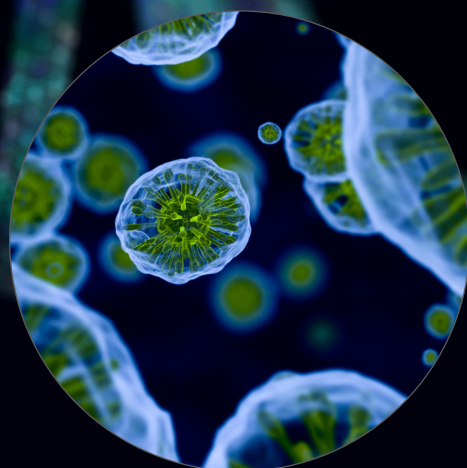
OPTICS & LIFE SCIENCE

RESOURCE GUIDE



Optics fundamentals to help you improve the throughput and performance of your life science systems

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OPTICS & LIFE SCIENCE
Resource Guide

Welcome!

This technical resource guide breaks down key concepts that can help you better source optics for your flow cytometry, genomics, optical coherence tomography, and other life science systems. For further technical guidance and to discuss your custom optics needs, please contact us at **www.edmundoptics.com/contact**

Edmund Optics® is a custom and volume manufacturer of quality optical components, assemblies, and systems. From fluorescence filters, to achromatic lenses, to low-loss mirrors, to microscope objectives, we design and manufacture optics from prototyping to volume production.

What can we make for you? Our eight global manufacturing facilities, wealth of application expertise, and vast catalog of over 34,000 optical components can support your product development and production.

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Why Edmund Optics®

Customer First!

Our top priority is to serve our customers and truly understand their needs, guiding everything we do.

A Trusted Partner

Since 1942, we've built our reputation on reliable partnerships with customers, institutions, and companies, fostering trust every step of the way.

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Optical Filter Fundamentals

Introduction to Optical Filters

An optical filter selectively transmits one portion of the optical spectrum, while rejecting other portions. Commonly used in microscopy, spectroscopy, chemical analysis, and machine vision, Edmund Optics' optical filters are available in a variety of filter types and precision levels. This application note provides a description of the different technologies used to create Edmund Optics filters, definitions of some key specifications, and a description of the various types of filters available from Edmund Optics.

Key Optical Filter Terminology

While filters share many of the same specifications with other optical components, there are a number of specifications unique to filters that should be understood in order to effectively understand and determine which filter is best for your application.

Central Wavelength

Center Wavelength (CWL), used in defining bandpass filters, describes the midpoint of spectral bandwidth over which the filter transmits. Traditional Coated Optical Filters tend to achieve a maximum transmission near the center wavelength, whereas Hard Coated Optical Filters tend to have a fairly flat transmission profile over the spectral bandwidth.

Bandwidth

Bandwidth is a wavelength range used to denote a specific part of the spectrum that passes incident energy through a filter. Bandwidth is also referred to as FWHM (Figure 1).

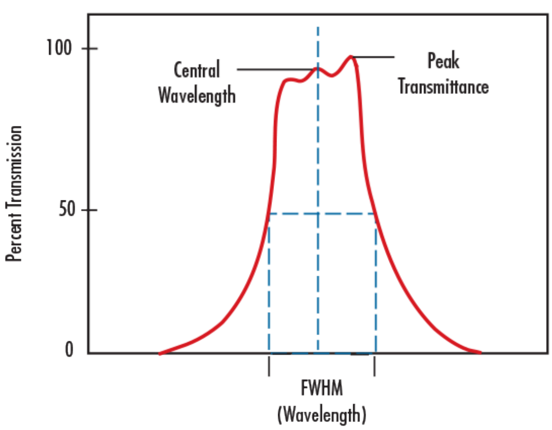


Figure 1: Illustration of Center Wavelength and Full Width at Half Maximum

Full Width-Half Maximum

Full Width-Half Maximum (FWHM) describes the spectral bandwidth over which a bandpass filter will transmit. The upper and lower limit of that bandwidth is defined at the wavelengths where the filter achieves 50% of the maximum transmission. For example, if the maximum transmission of the filter is 90%, the wavelengths at which the filter achieves 45% transmission will define the upper and lower limits of the FWHM. FWHM's of 10nm or less are considered narrowband and often used for laser clean-up and chemical detection. FWHM's of 25 – 50nm are often used in machine vision applications; FHWM's of more than 50nm are considered broadband and typically used in fluorescence microscopy applications.

Blocking Range

Blocking Range is a wavelength interval used to denote a spectral region of energy that is attenuated by the filter (Figure 2). The degree of its blocking is typically specified in terms of optical density.

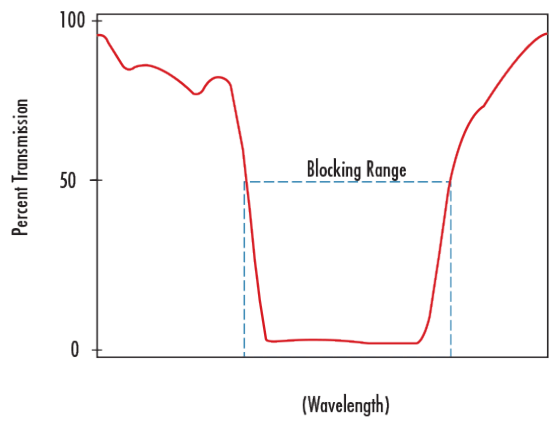


Figure 2: Illustration of Blocking Range

Slope

Slope is a specification often defined on edge filters, such as shortpass or longpass filters, to describe the bandwidth over which the filter transitions from high blocking to high transmission. Given as the percent of the cut-wavelength, slope can be specified from a variety of starting and end points. Edmund Optics typically specifies the slope as the distance from the 10% transmission point to the 80% transmission point. For example, a 500nm longpass filter with a 1% slope would be expected to transition from 10% transmission to 80% transmission over a 5nm (1% of 500nm) bandwidth.

Optical Density

Optical Density (OD) describes the amount of energy blocked or rejected by a filter. A high optical density value indicates low transmission, and low optical density indicates high transmission (Figure 3). Optical densities of 6 or greater are used for extreme blocking needs such as Raman spectroscopy or fluorescence microscopy. Optical densities of 3.0 – 4.0 are ideal for laser separation and clean-up, machine vision, and chemical detection, while optical densities of 2.0 or less are ideal for color sorting and separating spectral orders.

