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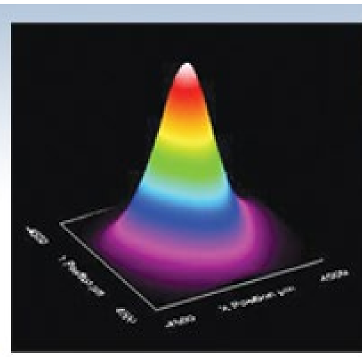
THORLABS

SM2000 - September 15, 2021

Item # SM2000 was discontinued on September 15, 2021. For informational purposes, this is a copy of the website content at that time and is valid only for the stated product.

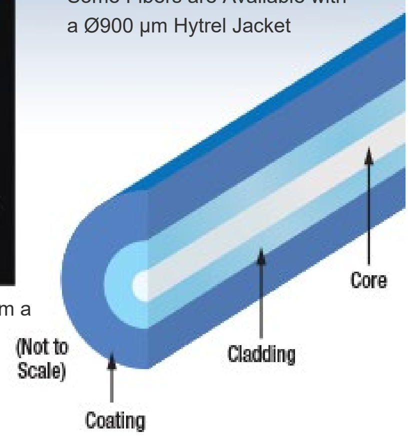
SINGLE MODE FIBER

- **Operating Wavelengths from 320 nm to 2.3 µm**
- **Shipped from Stock with No Minimum Order**
- **Patch Cables Available for All Fibers**
- **Ø80 µm or Ø125 µm Cladding Available**



Typical Output Beam Profile from a Single Mode Fiber

Some Fibers are Available with a Ø900 µm Hytrel Jacket



Single Mode Fiber Cross Section

Single Mode Fiber: 320 to 430 nm

OVERVIEW

Features

- Single Mode Transmission from 320 to 430 nm
- Dual Acrylate Coating
- Shipped from Stock
- No Minimum Purchase Required

Stock Patch Cables Available with This Fiber
SM300 Fiber More [+]

Custom cables are also available. Click here for details.

Thorlabs' SM300 fiber consists of an undoped, pure silica core surrounded by a depressed, fluorine-doped cladding. Since these fibers do not contain germania (GeO_2), which causes electronic defects and color centers associated with the Ge-O bond, the primary cause of photodarkening is greatly reduced. As a result, power handling in the blue region is increased from several milliwats to several watts. The transmission-limiting effects caused by other nonlinearities (e.g., stimulated scattering) or even thermal damage are also increased over those of a conventional silica fiber doped with germanium. In the UV region, the SM300 will still exhibit some photodarkening, but will have superior performance compared to conventional fibers.

SPECS

Item #	Operating Wavelength	Mode Field Diameter[a]	Cladding	Coating	Cut-Off Wavelength
SM300	320 - 430 nm	2.0 - 2.4 µm @ 350 nm	125 ± 1 µm	245 ± 15 µm	≤310 nm

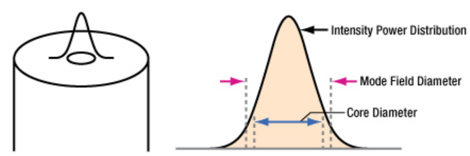
Item #	Short-Term Bend Radius	Long-Term Bend Radius	Attenuation (Max)	Proof Test Level	NA	Core Index[b]	Cladding Index[b]
SM300	≥10 mm	≥30 mm	≤100 dB/km @ 350 nm ≤130 dB/km @ 430 nm	1% (100 kpsi)	0.12 - 0.14	320 nm: 1.48274 375 nm: 1.47314 430 nm: 1.46719	320 nm: 1.47703 375 nm: 1.46739 430 nm: 1.46142

a. MFD is a nominal, calculated value, estimated at the operating wavelength(s) using a typical value of NA & cut-off wavelength. Please see the *MFD Definition* tab for details.
b. The indices provided are for an NA of 0.13.

MFD DEFINITION

Definition of the Mode Field Diameter

The mode field diameter (MFD) is one measure of the beam width of light propagating in a single mode fiber. It is a function of wavelength, core radius, and the refractive indices of the core and cladding. While much of the light in an optical fiber is trapped within the fiber core, a small fraction propagates in the cladding. The light can be approximated as a Gaussian power distribution as shown to the right, where the MFD is the diameter at which the optical power is reduced to $1/e^2$ from its peak level.



Click to Enlarge
The left image shows the intensity profile of the beam propagated through the fiber overlaid on the fiber itself. The right image shows the standard intensity profile of the beam propagated through the fiber with the MFD and core diameter called out.

Measurement of MFD

The measurement of MFD is accomplished by the Variable Aperture Method in the Far Field (VAMFF). An aperture is placed in the far field of the fiber output, and the intensity is measured. As successively smaller apertures are placed in the beam, the intensity levels are measured for each aperture; the data can then be plotted as power vs. the sine of the aperture half-angle (or the numerical aperture for an SM fiber).

The MFD is then determined using Petermann's second definition, which is a mathematical model that does not assume a specific shape of power distribution. The MFD in the near field can be determined from this far-field measurement using the Hankel Transform.

DAMAGE THRESHOLD

Laser-Induced Damage in Silica Optical Fibers

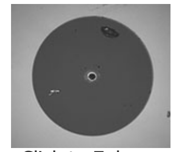
Quick Links
Damage at the Air / Glass Interface
Intrinsic Damage Threshold
Preparation and Handling of Optical Fibers

The following tutorial details damage mechanisms relevant to unterminated (bare) fiber, terminated optical fiber, and other fiber components from laser light sources. These mechanisms include damage that occurs at the air / glass interface (when free-space coupling or when using connectors) and in the optical fiber itself. A fiber component, such as a bare fiber, patch cable, or fused coupler, may have multiple potential avenues for damage (e.g., connectors, fiber end faces, and the device itself). The maximum power that a fiber can handle will always be limited by the lowest limit of any of these damage mechanisms.

While the damage threshold can be estimated using scaling relations and general rules, absolute damage thresholds in optical fibers are very application dependent and user specific. Users can use this guide to estimate a safe power level that minimizes the risk of damage. Following all appropriate preparation and handling guidelines, users should be able to operate a fiber component up to the specified maximum power level; if no maximum is specified for a component, users should abide by the "practical safe level" described below for safe operation of the component. Factors that can reduce power handling and cause damage to a fiber component include, but are not limited to, misalignment during fiber coupling, contamination of the fiber end face, or imperfections in the fiber itself. For further discussion about an optical fiber's power handling abilities for a specific application, please contact Thorlabs' Tech Support.

Damage at the Air / Glass Interface

There are several potential damage mechanisms that can occur at the air / glass interface. Light is incident on this interface when free-space coupling or when two fibers are mated using optical connectors. High-intensity light can damage the end face leading to reduced power handling and permanent damage to the fiber. For fibers terminated with optical connectors where the connectors are fixed to the fiber ends using epoxy, the heat generated by high-intensity light can burn the epoxy and leave residues on the fiber facet directly in the beam path.



Click to Enlarge
Damaged Fiber End

Click to Enlarge
Undamaged Fiber End

Damage Mechanisms on the Bare Fiber End Face

Damage mechanisms on a fiber end face can be modeled similarly to bulk optics, and industry-standard damage thresholds for UV Fused Silica substrates can be applied to silica-based fiber. However, unlike bulk optics, the relevant surface areas and beam diameters involved at the air / glass interface of an optical fiber are very small, particularly for coupling into single mode (SM) fiber. therefore, for a given power density, the power incident on the fiber needs to be lower for a smaller beam diameter.

The table to the right lists two thresholds for optical power densities: a theoretical damage threshold and a "practical safe level". In general, the theoretical damage threshold represents the estimated maximum power density that can be incident on the fiber end face without risking damage with very good fiber end face and coupling conditions. The "practical safe level" power density represents minimal risk of fiber damage. Operating a fiber or component beyond the practical safe level is possible, but users must follow the appropriate handling instructions and verify performance at low powers prior to use.

Estimated Optical Power Densities on Air / Glass Interface[a]		
Type	**Theoretical Damage Threshold[b]**	**Practical Safe Level[c]**
CW (Average Power)	~1 MW/cm^2	~250 kW/cm^2
10 ns Pulsed (Peak Power)	~5 GW/cm^2	~1 GW/cm^2

a. All values are specified for unterminated (bare) silica fiber and apply for free space coupling into a clean fiber end face.
b. This is an estimated maximum power density that can be incident on a fiber end face without risking damage. Verification of the performance and reliability of fiber components in the system before operating at high power must be done by the user, as it is highly system dependent.
c. This is the estimated safe optical power density that can be incident on a fiber end face without damaging the fiber under most operating conditions.

Calculating the Effective Area for Single Mode and Multimode Fibers

The effective area for single mode (SM) fiber is defined by the mode field diameter (MFD), which is the cross-sectional area through which light propagates in the fiber; this area includes the fiber core and also a portion of the cladding. To achieve good efficiency when coupling into a single mode fiber, the diameter of the input beam must match the MFD of the fiber.

As an example, SM400 single mode fiber has a mode field diameter (MFD) of ~Ø3 µm operating at 400 nm, while the MFD for SMF-28 Ultra single mode fiber operating at 1550 nm is Ø10.5 µm. The effective area for these fibers can be calculated as follows:

SM400 Fiber: Area = Pi x $(MFD/2)^2$ = Pi x $(1.5\ \mu m)^2$ = 7.07 μm^2 = $7.07 \times 10^{-8}\ cm^2$

SMF-28 Ultra Fiber: Area = Pi x $(MFD/2)^2$ = Pi x $(5.25\ \mu m)^2$ = 86.6 μm^2 = $8.66 \times 10^{-7}\ cm^2$

To estimate the power level that a fiber facet can handle, the power density is multiplied by the effective area. Please note that this calculation assumes a uniform intensity profile, but most laser beams exhibit a Gaussian-like shape within single mode fiber, resulting in a higher power density at the center of the beam compared to the edges. Therefore, these calculations will slightly overestimate the power corresponding to the damage threshold or the practical safe level. Using the estimated power densities assuming a CW light source, we can determine the corresponding power levels as:

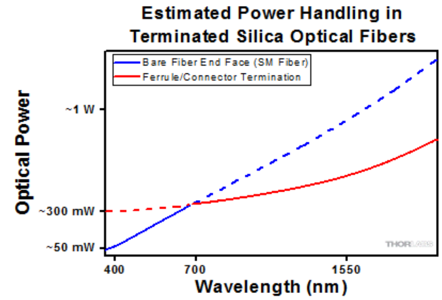
SM400 Fiber: $7.07 \times 10^{-8}\ cm^2 \times 1\ MW/cm^2 = 7.1 \times 10^{-8}\ MW$ = 71 mW (Theoretical Damage Threshold)
$7.07 \times 10^{-8}\ cm^2 \times 250\ kW/cm^2 = 1.8 \times 10^{-5}\ kW$ = 18 mW (Practical Safe Level)

SMF-28 Ultra Fiber: $8.66 \times 10^{-7}\ cm^2 \times 1\ MW/cm^2 = 8.7 \times 10^{-7}\ MW$ = 870 mW (Theoretical Damage Threshold)
$8.66 \times 10^{-7}\ cm^2 \times 250\ kW/cm^2 = 2.1 \times 10^{-4}\ kW$ = 210 mW (Practical Safe Level)

The effective area of a multimode (MM) fiber is defined by the core diameter, which is typically far larger than the MFD of an SM fiber. For optimal coupling, Thorlabs recommends focusing a beam to a spot roughly 70 - 80% of the core diameter. The larger effective area of MM fibers lowers the power density on the fiber end face, allowing higher optical powers (typically on the order of kilowatts) to be coupled into multimode fiber without damage.

Damage Mechanisms Related to Ferrule / Connector Termination

Fibers terminated with optical connectors have additional power handling considerations. Fiber is typically terminated using epoxy to bond the fiber to a ceramic or steel ferrule. When light is coupled into the fiber through a connector, light that does not enter the core and propagate down the fiber is scattered into the outer layers of the fiber, into the ferrule, and the epoxy used to hold the fiber in the ferrule. If the light is intense enough, it can burn the epoxy, causing it to vaporize and deposit a residue on the face of the connector. This results in localized absorption sites on the fiber end face that reduce coupling efficiency and increase scattering, causing further damage.



