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THORLABS

ZERO-ORDER VORTEX HALF-WAVE RETARDERS

WPV10L-405 - January 18, 2023

Item WPV10L-405 was discontinued on January 18, 2022. For informational purposes, this is a copy of the website content at that time and is valid only for the stated product.

- **Radially and Azimuthally Polarize Light from a Linearly Polarized Source**
- **Available as Either an m = 1 or m = 2 Vortex Retarder**
- **Create "Donut Hole" Beam Profiles from Gaussian Beams**
- **Center Wavelengths Available from 405 nm to 1550 nm**

WPV10L-780
m = 1 Vortex Retarder, 780 nm

WPV10-405
m = 2 Vortex Retarder, 405 nm

WPV10-1064
m = 2 Vortex Retarder, 1064 nm

Application Idea

The WPV10-633 Vortex Retarder Mounted in an ST1XY-D XY Translation Mount

OVERVIEW

Features

- True Zero-Order Vortex Half-Wave Plates
- Controls Radial and Azimuthal Polarizations
- Options for m = 1 or m = 2 Vortex Retarder
  (See the *Comparison* Tab)
- Center Wavelength Options from 405 nm to 1550 nm
  (See *Specs* Tab)
- Compatible with Beam Sizes from Ø300 µm to Ø21.5 mm
- Large AOI of ±20°
- Custom Vortex Retarders Available

m = 2 Vortex Retarder   m = 1 Vortex Retarder

Figure 1: Each retarder is engraved with its part number and leader lines to aid in alignment.

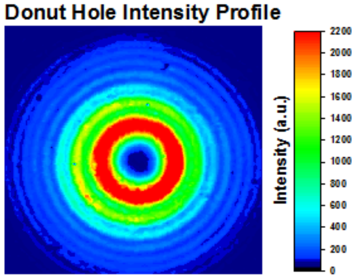


Figure 2: The intensity profile of a Laguerre-Gaussian donut hole beam generated by WPV10-532 m = 2 vortex retarder. See the *LG Mode & Alignment* tab for more information.

Thorlabs' Liquid Crystal Polymer (LCP) Vortex Retarders are half-wave retarders designed to affect the radial and azimuthal polarization of optical fields. A vortex retarder has a constant retardance across the clear aperture but its fast axis rotates continuously over the area of the optic. These retarders are offered as either m = 1 (Item # Prefix WPV10L) or m = 2 (Item # Prefix WPV10) order vortex retarders. The difference between the two orders is the fast axis distribution over the clear aperture of the retarder. As a result, they generate different polarization patterns from linearly polarized light (see the *Comparison* tab for more information).

These retarders are mounted in an aluminum housing with an engraving along the perimeter to assist in locating the center point of the plate for beam alignment purposes. The m = 1 retarders have an additional mark, denoted by 3 lines, to indicate the orientation of the zero-degree fast axis (see Figure 1). Each LCP vortex retarder is composed of a thin LCP film sandwiched between two Ø23 mm, 1 mm thick N-BK7 glass plates. Photo-alignment techniques set the LCP molecules' orientations to create the continuously rotating fast axis, with the point of rotation at the center of the optic. Due to their construction, these retarders can accept a large AOI of ±20°. Additionally, they are compatible with beam diameters from 21.5 mm (0.84") down to 0.3 mm (0.01").

Vortex retarders generate nondiffracting, or Bessel, beams, which have been demonstrated to enlarge the trapping region of optical tweezers. Specifically, these retarders convert standard TEM_{00} Gaussian beams into so-called "donut hole" Laguerre-Gaussian modes, as shown in Figure 2. Both the m = 1 and m = 2 retarders are capable of generating a donut hole shaped beam; however, the polarization direction of the resulting beam will be different (see the *Comparison* tab for more information). In general, the m = 1 retarder will produce a smaller, more circular donut hole compared to the m = 2. Vortex retarders should be used at a single wavelength close to the design wavelength; the donut beam profile will degrade as the deviation from the design wavelength increases.

The point of rotation for the fast axis is nominally located in the center of the glass substrate, but has a Ø1 mm variable range from retarder to retarder. The engraved lines on the housing of these devices give a rough indication as to the position of the center.

An AR coating is applied to both outer surfaces to improve the transmission through the optic at its specified wavelength. They are mounted in a thin walled, Ø1" housing that is compatible with many of our Ø1" optic mounts, including XY translation mounts.

SPECS

Vortex Retarder General Specifications										
Item #	**WPV10-405 WPV10L-405**	**WPV10-532 WPV10L-532**	**WPV10-633 WPV10L-633**	**WPV10-705 WLP10L-705**	**WPV10-780 WPV10L-780**	**WPV10-830 WPV10L-830**	**WPV10-980 WPV10L-980**	**WPV10-1064 WPV10L-1064**	**WPV10-1310 WPV10L-1310**	**WPV10-1550 WPV10L-1550**
Design Wavelength	405 nm	532 nm	633 nm	705 nm	780 nm	830 nm	980 nm	1064 nm	1310 nm	1550 nm
Transmission at Design Wavelength[a]	≥85%	≥97%	≥97%	≥97%	≥97%	≥97%	≥97%	≥96%	≥96%	≥96%
AR Coating Range	350 - 700 nm			650 - 1050 nm				1050 - 1700 nm		
Average Reflectance (per Surface)[b]	<0.5%									
Angle of Incidence[c]	±20°									
Material	Liquid Crystal Polymer Between N-BK7 Glass Plates									
Retardance	λ/2									
Outer Diameter	25.4 ± 0.2 mm (1.00" ± 0.008")									
Clear Aperture	Ø21.5 mm (Ø0.85")									
Housing Thickness	3.4 mm (0.13")									
Surface Quality	60-40 Scratch-Dig									
Operating Temperature Range	-20 to 60 °C									
Temperature Stability	<0.08 nm/°C over the Operating Temperature Range									
Beam Deviation	<20 arcmin									

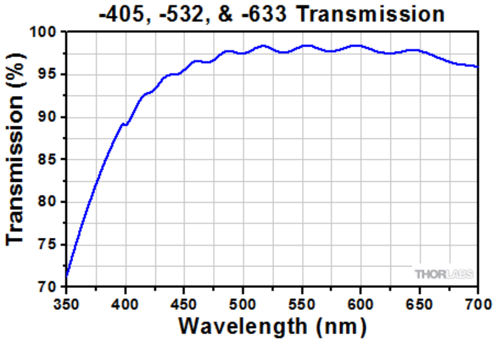
a. See *Graphs* tab for transmission data. Valid for an angle of incidence close to 0°.
b. Over the AR Coating Range
c. The angle of incidence (AOI) is the range over which the optic will convert a linearly polarized input beam into a "donut hole" output beam. The AR coating performance will decrease as the optic is rotated away from 0° AOI, resulting in lower total transmission.
d. The power density of your beam should be calculated in terms of W/cm. For an explanation of why the linear power density provides the best metric for long pulse and CW sources, please see the *Damage Thresholds* tab.