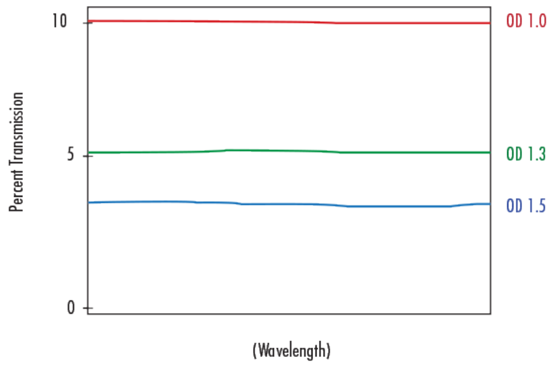


Figure 3: Illustration of Optical Density

$$\text{Percent Transmission} = T = 10^{-\text{OD}} \times 100\% \quad \textbf{(1)}$$

$$\text{OD} = -\log\left(\frac{T}{100\%}\right) \quad \textbf{(2)}$$

Dichroic Filter

A Dichroic Filter is a type of filter used to transmit or reflect light, depending on the wavelength; light of a specific wavelength range is transmitted, while light of a different range is reflected or absorbed (Figure 4). Dichroic filters are commonly used for longpass and shortpass applications.

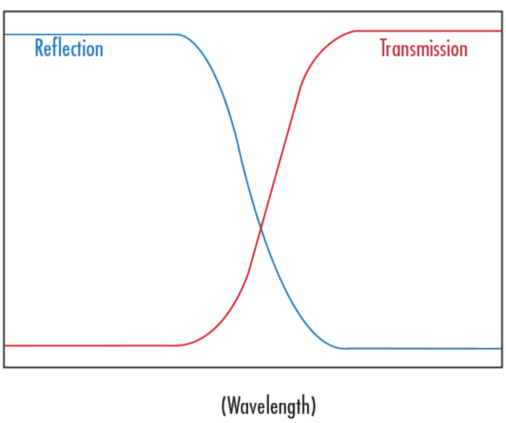


Figure 4: Illustration of Dichroic Filter Coating

Cut-On Wavelength

Cut-On Wavelength is a term used to denote the wavelength at which the transmission increases to 50% throughput in a longpass filter. Cut-on wavelength is indicated by $\lambda_{\text{cut-on}}$ in Figure 5.

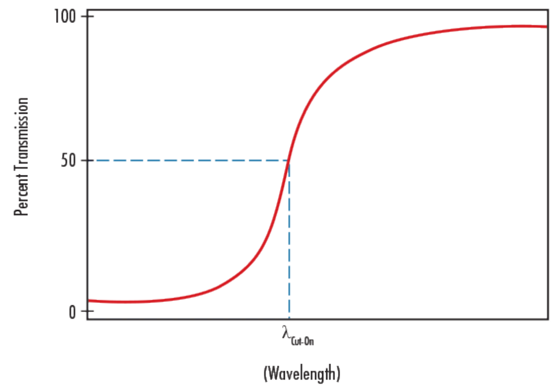


Figure 5: Illustration of Cut-On Wavelength

Cut-Off Wavelength

Cut-Off Wavelength is a term used to denote the wavelength at which the transmission decreases to 50% throughput in a shortpass filter. Cut-off wavelength is indicated by $\lambda_{\text{cut-off}}$ in Figure 6.

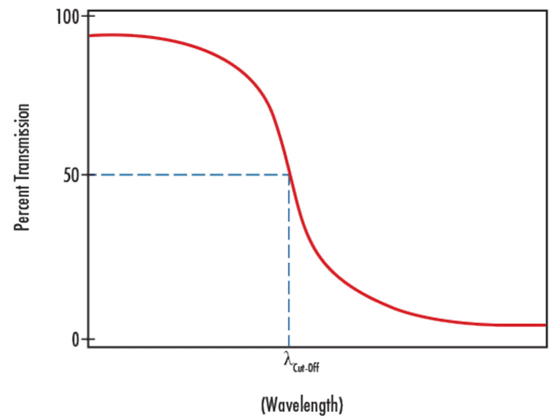


Figure 6: Illustration of Cut-Off Wavelength

Optical Filter Fabrication Techniques

In general, filters either absorb unwanted light through the addition of colored glasses or dyes, or reflect unwanted light through the addition of interference coatings. Most Edmund Optics filters operate on the principal of interference coatings, with coating designs and materials specially selected to achieve the desired transmission shape and performance.

Hard Coated Optical Filters feature a single substrate with dense coatings and excellent optical performance. Designed to meet the adhesion, abrasion, temperature, and humidity requirements specified in MIL-C-48497A, they are ideal for precision requirements and OEM integration.

Traditional Coated Optical Filters are typically a stack of absorbing materials, interference coatings, and metallic layers, laminated together to create a low-cost, efficient filter. The complexity of the assembly, however, limits both the optical performance and environmental stability of such filters. Nonetheless, traditional coated filters are ideal for laboratory equipment and analytical instrumentation. Colored Glass Filters and other absorbing filters like Plastic Filters and Wratten Filters, introduce elements, compounds, dyes, or other colorants to a base substrate to manipulate the filter's spectral properties. The resulting filters are relatively inexpensive, but have less desirable optical properties than similar coated filters. Absorptive filters are typically integrated into illumination and sensing applications.

Absorptive and Dichroic Filters

The wide range of optical filters can be broken into two main categories: absorptive and dichroic. The difference between the two does not lie in what they filter, but how they filter. In an absorptive filter, light is blocked based on the absorption properties of the glass substrate used. In other words, light that is blocked does not reflect off the filter; rather, it is absorbed and contained within the filter. In applications where noise in a system from unwanted light is an issue, an absorptive filter is ideal. Absorptive filters also have the added bonus of not being very angle sensitive; light can be incident upon the filter from a wide range of angles and the filter will maintain its transmission and absorption properties.