Click to Enlarge
Plot showing approximate input power that can be incident on a single mode silica optical fiber with a termination. Each line shows the estimated power level due to a specific damage mechanism. The maximum power handling is limited by the lowest power level from all relevant damage mechanisms (indicated by a solid line).

For several reasons, epoxy-related damage is dependent on the wavelength. In general, light scatters more strongly at short wavelengths than at longer wavelengths. Misalignment when coupling is also more likely due to the small MFD of short-wavelength SM fiber that also produces more scattered light.

To minimize the risk of burning the epoxy, fiber connectors can be constructed to have an epoxy-free air gap between the optical fiber and ferrule near the fiber end face. Our high-power multimode fiber patch cables use connectors with this design feature.

Determining Power Handling with Multiple Damage Mechanisms

When fiber cables or components have multiple avenues for damage (e.g., fiber patch cables), the maximum power handling is always limited by the lowest damage threshold that is relevant to the fiber component. In general, this represents the highest input power that can be incident on the patch cable end face and not the coupled output power.

As an illustrative example, the graph to the right shows an estimate of the power handling limitations of a single mode fiber patch cable due to damage to the fiber end face and damage via an optical connector. The total input power handling of a terminated fiber at a given wavelength is limited by the lower of the two limitations at any given wavelength (indicated by the solid lines). A single mode fiber operating at around 488 nm is primarily limited by damage to the fiber end face (blue solid line), but fibers operating at 1550 nm are limited by damage to the optical connector (red solid line).

In the case of a multimode fiber, the effective mode area is defined by the core diameter, which is larger than the effective mode area for SM fiber. This results in a lower power density on the fiber end face and allows higher optical powers (on the order of kilowatts) to be coupled into the fiber without damage (not shown in graph). However, the damage limit of the ferrule / connector termination remains unchanged and as a result, the maximum power handling for a multimode fiber is limited by the ferrule and connector termination.

Please note that these are rough estimates of power levels where damage is very unlikely with proper handling and alignment procedures. It is worth noting that optical fibers are frequently used at power levels above those described here. However, these applications typically require expert users and testing at lower powers first to minimize risk of damage. Even still, optical fiber components should be considered a consumable lab supply if used at high power levels.

Intrinsic Damage Threshold

In addition to damage mechanisms at the air / glass interface, optical fibers also display power handling limitations due to damage mechanisms within the optical fiber itself. These limitations will affect all fiber components as they are intrinsic to the fiber itself. Two categories of damage within the fiber are damage from bend losses and damage from photodarkening.

Bend Losses

Bend losses occur when a fiber is bent to a point where light traveling in the core is incident on the core/cladding interface at an angle higher than the critical angle, making total internal reflection impossible. Under these circumstances, light escapes the fiber, often in a localized area. The light escaping the fiber typically has a high power density, which burns the fiber coating as well as any surrounding furcation tubing.

A special category of optical fiber, called double-clad fiber, can reduce the risk of bend-loss damage by allowing the fiber's cladding (2nd layer) to also function as a waveguide in addition to the core. By making the critical angle of the cladding/coating interface higher than the critical angle of the core/clad interface, light that escapes the core is loosely confined within the cladding. It will then leak out over a distance of centimeters or meters instead of at one localized spot within the fiber, minimizing the risk of damage. Thorlabs manufactures and sells 0.22 NA double-clad multimode fiber, which boasts very high, megawatt range power handling.

Photodarkening

A second damage mechanism, called photodarkening or solarization, can occur in fibers used with ultraviolet or short-wavelength visible light, particularly those with germanium-doped cores. Fibers used at these wavelengths will experience increased attenuation over time. The mechanism that causes photodarkening is largely unknown, but several fiber designs have been developed to mitigate it. For example, fibers with a very low hydroxyl ion (OH) content have been found to resist photodarkening and using other dopants, such as fluorine, can also reduce photodarkening.

Even with the above strategies in place, all fibers eventually experience photodarkening when used with UV or short-wavelength light, and thus, fibers used at these wavelengths should be considered consumables.

Preparation and Handling of Optical Fibers

General Cleaning and Operation Guidelines

These general cleaning and operation guidelines are recommended for all fiber optic products. Users should still follow specific guidelines for an individual product as outlined in the support documentation or manual. Damage threshold calculations only apply when all appropriate cleaning and handling procedures are followed.

1. All light sources should be turned off prior to installing or integrating optical fibers (terminated or bare). This ensures that focused beams of light are not incident on fragile parts of the connector or fiber, which can possibly cause damage.

2. The power-handling capability of an optical fiber is directly linked to the quality of the fiber/connector end face. Always inspect the fiber end prior to connecting the fiber to an optical system. The fiber end face should be clean and clear of dirt and other contaminants that can cause scattering of coupled light. Bare fiber should be cleaved prior to use and users should inspect the fiber end to ensure a good quality cleave is achieved.

3. If an optical fiber is to be spliced into the optical system, users should first verify that the splice is of good quality at a low optical power prior to high-power use. Poor splice quality may increase light scattering at the splice interface, which can be a source of fiber damage.

4. Users should use low power when aligning the system and optimizing coupling; this minimizes exposure of other parts of the fiber (other than the core) to light. Damage from scattered light can occur if a high power beam is focused on the cladding, coating, or connector.

Tips for Using Fiber at Higher Optical Power

Optical fibers and fiber components should generally be operated within safe power level limits, but under ideal conditions (very good optical alignment and very clean optical end faces), the power handling of a fiber component may be increased. Users must verify the performance and stability of a fiber component within their system prior to increasing input or output power and follow all necessary safety and operation instructions. The tips below are useful suggestions when considering increasing optical power in an optical fiber or component.

1. Splicing a fiber component into a system using a fiber splicer can increase power handling as it minimizes possibility of air/fiber interface damage. Users should follow all appropriate guidelines to prepare and make a high-quality fiber splice. Poor splices can lead to scattering or regions of highly localized heat at the splice interface that can damage the fiber.

2. After connecting the fiber or component, the system should be tested and aligned using a light source at low power. The system power can be ramped up slowly to the desired output power while periodically verifying all components are properly aligned and that coupling efficiency is not changing with respect to optical launch power.

3. Bend losses that result from sharply bending a fiber can cause light to leak from the fiber in the stressed area. When operating at high power, the localized heating that can occur when a large amount of light escapes a small localized area (the stressed region) can damage the fiber. Avoid disturbing or accidently bending fibers during operation to minimize bend losses.

4. Users should always choose the appropriate optical fiber for a given application. For example, large-mode-area fibers are a good alternative to standard single mode fibers in high-power applications as they provide good beam quality with a larger MFD, decreasing the power density on the air/fiber interface.

5. Step-index silica single mode fibers are normally not used for ultraviolet light or high-peak-power pulsed applications due to the high spatial power densities associated with these applications.

Part Number	Description	Price	Availability
SM300	Customer Inspired! Single Mode Optical Fiber, 320 - 430 nm, Ø125 µm Cladding	$18.83 Per Meter Volume Pricing Available	Today

Single Mode Fiber: 400 to 680 nm

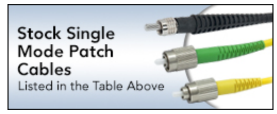
OVERVIEW

Features

- SM Fiber at 400 nm to 680 nm
- Shipped from Stock
- Acrylate Jacket
- SM400 and S405-XP Contain Pure Silica Core and Fluorine Doped Cladding
- No Minimum Purchase Required

Stock Patch Cables Available with These Fibers	
SM400 Fiber	More [+]
SM450 Fiber	More [+]

Custom cables are also available. Click here for details.



SPECS

Item #	Operating Wavelength	Mode Field Diameter	Cladding	Coating	Cut-Off Wavelength
S405-XP	400 - 680 nm	3.3 ± 0.5 µm @ 405 nm 4.6 ± 0.5 µm @ 630 nm	125.0 ± 1.0 µm	245.0 ± 15.0 µm	380 ± 20 nm
SM400	405 - 532 nm	2.5 - 3.4 µm @ 480 nm	125 ± 1 µm	245 ± 15 µm	305 - 400 nm
SM450[a]	488 - 633 nm	2.8 - 4.1 µm[b] @ 488 nm	125 ± 1.0 µm	245 ± 15 µm	350 - 470 nm
460HP	450 - 600 nm	3.5 ± 0.5 µm @ 515 nm	125 ± 1 µm	245 ± 15 µm	430 ± 20 nm

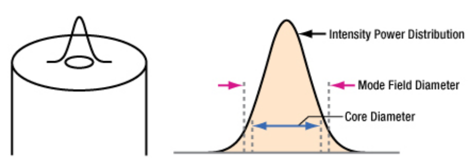
Item #	Short-Term Bend Radius	Long-Term Bend Radius	Attenuation (Max)	NA	Core Index	Cladding Index
S405-XP	≥6 mm	≥13 mm	≤30.0 dB/km @ 630 nm ≤30.0 dB/km @ 488 nm	0.12	Call[d]	Call[d]
SM400	≥10 mm	≥30 mm	≤50 dB/km @ 430 nm ≤30 dB/km @ 532 nm	0.12 - 0.14	405 nm: 1.46958[e] 467 nm: 1.46435[e] 532 nm: 1.46071[e]	405 nm: 1.46382[e] 467 nm: 1.45857[e] 532 nm: 1.45491[e]
SM450	≥5 mm	≥25 mm	≤50 dB/km @ 488 nm[c]	0.10 - 0.14	488 nm: 1.46645[f] 514 nm: 1.46501[f]	488 nm: 1.46302[f] 514 nm: 1.46159[f]
460HP	≥6 mm	≥13 mm	≤30 dB/km @ 515 nm	0.13	Call[d]	Call[d]

a. The wavelength range is the spectral region between the cutoff wavelength and the bend edge and represents the region where the fiber transmits the TEM_{00} mode with low attenuation. For this fiber, the bend edge wavelength is typically 200 nm longer than the cut-off wavelength.
b. MFD is a nominal, calculated value, estimated at the operating wavelength(s) using a typical value of NA & cutoff wavelength. Please see the *MFD Definition* tab for details.
c. Stated attenuation is a worst-case value, quoted for the shortest design wavelength.
d. Please contact us to learn more about the refractive index of this fiber, as we are not permitted to publish this information on our website.
e. The indices provided are for an NA of 0.13.
f. The indices provided are for an NA of 0.10.

MFD DEFINITION

Definition of the Mode Field Diameter

The mode field diameter (MFD) is one measure of the beam width of light propagating in a single mode fiber. It is a function of wavelength, core radius, and the refractive indices of the core and cladding. While much of the light in an optical fiber is trapped within the fiber core, a small fraction propagates in the cladding. The light can be approximated as a Gaussian power distribution as shown to the right, where the MFD is the diameter at which the optical power is reduced to $1/e^2$ from its peak level.



Click to Enlarge
The left image shows the intensity profile of the beam propagated through the fiber overlaid on the fiber itself. The right image shows the standard intensity profile of the beam propagated through the fiber with the MFD and core diameter called out.

Measurement of MFD

The measurement of MFD is accomplished by the Variable Aperture Method in the Far Field (VAMFF). An aperture is placed in the far field of the fiber output, and the intensity is measured. As successively smaller apertures are placed in the beam, the intensity levels are measured for each aperture; the data can then be plotted as power vs. the sine of the aperture half-angle (or the numerical aperture for an SM fiber).

The MFD is then determined using Petermann's second definition, which is a mathematical model that does not assume a specific shape of power distribution. The MFD in the near field can be determined from this far-field measurement using the Hankel Transform.

DAMAGE THRESHOLD

Laser-Induced Damage in Silica Optical Fibers

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Intrinsic Damage Threshold
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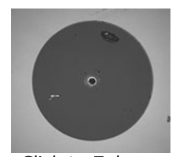

Click to Enlarge
Damaged Fiber End

Click to Enlarge
Undamaged Fiber End

Damage Mechanisms on the Bare Fiber End Face

Damage mechanisms on a fiber end face can be modeled similarly to bulk optics, and industry-standard damage thresholds for UV Fused Silica substrates can be applied to silica-based fiber. However, unlike bulk optics, the relevant surface areas and beam diameters involved at the air / glass interface of an optical fiber are very small, particularly for coupling into single mode (SM) fiber. therefore, for a given power density, the power incident on the fiber needs to be lower for a smaller beam diameter.

