EDMUND OPTICS®
ASPHERES

CAPABILITIES | NEW ASPHERIC LENSES | TECH NOTES

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CNC POLISHING CAPABILITIES

Edmund Optics® is a recognized leader in aspheric lens manufacturing, with extensive experience producing aspheric lenses for ophthalmic instruments, surgical devices, analytical instruments, and defense applications. Edmund Optics®' high volume aspheric lens manufacturing cell operates 24 hours a day to produce thousands of precision aspheric lenses per month. Our manufacturing cells feature state-of-the-art production and metrology equipment, which complements our expert knowledge in aspheric lens design and manufacturing. Whether your application calls for a stock component from our vast inventory, a build-to-print lens, or a fully customized design effort, our expert optical design and manufacturing engineers can develop solutions to meet your needs. Contact us today to speak with an expert or receive an expedited quote.

ASPHERIC MANUFACTURING CAPABILITIES

	Commercial	Precision	High Precision
Diameter:	10 - 150mm	10 - 150mm	10 - 150mm
Diameter Tolerance:	+0/-0.100mm	+0/-0.025mm	+0/-0.010mm
Asphere Figure Error (P - V):	3μm	1μm	<0.06μm
Vertex Radius (Asphere):	±0.5%	±0.1%	±0.05%
Sag:	25mm max	25mm max	25mm max
Typical Slope Tolerance:	1μm/mm	0.35μm/mm	0.15μm/mm
Centering (Beam Deviation):	3 arcmin	1 arcmin	0.5 arcmin
Center Thickness Tolerance:	±0.100mm	±0.050mm	±0.010mm
Surface Quality (Scratch Dig):	80-50	40-20	10-5
Aspheric Surface Metrology:	Profilometry (2D)	Profilometry (2D & 3D)	Interferometry

METROLOGY AND PRODUCTION EQUIPMENT

Manufacturing Equipment
- 5-Axis CNC Grinding Machines
- 5-Axis CNC Polishing Machines
- QED MRF Finishing Machines for Fine Finishing
- Centering Machines

Metrology
- Talysurf PGI 1240 Profilometers
- QED ASI™ Aspheric Stitching Interferometers
- Zygo® NewView White Light Interferometers
- OptiPro UltraSurf 4X 100 Non-Contact Profilometers
- TRIOPTICS Opticentric® Centration Measurement Machines
- Zeiss Contura G2 CMMs
- Olympus MX51 Microscopes
- Design-Specific Computer Generated Holograms (CGH)

To watch the **MAKING OF AN ASPHERIC LENS VIDEO,** visit www.edmundoptics.com/making-aspherics

ASPHERIC METROLOGY CAPABILITIES

At Edmund Optics®, we truly believe that you can't make it if you can't measure it. For that reason, we've invested in the latest aspheric metrology equipment, including 2D Profilometry and 3D Stitching Interferometry.

The Taylor Hobson® Talysurf utilizes a stylus to trace the aspheric profile, and measure deviations from the ideal-fit aspheric equation. Typically, measurements are made in 2 axes (0° and 90°) to measure any asymmetric errors in the aspheric polishing. Accuracy is highly dependent upon the geometry of the lens and length of the stylus, but Edmund Optics® routinely measures aspheric lenses with 1μm surface figure requirements and up to 25mm of Sag.

The Optipro Ultrasurf is a non-contact profilometer providing comprehensive 2D and 3D analysis of surface figure, radius of curvature, center thickness, and wedge in a single measurement. By incorporating multi non-contact optical sensors, the Ultrasurf is capable of measuring virtually any asphere.

The QED Technologies® Aspheric Stitching Interferometer (ASI™) provides a full aperture map of the asphere being tested, and is capable of measuring complex aspheres with more than 600μm of aspheric departure. Edmund Optics® routinely measures complex asymmetric aspheric profiles and lenses with <0.5μm surface figure requirements with the ASI™.