Conversely, a dichroic filter works by reflecting unwanted wavelengths, while transmitting the desired portion of the spectrum. In some applications, this is a desirable effect because light can be separated by wavelength into two sources. This is achieved by adding a layer, or multiple layers, of material of varying indexes of refraction to exploit the interference nature of light waves. In interference filters, light traveling from a lower index material will reflect off a higher index material; only light of a certain angle and wavelength will constructively interfere with the incoming beam and pass through the material, while all other light will destructively interfere and reflect off the material (Figure 7).

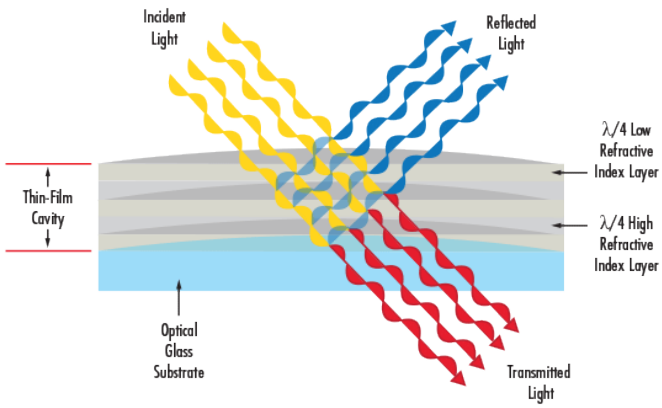


Figure 7: Deposition of Multiple Layers of alternating High and Low Index Materials onto a Glass Substrate

Unlike absorptive filters, dichroic filters are extremely angle sensitive. When used for any angle(s) outside of their intended design, dichroic filters cannot meet the transmission and wavelength specifications originally indicated. As a rule of thumb, increasing the angle of incidence through a dichroic filter will shift it towards shorter wavelengths (i.e. towards bluer wavelengths); and decreasing the angle will shift it towards longer wavelengths (i.e. towards redder wavelengths).

Exploring Dichroic Bandpass Filters

Bandpass filters are used in a wide range of industries and can be either dichroic or color substrate. Dichroic bandpass filters are manufactured by two different techniques: traditional and hard sputtered, or hard coated. Both techniques achieve their unique transmission and reflection properties by a deposition of numerous layers of alternating high and low index of fraction materials onto glass substrates. In fact, depending upon the application, there can be more than 100 layers of material deposited per face of a given substrate.

The difference between traditional-coated filters and hard-sputtered filters is the number of substrate layers. In traditional-coated bandpass filters, layers of varying index materials are deposited onto multiple substrates which are then sandwiched together. For example, imagine the illustration in Figure 7 repeated up to and even more than 100 times. This technique leads to a thick filter with reduced transmission. This reduction in transmission is caused by incident light traveling through and being absorbed and/or reflected by numerous substrate layers. Conversely, in hard-sputtered bandpass filters, materials of varying indices are deposited onto only a single substrate (Figure 8). This technique leads to thin filters with high transmission.

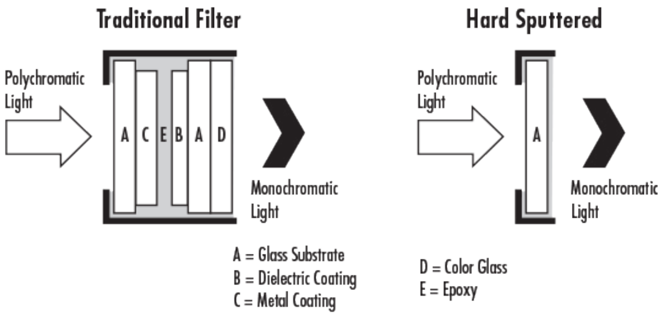


Figure 8: *Traditional Filter (Left) and Hard-Sputtered Filter (Right)*

Fluorophores and Optical Filters for Fluorescence Microscopy

Fluorescence microscopy is a microscopy technique that uses fluorescence, which is induced using fluorophores, as opposed to absorption, scatter, or reflection. A fluorophore (or fluorochrome) is a fluorescent dye used to mark proteins, tissues, and cells with a label for examination by fluorescence microscopy. A fluorophore works by absorbing energy of specific wavelengths, commonly referred to as the **excitation range**, and re-emitting that energy in another specific wavelength region, referred to as the emission range.

Fluorescence microscopy systems like an epifluorescent microscope can be simple, whereas confocal or multiphoton systems can be very complex. However, all fluorescence microscopes share the same basic concept: excitation energy illuminates a sample which releases a weak but quantifiable emission energy. The excitation and emission wavelengths do not share the same center wavelength. This allows specialized filters to increase the overall contrast and signal.

The most basic concept and schematic is seen in Figure 9. A filter arrangement is constructed of three filter types: an excitation filter, a dichroic filter, and an emission filter.

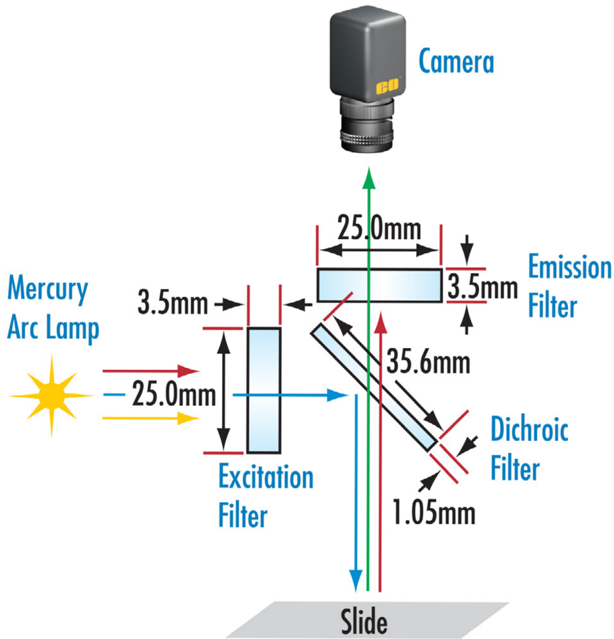


Figure 9: *Traditional Filter (Left) and Hard-Sputtered Filter (Right)*

Filter #1: Excitation Filter

The excitation filter is placed within the illumination path of a fluorescence microscope and filters out all wavelengths of the light source except for the fluorophore excitation range. The filter minimum transmission dictates the brightness and brilliance of images. A minimum of 40% transmission for any excitation filter is recommended such that the transmission is ideally >85%. The bandwidth of the excitation filter should be entirely within the fluorophore excitation range such that the CWL of the filter is as close as possible to the peak excitation wavelength of the fluorophore. The excitation filter OD dictates the background image darkness; OD is a measure of how well a filter blocks the wavelengths outside of transmission range or bandwidth. A minimum OD of 3.0 is recommended but an OD of 6.0 or greater is ideal.