The table to the right lists two thresholds for optical power densities: a theoretical damage threshold and a "practical safe level". In general, the theoretical damage threshold represents the estimated maximum power density that can be incident on the fiber end face without risking damage with very good fiber end face and coupling conditions. The "practical safe level" power density represents minimal risk of fiber damage. Operating a fiber or component beyond the practical safe level is possible, but users must follow the appropriate handling instructions and verify performance at low powers prior to use.

Estimated Optical Power Densities on Air / Glass Interface[a]		
Type	Theoretical Damage Threshold[b]	Practical Safe Level[c]
CW (Average Power)	~1 MW/cm^2	~250 kW/cm^2
10 ns Pulsed (Peak Power)	~5 GW/cm^2	~1 GW/cm^2

a. All values are specified for unterminated (bare) silica fiber and apply for free space coupling into a clean fiber end face.
b. This is an estimated maximum power density that can be incident on a fiber end face without risking damage. Verification of the performance and reliability of fiber components in the system before operating at high power must be done by the user, as it is highly system dependent.
c. This is the estimated safe optical power density that can be incident on a fiber end face without damaging the fiber under most operating conditions.

Calculating the Effective Area for Single Mode and Multimode Fibers

The effective area for single mode (SM) fiber is defined by the mode field diameter (MFD), which is the cross-sectional area through which light propagates in the fiber; this area includes the fiber core and also a portion of the cladding. To achieve good efficiency when coupling into a single mode fiber, the diameter of the input beam must match the MFD of the fiber.

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SMF-28 Ultra Fiber: Area = Pi x $(MFD/2)^2$ = Pi x $(5.25\ \mu m)^2$ = 86.6 μm^2 = 8.66 x 10^{-7} cm^2

To estimate the power level that a fiber facet can handle, the power density is multiplied by the effective area. Please note that this calculation assumes a uniform intensity profile, but most laser beams exhibit a Gaussian-like shape within single mode fiber, resulting in a higher power density at the center of the beam compared to the edges. Therefore, these calculations will slightly overestimate the power corresponding to the damage threshold or the practical safe level. Using the estimated power densities assuming a CW light source, we can determine the corresponding power levels as:

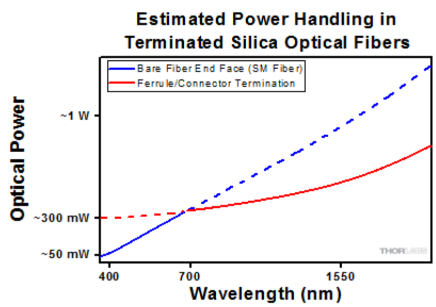
SM400 Fiber: 7.07 x 10^{-8} cm^2 x 1 MW/cm^2 = 7.1 x 10^{-8} MW = 71 mW (Theoretical Damage Threshold)
7.07 x 10^{-8} cm^2 x 250 kW/cm^2 = 1.8 x 10^{-5} kW = 18 mW (Practical Safe Level)

SMF-28 Ultra Fiber: 8.66 x 10^{-7} cm^2 x 1 MW/cm^2 = 8.7 x 10^{-7} MW = 870 mW (Theoretical Damage Threshold)
8.66 x 10^{-7} cm^2 x 250 kW/cm^2 = 2.1 x 10^{-4} kW = 210 mW (Practical Safe Level)

The effective area of a multimode (MM) fiber is defined by the core diameter, which is typically far larger than the MFD of an SM fiber. For optimal coupling, Thorlabs recommends focusing a beam to a spot roughly 70 - 80% of the core diameter. The larger effective area of MM fibers lowers the power density on the fiber end face, allowing higher optical powers (typically on the order of kilowatts) to be coupled into multimode fiber without damage.

Damage Mechanisms Related to Ferrule / Connector Termination

Fibers terminated with optical connectors have additional power handling considerations. Fiber is typically terminated using epoxy to bond the fiber to a ceramic or steel ferrule. When light is coupled into the fiber through a connector, light that does not enter the core and propagate down the fiber is scattered into the outer layers of the fiber, into the ferrule, and the epoxy used to hold the fiber in the ferrule. If the light is intense enough, it can burn the epoxy, causing it to vaporize and deposit a residue on the face of the connector. This results in localized absorption sites on the fiber end face that reduce coupling efficiency and increase scattering, causing further damage.



Click to Enlarge
Plot showing approximate input power that can be incident on a single mode silica optical fiber with a termination. Each line shows the estimated power level due to a specific damage mechanism. The maximum power handling is limited by the lowest power level from all relevant damage mechanisms (indicated by a solid line).

For several reasons, epoxy-related damage is dependent on the wavelength. In general, light scatters more strongly at short wavelengths than at longer wavelengths. Misalignment when coupling is also more likely due to the small MFD of short-wavelength SM fiber that also produces more scattered light.

To minimize the risk of burning the epoxy, fiber connectors can be constructed to have an epoxy-free air gap between the optical fiber and ferrule near the fiber end face. Our high-power multimode fiber patch cables use connectors with this design feature.

Determining Power Handling with Multiple Damage Mechanisms

When fiber cables or components have multiple avenues for damage (e.g., fiber patch cables), the maximum power handling is always limited by the lowest damage threshold that is relevant to the fiber component. In general, this represents the highest input power that can be incident on the patch cable end face and not the coupled output power.

As an illustrative example, the graph to the right shows an estimate of the power handling limitations of a single mode fiber patch cable due to damage to the fiber end face and damage via an optical connector. The total input power handling of a terminated fiber at a given wavelength is limited by the lower of the two limitations at any given wavelength (indicated by the solid lines). A single mode fiber operating at around 488 nm is primarily limited by damage to the fiber end face (blue solid line), but fibers operating at 1550 nm are limited by damage to the optical connector (red solid line).

In the case of a multimode fiber, the effective mode area is defined by the core diameter, which is larger than the effective mode area for SM fiber. This results in a lower power density on the fiber end face and allows higher optical powers (on the order of kilowatts) to be coupled into the fiber without damage (not shown in graph). However, the damage limit of the ferrule / connector termination remains unchanged and as a result, the maximum power handling for a multimode fiber is limited by the ferrule and connector termination.

Please note that these are rough estimates of power levels where damage is very unlikely with proper handling and alignment procedures. It is worth noting that optical fibers are frequently used at power levels above those described here. However, these applications typically require expert users and testing at lower powers first to minimize risk of damage. Even still, optical fiber components should be considered a consumable lab supply if used at high power levels.

Intrinsic Damage Threshold

In addition to damage mechanisms at the air / glass interface, optical fibers also display power handling limitations due to damage mechanisms within the optical fiber itself. These limitations will affect all fiber components as they are intrinsic to the fiber itself. Two categories of damage within the fiber are damage from bend losses and damage from photodarkening.

Bend Losses

Bend losses occur when a fiber is bent to a point where light traveling in the core is incident on the core/cladding interface at an angle higher than the critical angle, making total internal reflection impossible. Under these circumstances, light escapes the fiber, often in a localized area. The light escaping the fiber typically has a high power density, which burns the fiber coating as well as any surrounding furcation tubing.

A special category of optical fiber, called double-clad fiber, can reduce the risk of bend-loss damage by allowing the fiber's cladding (2nd layer) to also function as a waveguide in addition to the core. By making the critical angle of the cladding/coating interface higher than the critical angle of the core/clad interface, light that escapes the core is loosely confined within the cladding. It will then leak out over a distance of centimeters or meters instead of at one localized spot within the fiber, minimizing the risk of damage. Thorlabs manufactures and sells 0.22 NA double-clad multimode fiber, which boasts very high, megawatt range power handling.

Photodarkening

A second damage mechanism, called photodarkening or solarization, can occur in fibers used with ultraviolet or short-wavelength visible light, particularly those with germanium-doped cores. Fibers used at these wavelengths will experience increased attenuation over time. The mechanism that causes photodarkening is largely unknown, but several fiber designs have been developed to mitigate it. For example, fibers with a very low hydroxyl ion (OH) content have been found to resist photodarkening and using other dopants, such as fluorine, can also reduce photodarkening.

Even with the above strategies in place, all fibers eventually experience photodarkening when used with UV or short-wavelength light, and thus, fibers used at these wavelengths should be considered consumables.

Preparation and Handling of Optical Fibers

General Cleaning and Operation Guidelines

These general cleaning and operation guidelines are recommended for all fiber optic products. Users should still follow specific guidelines for an individual product as outlined in the support documentation or manual. Damage threshold calculations only apply when all appropriate cleaning and handling procedures are followed.

1. All light sources should be turned off prior to installing or integrating optical fibers (terminated or bare). This ensures that focused beams of light are not incident on fragile parts of the connector or fiber, which can possibly cause damage.

2. The power-handling capability of an optical fiber is directly linked to the quality of the fiber/connector end face. Always inspect the fiber end prior to connecting the fiber to an optical system. The fiber end face should be clean and clear of dirt and other contaminants that can cause scattering of coupled light. Bare fiber should be cleaved prior to use and users should inspect the fiber end to ensure a good quality cleave is achieved.

3. If an optical fiber is to be spliced into the optical system, users should first verify that the splice is of good quality at a low optical power prior to high-power use. Poor splice quality may increase light scattering at the splice interface, which can be a source of fiber damage.

4. Users should use low power when aligning the system and optimizing coupling; this minimizes exposure of other parts of the fiber (other than the core) to light. Damage from scattered light can occur if a high power beam is focused on the cladding, coating, or connector.

Tips for Using Fiber at Higher Optical Power

Optical fibers and fiber components should generally be operated within safe power level limits, but under ideal conditions (very good optical alignment and very clean optical end faces), the power handling of a fiber component may be increased. Users must verify the performance and stability of a fiber component within their system prior to increasing input or output power and follow all necessary safety and operation instructions. The tips below are useful suggestions when considering increasing optical power in an optical fiber or component.

1. Splicing a fiber component into a system using a fiber splicer can increase power handling as it minimizes possibility of air/fiber interface damage. Users should follow all appropriate guidelines to prepare and make a high-quality fiber splice. Poor splices can lead to scattering or regions of highly localized heat at the splice interface that can damage the fiber.

2. After connecting the fiber or component, the system should be tested and aligned using a light source at low power. The system power can be ramped up slowly to the desired output power while periodically verifying all components are properly aligned and that coupling efficiency is not changing with respect to optical launch power.

3. Bend losses that result from sharply bending a fiber can cause light to leak from the fiber in the stressed area. When operating at high power, the localized heating that can occur when a large amount of light escapes a small localized area (the stressed region) can damage the fiber. Avoid

disturbing or accidently bending fibers during operation to minimize bend losses.

4. Users should always choose the appropriate optical fiber for a given application. For example, large-mode-area fibers are a good alternative to standard single mode fibers in high-power applications as they provide good beam quality with a larger MFD, decreasing the power density on the air/fiber interface.

5. Step-index silica single mode fibers are normally not used for ultraviolet light or high-peak-power pulsed applications due to the high spatial power densities associated with these applications.

Part Number	Description	Price	Availability
S405-XP	Single Mode Optical Fiber, 400 - 680 nm, Ø125 µm Cladding	$15.36 Per Meter Volume Pricing Available	Today
SM400	Single Mode Optical Fiber, 405 - 532 nm, Ø125 µm Cladding	$18.83 Per Meter Volume Pricing Available	Today
SM450	Single Mode Optical Fiber, 488 - 633 nm, Ø125 µm Cladding	$7.85 Per Meter Volume Pricing Available	Today
460HP	Single Mode Optical Fiber, 450 - 600 nm, Ø125 µm Cladding	$11.26 Per Meter Volume Pricing Available	Today

Single Mode Fiber: 600 to 860 nm

OVERVIEW

Features

- Shipped from Stock
- No Minimums
- True Single Mode Operation for HeNe and All Visible Laser Diodes
- Acrylate Coating
- Exceptional Core/Clad Concentricity
- 630HP Offers Tight Second Mode Cut-Off Tolerances

Stock Patch Cables Available with These Fibers	
SM600 Fiber	More [+]

Custom cables are also available. Click here for details.