METROLOGY SERVICES AND CAPABILITIES

- First Article Inspection (FAI) Reports
- Part Serialization with Complete Tested Data Reports including:
  - Dimensional Measurements
  - Centering / Total Image Runout
  - Surface Profiles
  - Surface Roughness
  - Coating Durability, Adhesion, and Abrasion per MIL-PRF-13830B
  - Damage Threshold per ISO-21254-1:2011
  - Unique or Functional Requirements, Including those Requiring Custom Metrology Solutions
- Configuration Control, Change Control, and Copy Exact! (CE) Requirements
- FAR, DFAR, Quality Assurance Provisions (QAP), and Testing Requirements Flow-downs

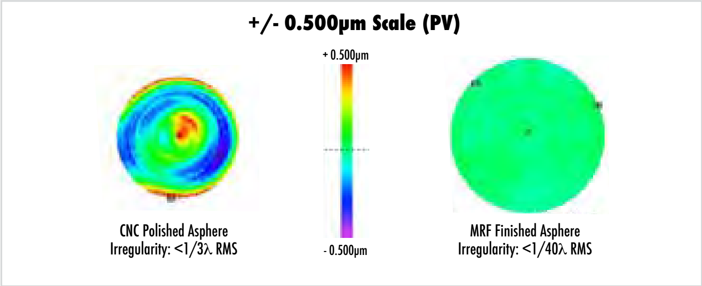
To learn more about our **Manufacturing Capabilities,** visit **www.edmundoptics.com/manufacturing**

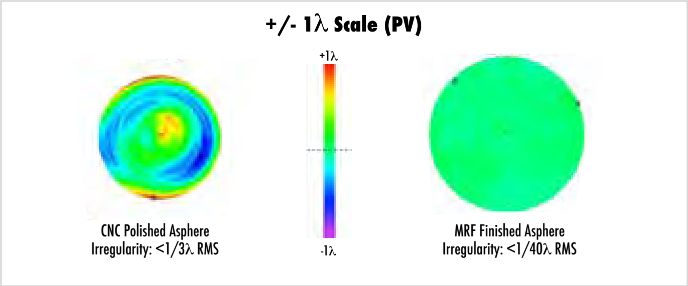
TECHSPEC® $^1/_{40}\lambda$ ASPHERIC LENSES

NEW

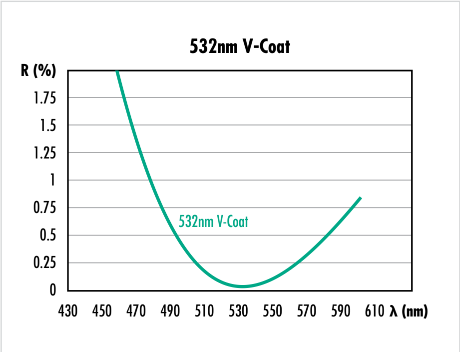
- $^1/_{40}$ Wave Aspheric Surface Figure Error (RMS)
- Guaranteed Strehl Ratio >0.8
- Laser Line V-Coats with <0.25% Reflection

TECHSPEC® $^1/_{40}\lambda$ Aspheric Lenses are polished through precision magnetorheological finishing (MRF), providing them with an ultra-smooth aspheric surface with an aspheric surface tolerance of $^1/_{40}\lambda$ RMS. The aberration free aspheric surfaces produced through this finishing process result in these aspheric lenses having diffraction-limited performance at their design wavelengths. TECHSPEC® $^1/_{40}\lambda$ Aspheric Lenses are coated with a high-performance Laser Line V-Coat to minimize reflection when used at their Nd:YAG design wavelengths. Standard imperial sizes with f/2 designs made from fused silica are ideal for integration into OEM applications.





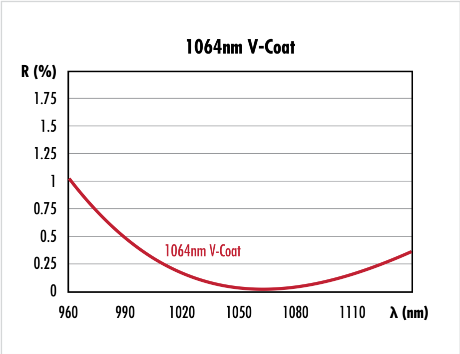
Material:	Fused Silica 7980 0F	**Surface Quality:**	10-5	**Centering (arcmin):**	<1
Aspheric Surface Tolerance (RMS):	$^1/_{40}\lambda$	**Center Thickness Tolerance (mm):**	+/-0.1	**Coating:**	R_{avg} <0.25% @ DWL
Clear Aperture:	Diameter - 2.0mm	**Diameter Tolerance (mm):**	+0.00/-0.05	**Damage Threshold (J/cm²):**	532nm: 10 @ 20ns, 20Hz 1064nm: 15 @ 20ns, 20Hz
Strehl Ratio:	>0.8				