Vortex Retarder Order			
Item #	**Order**	**Item #**	**Order**
WPV10L-405	m = 1	**WPV10-405**	m = 2

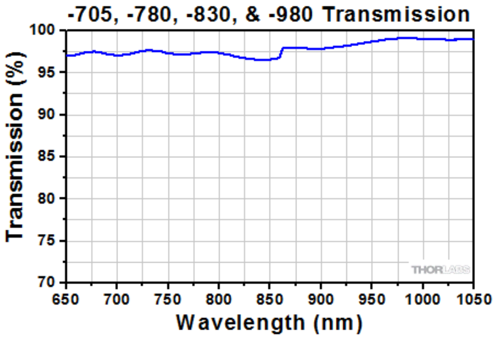
Vortex Retarder Order	
WPV10L-532	**WPV10-532**
WPV10L-633	**WPV10-633**
WPV10L-705	**WPV10-705**
WPV10L-780	**WPV10-780**
WPV10L-830	**WPV10-830**
WPV10L-980	**WPV10-980**
WPV10L-1064	**WPV10-1064**
WPV10L-1310	**WPV10-1310**
WPV10L-1550	**WPV10-1550**

GRAPHS

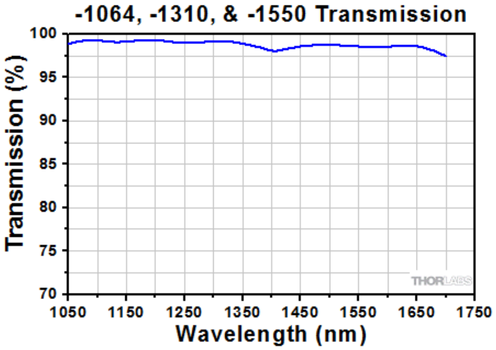
The graphs below are provided as examples of the typical performance of Thorlabs' Vortex Retarders. Actual performance will vary from lot to lot within the specifications provided on the *Specs* tab.



Transmission curve for the WPV10L-405, WPV10L-532, WPV10L-633, WPV10-405, WPV10-532, and WPV10-633 Vortex Retarders. Click here for Raw Data.

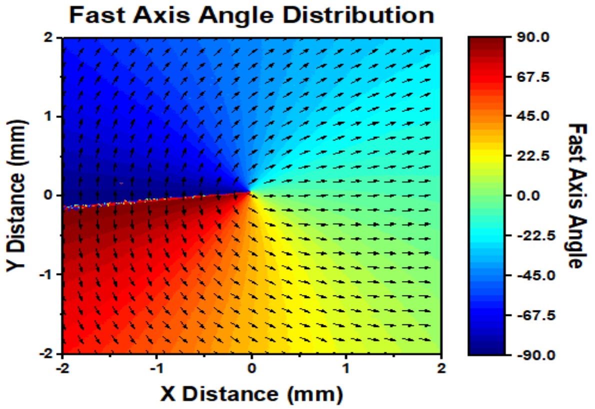


Transmission curve for WPV10L-705, WPV10L-780, WPV10L-830, WPV10L-980, WPV10-705, WPV10-780, WPV10-830, and WPV10-980 Vortex Retarders. Click here for Raw Data.

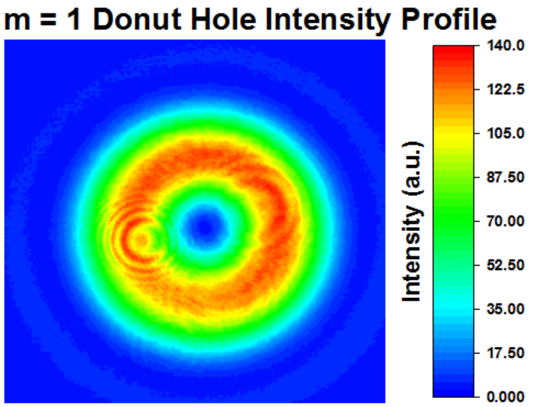


Transmission curve for the WPV10L-1064, WPV10L-1310, WPV10L-1550, WPV10-1064, WPV10-1310, and WPV10-1550 Vortex Retarders. Click here for Raw Data.

m = 1 Vortex Retarders



The plot above shows the fast axis orientation over the surface of our m=1 vortex retarders.
The 0° fast axis angle location is indicated by three lines on the retarder's mount.



The intensity profile of a Laguerre-Gaussian donut hole beam generated by the WPV10L-633 m = 1 Vortex Retarder.

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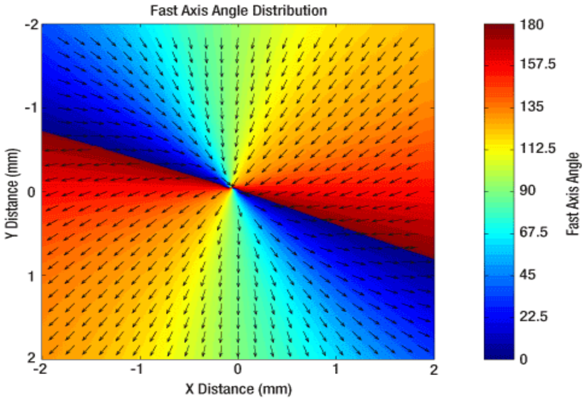
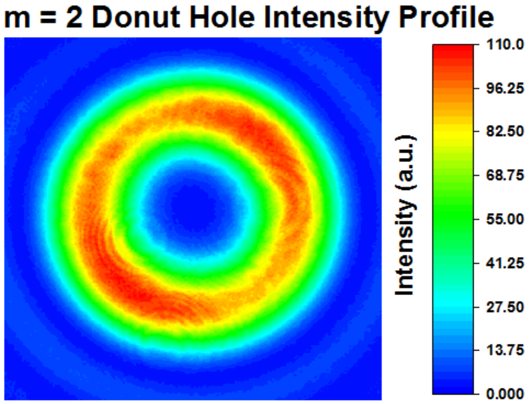
m = 2 Vortex Retarders



The plot above shows the fast axis orientation over the surface of our m=2 vortex retarders.



The intensity profile of a Laguerre-Gaussian donut hole beam generated by the WPV10-633 m = 2 Vortex Retarder.

COMPARISON

Retarder Order

Thorlabs offers both m = 1 and m = 2 vortex wave plates, where m is known as the order as seen in the equation below.

$$\theta = \frac{m}{2}\varphi + \delta \tag{1}$$

Vortex Retarder Comparison		
Item Prefix	**WPV10L**	**WPV10**
Order	m = 1	m = 2
Generates Donut Beam	Yes	Yes
Relative Donut Hole Shape (Click for Graph)	Smaller and More Circular	Larger and More Elliptical
Input Polarization Dependent	Yes	No
Output Light Polarization Pattern	m = 2 Vortex Pattern	m = 4 Vortex Pattern

Here θ is the orientation of the fast-axis as a given azimuthal angle (φ) on the waveplate, δ is the orientation of the fast axis at φ = 0. Thus different ordered waveplates will have a different distribution of the fast axis about the center of the device. Figures 1 and 2 depict the fast axis pattern on our m = 1 and m = 2 retarders, respectively.

The table to the right highlights some of the main differences between the m = 1 and m = 2 vortex retarders, including graphs of the generated donut beams by each style retarder. Both of these intensity profiles were created from the same 633 nm laser source. The profile created by the m = 1 retarder has a smaller central hole (about Ø0.25 mm) than the profile from the m = 2 waveplate (about Ø0.4 mm). Furthermore, the former is more circular than the latter.

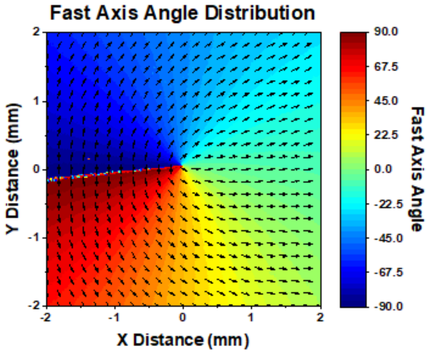


Figure 1: The plot above shows the fast axis orientation (denoted by arrows) over the surface of our m = 1 vortex retarders.

