, the gain in a laser exactly compensates for the resonator losses, and the optical power stays constant. After an external perturbation (e.g., a short spike in the pump power), a laser will often not directly return to the steady state but rather exhibit some damped oscillations of the power. For small deviations from the steady state, these are small sinusoidal oscillations, while for larger deviations (e.g., when suddenly turning on the pump power) there can be strong spikes. Such behavior is particularly pronounced for solid-state doped-insulator lasers that have low laser cross sections and long upper-state lifetimes.



The essential dynamics of **spiking** and **relaxation oscillations** can be studied with a simple set of two coupled differential equations that describe the coupled evolution of optical power and laser gain. The following approximate formula is useful for determining the relaxation oscillation frequency:

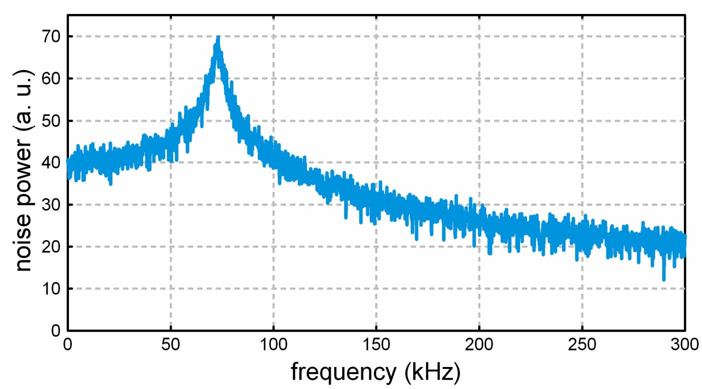
$$f_{\mathrm{ro}} = \frac{1}{2\pi}\sqrt{\frac{l\,P_{\mathrm{int}}}{E_{\mathrm{sat}}T_{\mathrm{rt}}}}\,,$$

where l denotes the total resonator losses per round trip (including output coupling), P_{int} is the intracavity power, E_{sat} is the saturation energy of the gain medium, and T_{rt} is the resonator round-trip time.

Noise Specifications

Intensity noise is fluctuations of the output power (not the optical intensity). Its measurement starts with recording the optical power (e.g., with a photodiode). The result is often quantified as an rms (root-mean-square) relative intensity noise (RIN). Note, however, that the obtained value depends on the temporal resolution and duration of the measurement—in other words, on the considered range of noise frequencies.

Much more information is contained in a **noise spectrum** (i.e., a plot of power spectral density versus noise frequency). A laser's intensity noise spectrum (see the figure) often exhibits a peak at the relaxation oscillation frequency, some lower-frequency noise, and a stronger decay at higher noise frequencies.



The units of the **power spectral density** (PSD) of **relative intensity noise** are 1/Hz. It is also common to specify a decibel value, which is 10 times the logarithm of the PSD. For example, a PSD of 10^{-12}/Hz corresponds to -120 dBc/Hz.

Similar PSDs can be used for **phase noise** (with units of rad^2/Hz) and for other fluctuating quantities. Unfortunately, many technical and mathematical pitfalls can invalidate noise measurements and specifications when they are done without sufficient expertise.

Schawlow-Townes Linewidth

Even if a single-frequency laser were perfectly shielded against all external noise sources, quantum noise influences would still introduce some level of phase noise, which causes a finite linewidth (equal to the optical spectrum width). Qualitatively, this can be explained in a simple way: stimulated emission in a laser-gain medium is always accompanied by spontaneous emission into the laser mode, which introduces random phase changes.

Even before the first laser was built, A. L. Schawlow and C. H. Townes calculated the quantum limit for the **linewidth** and arrived at the famous **Schawlow-Townes formula**. A more convenient form of it is

$$\Delta\nu_{\text{laser}} = \frac{h\nu\, l_{\text{tot}} T_{\text{oc}}}{4\pi\, T_{\text{rt}}^2\, P_{\text{out}}},$$

where $h\nu$ denotes the photon energy, l_{tot} is the total cavity losses per round trip, T_{oc} is the output coupler transmission, T_{rt} is the cavity round-trip time, and P_{out} is the output power.