TECHSPEC® $^1/_{40}\lambda$ 532mm ASPHERIC LENSES

Dia. (mm)	EFL (mm)	BFL (mm)	Design Wavelength (mm)	CT (mm)	ET (mm)	Stock No.
25.4	**50.8**	45.4	532	7.9	4.4	#39-558
50.8	**101.6**	93.9	532	11.2	4.1	#39-565

See Website For Pricing



TECHSPEC® $^1/_{40}\lambda$ 1064mm ASPHERIC LENSES

Dia. (mm)	EFL (mm)	BFL (mm)	Design Wavelength (mm)	CT (mm)	ET (mm)	Stock No.
25.4	**50.8**	45.0	1064	8.4	4.7	#39-560
50.8	**101.6**	94.7	1064	10.0	2.7	#39-567

See Website For Pricing

Aspheric Lens Irregularity and Strehl Ratio

All optical systems have a theoretical performance limit known as the diffraction limit. Strehl ratio is a specification used to compare the real performance of an optical system with its diffraction-limited performance. For aspheric lenses and other focusing optics, Strehl ratio is defined as the ratio of peak focal spot irradiance of the manufactured optic to the diffraction-limited peak irradiance *(Figure 1)*.[1] The industry standard threshold to classify a lens as "diffraction-limited" is a Strehl ratio greater than 0.8.

Strehl ratio can also be related to RMS transmitted wavefront error using the following approximation, where σ is RMS wavefront error in waves.[2] This approximation is valid for transmitted wavefront error values <0.1 waves.

$$S = \exp[-(2\pi\sigma)^2] \qquad (1)$$

Impact of Surface Irregularity on Strehl Ratio

The Strehl ratio of an optic is highly dependent on its surface irregularity, or the deviation of the optical surface from its nominal form; surface irregularity is a result of the manufacturing method used. Spherical optics are typically polished using an oversized tool, which imparts low spatial frequency errors on the optical surface. Aspherical lens manufacturing, however, typically utilizes subaperture grinding and polishing, creating a more complex irregularity structure. Understanding the relationship between a specified surface irregularity and its underlying structure can provide insight into the lens' performance and resulting Strehl ratio.

For example, consider the impact of spatial frequency. When surface irregularity is modeled as a rotationally-symmetric cosine function, we can explore the resulting Strehl Ratio as a function of RMS surface irregularity for a variety of cosine periods *(Figure 2 and Figure 3)*.

The key factor here is not the period of the cosine in mm, but the number of periods over the aperture of the lens. For a given subaperture tool used in asphere manufacturing, smaller diameter aspheres will have less Strehl Ratio degradation compared to larger diameter aspheres.

The impact of surface irregularity on Strehl Ratio is also dependent on the f/# of the lens. As a general rule, faster aspheres, or aspheres with smaller f/#'s, have greater sensitivity to surface irregularity's impact on Strehl Ratio. For example, *Figure 4* compares an f/2 lens to an f/0.75 lens (both with 25mm diameter).

Power Spectral Density and Irregularity Slope

Based on the examples above, the spatial frequency content of the irregularity maps clearly has an impact on the Strehl Ratio of the lens. In addition to PV or RMS irregularity, additional specifications can be requested to target these spatial frequencies.

One specification used to directly evaluate spatial frequencies is called Power Spectral Density, or PSD.[4] PSD evaluates surface irregularity as a function of spatial frequency and can be used in a targeted way to limit the contribution from a range of spatial frequencies. PSD may also be used to constrain all spatial frequencies simultaneously.

A more simple, yet effective, method to reduce higher spatial frequencies in the irregularity is to constrain the slope of the cosine functions making up the surface irregularity map, in addition to the PV value. For a given PV irregularity limit, higher slopes are associated with higher spatial frequencies on the surface *(Figure 5)*. Slope is often given in terms of a maximum RMS slope value, which is a more comprehensive evaluation of the lens surface than a simple maximum slope requirement.[5]

The spatial frequency of surface irregularity has a significant impact on Strehl Ratio and asphere performance. The smaller the period, the more Strehl Ratio degradation at a given surface irregularity. The shape of the lens' surface irregularity map is required to understand the true impact of its surface irregularity on its performance, not just an irregularity specification by itself.[3] Smaller f/#'s also lead to more degradation.