Filter #2: Dichroic Filter or Beamsplitter

The dichroic filter is placed between the excitation filter and emission filter at a 45° angle and reflects the excitation signal towards the fluorophore while transmitting the emission signal toward the detector. Ideal dichroic filters and beamsplitters have sharp transitions between maximum reflection and maximum transmission, with a >95% reflection for the bandwidth of the excitation filter and a transmission of >90%

for the bandwidth of the emission filter. Select the filter with the intersection wavelength (λ) of the fluorophore in mind, to minimize stray light and maximize the fluorescent image signal-to-noise ratio.

Filter #3: Emission Filter

The emission filter is placed within the imaging path of the fluorescence microscope and filters out the fluorophore excitation range while transmitting the emission range. The same recommendations for excitation filters hold true for emission filters: minimum transmission, bandwidth, OD, and CWL. An emission filter with the ideal CWL, minimum transmission, and OD combination provides the brightest possible images, with the deepest possible blocking, and ensures the detection of the faintest emission signals.

Figure 10 shows a typical excitation, emission profile. The absorption and emission profiles share common wavelengths which is one reason why high-quality filters with high transmission, narrow bandwidths, high ODs, and sharp cut-on and cut-off bands are needed. Using low quality filters can ultimately damage the sample, specimen, or expensive sensors. Contact us to help you select the appropriate filters your application.

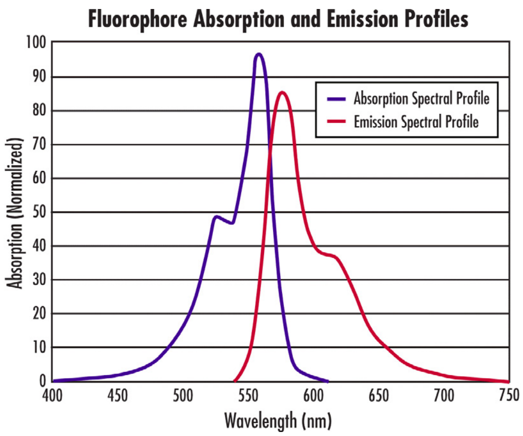
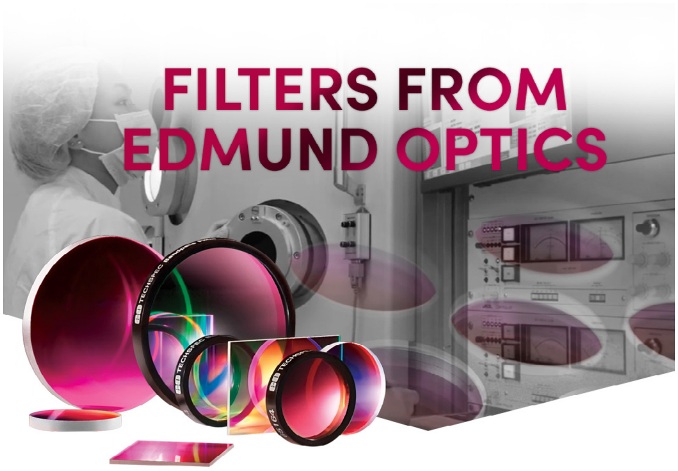


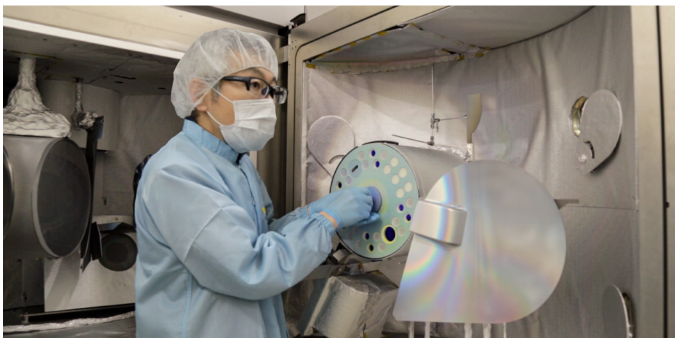
Figure 10: *Generalized Fluorophore Spectral Curve*



From design to prototype to production, Edmund Optics® manufactures optical filters with in-house expertise and metrology to support you through every stage of your OEM project.

- Custom coating design and deposition and substrate fabrication
- Wavelength ranges from 220nm to 10.6µm
- High Blocking up to OD8
- In addition to custom manufacturing, we have over 960 standard filter coating designs available
- Fluorescence filter kits tailored for specific fluorophores

Coating Technologies



- Ion beam sputtering for high-precision, low loss filters
- Magnetron sputtering for high-volume, cost-effective filters
- Supported by a host of metrology, including a custom-built OD8 spectrophotometer

Balancing Tolerances on Custom Lenses

Designing for Manufacturability Matters

Successful optical component design succeeds not only in the creation of a working design model but also in manufacturing, assembly, testing, and implementation. Occasionally, an optic may appear to succeed in conception but fail in one of the subsequent phases. For this reason, it is imperative to recognize the nuances of optical tolerancing and manufacturing. This exploration focuses on the key considerations for custom lenses, but similar principles and thought processes apply to other optical component types as well.

Potential Pitfalls of Design Software

Design software digitizes the optical planning process and offers tools to ease the detailed and time-consuming procedure; however, one must be aware that most optical software does not always warn of–or–prevent the user from–creating physically impossible or difficult to manufacture solutions. Remember, optical software is just a tool and the user must pay careful attention to review the outputs.

Tolerancing Mechanical Dimensions

Tight tolerances are difficult to work with and may unnecessarily increase costs, especially if combined with stringent cosmetic or irregularity requirements, as well as soft optical materials. Several rules of thumb help keep lens designs manufacturable, such as:

- Thin edges (<1mm thick) should be avoided to prevent chipping
- Aspect ratios of 6:1 or less are ideal for precision optics

Aspect ratio is the relationship between lens diameter and center thickness, and high aspect ratios may result in lens bending and flexing.