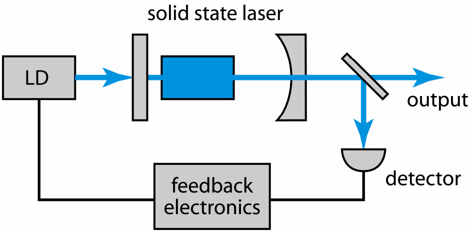
The formula shows that a very small linewidth is possible for lasers with a long low-loss resonator and high output power. However, the quantum limit is hard to reach, particularly with long high-power lasers. The smallest linewidths, as achieved with some compact solid-state bulk or fiber lasers without active stabilization, are a few hundred hertz.

Single-frequency laser diodes often exhibit a significantly higher noise, resulting mainly from amplitude-phase coupling. That effect can be quantified with the **linewidth enhancement factor** α, and the linewidth is increased by a factor $1 + \alpha^2$.

Laser Stabilization

Laser noise can be reduced by optimizing the laser design and with various active or passive stabilization schemes. Active schemes usually involve some form of electronic **feedback system**. Here are some example **stabilization** methods:

- An electronic feedback system can monitor the laser power and stabilize it by adjusting the pump power. This may suppress **intensity noise** and reduce spiking, for example, after turn-on.



- The optical frequency of a single-frequency laser may be stabilized with a feedback system controlling the resonator length via a piezo actuator. The error signal may be obtained with a stable reference cavity, with an absorption cell containing some molecular or atomic vapor, or by recording a beat note with a reference laser.

- The **timing of pulses** from a passively mode-locked laser can be locked to an electronic signal by automatically adjusting the length of the laser resonator.

- **Beam pointing fluctuations** may be reduced by monitoring the beam position with a four-quadrant detector and correcting it by tilting mirrors via piezo actuators.

Overview on Laser Hazards

The operation of lasers can involve a number of hazards, including the well-known risk of **eye damage** resulting from exposure to extreme optical intensities. As the output power of many lasers is orders of magnitude higher than what an eye can tolerate for a millisecond, even weak reflections (e.g., from optical elements or tools) can be dangerous. The high spatial coherence of laser light is a special risk factor because it allows the eye's lens to focus the light to a very tiny spot on the sensitive retina. The greatest hazard arises from intense laser pulses (e.g., from Q-switched lasers): a single shot from a tiny hand-held device can totally destroy an eye.

Intense light can also cause **skin injuries**. While infrared light causes simple burning, ultraviolet light also causes photochemical effects that can lead to skin cancer and other skin conditions.

It is often overlooked that lasers can involve many **other hazards**, which are often not related to the laser light. Examples include working with high-voltage power supplies (e.g., during maintenance operations), poisonous chemicals (e.g., carcinogenic dye solutions), and potentially exploding or imploding glass tubes in lamp-pumped lasers. Note also that laser radiation can have unexpected side effects, such as incinerating materials, creating poisonous fumes or dust, or generating secondary radiation (e.g., X rays).

Safety regulations mandate that laser devices be assigned **laser safety classes**, which are meant to roughly quantify the risk (mainly for eyes and skin) of working with such devices. This classification does not apply just to the laser but rather to the whole device. For example, a 1-kW laser is deemed class 1 (the least dangerous) when suitably enclosed, completely shielding the laser user from exposure, while an open 1-W laser setup in a laboratory is class 4 (the most dangerous).

Safe Working Practices

Laser users should not primarily focus on the details of laser safety classifications but on the risks and how to minimize them with suitable working practices. Suitable measures strongly depend on the circumstances, not only on the laser device itself. Some common **technical measures** include:

- Encapsulating laser resonators, beam lines, etc. as much as possible, which prevents dangerous levels of optical power from leaving the setup;
- Installing interlocks that automatically shut off a laser or block its beam when a door or encapsulation is opened;
- Using protective eyewear (laser goggles) in dangerous areas; and
- Using warning lights, symbols, written explanations, etc. around dangerous areas.