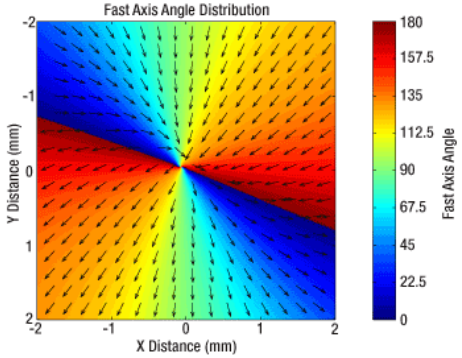
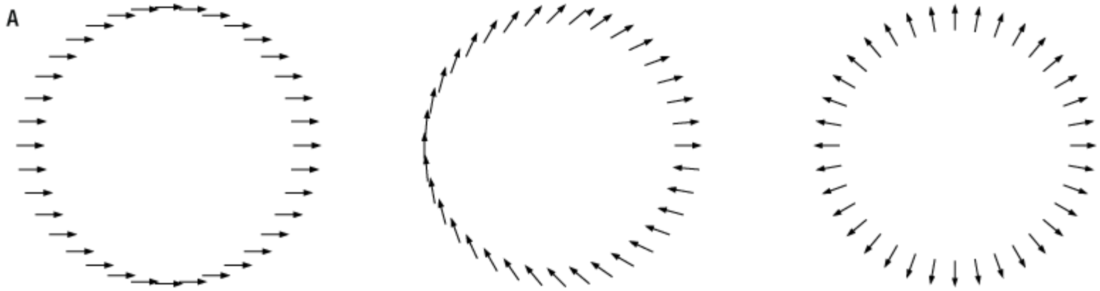


Figure 2: The plot above shows the fast axis orientation (denoted by arrows) over the surface of our m=2 vortex retarders.

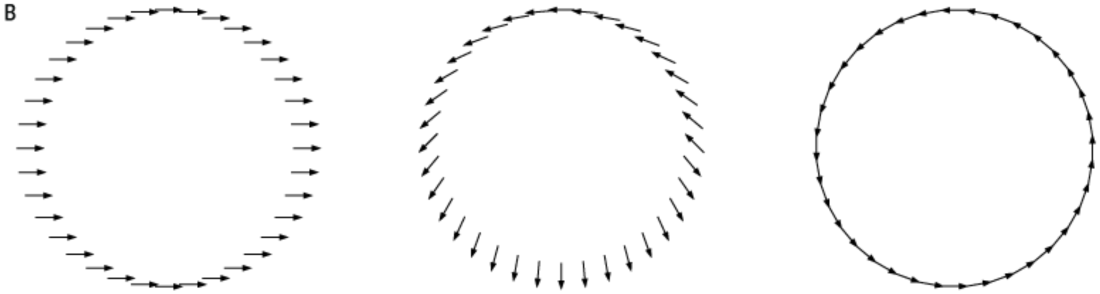
Another notable difference is that the m = 2 vortex retarder is a polarization independent device. Due to its fast axis distribution, it will generate similar polarization distributions regardless of the incident polarization direction of the light. The m = 1 retarder is polarization dependent; the waveplate can produce different polarization directions for differing orientations of the retarder to the polarization axis of the light, as seen in Figure 3.



A linearly polarized input beam incident on a m=1 vortex retarder.

The fast-axis orientation of the m=1 vortex retarder.

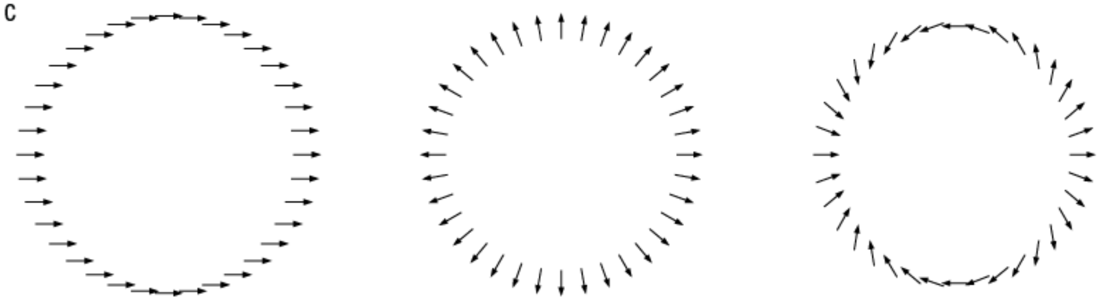
The output polarization after a linearly polarized beam passed through the m=1 vortex retarder.



A linearly polarized input beam incident on a m=1 vortex retarder.

The fast-axis orientation of the m=1 vortex retarder.

The output polarization after a linearly polarized beam passed through the m=1 vortex retarder.



A linearly polarized input beam incident on a m=2 vortex retarder.

The fast-axis orientation of the m=2 vortex retarder.

The output polarization after a linearly polarized beam passed through the m=2 vortex retarder.

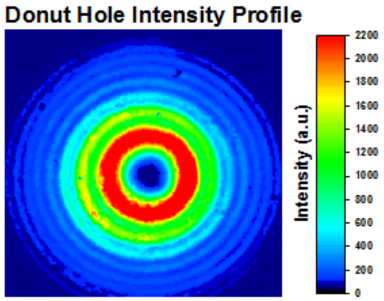
Figure 3: Rows A and B above show the resulting polarization from a linearly polarized source for an m = 1 vortex retarder. The input polarization is the same, but the relative angle of the fast axis is different, producing different output polarizations. Row C demonstrates the polarization insensitive nature of the m = 2 retarder.

LG MODE & ALIGNMENT&NBSP;

Generating Laguerre-Gaussian Donut Hole Laser Modes

Thorlabs makes several versions of these Vortex Retarders to accommodate a range of design wavelengths from 405 nm to 1550 nm (see *Specs* tab for more information). To generate the Laguerre-Gaussian donut hole laser modes, simply match the design wavelength of the retarder to that of the laser source. A CCD beam profiler* can be used to measure the resultant laser beam's intensity distribution. Both our m = 1 and m = 2 retarders are capable of producing a donut hole laser mode.

The image to the right shows the donut hole mode generated by the WPV10-532 m = 2 Vortex Retarder aligned with the center of the beam. A 532 nm laser with a Ø0.684 mm beam size was used for this example. The false color plot was captured using the previous-generation BC106N-VIS/M CCD beam profiler.

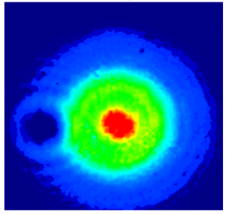


The intensity profile of a Laguerre-Gaussian donut hole beam.

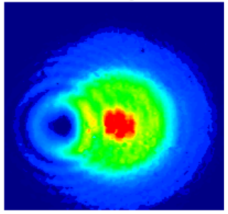
The series of images below show the alignment of this retarder with a laser beam. The point of rotation for the fast axis is nominally located in the center of the glass substrate, but has a Ø1 mm variable range from retarder to retarder. The engraved lines on the housing of these devices gives a rough indication as to the position of the center. A CCD profiler was used to measure the beam shape as the retarder was translated across the beam's diameter.