Karow Factor – Ease of Centering

The Karow factor, or Z-factor, of a lens measures the ability of the lens to center itself automatically between bell chucks, also known as bell clamps. It is given by:

$$Z = \left| \frac{D_1}{R_1} + \frac{D_2}{R_2} \right| \quad (1)$$

D_1 and D_2 are the bell chuck diameters (commonly equal to the lens' clear aperture diameter). R_1 and R_2 are the radii of curvature for the first and second surfaces. Convex and concave surfaces, respectfully, have positive and negative radii (Figure 1).

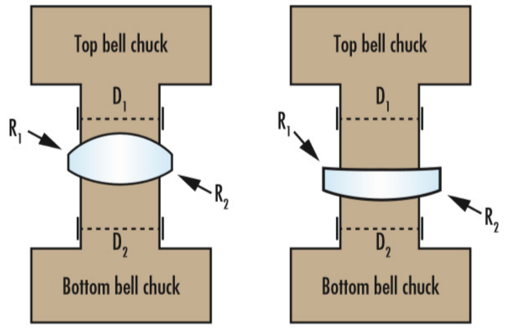


Figure 1: *The left lens Karow factor (Z = 2.5) is greater than the right lens (Z = 0.4). As such, the left lens would be easier to center via automated bell-chucking, while the right would be more difficult.*

Lenses with a Karow factor greater than 0.56 will automatically center well via automated bell-chucking; those with a Karow factor less than 0.56 may not automatically center and will need to be centered manually. This is a time-intensive process and, therefore, more expensive. Lenses with nearly concentric radii are difficult to center since a large amount of material must be removed to correct for surface-to-surface relative decentering. To ensure that a lens can be centered, concentricity (Δr) should be greater than 2mm as a rule of thumb:

$$|\Delta r| = |R_1 - R_2 - CT| > 2mm \text{ for values of R} > 0 \quad (2)$$

$$|\Delta r| = |R_1 - R_2 + CT| > 2mm \text{ for values of R} < 0$$

Where CT is the center thickness of the lens (Figure 2)

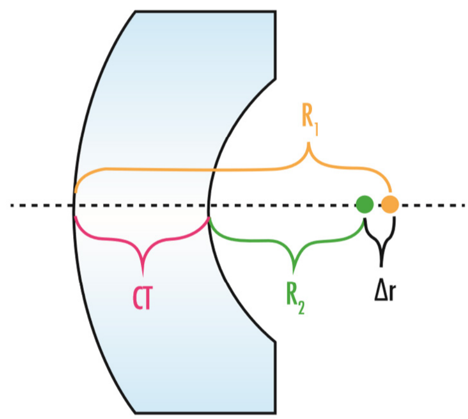


Figure 2: *This meniscus lens has radii that are nearly concentric. Ensure that |Δr| is greater than 2mm so that the lens can be centered.*

Lenses with hemispherical (radii of curvature less than or equal to 0.7 times the diameter) or near flat (a sag equal to or less than 100µm) surfaces should also be avoided if possible, as this is also difficult to manufacture.

The sag, or saggita, of a lens is a measure of the glass removed to create the curve of the surface (Figure 3).

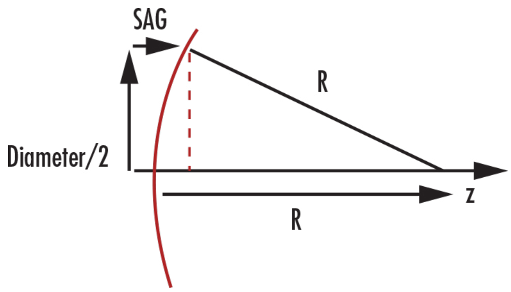


Figure 3: *Depiction of the sag of a lens*

Clear Aperture Considerations

Clear aperture (CA) is defined as the diameter or size of an optical component that must meet specifications. Outside of this, manufacturers do not guarantee the optic will adhere to the stated specifications. Due to manufacturing constraints, it is virtually impossible to produce a clear aperture equal to an optic's diameter or length by width. Typical CA values for lenses are shown in Table 1.

Table 1: Clear Aperture Tolerances

Diameter	Common Minimum Clear Aperture
3.00 - 10.00mm	90% of Diameter
10.01 - 50.00mm	Diameter – 1mm
≥ 50.1mm	Diameter – 1.55mm

Fabricators need room around the CA for coating margins, polishing edge effects, and bevels. The area outside of the CA may also be used in lens mounting and may be obscured by a retaining ring.

Power

Power, a type of surface accuracy specification, applies to curved optical surfaces. It is tested by comparing a curved surface against a reference surface with a highly-calibrated radius of curvature. Using the principle of interference caused by the air gaps between the two surfaces, the interference pattern of fringes is used to describe the deviation of the test surface from the reference surface.

A deviation from the reference piece will create a series of rings, known as Newton's rings. The more rings present, the larger the deviation. The number of dark or light rings, not the sum of both light and dark, corresponds to twice the number of waves of error.

Power error is related to the error in the radius of curvature by the following equation where ΔR is the radius error, D is the lens diameter, R is the surface radius, and λ is the wavelength (typically 632.8nm):

$$Power\ Error[waves\ or\ \lambda] = \frac{(\Delta R)D^2}{8R^2\lambda} \tag{3}$$

Irregularity

Irregularity, another type of surface accuracy specification, describes how the shape of a surface deviates from the shape of a reference surface. It is obtained from the same measurement as power. Regularity refers to the sphericity of the circular fringes that are formed from the comparison of the test surface to the reference surface.

When the power of a surface is more than 5 fringes, it is difficult to detect small irregularities of less than 1 fringe. Therefore, it is common practice to specify surfaces with a ratio of power to irregularity of approximately 5:1.