References

1. *Strehl, Karl W. A. "Theory of the telescope due to the diffraction of light," Leipzig, 1894.*
2. *Mahajan, Virendra N. "Strehl ratio for primary aberrations in terms of their aberration variance." JOSA 73.6 (1983): 860-861.*
3. *Kasunic, Keith J., Laser Systems Engineering, SPIE Press, 2016. (ISBN 9781510604278)*
4. *Lawson, Janice K., et al. "Specification of optical components using the power spectral density function." Optical Manufacturing and Testing. Vol. 2536. International Society for Optics and Photonics, 1995.*
5. *Messelink, Wilhelmus A., et al., "Mid-spatial frequency errors of mass-produced aspheres," Proc. SPIE 10829, Fifth European Seminar on Precision Optics Manufacturing, 7 Aug. 2018, doi:10.1117/12.2318663.*

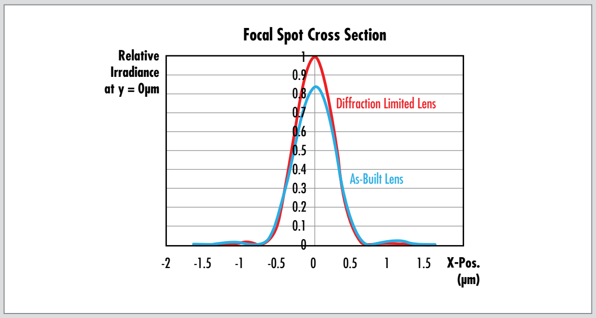


Figure 1: Irradiance cross section plot of the focal spot from a 25mm diameter f/2 aspheric lens at 588nm. The Strehl Ratio of the as-built lens is 0.826, meeting the diffraction-limited criterion

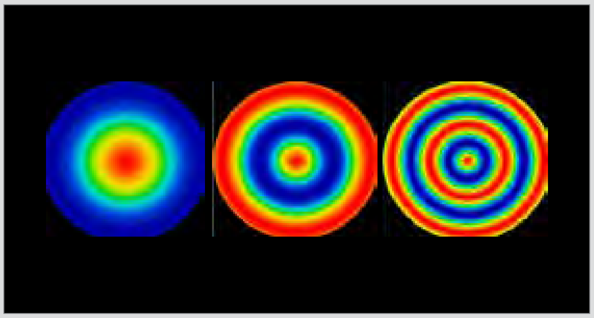


Figure 2: Radial cosine irregularity maps on a 25mm diameter f/2 asphere surface. The cosine periods from left to right are 20mm, 10mm, and 5mm

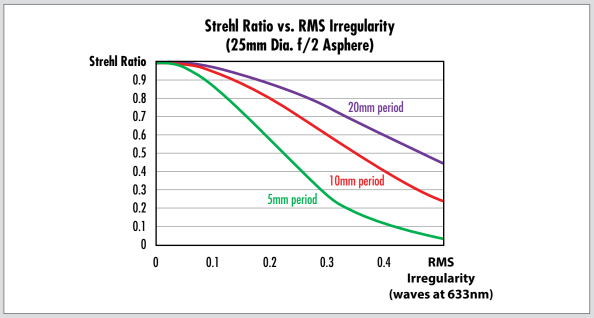


Figure 3: For a particular RMS surface irregularity, the more cosine periods over the aperture of the asphere, the lower the Strehl Ratio

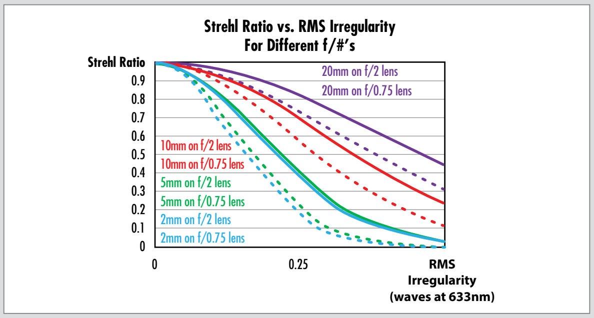


Figure 4: Comparing dotted lines to solid lines shows that a faster asphere (smaller f/#) has greater degradation compared to a slower asphere (larger f/#) over a given cosine period