*A scanning slit beam profiler should not be used, as these devices calculate the beam shape based on the assumption of a near-Gaussian beam profile.

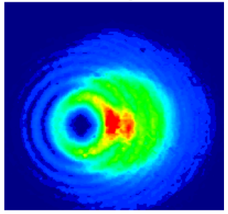
Off Center by 2.0 mm



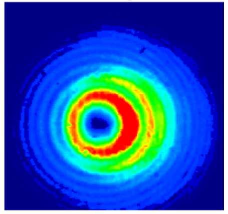
Off Center by 1.5 mm



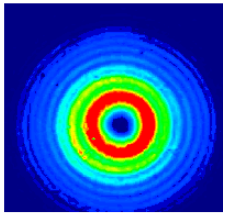
Off Center by 1.0 mm



Off Center by 0.5 mm



Centered



Thorlabs offers a variety of polymer vortex retarders with operating wavelengths from 405 to 1550 nm, mounted in Ø1" mechanical housings. In addition, we also offer OEM and custom polymer vortex retarders upon request. The target wavelength, order, coating, mechanical housing, and dimensions can all be customized to meet unique optical design requirements.

Our engineers work directly with our customers to discuss the specifications and other design aspects of custom vortex retarders. We analyze both the design and feasibility to ensure the custom products are manufactured to the highest quality standards and in a timely manner. For more information about ordering a custom vortex retarder, please contact Technical Support.

Figure 1: Our highly trained engineers constructing and testing polymer vortex retarders.

Coating and Fast-Axis Alignment of the Photo-Alignment Material

Vortex retarders utilize a liquid crystal polymer, similar to nematic liquid crystals, which requires the polymer molecules to be aligned. To accomplish this, an alignment layer is created by coating a substrate in photo-alignment material and exposing it to polarized laser light. A 20 to 30 nm layer of photo-alignment material is deposited on a glass substrate by spin coating (see Figure 2). The coated substrate is then placed in the photo-alignment system for alignment, where it is rotated at 120 RPM while being exposed to a linearly polarized line of light (width <3 µm, length >25.4 mm). The molecules in the coating align with the polarization axis of the incident line of light. The center of rotation for the substrate is positioned on the light line to minimize center misalignment.

In addition to these vortex retarders, we can also offer a wide variety of stock and custom patterned retarders and wave plates.

Custom Retardance

The retardance of a vortex retarder is determined by the thickness of a layer of cured liquid crystal polymer. This layer is coated on top of the alignment material using a spin coating technique, enabling precise control of the layer's thickness. Our stock vortex retarders cover many commonly used wavelengths. Custom retarders for single wavelengths between 400 and 1064 nm can be special ordered as well.

Custom m Values

The order of a vortex retarder is controlled by a precise photo alignment of the liquid crystal polymer. Our in-house manufacturing capabilities allow us to create custom retarders of higher order ($m > 2$).

Custom Size and Mounting Options

We offer Ø1" mounted vortex retarders from stock. Custom vortex retarders are available in sizes ranging from Ø0.2" to Ø1" and can be ordered either mounted or unmounted.

Testing

Each vortex retarder is tested for birefringence, uniformity, and fast axis angle. An imaging polarimeter measures the 2-dimensional birefringence distribution across the wave plate's face. Figures 3, 4, and 5 show testing rigs for our polymer wave plates.

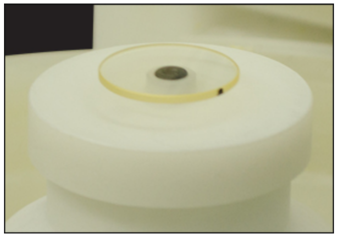


Figure 2: A glass substrate mounted on the spin coating machine ready to be coated with the photo alignment material.

Figure 3: The test setup for checking the retardance and alignment uniformity of our vortex retarders.

Figure 4: A second test setup for checking the alignment and uniformity of our vortex retarders.

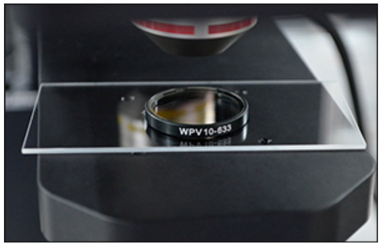


Figure 5: A close up of a vortex retarder in one of the test setups.

PATTERNED RETARDERS

Features

- Build a Custom Microretarder
- Customize Size, Shape, and Substrate Material
- Retardance Range: 50 - 550 nm
- Fast Axis Resolution: <1°
- Retardance Fluctuations Under 30 nm

Applications

- 3D Displays
- Polarization Imaging
- Diffractive Optical Applications: Polarization Gratings, Polarimetry, and Beam Steering

Custom Capability	Custom Specification
Patterned Retarder Size	Ø100 µm to Ø2"
Patterned Retarder Shape	Any
Microretarder Size	≥Ø30 µm
Microretarder Shape	Round or Square
Retardance Range @ 632.8 nm	50 to 550 nm
Substrate	N-BK7, UV Fused Silica, or Other Glass
Substrate Size	Ø5 mm to Ø2"
AR Coating	-A: 350 - 700 nm -B: 650 - 1050 nm -C: 1050 - 1700 nm

Thorlabs offers customizable patterned retarders, available in any pattern size from Ø100 µm to Ø2" and any substrate size from Ø5 mm to Ø2". These custom retarders are composed of an array of microretarders, each of which has a fast axis aligned to a different angle than its neighbor. The size and shape of the microretarders are also customizable. They can be as small as 30 µm and in shapes including circles and squares. This control over size and shape of the individual microretarders allows us to construct a large array of various patterned retarders to meet nearly any experimental or device need.

These patterned retarders are constructed from our liquid crystals and liquid crystal polymers. Using photo alignment technology, we can secure the fast axis of each microretarder to any angle within a resolution of <1°. Figures 1 - 3 show examples of our patterned retarders. The figures represent measured results of the patterned retarder captured on an imaging polarimeter and demonstrate that the fast axis orientation of any one individual microretarder can be controlled deterministically and separately from its neighbors.

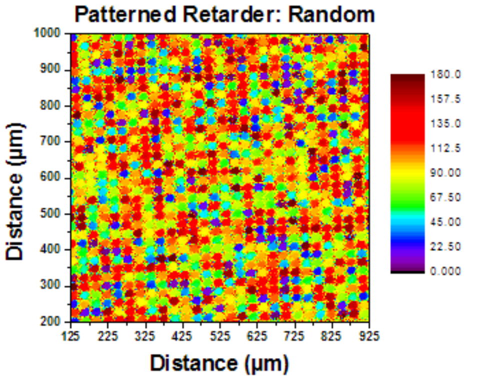


Figure 1: Patterned Retarder with Random Distribution

The manufacturing process for our patterned retarders is controlled completely in house. It begins by preparing the substrate, which is typically N-BK7 or UV fused silica (although other glass substrates may be compatible as well). The substrate is then coated with a layer of photoalignment material and placed in our patterned retarder system where sections are exposed to linearly polarized light to set the fast axis of a microretarder. The area of the exposed sections depends on the desired size of the microretarder; the fast axis can be set between 0° and 180° with a resolution <1°. Once set, the liquid crystal cell is constructed by coating the device with a liquid crystal polymer and curing it with UV light.

