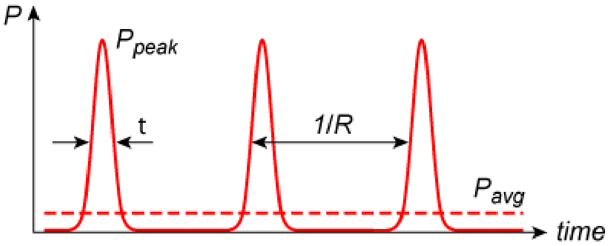
Laser Damage Threshold

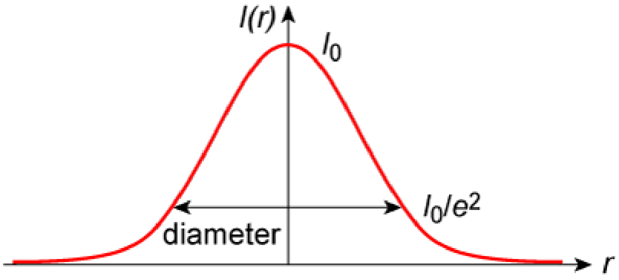
Pulsed vs. continuous-wave lasers: Pulsed lasers emit light in a series of pulses of duration τ at a repetition rate R in order to build up a very large peak power P_{peak}, or because the physics of the laser material and/or system does not allow continuous operation. Continuous-wave (cw) lasers emit a steady beam of light with a constant power. Pulsed-laser average power P_{avg} and cw laser constant power typically range from several milli-Watts (mW) to Watts (W) for most lasers. The diagram and table below illustrate and summarize the key parameters that are used to characterize the output of pulsed lasers.

Symbol	Definition	Units	Key Relationships
τ	Pulse duration	sec	$\tau = D / R$
R	Repetition rate	Hz = sec^{-1}	$R = D / \tau$
D	Duty cycle	dimensionless	$D = R \times \tau$
P	Power	Watts = Joules / sec	$P_{peak} = E / \tau$; $P_{avg} = P_{peak} \times D$; $P_{avg} = E \times R$
E	Energy per pulse	Joules	$E = P_{peak} \times \tau$; $E = P_{avg} / R$
A	Area of laser spot	cm^2	$A = (\pi / 4) \times \text{diameter}^2$
I	Intensity	Watts / cm^2	$I = P / A$; $I_{peak} = F / \tau$; $I_{avg} = I_{peak} \times D$; $I_{avg} = F \times R$
F	Fluence per pulse	Joules / cm^2	$F = E / A$; $F = I_{peak} \times \tau$; $F = I_{avg} / R$



Laser damage to optical filters is strongly dependent on many factors, and thus it is difficult to guarantee the performance of a filter in all possible circumstances. Nevertheless, it is useful to identify a Laser Damage Threshold (LDT) of pulse fluence or intensity below which no damage is likely to occur.

Note that because fluence and intensity on the surface of the component are the critical parameters, the area of the laser spot is also critical. Even very high-power lasers may be transmitted through or reflected off of a durable optical filter if the spot size is sufficiently large to minimize the fluence and/or intensity. The diameter of a laser spot with a gaussian profile is most accurately measured at the $1/e^2$ intensity points as shown in the diagram below.



Long-pulse lasers: LDT is perhaps most accurately specified in terms of pulse fluence for “long-pulse lasers.” Long-pulse lasers have pulse durations τ in the nanosecond (ns) to microsecond (µs) range, with repetition rates R typically ranging from about 1 to 100 Hz. Because the time between pulses is so large (milliseconds), the irradiated material is able to thermally relax—as a result damage is generally not heat-induced, but rather caused by nearly instantaneous optical field effects. Usually damage results from surface or volume imperfections in the material and the associated irregular optical field properties near these sites, rather than catastrophic destruction of the fundamental material structure. Most Semrock filters have LDT values on the order of 1 J/cm^2, and are thus considered “high-power laser quality” components.

As an example, suppose a frequency-doubled Nd:YAG laser at 532 nm emits 10 ns pulses at a 10 Hz repetition rate with 1 W of average power. This laser has a duty cycle of 1 x 10^{-7}, a pulse energy of 100 mJ, and a peak power of 100 MW. If the beam is focused down to a 100 µm diameter spot on the surface of a component, the pulse fluence is 1.3 kJ/cm^2, and thus it will almost surely damage a component with a 1 J/cm^2 LDT. However, if the spot diameter is 5 mm, the pulse fluence is only 0.5 J/cm^2, and thus the component should not be damaged.

Some additional general “rules or thumb” are useful to keep in mind. First, the LDT tends to scale with wavelength. For example, LDT at 532 nm should be about half the LDT at 1064 nm, since the energy of one photon of light at 532 nm is twice that of a photon at 1064 nm. Second, the LDT tends to scale with the square root of the pulse duration τ. For example, a 20 ns pulse should have an LDT that is √2 times higher than that for a 10 ns pulse with the same pulse energy.

cw lasers: The LDT for cw lasers is more difficult to measure, and therefore is not specified as often as the long-pulse laser LDT. Damage from cw lasers tends to result from thermal (heating) effects. At this time Semrock does not test nor specify cw LDT for its filters. As a very rough rule of thumb, many all-glass components like dielectric thin-film mirrors and filters have a cw LDT (intensity in kW/cm^2) that is 10 – 100 times the long-pulse laser LDT (fluence in J/cm^2).

High-power cw lasers often have “hot spots,” or portions of the laser beam cross section with significantly higher intensity relative to the nominal intensity. A good rule of thumb is to multiply the nominal laser spot intensity by a factor of at least two to allow for possible hot spots.

Quasi-cw lasers: Quasi-cw lasers are pulsed lasers with pulse durations τ in the femtosecond (fs) to picosecond (ps) range, and with repetition rates *R* typically ranging from about 10 – 100 MHz for high-power lasers. These lasers are typically mode-locked, which means that *R* is determined by the round-trip time for light within the laser cavity. With such high repetition rates, the time between pulses is so short that thermal relaxation can not occur. Thus quasi-cw lasers are often treated approximately like cw lasers with respect to LDT, using the average intensity in place of the cw intensity.

Picosecond lasers tend to have relatively large duty cycles (~ 10^{-3}), so the peak powers are not very large. Ultrafast lasers (τ < 100 fs), on the other hand, can have very large peak powers, and the high electric fields associated with these pulses directly attack electronic bonds of dielectric materials causing some very interesting effects. Yet the peak intensity LDT values required for these effects to cause significant damage are generally so high that the laser damage tends to be dominated by thermal damage mechanisms associated with the average intensity.