However, technical measures are usually not sufficient. Essential **nontechnical measures** also have to be implemented:

- Assess every hazard and reassess the situation when changes in the environment (e.g., in devices, applications, staff, rooms, etc.) may modify the hazards.
- Educate laser users on the hazards and required safety measures.
- Define the responsibilities of every staff member.
- Establish a spirit that motivates staff members to take these safety issues seriously, suggest practical solutions, etc.

Common Challenges for Laser Safety

It is important to be aware of the common problems and circumstances that can undermine **laser safety**:

- Safety measures can be in conflict with the requirements of convenient, routine operation. It can be difficult and time-consuming to resolve such conflicts in a satisfactory manner, and such efforts are often not sufficiently rewarded.

- Laser safety regulations can be perceived as annoying restrictions rather than important protections, especially if they are designed primarily to create legal protections for superiors instead of safe working practices.

- Excessive pressure to quickly achieve results can lead people to simplify their task by ignoring safety issues.

- Some risks may be easily overlooked, and the awareness of certain risks (e.g., from invisible high-power laser beams) can disappear if they cannot be directly perceived. This can also happen to experienced users.

- Various changes in the working environment (e.g., staff, devices, applications, rooms, etc.) can introduce new risks in nonobvious ways. Consequently, safety measures must be constantly adjusted to changing conditions.

- Some common types of irrational risk assessment and inappropriate judgment regarding working routines (e.g., “We have always done it like this!”), particularly when promoted by superiors, can totally undermine the effect of any formal safety regulations.

Designing a Laser

Designing a laser is the process of working out the essential construction details. For example, the design of a Q-switched diode-pumped solid-state bulk laser involves:

- The choice of pump diodes;
- The geometry of the gain medium and the pumping arrangement;
- The selection of a laser crystal (e.g., material, dimensions, orientation, and doping level);
- The details of the Q switch (e.g., type, size of the open aperture, switching speed, and electronic driver); and
- The resonator design and the selection of optical components (e.g., laser mirrors with a certain curvature radius, coatings, damage threshold, etc.) and their exact arrangement.

In addition, details like component mounting or temperature stabilization may be considered.

The laser is made to meet certain **design goals**, such as output power, beam quality, pulse duration, spectral width, possible pulse repetition rate, compactness, alignment sensitivity, noise, reliability, and lifetime.

Typical challenges include:

- The complexity of physical interactions (e.g., one design detail influencing several important properties and complicated trade-offs);
- Difficulties in the design process and the interpretation of experimental results;
- Unexpected effects discovered in the prototype, causing a need for late adaptations; and
- Material parameters that are not precisely known (e.g., cross sections, thermal conductivity, and quantum efficiency).

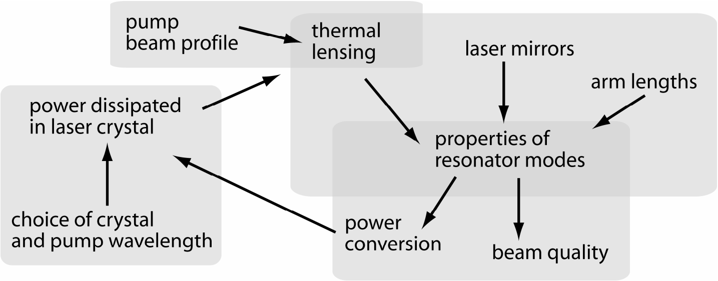
Laser Modeling

A **model** resembles the properties of a real object and can be used to gain a better understanding of that object. Some important aspects of **laser models** include:

- Mathematical structure: a laser model contains variables and parameters, and mathematical relations between them, based on certain physical assumptions.

- Abstraction: a model is always simpler than reality; ideally, it is as sophisticated as needed to reproduce the essential features of the real object.

Different models may be used to investigate different aspects of a single laser, such as heat flow in the gain medium, the population of metastable levels, the properties of resonator modes, or the dynamics of gain and optical power. Such aspects should be separated as much as possible: a model containing every aspect would be complex and difficult to handle, and it is needed only where different physical effects interact in an essential way.



The figure shows that different aspects of a laser may, in reality, be coupled with each other. However, many essential properties can be studied separately (and with greater understanding) with a model containing only the aspects shown in one of the boxes above. There are often trade-offs between physical accuracy and other desired features, such as a simple structure (allowing for intuitive understanding) and computational efficiency.