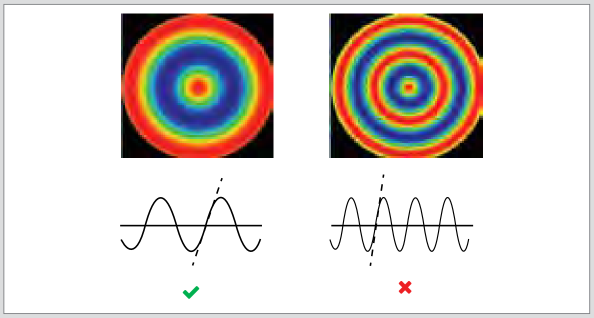


Figure 5: If a maximum slope specification is specified for the surface irregularity map, this creates a threshold to reduce the impact of higher spatial frequency content on the surface

Optical Coatings and Laser Induced Damage Threshold

All of our TECHSPEC® Laser Grade Aspherical Lenses are coated with a high efficiency anti-reflection coating to guarantee maximum transmission of the incident laser illumination. The coatings have been designed not only to exhibit extremely low loss (<0.25% reflection), but also to withstand the high laser fluence commonly found in modern laser systems. See below for an introduction to Laser Induced Damage Threshold (LIDT).

Laser induced damage in optical components causes degradation in system performance that can even result in catastrophic failure. An incorrect understanding of LIDT may lead to significantly higher costs or to component failures. Especially when dealing with high power lasers, LIDT is an important specification for all types of laser optics including reflective, transmissive, and absorptive components. The lack of an industry consensus on how LIDT should be tested, how damage should be detected, and how the test data should be interpreted makes LIDT a complicated specification. An LIDT 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.

Testing Laser Damage Threshold

Laser damage testing is inherently destructive. The optic undergoing testing is exposed to a level of laser fluence and is then examined, typically with Nomarski-type differential interference contrast (DIC) microscopy. The fluence is then increased, and the exposure and examination steps are repeated. This process continues until damage is observed on the optic. While this is conceptually a simple process, there are several levels of complexity.

According to ISO 21254, any detectable change in an optic under test is considered "damage". Different LIDT values may be produced depending on how the damage was evaluated, as not all tests use the same damage detection schemes and different operators might choose different signal-to-noise thresholds. It is important to realize that what ISO defines as "damage" does not necessarily imply performance degradation because it is application-dependent.

LIDT testing is specified by either a single or multi-shot test. A single-shot test, also known as a 1-on-1 test, involves one shot of laser radiation on at least 10 different sample sites across an optical component with varying laser fluence. The number of damaged sites over the total number of tested sites at that fluence determines the damage probability at a particular fluence. The damage probability is plotted as a function of fluence and the data is linearly extrapolated to find where the damage probability is 0%, which gives the LIDT value *(Figure 1)*.

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.

Table 1: Descriptions of different damage mechanisms

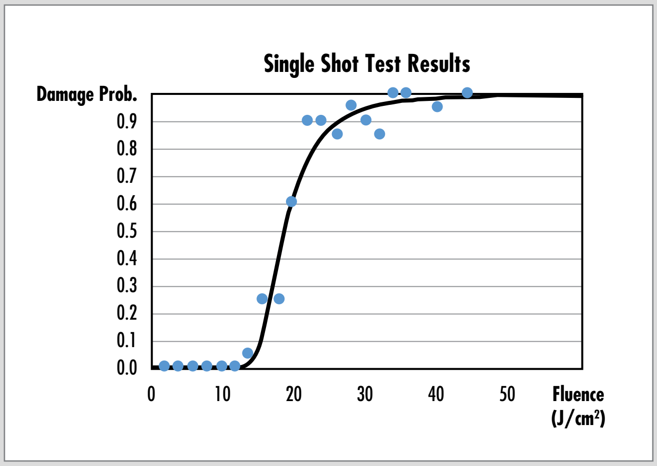


Figure 1: Sample data from a single shot test

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A multi-shot, or S-on-1, test differs from a single-shot test in that it uses a series of laser shots, or pulses, per testing site as opposed to a single shot. The common number of shots per site, or S, are between 10 and 1000. Multi-shot tests provide a better prediction of the real-world performance of the optic, and allow LIDT testers to avoid a phenomenon called the infant mortality realm. When using between 1 and 10 shots per site, test results are non-deterministic and have high levels of statistical variation; this causes the range of shots per site to be known as the infant mortality realm. When S is greater than 10, the test results are more deterministic and predictable. Therefore, when around 100 shots per site are used, enough information can be gathered to predict the long-term performance of the optic. However, using more shots per site requires longer and more expensive LIDT testing.