SPECS

Item #	Operating Wavelength	Mode Field Diameter	Cladding	Coating	Cut-Off Wavelength[c]
SM600	633 -780 nm[a]	3.6 - 5.3 µm @ 633 nm[b]	125 ± 1 µm	245 ± 15 µm	500 - 600 nm
S630-HP	630 - 860 nm	4.2 ± 0.5 µm @ 630 nm	125 ± 1.0 µm	245 ± 15 µm	590 ± 30 nm
630HP	600 - 770 nm	4.0 ± 0.5 µm @ 630 nm	125 ± 1 µm	245 ± 15 µm	570 ± 30 nm

Item #	Short-Term Bend Radius	Long-Term Bend Radius	Max Attenuation	NA	Core Index	Cladding Index
SM600	≥5 mm	≥25 mm	≤15 dB/km[d]	0.10 - 0.14	600 nm: 1.46147[e] 700 nm: 1.45872[e] 800 nm: 1.45675[e]	600 nm: 1.45804[e] 700 nm: 1.45530[e] 800 nm: 1.45332[e]
S630-HP	≥6 mm	≥13 mm	≤10 dB/km @ 630 nm	0.12	Call[f]	Call[f]
630HP	≥6 mm	≥13 mm	≤12 dB/km @ 630 nm	0.13	[f]	[f]

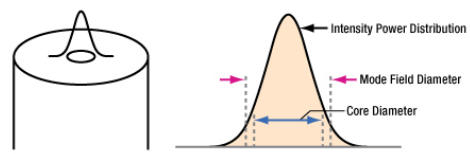
					Call	Call

a. The wavelength range is the spectral region between the cutoff wavelength and the bend edge, in which the fiber transmits the TEM_{00} mode with low attenuation. For this fiber, the bend edge wavelength is typically 200 nm longer than the cut-off wavelength. At the operating wavelengths between 633 nm and 780 nm, the launched power must be considered carefully as these fibers have germanosilicate cores and as such are susceptible to color center generation.
b. MFD is a nominal, calculated value, estimated at the operating wavelength(s) using a typical value of NA & cutoff wavelength. Please see the *MFD Definition* tab for details.
c. The wavelength at which the fiber only allows a single mode to propogate.
d. Attenuation is worst-case value, quoted for the shortest wavelength.
e. The indices provided are for an NA of 0.10.
f. Please contact us to learn more about the refractive index of this fiber, as we are not permitted to publish this information on our website.

M F D   D E F I N I T I O N

Definition of the Mode Field Diameter

The mode field diameter (MFD) is one measure of the beam width of light propagating in a single mode fiber. It is a function of wavelength, core radius, and the refractive indices of the core and cladding. While much of the light in an optical fiber is trapped within the fiber core, a small fraction propagates in the cladding. The light can be approximated as a Gaussian power distribution as shown to the right, where the MFD is the diameter at which the optical power is reduced to $1/e^2$ from its peak level.



Click to Enlarge
The left image shows the intensity profile of the beam propagated through the fiber overlaid on the fiber itself. The right image shows the standard intensity profile of the beam propagated through the fiber with the MFD and core diameter called out.

Measurement of MFD

The measurement of MFD is accomplished by the Variable Aperture Method in the Far Field (VAMFF). An aperture is placed in the far field of the fiber output, and the intensity is measured. As successively smaller apertures are placed in the beam, the intensity levels are measured for each aperture; the data can then be plotted as power vs. the sine of the aperture half-angle (or the numerical aperture for an SM fiber).

The MFD is then determined using Petermann's second definition, which is a mathematical model that does not assume a specific shape of power distribution. The MFD in the near field can be determined from this far-field measurement using the Hankel Transform.

D A M A G E   T H R E S H O L D

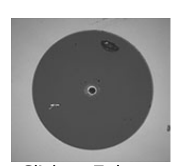
Laser-Induced Damage in Silica Optical Fibers

Quick Links
Damage at the Air / Glass Interface
Intrinsic Damage Threshold
Preparation and Handling of Optical Fibers

The following tutorial details damage mechanisms relevant to unterminated (bare) fiber, terminated optical fiber, and other fiber components from laser light sources. These mechanisms include damage that occurs at the air / glass interface (when free-space coupling or when using connectors) and in the optical fiber itself. A fiber component, such as a bare fiber, patch cable, or fused coupler, may have multiple potential avenues for damage (e.g., connectors, fiber end faces, and the device itself). The maximum power that a fiber can handle will always be limited by the lowest limit of any of these damage mechanisms.

While the damage threshold can be estimated using scaling relations and general rules, absolute damage thresholds in optical fibers are very application dependent and user specific. Users can use this guide to estimate a safe power level that minimizes the risk of damage. Following all appropriate preparation and handling guidelines, users should be able to operate a fiber component up to the specified maximum power level; if no maximum is specified for a component, users should abide by the "practical safe level" described below for safe operation of the component. Factors that can reduce power handling and cause damage to a fiber component include, but are not limited to, misalignment during fiber coupling, contamination of the fiber end face, or imperfections in the fiber itself. For further discussion about an optical fiber’s power handling abilities for a specific application, please contact Thorlabs’ Tech Support.

Damage at the Air / Glass Interface


Click to Enlarge
Damaged Fiber End


Click to Enlarge
Undamaged Fiber End

There are several potential damage mechanisms that can occur at the air / glass interface. Light is incident on this interface when free-space coupling or when two fibers are mated using optical connectors. High-intensity light can damage the end face leading to reduced power handling and permanent damage to the fiber. For fibers terminated with optical connectors where the connectors are fixed to the fiber ends using epoxy, the heat generated by high-intensity light can burn the epoxy and leave residues on the fiber facet directly in the beam path.

Damage Mechanisms on the Bare Fiber End Face

Damage mechanisms on a fiber end face can be modeled similarly to bulk optics, and industry-standard damage thresholds for UV Fused Silica substrates can be applied to silica-based fiber. However, unlike bulk optics, the relevant surface areas and beam diameters involved at the air / glass interface of an optical fiber are very small, particularly for coupling into single mode (SM) fiber. therefore, for a given power density, the power incident on the fiber needs to be lower for a smaller beam diameter.

The table to the right lists two thresholds for optical power densities: a theoretical damage threshold and a "practical safe level". In general, the theoretical damage threshold represents the estimated maximum power density that can be incident on the fiber end face without risking damage with very good fiber end face and coupling conditions. The "practical safe level" power density represents minimal risk of fiber damage. Operating a fiber or component beyond the practical safe level is possible, but users must follow the appropriate handling instructions and verify performance at low powers prior to use.

Estimated Optical Power Densities on Air / Glass Interface[a]		
Type	**Theoretical Damage Threshold[b]**	**Practical Safe Level[c]**
CW (Average Power)	~1 MW/cm^2	~250 kW/cm^2
10 ns Pulsed (Peak Power)	~5 GW/cm^2	~1 GW/cm^2

a. All values are specified for unterminated (bare) silica fiber and apply for free space coupling into a clean fiber end face.
b. This is an estimated maximum power density that can be incident on a fiber end face without risking damage. Verification of the performance and reliability of fiber components in the system before operating at high power must be done by the user, as it is highly system dependent.
c. This is the estimated safe optical power density that can be incident on a fiber end face without damaging the fiber under most operating conditions.

Calculating the Effective Area for Single Mode and Multimode Fibers

The effective area for single mode (SM) fiber is defined by the mode field diameter (MFD), which is the cross-sectional area through which light propagates in the fiber; this area includes the fiber core and also a portion of the cladding. To achieve good efficiency when coupling into a single mode fiber, the diameter of the input beam must match the MFD of the fiber.

As an example, SM400 single mode fiber has a mode field diameter (MFD) of ~Ø3 µm operating at 400 nm, while the MFD for SMF-28 Ultra single mode fiber operating at 1550 nm is Ø10.5 µm. The effective area for these fibers can be calculated as follows:

SM400 Fiber: Area = Pi x $(MFD/2)^2$ = Pi x $(1.5\ \mu m)^2$ = 7.07 μm^2 = 7.07×10^{-8} cm^2

SMF-28 Ultra Fiber: Area = Pi x $(MFD/2)^2$ = Pi x $(5.25\ \mu m)^2$ = 86.6 μm^2 = 8.66×10^{-7} cm^2

To estimate the power level that a fiber facet can handle, the power density is multiplied by the effective area. Please note that this calculation assumes a uniform intensity profile, but most laser beams exhibit a Gaussian-like shape within single mode fiber, resulting in a higher power density at the center of the beam compared to the edges. Therefore, these calculations will slightly overestimate the power corresponding to the damage threshold or the practical safe level. Using the estimated power densities assuming a CW light source, we can determine the corresponding power levels as:

SM400 Fiber: 7.07×10^{-8} cm^2 x 1 MW/cm^2 = 7.1×10^{-8} MW = 71 mW (Theoretical Damage Threshold)
7.07×10^{-8} cm^2 x 250 kW/cm^2 = 1.8×10^{-5} kW = 18 mW (Practical Safe Level)

SMF-28 Ultra Fiber: 8.66×10^{-7} cm^2 x 1 MW/cm^2 = 8.7×10^{-7} MW = 870 mW (Theoretical Damage Threshold)
8.66×10^{-7} cm^2 x 250 kW/cm^2 = 2.1×10^{-4} kW = 210 mW (Practical Safe Level)

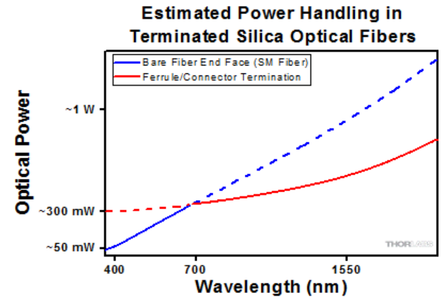
The effective area of a multimode (MM) fiber is defined by the core diameter, which is typically far larger than the MFD of an SM fiber. For optimal coupling, Thorlabs recommends focusing a beam to a spot roughly 70 - 80% of the core diameter. The larger effective area of MM fibers lowers the power density on the fiber end face, allowing higher optical powers (typically on the order of kilowatts) to be coupled into multimode fiber without damage.

Damage Mechanisms Related to Ferrule / Connector Termination

Fibers terminated with optical connectors have additional power handling considerations. Fiber is typically terminated using epoxy to bond the fiber to a ceramic or steel ferrule. When light is coupled into the fiber through a connector, light that does not enter the core and propagate down the fiber is scattered into the outer layers of the fiber, into the ferrule, and the epoxy used to hold the fiber in the ferrule. If the light is intense enough, it can burn the epoxy, causing it to vaporize and deposit a residue on the face of the connector. This results in localized absorption sites on the fiber end face that reduce coupling efficiency and increase scattering, causing further damage.

For several reasons, epoxy-related damage is dependent on the wavelength. In general, light scatters more strongly at short wavelengths than at longer wavelengths. Misalignment when coupling is also more likely due to the small MFD of short-wavelength SM fiber that also produces more scattered light.

To minimize the risk of burning the epoxy, fiber connectors can be constructed to have an epoxy-free air gap between the optical fiber and ferrule near the fiber end face. Our high-power multimode fiber patch cables use connectors with this design feature.



Click to Enlarge
Plot showing approximate input power that can be incident on a single mode silica optical fiber with a termination. Each line shows the estimated power level due to a specific damage mechanism. The maximum power handling is limited by the lowest power level from all relevant damage mechanisms (indicated by a solid line).

Determining Power Handling with Multiple Damage Mechanisms

When fiber cables or components have multiple avenues for damage (e.g., fiber patch cables), the maximum power handling is always limited by the lowest damage threshold that is relevant to the fiber component. In general, this represents the highest input power that can be incident on the patch cable end face and not the coupled output power.

As an illustrative example, the graph to the right shows an estimate of the power handling limitations of a single mode fiber patch cable due to damage to the fiber end face and damage via an optical connector. The total input power handling of a terminated fiber at a given wavelength is limited by the lower of the two limitations at any given wavelength (indicated by the solid lines). A single mode fiber operating at around 488 nm is primarily limited by damage to the fiber end face (blue solid line), but fibers operating at 1550 nm are limited by damage to the optical connector (red solid line).