The Development Process

The essential goals of a **laser development project** are:

- Finding a suitable laser design and demonstrate (with a prototype) that it meets the requirements; and
- Achieving this with a minimum of invested time and resources, such as manpower, materials, occupied lab infrastructure, etc.; "time to market" must also be considered.

The success of development projects strongly depends on the technical knowledge and experience of the staff and on the chosen methodology, apart from factors such as lab infrastructure, availability of parts and diagnostics, etc.

Development begins with a theoretical plan and also involves experimental steps. Maximum efficiency requires a sensible strategy and appropriate allocation of resources to each step in the process. A frequent mistake is to quickly work out a plan that is too superficial: this often causes a waste of resources as unexpected problems can occur in the prototype that need to be analyzed based on (potentially misleading) experimental observations and then require design changes, which can again have unwanted side effects. The opposite mistake is comparatively rare: setting up overly complicated theoretical models for issues that are more efficiently clarified with experimental tests. The following should be kept in mind:

- Analyzing unexpected behavior in a laser model is usually much faster and cheaper than doing it experimentally with the prototype, because a model is simpler, cleaner (i.e., it is less prone to unexpected external influences), more transparent (i.e., it allows the monitoring of internal properties), and easier to modify. Therefore, the design iterations should be made as much as possible in that stage (on the desk, not in the lab), which should result in a theoretically well-tested preliminary laser design.

The Development Process (cont.)

- However, experiments are required to test whether the made assumptions are correct. Discrepancies between experiment and model may occur for various reasons (e.g., unexpected effects, errors in the model, wrong material data, and construction faults), and their observation (which requires experiments *and* models) can be the starting point for a better understanding of the system.

An iterative process is hardly avoidable in nontrivial cases. Its cost will strongly depend on how much experimental work is involved in these iterations.

A strategy that often does *not* work with lasers is to start with an incomplete design and solve problems step by step (i.e., by introducing subsequent refinements). This is partly due to the cost of modifying components later on (e.g., when a reduction of the resonator mode size in the laser crystal requires a change of pump optics and a rebuilding of the whole laser resonator). The main reason, however, is the complexity of laser physics: changing one aspect can affect several others in complicated ways. Optimized designs depend on the understanding of certain trade-offs, because it is nearly impossible to find those parameter combinations by trial and error within a reasonable time.

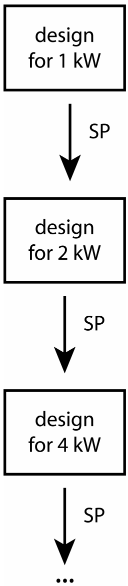
The same problems often apply to designs inspired by an older design (e.g., with lower output power). Substantial performance increases often require one primary measure plus several others to keep various issues under control. Finding those via trial and error can be overly time consuming. On the other hand, a sensible laser design, described in a well-written design document discussing every important issue, may easily allow the design of modified versions.

Power Scaling

The term **power scaling** is often used in a very vague sense, meaning nothing more than some improvement in the output power of a laser system. However, the concept of scaling can and should be used in a more meaningful sense, as it is done in other technological disciplines (e.g., computing, telecommunications, and manufacturing).

Power scaling in a meaningful sense must be based on a **scaling procedure** (SP), which is a systematic method of modifying an existing (and working) laser design into one with, for example, twice the output power. A real power scaling procedure should fulfill the following basic criteria:

- It should be clearly defined, exactly explaining how to modify the original laser design.
- It should be repeatable, which implies
    - That the application of the procedure should not spoil essential features of the original design (e.g., beam quality or power efficiency);
    - That the procedure should not rely on arbitrarily improved subcomponents; and
    - That none of the central challenges (e.g., cooling the laser medium) becomes significantly more severe.



If such a scaling procedure can be found, it will be relatively easy to realize laser designs with a wide range of output powers—without doing any additional inventive steps. The corresponding laser architecture can then be called truly **power scalable**.

Power Scaling (cont.)