Thorlabs' LCP depolarizers provide one example of these patterned retarders. In principle, a truly randomized pattern may be used as a depolarizer, since it scrambles the input polarization spatially. However, such a pattern will also introduce a large amount of diffraction. For our depolarizers, we designed a linearly ramping fast axis angle and retardance that can depolarize both broadband and monochromatic beams down to diameters of 0.5 mm without introducing additional diffraction. For more details, see the webpage for our LCP depolarizers.

By supplying Thorlabs with a drawing of the desired patterned retarder or an excel file of the fast axis distribution, we can construct almost any patterned retarder. For more information on creating a patterned retarder, please contact Tech Support.

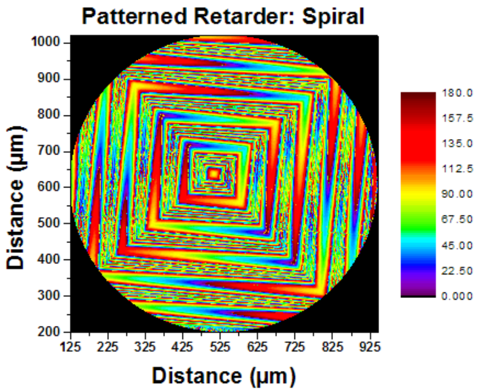


Figure 2: Patterned Retarder with a Spiral Distribution

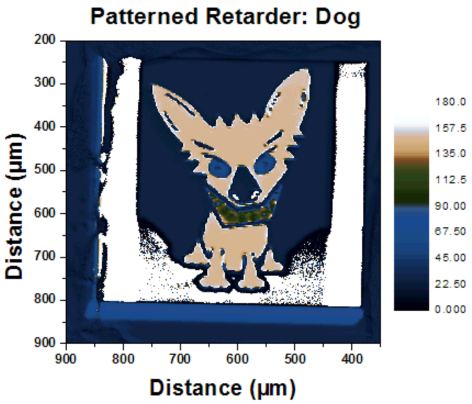


Figure 3: Patterned Retarder with a Pictoral Distribution

Damage Threshold Data for Thorlabs' LCP Vortex Retarders

The specifications to the right are measured data for Thorlabs' LCP vortex retarders. Damage threshold specifications are constant for all of the vortex retarders with the same AR coating.

Damage Threshold Specifications		
Item # Suffix	**Laser Type**	**Damage Threshold**
-405 to 633	**CW**	5 W/cm (810 nm, Ø0.004 mm)[a]
	Pulsed (ns)	1.8 J/cm^2 (532 nm, 8 ns, 10 Hz, Ø0.200 mm)
	Pulsed (fs)	0.041 J/cm^2 (532 nm, 100 Hz, 76 fs, Ø162 µm)
-705 to 980	**CW**	5 W/cm (810 nm, Ø0.004 mm)[a]
	Pulsed (ns)	8 J/cm^2 (810 nm, 10 ns, 10 Hz, Ø0.08 mm)
	Pulsed (fs)	0.041 J/cm^2 (800 nm, 100 Hz, 36.4 fs, Ø189 µm)
-1064 to 1550	**CW**	5 W/cm (1542 nm, Ø0.161 mm)
	Pulsed (ns)	10 J/cm^2 (1550 nm, 7.8 ns, 10 Hz, Ø0.191 mm)
	Pulsed (fs)	0.11 J/cm^2 (1550 nm, 100 Hz, 70 fs, Ø145 µm)

a. The power density of your beam should be calculated in terms of W/cm. For an explanation of why the linear power density provides the best metric for long pulse and CW sources, please see the "Continuous Wave and Long-Pulse Lasers" section below.

Laser Induced Damage Threshold Tutorial

The following is a general overview of how laser induced damage thresholds are measured and how the values may be utilized in determining the appropriateness of an optic for a given application. When choosing optics, it is important to understand the Laser Induced Damage Threshold (LIDT) of the optics being used. The LIDT for an optic greatly depends on the type of laser you are using. Continuous wave (CW) lasers typically cause damage from thermal effects (absorption either in the coating or in the substrate). Pulsed lasers, on the other hand, often strip electrons from the lattice structure of an optic before causing thermal damage. Note that the guideline presented here assumes room temperature operation and optics in new condition (i.e., within scratch-dig spec, surface free of contamination, etc.). Because dust or other particles on the surface of an optic can cause damage at lower thresholds, we recommend keeping surfaces clean and free of debris. For more information on cleaning optics, please see our *Optics Cleaning* tutorial.

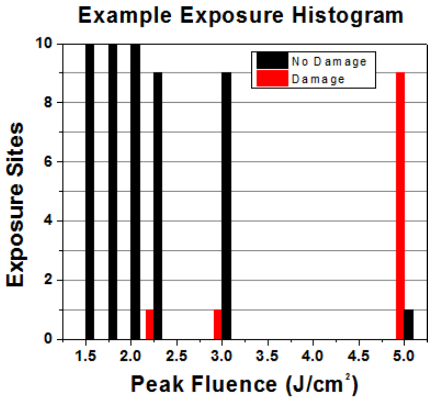
Testing Method

Thorlabs' LIDT testing is done in compliance with ISO/DIS 11254 and ISO 21254 specifications.

First, a low-power/energy beam is directed to the optic under test. The optic is exposed in 10 locations to this laser beam for 30 seconds (CW) or for a number of pulses (pulse repetition frequency specified). After exposure, the optic is examined by a microscope (~100X magnification) for any visible damage. The number of locations that are damaged at a particular power/energy level is recorded. Next, the power/energy is either increased or decreased and the optic is exposed at 10 new locations. This process is repeated until damage is observed. The damage threshold is then assigned to be the highest power/energy that the optic can withstand without causing damage. A histogram such as that below represents the testing of one BB1-E02 mirror.

The photograph above is a protected aluminum-coated mirror after LIDT testing. In this particular test, it handled 0.43 J/cm^2 (1064 nm, 10 ns pulse, 10 Hz, Ø1.000 mm) before damage.

According to the test, the damage threshold of the mirror was 2.00 J/cm^2 (532 nm, 10 ns pulse, 10 Hz, Ø0.803 mm). Please keep in mind that these tests are performed on clean optics, as dirt and contamination can significantly lower the damage threshold of a component. While the test results are only representative of one coating run, Thorlabs specifies damage threshold values that account for coating variances.



Example Test Data			
Fluence	**# of Tested Locations**	**Locations with Damage**	**Locations Without Damage**
1.50 J/cm^2	10	0	10
1.75 J/cm^2	10	0	10
2.00 J/cm^2	10	0	10
2.25 J/cm^2	10	1	9
3.00 J/cm^2	10	1	9
5.00 J/cm^2	10	9	1

Continuous Wave and Long-Pulse Lasers

When an optic is damaged by a continuous wave (CW) laser, it is usually due to the melting of the surface as a result of absorbing the laser's energy or damage to the optical coating (antireflection) [1]. Pulsed lasers with pulse lengths longer than 1 µs can be treated as CW lasers for LIDT discussions.

When pulse lengths are between 1 ns and 1 µs, laser-induced damage can occur either because of absorption or a dielectric breakdown (therefore, a user must check both CW and pulsed LIDT). Absorption is either due to an intrinsic property of the optic or due to surface irregularities; thus LIDT values are only valid for optics meeting or exceeding the surface quality specifications given by a manufacturer. While many optics can handle high power CW lasers, cemented (e.g., achromatic doublets) or highly absorptive (e.g., ND filters) optics tend to have lower CW damage thresholds. These lower thresholds are due to absorption or scattering in the cement or metal coating.