In the case of a multimode fiber, the effective mode area is defined by the core diameter, which is larger than the effective mode area for SM fiber. This results in a lower power density on the fiber end face and allows higher optical powers (on the order of kilowatts) to be coupled into the fiber without damage (not shown in graph). However, the damage limit of the ferrule / connector termination remains unchanged and as a result, the maximum power handling for a multimode fiber is limited by the ferrule and connector termination.

Please note that these are rough estimates of power levels where damage is very unlikely with proper handling and alignment procedures. It is worth noting that optical fibers are frequently used at power levels above those described here. However, these applications typically require expert users and testing at lower powers first to minimize risk of damage. Even still, optical fiber components should be considered a consumable lab supply if used at high power levels.

Intrinsic Damage Threshold

In addition to damage mechanisms at the air / glass interface, optical fibers also display power handling limitations due to damage mechanisms within the optical fiber itself. These limitations will affect all fiber components as they are intrinsic to the fiber itself. Two categories of damage within the fiber are damage from bend losses and damage from photodarkening.

Bend Losses

Bend losses occur when a fiber is bent to a point where light traveling in the core is incident on the core/cladding interface at an angle higher than the critical angle, making total internal reflection impossible. Under these circumstances, light escapes the fiber, often in a localized area. The light escaping the fiber typically has a high power density, which burns the fiber coating as well as any surrounding furcation tubing.

A special category of optical fiber, called double-clad fiber, can reduce the risk of bend-loss damage by allowing the fiber's cladding (2nd layer) to also function as a waveguide in addition to the core. By making the critical angle of the cladding/coating interface higher than the critical angle of the core/clad interface, light that escapes the core is loosely confined within the cladding. It will then leak out over a distance of centimeters or meters instead of at one localized spot within the fiber, minimizing the risk of damage. Thorlabs manufactures and sells 0.22 NA double-clad multimode fiber, which boasts very high, megawatt range power handling.

Photodarkening

A second damage mechanism, called photodarkening or solarization, can occur in fibers used with ultraviolet or short-wavelength visible light, particularly those with germanium-doped cores. Fibers used at these wavelengths will experience increased attenuation over time. The mechanism that causes photodarkening is largely unknown, but several fiber designs have been developed to mitigate it. For example, fibers with a very low hydroxyl ion (OH) content have been found to resist photodarkening and using other dopants, such as fluorine, can also reduce photodarkening.

Even with the above strategies in place, all fibers eventually experience photodarkening when used with UV or short-wavelength light, and thus, fibers used at these wavelengths should be considered consumables.

Preparation and Handling of Optical Fibers

General Cleaning and Operation Guidelines

These general cleaning and operation guidelines are recommended for all fiber optic products. Users should still follow specific guidelines for an individual product as outlined in the support documentation or manual. Damage threshold calculations only apply when all appropriate cleaning and handling procedures are followed.

1. All light sources should be turned off prior to installing or integrating optical fibers (terminated or bare). This ensures that focused beams of light are not incident on fragile parts of the connector or fiber, which can possibly cause damage.

2. The power-handling capability of an optical fiber is directly linked to the quality of the fiber/connector end face. Always inspect the fiber end prior to connecting the fiber to an optical system. The fiber end face should be clean and clear of dirt and other contaminants that can cause scattering of coupled light. Bare fiber should be cleaved prior to use and users should inspect the fiber end to ensure a good quality cleave is achieved.

3. If an optical fiber is to be spliced into the optical system, users should first verify that the splice is of good quality at a low optical power prior to high-power use. Poor splice quality may increase light scattering at the splice interface, which can be a source of fiber damage.

4. Users should use low power when aligning the system and optimizing coupling; this minimizes exposure of other parts of the fiber (other than the core) to light. Damage from scattered light can occur if a high power beam is focused on the cladding, coating, or connector.

Tips for Using Fiber at Higher Optical Power

Optical fibers and fiber components should generally be operated within safe power level limits, but under ideal conditions (very good optical alignment and very clean optical end faces), the power handling of a fiber component may be increased. Users must verify the performance and stability of a fiber component within their system prior to increasing input or output power and follow all necessary safety and operation instructions. The tips below are useful suggestions when considering increasing optical power in an optical fiber or component.

1. Splicing a fiber component into a system using a fiber splicer can increase power handling as it minimizes possibility of air/fiber interface damage. Users should follow all appropriate guidelines to prepare and make a high-quality fiber splice. Poor splices can lead to scattering or regions of highly localized heat at the splice interface that can damage the fiber.

2. After connecting the fiber or component, the system should be tested and aligned using a light source at low power. The system power can be ramped up slowly to the desired output power while periodically verifying all components are properly aligned and that coupling efficiency is not changing with respect to optical launch power.

3. Bend losses that result from sharply bending a fiber can cause light to leak from the fiber in the stressed area. When operating at high power, the localized heating that can occur when a large amount of light escapes a small localized area (the stressed region) can damage the fiber. Avoid disturbing or accidently bending fibers during operation to minimize bend losses.

4. Users should always choose the appropriate optical fiber for a given application. For example, large-mode-area fibers are a good alternative to standard single mode fibers in high-power applications as they provide good beam quality with a larger MFD, decreasing the power density on the air/fiber interface.

5. Step-index silica single mode fibers are normally not used for ultraviolet light or high-peak-power pulsed applications due to the high spatial power densities associated with these applications.

Part Number	Description	Price	Availability
SM600	**Single Mode Optical Fiber, 633 - 780 nm, Ø125 µm Cladding**	**$5.25 Per Meter Volume Pricing Available**	**Today**
S630-HP	**Single Mode Optical Fiber, 630 - 860 nm, Ø125 µm Cladding**	**$9.85 Per Meter Volume Pricing Available**	**Today**
630HP	**Single Mode Optical Fiber, 600 - 770 nm, Ø125 µm Cladding**	**$6.00 Per Meter Volume Pricing Available**	**Today**

Single Mode Fiber: 780 to 970 nm

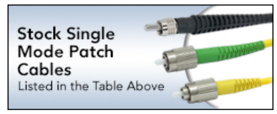
OVERVIEW

Features

- Shipped from Stock
- No Minimums
- Acrylate Jacket
- Exceptional Uniformity
- Exceptional Core/Clad Concentricity
- 780HP Offers Tight Second Mode Cut-Off Tolerances
- SM800G80 Offers Enhanced Bend Insensitivity

Stock Patch Cables Available with These Fibers	
780HP Fiber	More [+]
SM800-5.6-125 Fiber	More [+]

Custom cables are also available. Click here for details.



SPECS

Item #	Operating Wavelength	Mode Field Diameter	Cladding	Coating	Cut-Off Wavelength
780HP	780 - 970 nm	5.0 ± 0.5 µm @ 850 nm	125 ± 1 µm	245 ± 15 µm	730 ± 30 nm
SM800-5.6-125	830 - 980 nm[a]	4.7 - 6.9 µm[b] @ 830 nm	125 ± 1.0 µm	245 ± 15 µm	660 - 800 nm
SM800G80	830 - 980 nm[a]	3.75 - 4.9 µm @ 830 nm	80 ± 1 µm	170 ± 10 µm	660 - 800 nm

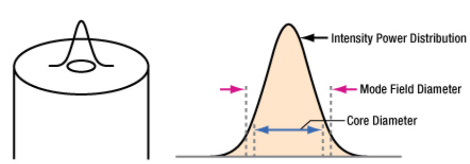
Item #	Short-Term Bend Radius	Long-Term Bend Radius	Attenuation (Max)	NA	Core Index	Cladding Index
780HP	≥6 mm	≥13 mm	≤4.0 dB/km @ 780 nm ≤3.5 dB/km @ 850 nm	0.13	Call[d]	Call[d]
SM800-5.6-125	≥5 mm	≥25 mm	<5 dB/km[c]	0.10 - 0.14	830 nm: 1.45625[e]	830 nm: 1.45282[e]
SM800G80	≥5 mm	≥12 mm (or 38 mm for 25 Year Life)	≤3.0 dB/km[c]	0.14 - 0.18	830 nm: 1.45954[f]	830 nm: 1.45282[f]

a. The wavelength range is the spectral region between the cutoff wavelength and the bend edge, in which the fiber transmits the TEM_{00} mode with low attenuation. For this fiber, the bend edge wavelength is typically 200 nm longer than the cut-off wavelength. At the design wavelength of 830 nm, the launched power must be considered carefully as these fibers have germanosilicate cores and as such are susceptible to color center generation.
b. MFD is a nominal, calculated value, estimated at the operating wavelength(s) using a typical value of NA & cutoff wavelength. Please see the *MFD Definition* tab for details.
c. Attenuation is a worse-case value, quoted for the shortest design wavelength.
d. Please contact us to learn more about the refractive index of this fiber, as we are not permitted to publish this information on our website.
e. The index provided is for an NA of 0.10.
f. The index provided is for an NA of 0.14.

MFD DEFINITION

Definition of the Mode Field Diameter

The mode field diameter (MFD) is one measure of the beam width of light propagating in a single mode fiber. It is a function of wavelength, core radius, and the refractive indices of the core and cladding. While much of the light in an optical fiber is trapped within the fiber core, a small fraction propagates in the cladding. The light can be approximated as a Gaussian power distribution as shown to the right, where the MFD is the diameter at which the optical power is reduced to $1/e^2$ from its peak level.



Click to Enlarge
The left image shows the intensity profile of the beam propagated through the fiber overlaid on the fiber itself. The right image shows the standard intensity profile of the beam propagated through the fiber with the MFD and core diameter called out.

Measurement of MFD

The measurement of MFD is accomplished by the Variable Aperture Method in the Far Field (VAMFF). An aperture is placed in the far field of the fiber output, and the intensity is measured. As successively smaller apertures are placed in the beam, the intensity levels are measured for each aperture; the data can then be plotted as power vs. the sine of the aperture half-angle (or the numerical aperture for an SM fiber).

The MFD is then determined using Petermann's second definition, which is a mathematical model that does not assume a specific shape of power distribution. The MFD in the near field can be determined from this far-field measurement using the Hankel Transform.

DAMAGE THRESHOLD

Laser-Induced Damage in Silica Optical Fibers

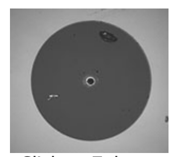
Quick Links
Damage at the Air / Glass Interface
Intrinsic Damage Threshold
Preparation and Handling of Optical Fibers

The following tutorial details damage mechanisms relevant to unterminated (bare) fiber, terminated optical fiber, and other fiber components from laser light sources. These mechanisms include damage that occurs at the air / glass interface (when free-space coupling or when using connectors) and in the optical fiber itself. A fiber component, such as a bare fiber, patch cable, or fused coupler, may have multiple potential avenues for damage (e.g., connectors, fiber end faces, and the device itself). The maximum power that a fiber can handle will always be limited by the lowest limit of any of these damage mechanisms.

While the damage threshold can be estimated using scaling relations and general rules, absolute damage thresholds in optical fibers are very application dependent and user specific. Users can use this guide to estimate a safe power level that minimizes the risk of damage. Following all appropriate preparation and handling guidelines, users should be able to operate a fiber component up to the specified maximum power level; if no maximum is specified for a component, users should abide by the "practical safe level" described below for safe operation of the component. Factors that can reduce power handling and cause damage to a fiber component include, but are not limited to, misalignment during fiber coupling, contamination of the fiber end face, or imperfections in the fiber itself. For further discussion about an optical fiber's power handling abilities for a specific application, please contact Thorlabs' Tech Support.

Damage at the Air / Glass Interface

There are several potential damage mechanisms that can occur at the air / glass interface. Light is incident on this interface when free-space coupling or when two fibers are mated using optical connectors. High-intensity light can damage the end face leading to reduced power handling and permanent damage to the fiber. For fibers terminated with optical connectors where the connectors are fixed to the fiber ends using epoxy, the heat generated by high-intensity light can burn the epoxy and leave residues on the fiber facet directly in the beam path.