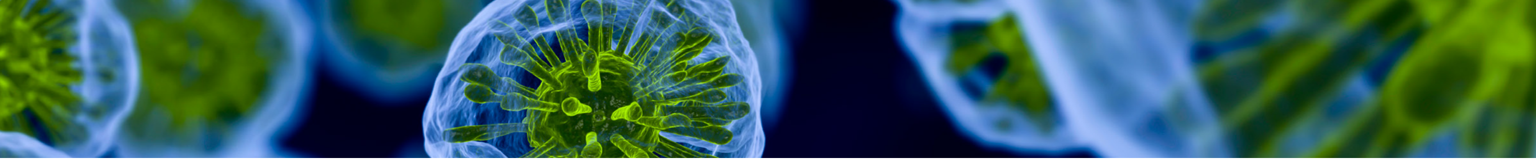
Surface Quality

The surface quality of an optical surface describes its cosmetic appearance and includes defects such as scratches, pits, or digs. In most cases, these surface defects are purely cosmetic and do not significantly affect system performance; however, they can cause a small loss in system throughput and a small increase in scattered light.

But certain surfaces are more sensitive to these effects, such as: (1) surfaces at image planes because these defects are in focus and (2) surfaces that see high power levels because these defects can cause increased absorption and damage the optic.

The most common specification used for surface quality is the scratch-dig specification described by MIL-PRF-13830B. The scratch designation is determined by comparing the scratches on a surface to a set of standard scratches under controlled lighting conditions.

The dig designation is calculated as the diameter of the dig in microns divided by 10. Scratch-dig specifications of 80-50 are typically considered standard quality, 60-40 precision quality, and 20-10 high precision quality. Over-specifying a higher surface quality than needed may unnecessarily increase costs without noticeably impacting performance.



Understanding and Specifying Laser Damage Threshold

Introduction to LDT

Laser damage threshold (LDT), or laser-induced damage threshold (LIDT), is defined within ISO 21254 as the "highest quantity of laser radiation incident upon the optical component for which the extrapolated probability of damage is zero". The purpose of LDT is to specify the maximum laser fluence (for pulsed lasers, typically in J/cm^2) or the maximum laser intensity (for continuous wave lasers, typically in W/cm^2) that a laser optic can withstand before damage occurs. Because of the statistical nature of laser damage testing, LDT cannot be considered as the fluence below which damage will never occur, but rather the fluence below which the damage probability is less than the critical risk level. The level of risk depends on several factors such as the beam diameter, the number of test sites per sample, and the number of samples tested in order to determine the specification.

Laser-induced damage in optical components causes degradation in system performance that can even result in catastrophic failure. An incorrect understanding of LDT may lead to significantly higher costs or to component failures. Especially when dealing with high-power lasers, LDT is an important specification for all types of laser optics including reflective, transmissive, and absorptive components. The lack of an industry consensus on how LDT should be tested, how damage should be detected, and how the test data should be interpreted makes LIDT a complicated specification. An LDT value on its own does not convey the diameter of the beam used for testing, how many shots per testing site were administered, or the way the test data was analyzed.

In order to determine whether a laser's fluence may cause damage to an optic, the following specifications of the laser should be reviewed: power, beam diameter, and whether the laser is continuous wave or pulsed. For pulsed lasers, the pulse duration must also be considered.

Laser Intensity: Not as Straightforward as it Seems

The intensity of a laser beam is the optical power per unit area, typically measured in W/cm^2. The distribution of the intensity of the laser across a cross-section of the beam is the intensity profile. Some of the most common intensity profiles are flat top beams and Gaussian beams. Flat top beams, or top hat beams, have an intensity profile that is constant across a cross-section of the beam. Gaussian beams have an intensity profile that decreases as the distance from the center of the beam increases following a Gaussian function. The peak fluence of a Gaussian beam is twice as large as that of a flat top beam with the same optical power (Figure 1).

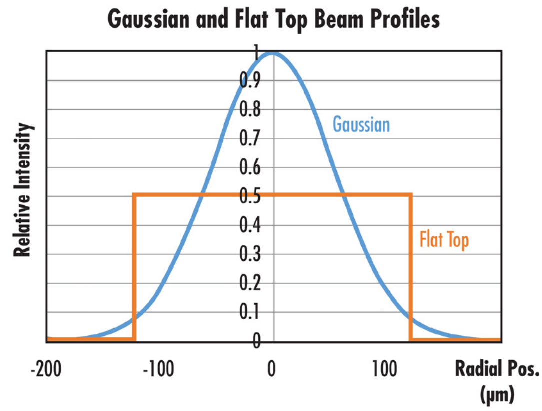


Figure 1: Comparison of Gaussian and flat top beam profiles with the same optical power

The effective beam diameter of a Gaussian beam also scales with fluence. As fluence increases, a larger portion of the beam's width has sufficient fluence to initiate laser-induced damage (Figure 2). This can be avoided by using a flat top beam instead of a Gaussian beam.

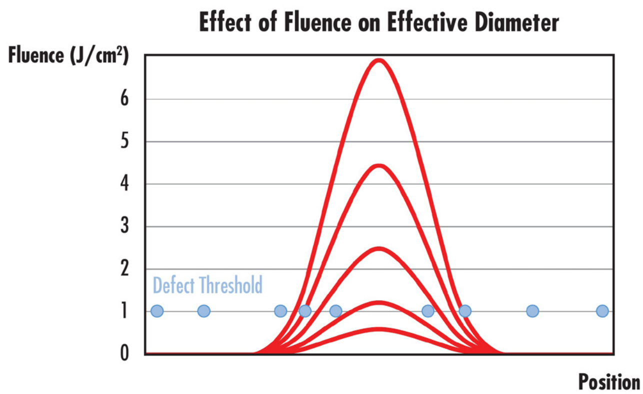


Figure 2: The effective diameter of a Gaussian beam increases as –––fluence increases, leading to a higher probability of laser-induced damage as indicated by more damage sites falling under the width of the curves with the highest fluence

The intensity of a laser plays an important role in determining the required LDT for optics used with it. Some lasers also contain unintentional regions of higher intensity called hot spots, which can contribute to laser-induced damage.

Continuous Wave Lasers

Damage from continuous wave (CW) lasers is typically a result of thermal effects caused by absorption in the optic's coating or substrate. Cemented optical components, such as achromats, tend to have lower CW damage thresholds because of absorption or scattering in the cement.