Pulsed lasers with high pulse repetition frequencies (PRF) may behave similarly to CW beams. Unfortunately, this is highly dependent on factors such as absorption and thermal diffusivity, so there is no reliable method for determining when a high PRF laser will damage an optic due to thermal effects. For beams with a high PRF both the average and peak powers must be compared to the equivalent CW power. Additionally, for highly transparent materials, there is little to no drop in the LIDT with increasing PRF.

In order to use the specified CW damage threshold of an optic, it is necessary to know the following:

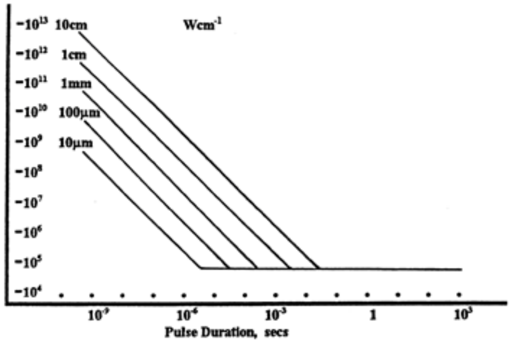
1. Wavelength of your laser
2. Beam diameter of your beam (1/e^2)

3. Approximate intensity profile of your beam (e.g., Gaussian)
4. Linear power density of your beam (total power divided by $1/e^2$ beam diameter)

Thorlabs expresses LIDT for CW lasers as a linear power density measured in W/cm. In this regime, the LIDT given as a linear power density can be applied to any beam diameter; one does not need to compute an adjusted LIDT to adjust for changes in spot size, as demonstrated by the graph to the right. Average linear power density can be calculated using the equation below.

$$\text{Linear Power Density} = \frac{\text{Power}}{\text{Beam Diameter}}$$

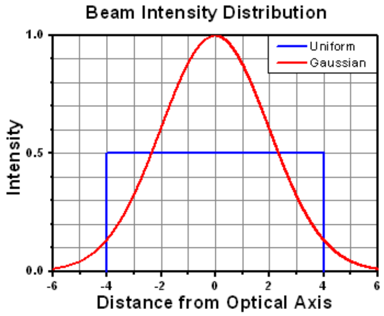
The calculation above assumes a uniform beam intensity profile. You must now consider hotspots in the beam or other non-uniform intensity profiles and roughly calculate a maximum power density. For reference, a Gaussian beam typically has a maximum power density that is twice that of the uniform beam (see lower right).



LIDT in linear power density vs. pulse length and spot size. For long pulses to CW, linear power density becomes a constant with spot size. This graph was obtained from [1].

Now compare the maximum power density to that which is specified as the LIDT for the optic. If the optic was tested at a wavelength other than your operating wavelength, the damage threshold must be scaled appropriately. A good rule of thumb is that the damage threshold has a linear relationship with wavelength such that as you move to shorter wavelengths, the damage threshold decreases (i.e., a LIDT of 10 W/cm at 1310 nm scales to 5 W/cm at 655 nm):

$$\text{Adjusted LIDT} = \text{LIDT Power}\left(\frac{\text{Your Wavelength}}{\text{LIDT Wavelength}}\right)$$



While this rule of thumb provides a general trend, it is not a quantitative analysis of LIDT vs wavelength. In CW applications, for instance, damage scales more strongly with absorption in the coating and substrate, which does not necessarily scale well with wavelength. While the above procedure provides a good rule of thumb for LIDT values, please contact Tech Support if your wavelength is different from the specified LIDT wavelength. If your power density is less than the adjusted LIDT of the optic, then the optic should work for your application.

Please note that we have a buffer built in between the specified damage thresholds online and the tests which we have done, which accommodates variation between batches. Upon request, we can provide individual test information and a testing certificate. The damage analysis will be carried out on a similar optic (customer's optic will not be damaged). Testing may result in additional costs or lead times. Contact Tech Support for more information.

Pulsed Lasers

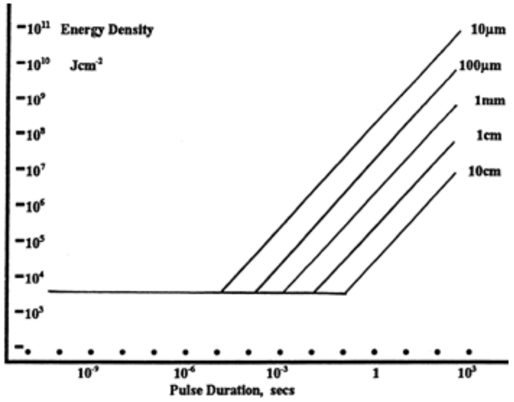
As previously stated, pulsed lasers typically induce a different type of damage to the optic than CW lasers. Pulsed lasers often do not heat the optic enough to damage it; instead, pulsed lasers produce strong electric fields capable of inducing dielectric breakdown in the material. Unfortunately, it can be very difficult to compare the LIDT specification of an optic to your laser. There are multiple regimes in which a pulsed laser can damage an optic and this is based on the laser's pulse length. The highlighted columns in the table below outline the relevant pulse lengths for our specified LIDT values.

Pulses shorter than 10^{-9} s cannot be compared to our specified LIDT values with much reliability. In this ultra-short-pulse regime various mechanics, such as multiphoton-avalanche ionization, take over as the predominate damage mechanism [2]. In contrast, pulses between 10^{-7} s and 10^{-4} s may cause damage to an optic either because of dielectric breakdown or thermal effects. This means that both CW and pulsed damage thresholds must be compared to the laser beam to determine whether the optic is suitable for your application.

Pulse Duration	$t < 10^{-9}$ s	$10^{-9} < t < 10^{-7}$ s	$10^{-7} < t < 10^{-4}$ s	$t > 10^{-4}$ s
Damage Mechanism	Avalanche Ionization	Dielectric Breakdown	Dielectric Breakdown or Thermal	Thermal
Relevant Damage Specification	No Comparison (See Above)	Pulsed	Pulsed and CW	CW

When comparing an LIDT specified for a pulsed laser to your laser, it is essential to know the following:

1. Wavelength of your laser
2. Energy density of your beam (total energy divided by $1/e^2$ area)
3. Pulse length of your laser
4. Pulse repetition frequency (prf) of your laser
5. Beam diameter of your laser ($1/e^2$)
6. Approximate intensity profile of your beam (e.g., Gaussian)



LIDT in energy density vs. pulse length and spot size. For short pulses, energy density becomes a constant with spot size. This graph was obtained from [1].

The energy density of your beam should be calculated in terms of J/cm^2. The graph to the right shows why expressing the LIDT as an energy density provides the best metric for short pulse sources. In this regime, the LIDT given as an energy density can be applied to any beam diameter; one does not need to compute an adjusted LIDT to adjust for changes in spot size. This calculation assumes a uniform beam intensity profile. You must now adjust this energy density to account for hotspots or other nonuniform intensity profiles and roughly calculate a maximum energy density. For reference a Gaussian beam typically has a maximum energy density that is twice that of the $1/e^2$ beam.

Now compare the maximum energy density to that which is specified as the LIDT for the optic. If the optic was tested at a wavelength other than your operating wavelength, the damage threshold must be scaled appropriately [3]. A good rule of thumb is that the damage threshold has an inverse square root relationship with wavelength such that as you move to shorter wavelengths, the damage threshold decreases (i.e., a LIDT of 1 J/cm^2 at 1064 nm scales to 0.7 J/cm^2 at 532 nm):

$$\mathit{Adjusted\ LIDT} = \mathit{LIDT\ Energy}\sqrt{\frac{\mathit{Your\ Wavelength}}{\mathit{LIDT\ Wavelength}}}$$

You now have a wavelength-adjusted energy density, which you will use in the following step.