Click to Enlarge
Damaged Fiber End


Click to Enlarge
Undamaged Fiber End

Damage Mechanisms on the Bare Fiber End Face

Damage mechanisms on a fiber end face can be modeled similarly to bulk optics, and industry-standard damage thresholds for UV Fused Silica substrates can be applied to silica-based fiber. However, unlike bulk optics, the relevant surface areas and beam diameters involved at the air / glass interface of an optical fiber are very small, particularly for coupling into single mode (SM) fiber. therefore, for a given power density, the power incident on the fiber needs to be lower for a smaller beam diameter.

The table to the right lists two thresholds for optical power densities: a theoretical damage threshold and a "practical safe level". In general, the theoretical damage threshold represents the estimated maximum power density that can be incident on the fiber end face without risking damage with very good fiber end face and coupling conditions. The "practical safe level" power density represents minimal risk of fiber damage. Operating a fiber or component beyond the practical safe level is possible, but users must follow the appropriate handling instructions and verify performance at low powers prior to use.

Estimated Optical Power Densities on Air / Glass Interface[a]		
Type	Theoretical Damage Threshold[b]	Practical Safe Level[c]
CW (Average Power)	~1 MW/cm^2	~250 kW/cm^2
10 ns Pulsed (Peak Power)	~5 GW/cm^2	~1 GW/cm^2

a. All values are specified for unterminated (bare) silica fiber and apply for free space coupling into a clean fiber end face.
b. This is an estimated maximum power density that can be incident on a fiber end face without risking damage. Verification of the performance and reliability of fiber components in the system before operating at high power must be done by the user, as it is highly system dependent.
c. This is the estimated safe optical power density that can be incident on a fiber end face without damaging the fiber under most operating conditions.

Calculating the Effective Area for Single Mode and Multimode Fibers

The effective area for single mode (SM) fiber is defined by the mode field diameter (MFD), which is the cross-sectional area through which light propagates in the fiber; this area includes the fiber core and also a portion of the cladding. To achieve good efficiency when coupling into a single mode fiber, the diameter of the input beam must match the MFD of the fiber.

As an example, SM400 single mode fiber has a mode field diameter (MFD) of ~Ø3 µm operating at 400 nm, while the MFD for SMF-28 Ultra single mode fiber operating at 1550 nm is Ø10.5 µm. The effective area for these fibers can be calculated as follows:

SM400 Fiber: Area = Pi x $(\text{MFD}/2)^2$ = Pi x $(1.5\ \mu\text{m})^2$ = 7.07 μm^2 = 7.07 x 10^{-8} cm^2

SMF-28 Ultra Fiber: Area = Pi x $(\text{MFD}/2)^2$ = Pi x $(5.25\ \mu\text{m})^2$ = 86.6 μm^2 = 8.66 x 10^{-7} cm^2

To estimate the power level that a fiber facet can handle, the power density is multiplied by the effective area. Please note that this calculation assumes a uniform intensity profile, but most laser beams exhibit a Gaussian-like shape within single mode fiber, resulting in a higher power density at the center of the beam compared to the edges. Therefore, these calculations will slightly overestimate the power corresponding to the damage threshold or the practical safe level. Using the estimated power densities assuming a CW light source, we can determine the corresponding power levels as:

SM400 Fiber: 7.07 x 10^{-8} cm^2 x 1 MW/cm^2 = 7.1 x 10^{-8} MW = 71 mW (Theoretical Damage Threshold)
7.07 x 10^{-8} cm^2 x 250 kW/cm^2 = 1.8 x 10^{-5} kW = 18 mW (Practical Safe Level)

SMF-28 Ultra Fiber: 8.66 x 10^{-7} cm^2 x 1 MW/cm^2 = 8.7 x 10^{-7} MW = 870 mW (Theoretical Damage Threshold)
8.66 x 10^{-7} cm^2 x 250 kW/cm^2 = 2.1 x 10^{-4} kW = 210 mW (Practical Safe Level)

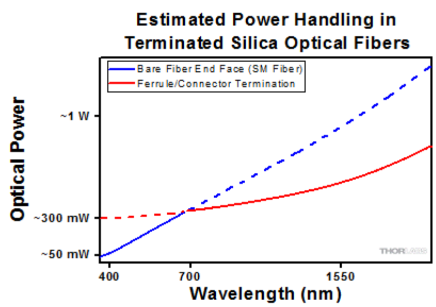
The effective area of a multimode (MM) fiber is defined by the core diameter, which is typically far larger than the MFD of an SM fiber. For optimal coupling, Thorlabs recommends focusing a beam to a spot roughly 70 - 80% of the core diameter. The larger effective area of MM fibers lowers the power density on the fiber end face, allowing higher optical powers (typically on the order of kilowatts) to be coupled into multimode fiber without damage.

Damage Mechanisms Related to Ferrule / Connector Termination

Fibers terminated with optical connectors have additional power handling considerations. Fiber is typically terminated using epoxy to bond the fiber to a ceramic or steel ferrule. When light is coupled into the fiber through a connector, light that does not enter the core and propagate down the fiber is scattered into the outer layers of the fiber, into the ferrule, and the epoxy used to hold the fiber in the ferrule. If the light is intense enough, it can burn the epoxy, causing it to vaporize and deposit a residue on the face of the connector. This results in localized absorption sites on the fiber end face that reduce coupling efficiency and increase scattering, causing further damage.

For several reasons, epoxy-related damage is dependent on the wavelength. In general, light scatters more strongly at short wavelengths than at longer wavelengths. Misalignment when coupling is also more likely due to the small MFD of short-wavelength SM fiber that also produces more scattered light.

To minimize the risk of burning the epoxy, fiber connectors can be constructed to have an epoxy-free air gap between the optical fiber and ferrule near the fiber end face. Our high-power multimode fiber patch cables use connectors with this design feature.



Click to Enlarge
Plot showing approximate input power that can be incident on a single mode silica optical fiber with a termination. Each line shows the estimated power level due to a specific damage mechanism. The maximum power handling is limited by the lowest power level from all relevant damage mechanisms (indicated by a solid line).

Determining Power Handling with Multiple Damage Mechanisms

When fiber cables or components have multiple avenues for damage (e.g., fiber patch cables), the maximum power handling is always limited by the lowest damage threshold that is relevant to the fiber component. In general, this represents the highest input power that can be incident on the patch cable end face and not the coupled output power.

As an illustrative example, the graph to the right shows an estimate of the power handling limitations of a single mode fiber patch cable due to damage to the fiber end face and damage via an optical connector. The total input power handling of a terminated fiber at a given wavelength is limited by the lower of the two limitations at any given wavelength (indicated by the solid lines). A single mode fiber operating at around 488 nm is primarily limited by damage to the fiber end face (blue solid line), but fibers operating at 1550 nm are limited by damage to the optical connector (red solid line).

In the case of a multimode fiber, the effective mode area is defined by the core diameter, which is larger than the effective mode area for SM fiber. This results in a lower power density on the fiber end face and allows higher optical powers (on the order of kilowatts) to be coupled into the fiber without damage (not shown in graph). However, the damage limit of the ferrule / connector termination remains unchanged and as a result, the maximum power handling for a multimode fiber is limited by the ferrule and connector termination.

Please note that these are rough estimates of power levels where damage is very unlikely with proper handling and alignment procedures. It is worth noting that optical fibers are frequently used at power levels above those described here. However, these applications typically require expert users and testing at lower powers first to minimize risk of damage. Even still, optical fiber components should be considered a consumable lab supply if used at high power levels.

Intrinsic Damage Threshold

In addition to damage mechanisms at the air / glass interface, optical fibers also display power handling limitations due to damage mechanisms within the optical fiber itself. These limitations will affect all fiber components as they are intrinsic to the fiber itself. Two categories of damage within the fiber are damage from bend losses and damage from photodarkening.

Bend Losses

Bend losses occur when a fiber is bent to a point where light traveling in the core is incident on the core/cladding interface at an angle higher than the critical angle, making total internal reflection impossible. Under these circumstances, light escapes the fiber, often in a localized area. The light escaping the fiber typically has a high power density, which burns the fiber coating as well as any surrounding furcation tubing.

A special category of optical fiber, called double-clad fiber, can reduce the risk of bend-loss damage by allowing the fiber's cladding (2nd layer) to also function as a waveguide in addition to the core. By making the critical angle of the cladding/coating interface higher than the critical angle of the core/clad interface, light that escapes the core is loosely confined within the cladding. It will then leak out over a distance of centimeters or meters instead of at one localized spot within the fiber, minimizing the risk of damage. Thorlabs manufactures and sells 0.22 NA double-clad multimode fiber, which boasts very high, megawatt range power handling.

Photodarkening

A second damage mechanism, called photodarkening or solarization, can occur in fibers used with ultraviolet or short-wavelength visible light, particularly those with germanium-doped cores. Fibers used at these wavelengths will experience increased attenuation over time. The mechanism that causes photodarkening is largely unknown, but several fiber designs have been developed to mitigate it. For example, fibers with a very low hydroxyl ion (OH) content have been found to resist photodarkening and using other dopants, such as fluorine, can also reduce photodarkening.

Even with the above strategies in place, all fibers eventually experience photodarkening when used with UV or short-wavelength light, and thus, fibers used at these wavelengths should be considered consumables.

Preparation and Handling of Optical Fibers

General Cleaning and Operation Guidelines

These general cleaning and operation guidelines are recommended for all fiber optic products. Users should still follow specific guidelines for an individual product as outlined in the support documentation or manual. Damage threshold calculations only apply when all appropriate cleaning and handling procedures are followed.

1. All light sources should be turned off prior to installing or integrating optical fibers (terminated or bare). This ensures that focused beams of light are not incident on fragile parts of the connector or fiber, which can possibly cause damage.

2. The power-handling capability of an optical fiber is directly linked to the quality of the fiber/connector end face. Always inspect the fiber end prior to connecting the fiber to an optical system. The fiber end face should be clean and clear of dirt and other contaminants that can cause scattering of coupled light. Bare fiber should be cleaved prior to use and users should inspect the fiber end to ensure a good quality cleave is achieved.

3. If an optical fiber is to be spliced into the optical system, users should first verify that the splice is of good quality at a low optical power prior to high-power use. Poor splice quality may increase light scattering at the splice interface, which can be a source of fiber damage.

4. Users should use low power when aligning the system and optimizing coupling; this minimizes exposure of other parts of the fiber (other than the core) to light. Damage from scattered light can occur if a high power beam is focused on the cladding, coating, or connector.

Tips for Using Fiber at Higher Optical Power

Optical fibers and fiber components should generally be operated within safe power level limits, but under ideal conditions (very good optical alignment and very clean optical end faces), the power handling of a fiber component may be increased. Users must verify the performance and stability of a fiber component within their system prior to increasing input or output power and follow all necessary safety and operation instructions. The tips below are useful suggestions when considering increasing optical power in an optical fiber or component.

1. Splicing a fiber component into a system using a fiber splicer can increase power handling as it minimizes possibility of air/fiber interface damage. Users should follow all appropriate guidelines to prepare and make a high-quality fiber splice. Poor splices can lead to scattering or regions of highly localized heat at the splice interface that can damage the fiber.

2. After connecting the fiber or component, the system should be tested and aligned using a light source at low power. The system power can be ramped up slowly to the desired output power while periodically verifying all components are properly aligned and that coupling efficiency is not changing with respect to optical launch power.

3. Bend losses that result from sharply bending a fiber can cause light to leak from the fiber in the stressed area. When operating at high power, the localized heating that can occur when a large amount of light escapes a small localized area (the stressed region) can damage the fiber. Avoid disturbing or accidently bending fibers during operation to minimize bend losses.

4. Users should always choose the appropriate optical fiber for a given application. For example, large-mode-area fibers are a good alternative to standard single mode fibers in high-power applications as they provide good beam quality with a larger MFD, decreasing the power density on the air/fiber interface.

5. Step-index silica single mode fibers are normally not used for ultraviolet light or high-peak-power pulsed applications due to the high spatial power densities associated with these applications.