To understand a CW LDT specification, it is necessary to know the laser's wavelength, beam diameter, power density, and intensity profile (e.g., Gaussian or flat top). LDT for CW lasers is specified in units of power per area, typically in W/cm^2. For example, if a 5mW, 532nm Nd:YAG laser with a flat top beam is used with a beam diameter of 1mm, then the power density is:

$$\text{Power Density} = \frac{\text{Power}}{\text{Area}} = \frac{5\text{mW}}{\pi\left(\frac{\text{Beam Diameter}}{2}\right)^2} = \frac{5\text{mW}}{\pi\left(\frac{1\text{mm}}{2}\right)^2} = 0.6366\frac{\text{W}}{\text{cm}^2} \quad (1)$$

Therefore, if the LDT specified for an optic is lower than 0.64W/cm^2, then the user risks optical damage at 532nm. An extra factor of 2 would need to be added if using a Gaussian beam.

Pulsed Lasers

Pulsed lasers emit discrete pulses of laser energy at a given repetition rate or frequency (Figure 3). The energy per pulse is directly proportional to the average power and inversely proportional to the repetition rate of the laser (Figure 4).

$$\text{Pulse Energy} = \frac{\text{Average Power}}{\text{Repetition Rate}} \quad (2)$$

Damage from short nanosecond laser pulses is typically due to dielectric breakdown of the material resulting from exposure to the high electric fields in the laser beam. Dielectric breakdown occurs when a current flows through an electrical insulator because the applied voltage exceeds the material's breakdown voltage. For longer pulse widths or high repetition rate laser systems, laser-induced damage may result from a combination of thermally induced damage and dielectric breakdown. This occurs because the pulse duration is still on the order of the time duration of electron-lattice dynamics, which is responsible for thermally induced damage. These thermal processes are negligible for ultrashort pulses of about 10ps or less. In this case, nonlinear excitation of electrons from the valence band to the conduction band, through mechanisms such as multiphoton absorption, multiphoton ionization, tunnel ionization, and avalanche ionization, leads to damage.

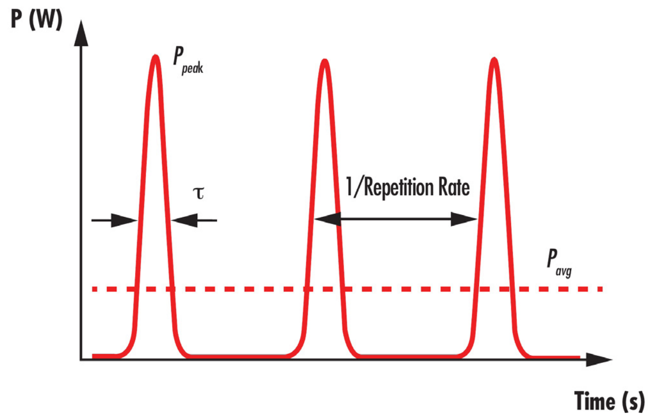


Figure 3: The pulses of a pulsed laser are temporally separated by the inverse of the repetition rate

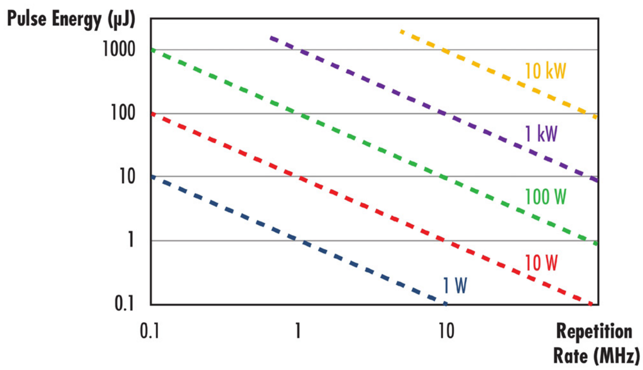
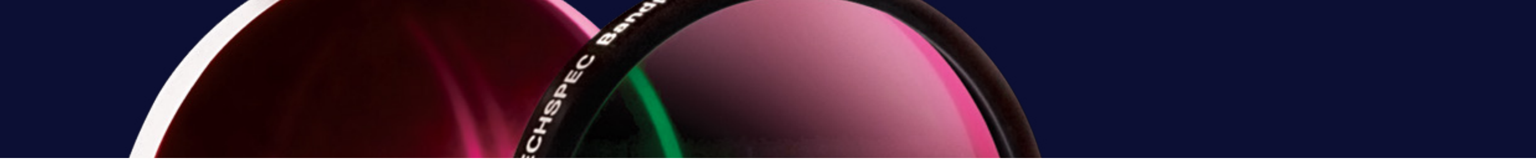


Figure 4: Depiction of the pulse energy as a function of repetition rate for a given average power of a pulsed laser

LDT for pulsed lasers is specified as a fluence with units of J/cm^2 as opposed to power density. It is important to recognize that while J/cm^2 does not contain a unit of time, the damage threshold is dependent on pulse duration. In most cases, the LDT fluence value will increase as the pulse duration increases. To understand a pulsed LDT specification, it is necessary to know the laser's wavelength, beam diameter, pulse energy, pulse duration, repetition rate, and intensity profile (e.g., Gaussian or flat top). The relationship between the fluence of a pulsed laser, the pulse energy, and the beam diameter is defined by:

$$\text{Fluence} = \frac{\text{Pulse Energy}}{\text{Area}} = \frac{\text{Pulse Energy}}{\pi\left(\frac{\text{Beam Diameter}}{2}\right)^2} \quad (3)$$



For example, a flat top Q-switched (pulsed) laser with a pulse energy of 10mJ, pulse duration of 10ns, and a beam diameter of 10 microns will have the following fluence:

$$\text{Fluence} = \frac{10\text{mJ}}{\pi\left(\frac{10\mu\text{m}}{2}\right)^2} = 12.7\frac{\text{kJ}}{\text{cm}^2} \qquad \textbf{(4)}$$

A fluence value in kilojoules is incredibly high and will almost certainly damage an optic, making factoring the beam diameter and not only laser energy in the calculations crucial.