Unfortunately, most laser types are *not* power-scalable. For example, consider a rod laser (see p. 59) where the heat is extracted in a direction transverse to that of the laser beam. Thermal lensing then inevitably gets stronger for higher powers. While the dioptric power of the thermal lens may be reduced by making the pumped area larger, larger resonator modes are also required to preserve the beam quality. The higher sensitivity of such modes to lensing effects just cancels the beneficial effect of a smaller dioptric power. There are many possible ways to mitigate such effects to some degree (e.g., cryogenic cooling, better laser crystals, and improved resonator design), but such measures are not repeatable and should not be called power scaling.

The situation is different, for example, in a thin-disk laser (see p. 62). As a result of the different cooling geometry (with longitudinal heat flow), thermal lensing does *not* become more severe for higher powers if the mode area is scaled in proportion to the pump power. This holds at least as long as the effects of thermally induced stress are small enough, and these can be minimized, for example, by using a rather thin disk.

It can be very useful to analyze not only the scalability of a laser system as a whole but also to apply the concept to isolated aspects (i.e., thermal lensing in gain media, on laser mirrors, or in saturable absorbers). The physical details of limiting effects can then be quantitatively investigated, their impact on the further development ("how they scale") can be analyzed, and the potential of technical measures to mitigate such effects in devices with higher powers can be assessed. Solutions with benign scaling properties can be expected to work in a wide range of power levels, while aspects with problematic scaling properties may cause serious difficulties at higher power levels, even if they were negligible in low-power devices.

Equation Summary

Rate of stimulated emission processes:

$$R_{\mathrm{se}} = \sigma_{\mathrm{em}} \frac{I}{h\nu}$$

Füchtbauer-Ladenburg equation:

$$\frac{1}{\tau_{\mathrm{rad}}} = \frac{8\pi\, n^2}{c^2} \int \nu^2 \sigma_{\mathrm{em}}(\nu)\, \mathrm{d}\nu$$

Calculating laser gain

Gain coefficient:

$$g(\lambda) = N_2 \sigma_{\mathrm{em}}(\lambda) L$$

Power amplification factor:

$$G = \exp(g) = \exp\left[N_2 \sigma_{\mathrm{em}}(\lambda) L\right]$$

Gain coefficient, including absorption from the lower laser level:

$$g(\lambda) = \left[N_2 \sigma_{\mathrm{em}}(\lambda) - N_1 \sigma_{\mathrm{abs}}(\lambda)\right] L$$

Gain coefficient in the case of spatially varying population densities:

$$g(\lambda) = \int \left[N_2(z) \sigma_{\mathrm{em}}(\lambda) - N_1(z) \sigma_{\mathrm{abs}}(\lambda)\right] \mathrm{d}z$$

Gain saturation

Steady-state value:

$$g(I_{\mathrm{p}}, I_{\mathrm{L}}) = \frac{g_0(I_{\mathrm{p}})}{1 + I_{\mathrm{L}} / I_{\mathrm{L,sat}}}$$

Saturation intensity:

$$I_{\mathrm{L,sat}} = \frac{h\nu_{\mathrm{L}}}{\sigma_{\mathrm{em}} \tau_2}$$

Equation Summary (cont.)

Gain saturation (cont.)

Short laser pulse:

$$g_{\text{end}} = g_0 \exp\left(-\frac{F_{\text{p}}}{F_{\text{L,sat}}}\right)$$

Saturation fluence:

$$F_{\text{L,sat}} = \frac{h\nu_{\text{L}}}{\sigma_{\text{em}}}$$

Laser threshold

Absorbed pump power:

$$P_{\text{p,abs}} = \frac{N_2 AL\, h\nu_{\text{p}}}{\tau_2}$$

$$= \frac{A\, l\, h\nu_{\text{p}}}{\sigma_{\text{em}}\tau_2}$$

Gaussian beams

Electric field:

$$E(r,z) \propto \exp\left(-\frac{r^2}{w(z)^2}\right)\exp[i\varphi(z,r)]$$

Phase:

$$\varphi(z,r) = kz - \arctan\frac{z}{z_{\text{R}}} + \frac{kr^2}{2R(z)}$$

Rayleigh length:

$$z_{\text{R}} = \frac{\pi w_0^2}{\lambda}$$

Equation Summary (cont.)