Part Number	Description	Price	Availability
780HP	Single Mode Optical Fiber, 780 - 970 nm, Ø125 µm Cladding	$6.00 Per Meter Volume Pricing Available	Today
SM800-5.6-125	Single Mode Optical Fiber, 830 nm, Ø125 µm Cladding	$6.11 Per Meter Volume Pricing Available	Today
SM800G80	Customer Inspired! Single Mode Optical Fiber, 830 nm, 0.14-0.18 NA, Ø80 µm Cladding	$5.08 Per Meter Volume Pricing Available	Today

Single Mode Fiber: 980 to 1650 nm

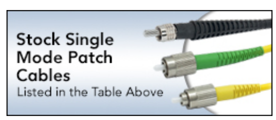
OVERVIEW

Features

- Shipped from Stock
- No Minimums
- HI1060-100 and HI1060-J9 have Ø900 µm Tight-Buffer Hytrel Outer Jackets
- SM980-5.8-125 has a MFD Matched to Other Fibers used in EDFA Pump Laser Pigtails
- 980HP and 1060XP Offer a Tight Second Mode Cut-Off Tolerance
- SM980G80 Offers Enhanced Bend Insensitivity

Stock Patch Cables Available with These Fibers
SM980-5.8-125 Fiber More [+]

Custom cables are also available. Click here for details.



SPECS

Item #	Operating Wavelength	Mode Field Diameter	Cladding	Coating	Cut-Off Wavelength
SM980-5.8-125	980 - 1550 nm	5.3 - 6.4 µm @ 980 nm[a]	125 ± 1 µm	245 ± 15 µm	870 - 970 nm
SM980G80	980 - 1550 nm	4.2 - 4.9 µm @ 980 nm	80 ± 1 µm	170 ± 10 µm	870 - 970 nm
1060XP	980 - 1600 nm	5.9 ± 0.5 µm @ 980 nm 6.2 ± 0.5 µm @ 1060 nm 9.5 ± 0.5 µm @ 1550 nm	125 ± 0.5 µm	245 ± 10 µm	920 ± 30 nm
980HP	980 - 1600 nm	4.2 ± 0.5 µm @ 980 nm 6.8 ± 0.5 µm @ 1550 nm	125 ± 1 µm	245 ± 15 µm	920 ± 30 nm
HI1060-J9	980 - 1650 nm	5.9 ± 0.3 µm @ 980 nm 6.2 ± 0.3 µm @ 1060 nm	125 ± 0.5 µm	245 ± 10 µm	920 ± 50 nm

Item #	Short-Term Bend Radius	Long-Term Bend Radius	Attenuation (Max)	NA	Core Index	Cladding Index
SM980-5.8-125	≥5 mm	≥25 mm	≤2.0 dB/km[b]	0.13 - 0.15	970 nm: 1.45660[c] 1310 nm: 1.45259[c] 1650 nm: 1.44854[c]	970 nm: 1.45081[c] 1310 nm: 1.44680[c] 1650 nm: 1.44275[c]
SM980G80	≥5 mm	≥12 mm (or 38 mm for 25 Year Life)	≤2 dB/km	0.17 - 0.19	980 nm: 1.46058[d] 1310 nm: 1.45670[d] 1650 nm: 1.45265[d]	980 nm: 1.45068[d] 1310 nm: 1.44680[d] 1650 nm: 1.44275[d]
1060XP	≥6 mm	≥13 mm	≤2.1 dB/km @ 980 nm ≤1.5 dB/km @ 1060 nm	0.14	Call[e]	Call[e]
980HP	≥6 mm	≥13 mm	≤3.5 dB/km @ 980 nm	0.20	Call[e]	Call[e]
HI1060-J9	-	-	2.1 dB/km @ 980 nm 1.5 dB/km @1060 nm	0.14[f]	Proprietary[g]	Proprietary[g]

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b. Attenuation is a worst-case value, quoted for the shortest design wavelength.
c. The indices provided are for an NA of 0.13.
d. The indices provided are for an NA of 0.17.
e. Please contact us to learn more about the refractive index of this fiber, as we are not permitted to publish this information on our website.
f. The NA of this fiber is measured at the 1% power level of a one-dimensional far-field scan at 1310 nm.
g. We regret that we cannot provide this proprietary information.

MFD DEFINITION

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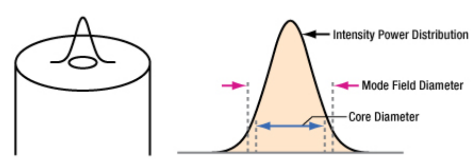

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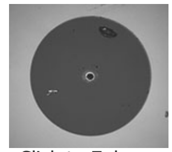

Click to Enlarge
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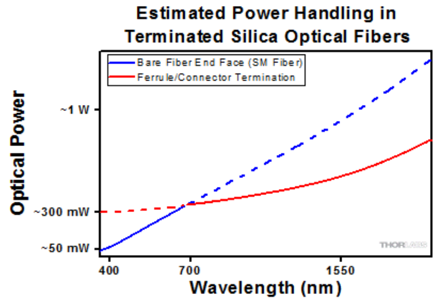

Click to Enlarge

Plot showing approximate input power that can be incident on a single mode silica optical fiber with a termination. Each line shows the estimated power level due to a specific damage mechanism. The maximum power handling is limited by the lowest power level from all relevant damage mechanisms (indicated by a solid line).

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To minimize the risk of burning the epoxy, fiber connectors can be constructed to have an epoxy-free air gap between the optical fiber and ferrule near the fiber end face. Our high-power multimode fiber patch cables use connectors with this design feature.

Determining Power Handling with Multiple Damage Mechanisms

When fiber cables or components have multiple avenues for damage (e.g., fiber patch cables), the maximum power handling is always limited by the lowest damage threshold that is relevant to the fiber component. In general, this represents the highest input power that can be incident on the patch cable end face and not the coupled output power.

As an illustrative example, the graph to the right shows an estimate of the power handling limitations of a single mode fiber patch cable due to damage to the fiber end face and damage via an optical connector. The total input power handling of a terminated fiber at a given wavelength is limited by the lower of the two limitations at any given wavelength (indicated by the solid lines). A single mode fiber operating at around 488 nm is primarily limited by damage to the fiber end face (blue solid line), but fibers operating at 1550 nm are limited by damage to the optical connector (red solid line).

In the case of a multimode fiber, the effective mode area is defined by the core diameter, which is larger than the effective mode area for SM fiber. This results in a lower power density on the fiber end face and allows higher optical powers (on the order of kilowatts) to be coupled into the fiber without damage (not shown in graph). However, the damage limit of the ferrule / connector termination remains unchanged and as a result, the maximum power handling for a multimode fiber is limited by the ferrule and connector termination.

Please note that these are rough estimates of power levels where damage is very unlikely with proper handling and alignment procedures. It is worth noting that optical fibers are frequently used at power levels above those described here. However, these applications typically require expert users and testing at lower powers first to minimize risk of damage. Even still, optical fiber components should be considered a consumable lab supply if used at high power levels.

Intrinsic Damage Threshold

In addition to damage mechanisms at the air / glass interface, optical fibers also display power handling limitations due to damage mechanisms within the optical fiber itself. These limitations will affect all fiber components as they are intrinsic to the fiber itself. Two categories of damage within the fiber are damage from bend losses and damage from photodarkening.

Bend Losses

Bend losses occur when a fiber is bent to a point where light traveling in the core is incident on the core/cladding interface at an angle higher than the critical angle, making total internal reflection impossible. Under these circumstances, light escapes the fiber, often in a localized area. The light escaping the fiber typically has a high power density, which burns the fiber coating as well as any surrounding furcation tubing.

A special category of optical fiber, called double-clad fiber, can reduce the risk of bend-loss damage by allowing the fiber's cladding (2nd layer) to also function as a waveguide in addition to the core. By making the critical angle of the cladding/coating interface higher than the critical angle of the core/clad interface, light that escapes the core is loosely confined within the cladding. It will then leak out over a distance of centimeters or meters instead of at one localized spot within the fiber, minimizing the risk of damage. Thorlabs manufactures and sells 0.22 NA double-clad multimode fiber, which boasts very high, megawatt range power handling.

Photodarkening
A second damage mechanism, called photodarkening or solarization, can occur in fibers used with ultraviolet or short-wavelength visible light, particularly those with germanium-doped cores. Fibers used at these wavelengths will experience increased attenuation over time. The mechanism that causes photodarkening is largely unknown, but several fiber designs have been developed to mitigate it. For example, fibers with a very low hydroxyl ion (OH) content have been found to resist photodarkening and using other dopants, such as fluorine, can also reduce photodarkening.

Even with the above strategies in place, all fibers eventually experience photodarkening when used with UV or short-wavelength light, and thus, fibers used at these wavelengths should be considered consumables.

Preparation and Handling of Optical Fibers

General Cleaning and Operation Guidelines
These general cleaning and operation guidelines are recommended for all fiber optic products. Users should still follow specific guidelines for an individual product as outlined in the support documentation or manual. Damage threshold calculations only apply when all appropriate cleaning and handling procedures are followed.

1. All light sources should be turned off prior to installing or integrating optical fibers (terminated or bare). This ensures that focused beams of light are not incident on fragile parts of the connector or fiber, which can possibly cause damage.

2. The power-handling capability of an optical fiber is directly linked to the quality of the fiber/connector end face. Always inspect the fiber end prior to connecting the fiber to an optical system. The fiber end face should be clean and clear of dirt and other contaminants that can cause scattering of coupled light. Bare fiber should be cleaved prior to use and users should inspect the fiber end to ensure a good quality cleave is achieved.

3. If an optical fiber is to be spliced into the optical system, users should first verify that the splice is of good quality at a low optical power prior to high-power use. Poor splice quality may increase light scattering at the splice interface, which can be a source of fiber damage.

4. Users should use low power when aligning the system and optimizing coupling; this minimizes exposure of other parts of the fiber (other than the core) to light. Damage from scattered light can occur if a high power beam is focused on the cladding, coating, or connector.

Tips for Using Fiber at Higher Optical Power
Optical fibers and fiber components should generally be operated within safe power level limits, but under ideal conditions (very good optical alignment and very clean optical end faces), the power handling of a fiber component may be increased. Users must verify the performance and stability of a fiber component within their system prior to increasing input or output power and follow all necessary safety and operation instructions. The tips below are useful suggestions when considering increasing optical power in an optical fiber or component.

1. Splicing a fiber component into a system using a fiber splicer can increase power handling as it minimizes possibility of air/fiber interface damage. Users should follow all appropriate guidelines to prepare and make a high-quality fiber splice. Poor splices can lead to scattering or regions of highly localized heat at the splice interface that can damage the fiber.

2. After connecting the fiber or component, the system should be tested and aligned using a light source at low power. The system power can be ramped up slowly to the desired output power while periodically verifying all components are properly aligned and that coupling efficiency is not changing with respect to optical launch power.

3. Bend losses that result from sharply bending a fiber can cause light to leak from the fiber in the stressed area. When operating at high power, the localized heating that can occur when a large amount of light escapes a small localized area (the stressed region) can damage the fiber. Avoid disturbing or accidently bending fibers during operation to minimize bend losses.

4. Users should always choose the appropriate optical fiber for a given application. For example, large-mode-area fibers are a good alternative to standard single mode fibers in high-power applications as they provide good beam quality with a larger MFD, decreasing the power density on the air/fiber interface.

5. Step-index silica single mode fibers are normally not used for ultraviolet light or high-peak-power pulsed applications due to the high spatial power densities associated with these applications.