Damage Mechanisms

In addition to thermal buildup and dielectric breakdown, laser-induced damage can be triggered by the interaction of the laser with some type of defect. Defects include subsurface damage left behind from grinding and polishing processes, microscopic particles of polishing abrasive left on the optic, or clusters of metallic elements left behind from coating. Each of these defect sources exhibits distinct absorption characteristics, as the nature and size of any given defect determines the laser fluence the optic can withstand without causing damage.

As previously mentioned, pulse duration has a large impact on which mechanisms lead to laser-induced damage (Figure 5). Pulse durations on the order of femtoseconds to picoseconds may excite charge carriers from the valence band of a material to the conduction band, leading to nonlinear effects including multiphoton absorption, multiphoton ionization, tunnel ionization, and avalanche ionization (Table 1). Pulse durations on the order of picoseconds to nanoseconds may lead to damage by relaxing charge carriers from the conduction band back down to the valence band through carrier-carrier scattering and carrier-phonon scattering.

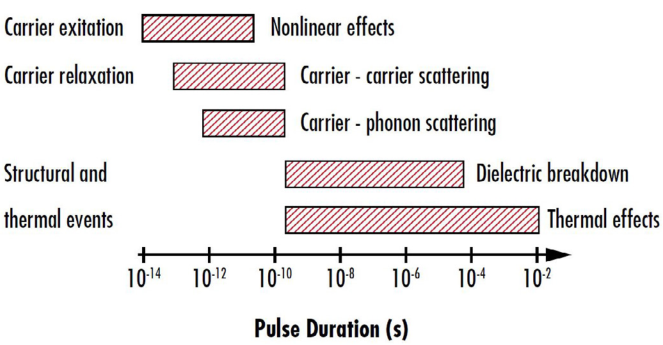


Figure 5: *Temporal dependence of various laser-induced damage mechanisms*

Damage Mechanism	**Description**
Multiphoton Absorption	Absorption process where two or more photons with energies lower than the material's bandgap energy are absorbed simultaneously, making absorption no longer linearly proportional to intensity.
Multiphoton Ionization	Absorption of two or more photons whose combined energy leads to the photoionization of atoms in the material.
Tunnel Ionization	The strong electric field generated by ultra-short laser pulses allows electrons to "tunnel" through the potential barrier keeping the electrons bound to atoms, allowing them to escape.
Avalanche Ionization	The strong electric field generated by ultra-short laser pulses causes electrons to accelerate and collide with other atoms. This ionizes them and releases more electrons that continue to ionize other atoms.
Carrier-Carrier Scattering	Electrons accelerated by the electric field collide with other electrons, scattering them and causing them to collide with more electrons.
Carrier-Phonon Scattering	Electrons accelerated by the electric field excite phonons, or vibrations in the lattice of the material.
Dielectric Breakdown	A current flowing through an electrical insulator due to the applied voltage exceeding the material's breakdown voltage.
Thermal Effects	Heat diffusion resulting from distortions and vibrations in the material caused by the energy of the laser pulses.

Varying root causes of damage create different morphologies of laser-induced damage (Figure 6). Understanding these morphologies is important for coating and process development, but for laser optics applications, the morphology is only important in determining whether the damage significantly degrades the laser system's performance. The amount of performance degradation a system can handle is application dependent. For example, in some situations a 10% reduction in transmission may be tolerable, while another system may fail if more than 1% of the incident light is scattered. According to the ISO 21254:2011 standard, any detectable change in an optic after exposure to a laser is considered damage.

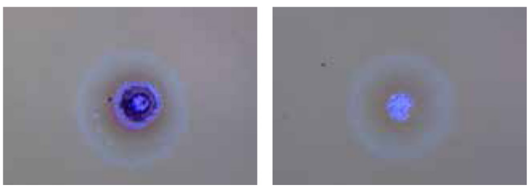


Figure 6: *Various morphologies of laser-induced damage resulting from different root causes*

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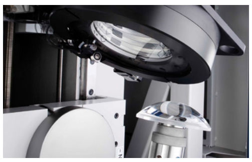

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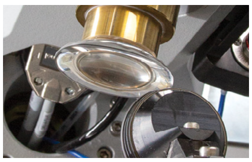

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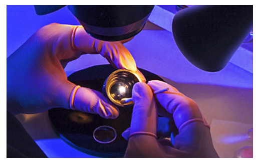

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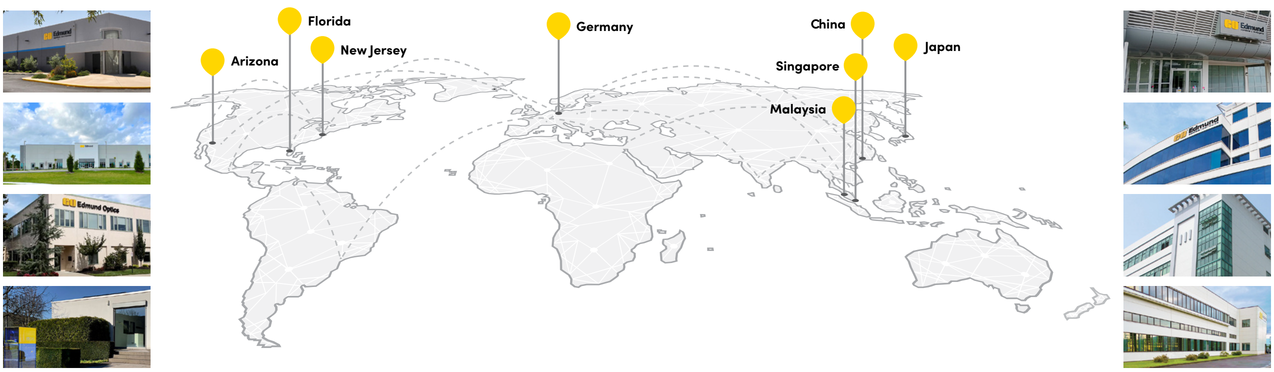

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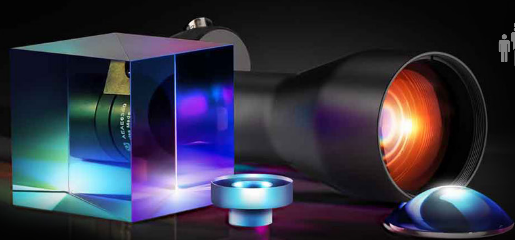

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