Beam diameter is also important to know when comparing damage thresholds. While the LIDT, when expressed in units of J/cm², scales independently of spot size; large beam sizes are more likely to illuminate a larger number of defects which can lead to greater variances in the LIDT [4]. For data presented here, a <1 mm beam size was used to measure the LIDT. For beams sizes greater than 5 mm, the LIDT (J/cm2) will not scale independently of beam diameter due to the larger size beam exposing more defects.

The pulse length must now be compensated for. The longer the pulse duration, the more energy the optic can handle. For pulse widths between 1 - 100 ns, an approximation is as follows:

$$Adjusted\ LIDT = LIDT\ Energy\sqrt{\frac{Your\ Pulse\ Length}{LIDT\ Pulse\ Length}}$$

Use this formula to calculate the Adjusted LIDT for an optic based on your pulse length. If your maximum energy density is less than this adjusted LIDT maximum energy density, then the optic should be suitable for your application. Keep in mind that this calculation is only used for pulses between 10^{-9} s and 10^{-7} s. For pulses between 10^{-7} s and 10^{-4} s, the CW LIDT must also be checked before deeming the optic appropriate for your application.

Please note that we have a buffer built in between the specified damage thresholds online and the tests which we have done, which accommodates variation between batches. Upon request, we can provide individual test information and a testing certificate. Contact Tech Support for more information.

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[1] R. M. Wood, Optics and Laser Tech. **29**, 517 (1998).
[2] Roger M. Wood, *Laser-Induced Damage of Optical Materials* (Institute of Physics Publishing, Philadelphia, PA, 2003).
[3] C. W. Carr *et al.*, Phys. Rev. Lett. **91**, 127402 (2003).
[4] N. Bloembergen, Appl. Opt. **12**, 661 (1973).

LIDT CALCULATIONS

LIDT Calculator

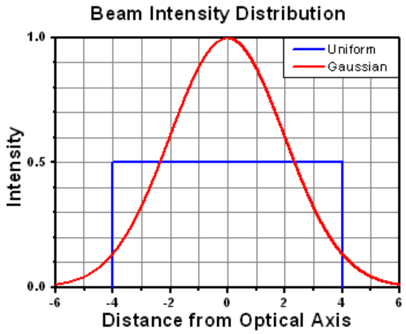
In order to illustrate the process of determining whether a given laser system will damage an optic, a number of example calculations of laser induced damage threshold are given below. For assistance with performing similar calculations, we provide a spreadsheet calculator that can be downloaded by clicking the button to the right. To use the calculator, enter the specified LIDT value of the optic under consideration and the relevant parameters of your laser system in the green boxes. The spreadsheet will then calculate a linear power density for CW and pulsed systems, as well as an energy density value for pulsed systems. These values are used to calculate adjusted, scaled LIDT values for the optics based on accepted scaling laws. This calculator assumes a Gaussian beam profile, so a correction factor must be introduced for other beam shapes (uniform, etc.). The LIDT scaling laws are determined from empirical relationships; their accuracy is not guaranteed. Remember that absorption by optics or coatings can significantly reduce LIDT in some spectral regions. These LIDT values are not valid for ultrashort pulses less than one nanosecond in duration.

CW Laser Example

Suppose that a CW laser system at 1319 nm produces a 0.5 W Gaussian beam that has a $1/e^2$ diameter of 10 mm. A naive calculation of the average linear power density of this beam would yield a value of 0.5 W/cm, given by the total power divided by the beam diameter:

$$\textit{Linear Power Density} = \frac{\textit{Power}}{\textit{Beam Diameter}}$$

However, the maximum power density of a Gaussian beam is about twice the maximum power density of a uniform beam, as shown in the graph to the right. Therefore, a more accurate determination of the maximum linear power density of the system is 1 W/cm.



A Gaussian beam profile has about twice the maximum intensity of a uniform beam profile.

An AC127-030-C achromatic doublet lens has a specified CW LIDT of 350 W/cm, as tested at 1550 nm. CW damage threshold values typically scale directly with the wavelength of the laser source, so this yields an adjusted LIDT value:

$$\textit{Adjusted LIDT} = \textit{LIDT Power}\left(\frac{\textit{Your Wavelength}}{\textit{LIDT Wavelength}}\right)$$

The adjusted LIDT value of 350 W/cm x (1319 nm / 1550 nm) = 298 W/cm is significantly higher than the calculated maximum linear power density of the laser system, so it would be safe to use this doublet lens for this application.

Pulsed Nanosecond Laser Example: Scaling for Different Pulse Durations

Suppose that a pulsed Nd:YAG laser system is frequency tripled to produce a 10 Hz output, consisting of 2 ns output pulses at 355 nm, each with 1 J of energy, in a Gaussian beam with a 1.9 cm beam diameter ($1/e^2$). The average energy density of each pulse is found by dividing the pulse energy by the beam area:

$$\textit{Energy Density} = \frac{\textit{Pulse Energy}}{\textit{Beam Area}}$$

As described above, the maximum energy density of a Gaussian beam is about twice the average energy density. So, the maximum energy density of this beam is ~0.7 J/cm^2.

The energy density of the beam can be compared to the LIDT values of 1 J/cm^2 and 3.5 J/cm^2 for a BB1-E01 broadband dielectric mirror and an NB1-K08 Nd:YAG laser line mirror, respectively. Both of these LIDT values, while measured at 355 nm, were determined with a 10 ns pulsed laser at 10 Hz. Therefore, an adjustment must be applied for the shorter pulse duration of the system under consideration. As described on the previous tab, LIDT values in the nanosecond pulse regime scale with the square root of the laser pulse duration:

$$\text{Adjusted LIDT} = \text{LIDT Energy}\sqrt{\frac{\text{Your Pulse Length}}{\text{LIDT Pulse Length}}}$$

This adjustment factor results in LIDT values of 0.45 J/cm^2 for the BB1-E01 broadband mirror and 1.6 J/cm^2 for the Nd:YAG laser line mirror, which are to be compared with the 0.7 J/cm^2 maximum energy density of the beam. While the broadband mirror would likely be damaged by the laser, the more specialized laser line mirror is appropriate for use with this system.

Pulsed Nanosecond Laser Example: Scaling for Different Wavelengths

Suppose that a pulsed laser system emits 10 ns pulses at 2.5 Hz, each with 100 mJ of energy at 1064 nm in a 16 mm diameter beam (1/e^2) that must be attenuated with a neutral density filter. For a Gaussian output, these specifications result in a maximum energy density of 0.1 J/cm^2. The damage threshold of an NDUV10A Ø25 mm, OD 1.0, reflective neutral density filter is 0.05 J/cm^2 for 10 ns pulses at 355 nm, while the damage threshold of the similar NE10A absorptive filter is 10 J/cm^2 for 10 ns pulses at 532 nm. As described on the previous tab, the LIDT value of an optic scales with the square root of the wavelength in the nanosecond pulse regime:

$$\text{Adjusted LIDT} = \text{LIDT Energy}\sqrt{\frac{\text{Your Wavelength}}{\text{LIDT Wavelength}}}$$

This scaling gives adjusted LIDT values of 0.08 J/cm^2 for the reflective filter and 14 J/cm^2 for the absorptive filter. In this case, the absorptive filter is the best choice in order to avoid optical damage.