Gaussian beams (cont.)

Beam radius:

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_\mathrm{R}}\right)^2}$$

Curvature radius:

$$R(z) = z\left[1 + \left(\frac{z_\mathrm{R}}{z}\right)^2\right]$$

Beam intensity:

$$I(r,z) = \frac{P}{\pi w(z)^2 / 2} \exp\left[-2\frac{r^2}{w(z)^2}\right]$$

Divergence angle:

$$\theta = \frac{\lambda}{\pi w_0}$$

Beam radius for arbitrary beam shapes

$$w_x \equiv 2\sqrt{\frac{\int x^2 I(x,y)\,\mathrm{d}x\,\mathrm{d}y}{\int I(x,y)\,\mathrm{d}x\,\mathrm{d}y}}$$

Brightness or radiance of laser beams

$$B = \frac{P}{\pi w_0^2\ \pi\theta^2}$$

TEM modes

Mode frequencies:

$$\nu_{nmq} = \nu_0 + q\ \Delta\nu + (n+m)\ \delta\nu$$

Equation Summary (cont.)

Thermal effects in laser crystals and glasses

Dioptric power (inverse focal length):

$$f^{-1} = \frac{\mathrm{d}n/\mathrm{d}T}{2\kappa A} P_{\mathrm{heat}}$$

Sum and difference frequency generation

Sum frequency generation:

$$\lambda_{\mathrm{sum}} = \frac{1}{\left(\frac{1}{\lambda_1} + \frac{1}{\lambda_2}\right)}$$

Difference frequency generation:

$$\lambda_{\mathrm{difference}} = \frac{1}{\left|\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right|}$$

Relaxation oscillations and spiking

Relaxation oscillation frequency:

$$f_{\mathrm{ro}} = \frac{1}{2\pi}\sqrt{\frac{l\,P_{\mathrm{int}}}{E_{\mathrm{sat}} T_{\mathrm{rt}}}}$$

Schawlow-Townes formula

$$\Delta\nu_{\mathrm{laser}} = \frac{h\nu\, l_{\mathrm{tot}} T_{\mathrm{oc}}}{4\pi\, T_{\mathrm{rt}}^2\, P_{\mathrm{out}}}$$

Bibliography

Some useful books on lasers in general:

- A. E. Siegman, *Lasers*, University Science Books (1986).
- O. Svelto, *Principles of Lasers*, Plenum Press (New York, London), Fourth Edition (1998).
- F. Träger (editor), *Handbook of Lasers and Optics*, Springer (2007).
- A. Sennaroglu (editor), *Solid-State Lasers and Applications*, CRC Press (2006).
- W. Koechner, *Solid-State Laser Engineering*, Springer, 6th Edition (2006).

The first four books focus on the physics of lasers; the book by W. Koechner also covers a lot of engineering issues.

Also see the following resource:

- R. Paschotta, *Encyclopedia of Laser Physics and Technology*, open access via http://www.rp-photonics.com/encyclopedia.html

This encyclopedia contains many additional details on lasers and provides additional specialized references on many topics.

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Rüdiger Paschotta is an expert in lasers and amplifiers, nonlinear optics, fiber technology, ultrashort pulses, and noise in optics. He started his scientific career in 1994 with a PhD thesis in the field of quantum optics. He focused further on applied research thereafter, covering a wide range of laser-related topics. He is the author or coauthor of over 100 scientific journal articles, over 120 international conference presentations, and several book chapters. He is also the author of the well-known *Encyclopedia of Laser Physics and Technology* (see p. 125).

His successful academic career includes his habilitation at ETH Zürich and his attainment of the Fresnel Prize of the European Physical Society in 2002. In 2004, he started RP Photonics Consulting GmbH, a technical consulting company based in Zürich, Switzerland (http://www.rp-photonics.com). He now serves companies in the photonics industry worldwide, working out feasibility studies and designs for lasers and other photonic devices, identifying and solving technical problems, finding suitable laser sources for specific applications, and performing staff training courses on specialized subjects. His work combines his extensive physics knowledge, his experience with an inventory of numerical modeling tools, a practically oriented mind, and a passion for constructive, interactive teamwork.

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