Interpreting LIDT Test Results

The specified LIDT of an optic is determined by linearly extrapolating the test data to determine the laser fluence at which the probability of damage is zero. However, this is a linear fit to data that is not truly linear. This single value does not provide all necessary information and damage could still occur at or below the LIDT. Weibull and Burr distributions are continuous probability distributions that provide a much more accurate fit to LIDT data *(Figure 2)*.

At a fluence around 5 J/cm², there is a non-zero probability of damage, even though this is below the specified LIDT value. The vertical error bars in damage probability are caused by the number of test sites and the horizontal error bars in fluence are caused by shot-to-shot variation of the test laser. Because no laser is perfect, there will always be some level of hotspots, or intensity fluctuations. This necessitates adding a factor of safety by choosing an optic with a LIDT higher than the laser's use conditions. The safety factor required is heavily dependent on the application and type of laser, therefore no general safety factor works for all situations. Common industry practice is to use a safety factor of two or three. However, if the laser induced damage is defect driven, there are statistical models that can be used to evaluate the damage probability at different safety factors.

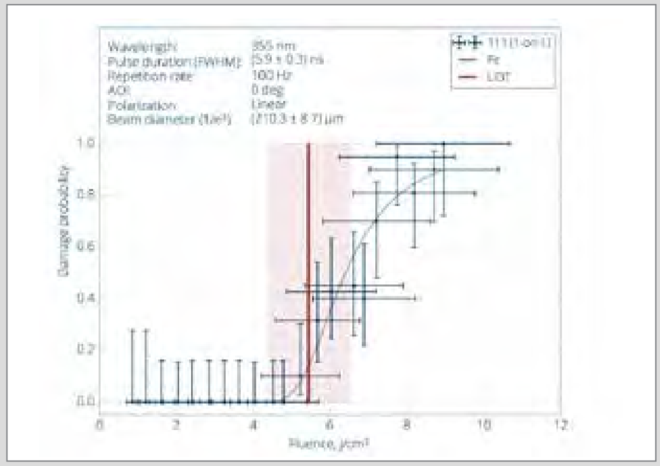

Figure 2: Real LIDT test data with the LIDT value shown by a red vertical line and a best fit 2-parameter Weibull distribution, showing that there is still some probability of damage below the LIDT value

STANDARD AR LASER COATINGS	*See website for full coating list	
DWL	Reflectivity Specifications	LIDT, Pulsed (J/cm²)
266nm	R_{abs} <0.25% @ DWL	3, 20ns @ 20Hz
343nm	R_{abs} <0.25% @ DWL	7.5, 20ns @ 20Hz
355nm	R_{abs} <0.25% @ DWL	7.5, 20ns @ 20Hz
515nm	R_{abs} <0.25% @ DWL	10, 20ns @ 20Hz
532nm	R_{abs} <0.25% @ DWL	10, 20ns @ 20Hz
980nm	R_{abs} <0.25% @ DWL	15, 20ns @ 20Hz
1030nm	R_{abs} <0.25% @ DWL	15, 20ns @ 20Hz
1064nm	R_{abs} <0.25% @ DWL	15, 20ns @ 20Hz

Table 2: Reflectivity specifications and guaranteed laser induced damage thresholds for EO's standard AR laser coatings. For other laser wavelengths, custom coating designs are available upon request

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- Designed and Manufactured by Edmund Optics®
- Highest Numerical Apertures Available
- Broadband AR Coatings Available

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PRECISION UV FUSED SILICA ASPHERIC LENSES

- Low f/#s for Optimum Light Gathering
- Low Coefficient of Thermal Expansion
- Prescription Information Available for OEM Integration

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- Standard 25mm Diameter for Easy System Integration
- Molded Design for Volume Integration

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- Premier Grade ZnSe Material
- Uncoated and Broadband 8 - 12um AR Coating Available

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- Color Corrected for 3 - 5um
- Near Diffraction Limited Focusing Performance
- Full Prescription Data Available

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