Pulsed Microsecond Laser Example

Consider a laser system that produces 1 µs pulses, each containing 150 µJ of energy at a repetition rate of 50 kHz, resulting in a relatively high duty cycle of 5%. This system falls somewhere between the regimes of CW and pulsed laser induced damage, and could potentially damage an optic by mechanisms associated with either regime. As a result, both CW and pulsed LIDT values must be compared to the properties of the laser system to ensure safe operation.

If this relatively long-pulse laser emits a Gaussian 12.7 mm diameter beam (1/e^2) at 980 nm, then the resulting output has a linear power density of 5.9 W/cm and an energy density of 1.2 x 10^{-4} J/cm^2 per pulse. This can be compared to the LIDT values for a WPQ10E-980 polymer zero-order quarter-wave plate, which are 5 W/cm for CW radiation at 810 nm and 5 J/cm^2 for a 10 ns pulse at 810 nm. As before, the CW LIDT of the optic scales linearly with the laser wavelength, resulting in an adjusted CW value of 6 W/cm at 980 nm. On the other hand, the pulsed LIDT scales with the square root of the laser wavelength and the square root of the pulse duration, resulting in an adjusted value of 55 J/cm^2 for a 1 µs pulse at 980 nm. The pulsed LIDT of the optic is significantly greater than the energy density of the laser pulse, so individual pulses will not damage the wave plate. However, the large average linear power density of the laser system may cause thermal damage to the optic, much like a high-power CW beam.

Zero-Order Vortex Half-Wave Retarders: m = 1

- Generates an m = 2 Vortex Polarization Pattern from Linearly Polarized Light
- Center Wavelength Options from 405 nm to 1550 nm
- Large AOI of ±20°

The intensity profile created by an m = 1 retarder when viewed between crossed polarizers.

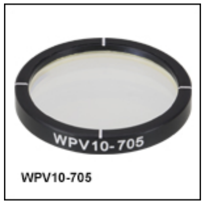
These true zero-order, m = 1 vortex half-wave plates are designed to affect the radial and azimuthal polarization of optical fields. They have a constant retardance across the clear aperture, but a fast axis that rotates continuously over the optic (see the *Graphs* tab). Viewed through crossed polarizers with a while light source (see image to the right), these retarders produce an intensity profile with 2 modulations. Thus, when used with a linearly polarized light source, these retarders will generate an m = 2 polarization pattern.

The donut hole intensity profile capable of being produced by the m = 1 retarder is smaller and more circular than that of the m = 2 retarders sold below (see the *Comparison* tab). Additionally, these are polarization sensitive devices and will produce different output polarizations depending on the orientation of the wave plate's fast axis to the polarization axis of the input beam.

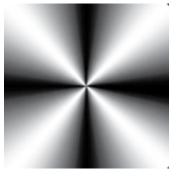
These retarders are mounted in an aluminum housing with an engraving along the perimeter to assist in locating the center point of the plate for beam alignment purposes. The zero-degree fast axis is indicated by 3 lines.

Part Number	Description	Price	Availability
WPV10L-405	**Ø1" m = 1 Zero-Order Vortex Half-Wave Plate, 405 nm**	**$1,128.52**	**Lead Time**
WPV10L-532	**Ø1" m = 1 Zero-Order Vortex Half-Wave Plate, 532 nm**	**$1,128.52**	**7-10 Days**
WPV10L-633	**Ø1" m = 1 Zero-Order Vortex Half-Wave Plate, 633 nm**	**$1,128.52**	**Today**
WPV10L-705	**Ø1" m = 1 Zero-Order Vortex Half-Wave Plate, 705 nm**	**$1,128.52**	**Today**
WPV10L-780	**Ø1" m = 1 Zero-Order Vortex Half-Wave Plate, 780 nm**	**$1,128.52**	**Today**
WPV10L-830	**Ø1" m = 1 Zero-Order Vortex Half-Wave Plate, 830 nm**	**$1,128.52**	**Today**
WPV10L-980	**Ø1" m = 1 Zero-Order Vortex Half-Wave Plate, 980 nm**	**$1,128.52**	**Lead Time**
WPV10L-1064	**Ø1" m = 1 Zero-Order Vortex Half-Wave Plate, 1064 nm**	**$1,128.52**	**Today**
WPV10L-1310	**Ø1" m = 1 Zero-Order Vortex Half-Wave Plate, 1310 nm**	**$1,128.52**	**Today**
WPV10L-1550	**Ø1" m = 1 Zero-Order Vortex Half-Wave Plate, 1550 nm**	**$1,128.52**	**Lead Time**

Zero-Order Vortex Half-Wave Retarders: m = 2



- Generates an m = 4 Vortex Polarization Pattern from Linearly Polarized Light
- Center Wavelength Options from 405 nm to 1550 nm
- Large AOI of ±20°


The intensity profile created by an m = 2 retarder when viewed between crossed polarizers.

These true zero-order, m = 2 vortex half-wave plates are designed to affect the radial and azimuthal polarization of optical fields. They have a constant retardance across the clear aperture, but a fast axis that rotates continuously over the optic (see the *Graphs* tab). Viewed through crossed polarizers with a while light source (see image to the right), these retarders produce an intensity profile with 4 modulations. When used with a linearly polarized light source, these retarders will generate an m = 4 polarization pattern.

The donut hole intensity profile capable of being produced by the m = 2 retarder is larger and more eliptical than that of the m = 1 retarders sold above (see the *Comparison* tab).

These devices are polarization insensitive devices and will produce similar output polarizations regardless of the orientation of the wave plate's fast axis to the polarization axis of the input beam. They are mounted in an aluminum housing with an engraving along the perimeter to assist in locating the center point of the plate for beam alignment purposes.

Part Number	Description	Price	Availability
WPV10-405	**Ø1" m = 2 Zero-Order Vortex Half-Wave Plate, 405 nm**	**$1,128.52**	**Lead Time**
WPV10-532	**Ø1" m = 2 Zero-Order Vortex Half-Wave Plate, 532 nm**	**$1,128.52**	**Today**
WPV10-633	**Ø1" m = 2 Zero-Order Vortex Half-Wave Plate, 633 nm**	**$1,128.52**	**Lead Time**
WPV10-705	**Ø1" m = 2 Zero-Order Vortex Half-Wave Plate, 705 nm**	**$1,128.52**	**Today**
WPV10-780	**Ø1" m = 2 Zero-Order Vortex Half-Wave Plate, 780 nm**	**$1,128.52**	**Today**
WPV10-830	**Ø1" m = 2 Zero-Order Vortex Half-Wave Plate, 830 nm**	**$1,128.52**	**Today**
WPV10-980	**Ø1" m = 2 Zero-Order Vortex Half-Wave Plate, 980 nm**	**$1,128.52**	**Today**
WPV10-1064	**Ø1" m = 2 Zero-Order Vortex Half-Wave Plate, 1064 nm**	**$1,128.52**	**Lead Time**
WPV10-1310	**Ø1" m = 2 Zero-Order Vortex Half-Wave Plate, 1310 nm**	**$1,128.52**	**Today**
WPV10-1550	**Ø1" m = 2 Zero-Order Vortex Half-Wave Plate, 1550 nm**	**$1,128.52**	**Today**


WPV10L-405