Part Number	Description	Price	Availability
		$6.11	

SM980-5.8-125	Single Mode Optical Fiber, 980 - 1550 nm, Ø125 µm Cladding	Per Meter Volume Pricing Available	Today
SM980G80	Customer Inspired! Single Mode Optical Fiber, 980 - 1550 nm, Ø80 µm Cladding	$5.08 Per Meter Volume Pricing Available	Today
1060XP	Single Mode Optical Fiber, 980 - 1600 nm, Extra-High Performance, Ø125 µm Cladding	$5.36 Per Meter Volume Pricing Available	5-8 Days
980HP	Single Mode Optical Fiber, 980 - 1600 nm, Ø125 µm Cladding	$5.30 Per Meter Volume Pricing Available	Today
HI1060-J9	HI1060 with Ø900 µm Jacket, Ø125 µm Cladding	$10.23 Per Meter Volume Pricing Available	Today
HI1060-100	100 m of HI1060 with Ø900 µm Jacket, Ø125 µm Cladding	$696.89	Lead Time

Single Mode Fiber: 1260 to 1650 nm

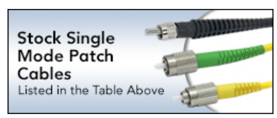
OVERVIEW

Features

- Shipped from Stock
- No Minimums
- Most Fibers have Acrylate Coatings
  - SM1550P has Polyimide Coating for High-Temperature Performance in the Telecom Region
- SMF-28-100, SMF-28-1000, and SMF-28-J9 have Ø900 µm Tight-Buffer Hytrel Outer Jackets
- CCC1310-J9 has a Ø900 µm Tight-Buffer PVC Outer Jacket
- Exceptional Core/Clad Concentricity Specifications
- 1550BHP Offers Tight Second Mode Cut-off Tolerances
- SM1250G80, CCC1310-J9, and SM1500G80 Offer Enhanced Bend Insensitivity (See the *Specs* Tab for Information)
- DCF4 Fiber Features Low Negative Dispersion (See the Full Web Presentation for Details)

Stock Patch Cables Available with These Fibers	
SMF-28 Ultra Fiber	More [+]
1550BHP Fiber	More [+]

Custom cables are also available. Click here for details.



SPECS

Item #	Operating Wavelength	Mode Field Diameter	Cladding	Coating	Cut-Off Wavelength
SMF-28-J9	1260 - 1625 nm	9.2 ± 0.4 µm @ 1310 nm 10.4 ± 0.5 µm @ 1550 nm	125 ± 0.7 µm	242 ± 5 µm	<1260 nm
CCC1310-J9	1260 - 1625 nm	8.6 ± 0.4 µm @ 1310 nm 9.7 ± 0.5 µm @ 1550 nm	125 ± 0.7 µm	242 ± 5 µm	≤1260 nm
1310BHP	1300 - 1625 nm	8.6 ± 0.5 µm @ 1310 nm 9.7 ± 0.5 µm @ 1550 nm	125 ± 1.0 µm	245 ± 15 µm	1260 ± 30 nm
SM1550P	1310 - 1550 nm	9.0 µm @ 1310 nm	125 +1 / -3 µm	145 ± 5 µm	<1260 nm
SM1250G80	1310 - 1550 nm	8.2 - 9.9 µm @ 1310 nm	80 ± 1 µm	170 ± 10 µm	1150 - 1250 nm
1550BHP	1460 - 1620 nm	9.5 ± 0.5 µm @ 1550 nm	125 ± 1.0 µm	245 ± 15 µm	1400 ± 50 nm
SM1500G80	1520 - 1650 nm	6.0 - 6.8 µm @ 1550 nm	80 ± 1 µm	170 ± 10 µm	1350 - 1520 nm
DCF4	1530 - 1565 nm	8.85 - 9.60 µm @ 1550 nm	125 ± 1.0 µm	250 ± 5 µm	≤1500 nm

	Short-Term Bend					

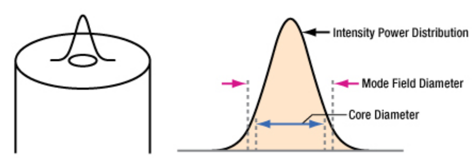
Item #	Radius	Long-Term Bend Radius	Attenuation (Max)	NA	Core Index	Cladding Index
SMF-28-J9	-	-	≤0.32 dB/km @ 1310 nm ≤0.18 dB/km @ 1550 nm	0.14[a]	Proprietary[b]	Proprietary[b]
CCC1310-J9	-	-	≤0.35 dB/km @ 1310 nm ≤0.20 dB/km @ 1550 nm	0.14	1310 nm: 1.4670 1550 nm: 1.4677	-
1310BHP	≥6 mm	≥13 mm	≤0.5 dB/km @ 1310 nm & 1550 nm	0.13	Call[c]	Call[c]
SM1550P	≥13 mm	≥25 mm	<0.7 dB/km[d]	0.12 ± 0.02	Proprietary[b]	Proprietary[b]
SM1250G80	≥5 mm	≥12 mm (or 38 mm for 25 Year Life)	≤2 dB/km	0.11 - 0.13	1310 nm: 1.45094[e] 1550 nm: 1.44813[e]	1310 nm: 1.44680[e] 1550 nm: 1.44399[e]
1550BHP	≥6 mm	≥13 mm	≤0.5 dB/km @ 1550 nm	0.13	Call[c]	Call[c]
SM1500G80	≥5 mm	≥12 mm (or 38 mm for 25 Year Life)	≤0.5 dB/km	0.19 - 0.21	1550 nm: 1.45636[f]	1550 nm: 1.44399[f]
DCF4	-	-	≤0.210 dB/km @ 1550 nm	-	Proprietary[b]	Proprietary[b]

a. The NA of this fiber is measured at the 1% power level of a one-dimensional far-field scan at 1310 nm.
b. We regret that we cannot provide this proprietary information.
c. Please contact us to learn more about the refractive index of this fiber, as we are not permitted to publish this information on our website.
d. Specified at Operating Wavelength
e. The indices provided are for an NA of 0.11.
f. The index provided is for an NA of 0.19.

MFD DEFINITION

Definition of the Mode Field Diameter

The mode field diameter (MFD) is one measure of the beam width of light propagating in a single mode fiber. It is a function of wavelength, core radius, and the refractive indices of the core and cladding. While much of the light in an optical fiber is trapped within the fiber core, a small fraction propagates in the cladding. The light can be approximated as a Gaussian power distribution as shown to the right, where the MFD is the diameter at which the optical power is reduced to $1/e^2$ from its peak level.



Click to Enlarge
The left image shows the intensity profile of the beam propagated through the fiber overlaid on the fiber itself. The right image shows the standard intensity profile of the beam propagated through the fiber with the MFD and core diameter called out.

Measurement of MFD

The measurement of MFD is accomplished by the Variable Aperture Method in the Far Field (VAMFF). An aperture is placed in the far field of the fiber output, and the intensity is measured. As successively smaller apertures are placed in the beam, the intensity levels are measured for each aperture; the data can then be plotted as power vs. the sine of the aperture half-angle (or the numerical aperture for an SM fiber).

The MFD is then determined using Petermann's second definition, which is a mathematical model that does not assume a specific shape of power distribution. The MFD in the near field can be determined from this far-field measurement using the Hankel Transform.

DAMAGE THRESHOLD

Laser-Induced Damage in Silica Optical Fibers

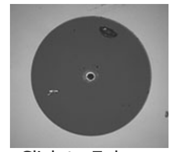
Quick Links
Damage at the Air / Glass Interface
Intrinsic Damage Threshold
Preparation and Handling of Optical Fibers

The following tutorial details damage mechanisms relevant to unterminated (bare) fiber, terminated optical fiber, and other fiber components from laser light sources. These mechanisms include damage that occurs at the air / glass interface (when free-space coupling or when using connectors) and in the optical fiber itself. A fiber component, such as a bare fiber, patch cable, or fused coupler, may have multiple potential avenues for damage (e.g., connectors, fiber end faces, and the device itself). The maximum power that a fiber can handle will always be limited by the lowest limit of any of these damage mechanisms.

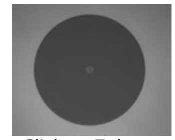
While the damage threshold can be estimated using scaling relations and general rules, absolute damage thresholds in optical fibers are very application dependent and user specific. Users can use this guide to estimate a safe power level that minimizes the risk of damage. Following all appropriate preparation and handling guidelines, users should be able to operate a fiber component up to the specified maximum power level; if no maximum is specified for a component, users should abide by the "practical safe level" described below for safe operation of the component. Factors that can reduce power handling and cause damage to a fiber component include, but are not limited to, misalignment during fiber coupling, contamination of the fiber end face, or imperfections in the fiber itself. For further discussion about an optical fiber's power handling abilities for a specific application, please contact Thorlabs' Tech Support.

Damage at the Air / Glass Interface

There are several potential damage mechanisms that can occur at the air / glass interface. Light is incident on this interface when free-space coupling or when two fibers are mated using optical connectors. High-intensity light can damage the end face leading to reduced power handling and permanent damage to the fiber. For fibers terminated with optical connectors where the connectors are fixed to the fiber ends using epoxy, the heat generated by high-intensity light can burn the epoxy and leave residues on the fiber facet directly in the beam path.



Click to Enlarge
Damaged Fiber End



Click to Enlarge
Undamaged Fiber End

Damage Mechanisms on the Bare Fiber End Face

Damage mechanisms on a fiber end face can be modeled similarly to bulk optics, and industry-standard damage thresholds for UV Fused Silica substrates can be applied to silica-based fiber. However, unlike bulk optics, the relevant surface areas and beam diameters involved at the air / glass interface of an optical fiber are very small, particularly for coupling into single mode (SM) fiber. therefore, for a given power density, the power incident on the fiber needs to be lower for a smaller beam diameter.

The table to the right lists two thresholds for optical power densities: a theoretical damage threshold and a "practical safe level". In general, the theoretical damage threshold represents the estimated maximum power density that can be incident on the fiber end face without risking damage with very good fiber end face and coupling conditions. The "practical safe level" power density represents minimal risk of fiber damage. Operating a fiber or component beyond the practical safe level is possible, but users must follow the appropriate handling instructions and verify performance at low powers prior to use.

Estimated Optical Power Densities on Air / Glass Interface[a]		
Type	Theoretical Damage Threshold[b]	Practical Safe Level[c]
CW (Average Power)	~1 MW/cm^2	~250 kW/cm^2
10 ns Pulsed (Peak Power)	~5 GW/cm^2	~1 GW/cm^2

a. All values are specified for unterminated (bare) silica fiber and apply for free space coupling into a clean fiber end face.
b. This is an estimated maximum power density that can be incident on a fiber end face without risking damage. Verification of the performance and reliability of fiber components in the system before operating at high power must be done by the user, as it is highly system dependent.
c. This is the estimated safe optical power density that can be incident on a fiber end face without damaging the fiber under most operating conditions.

Calculating the Effective Area for Single Mode and Multimode Fibers

The effective area for single mode (SM) fiber is defined by the mode field diameter (MFD), which is the cross-sectional area through which light propagates in the fiber; this area includes the fiber core and also a portion of the cladding. To achieve good efficiency when coupling into a single mode fiber, the diameter of the input beam must match the MFD of the fiber.

As an example, SM400 single mode fiber has a mode field diameter (MFD) of ~Ø3 µm operating at 400 nm, while the MFD for SMF-28 Ultra single mode fiber operating at 1550 nm is Ø10.5 µm. The effective area for these fibers can be calculated as follows:

SM400 Fiber: Area = Pi x (MFD/2)^2 = Pi x (1.5 µm)^2 = 7.07 µm^2 = 7.07 x 10^{-8} cm^2

SMF-28 Ultra Fiber: Area = Pi x (MFD/2)^2 = Pi x (5.25 µm)^2 = 86.6 µm^2 = 8.66 x 10^{-7} cm^2

To estimate the power level that a fiber facet can handle, the power density is multiplied by the effective area. Please note that this calculation assumes a uniform intensity profile, but most laser beams exhibit a Gaussian-like shape within single mode fiber, resulting in a higher power density at the center of the beam compared to the edges. Therefore, these calculations will slightly overestimate the power corresponding to the damage threshold or the practical safe level. Using the estimated power densities assuming a CW light source, we can determine the corresponding power levels as:

SM400 Fiber: 7.07 x 10^{-8} cm^2 x 1 MW/cm^2 = 7.1 x 10^{-8} MW = 71 mW (Theoretical Damage Threshold)
7.07 x 10^{-8} cm^2 x 250 kW/cm^2 = 1.8 x 10^{-5} kW = 18 mW (Practical Safe Level)

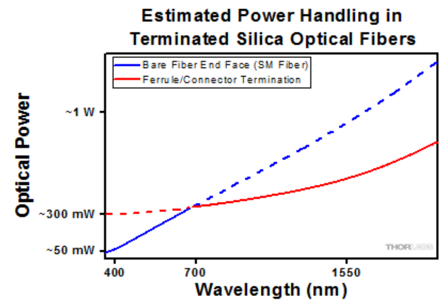
SMF-28 Ultra Fiber: 8.66 x 10^{-7} cm^2 x 1 MW/cm^2 = 8.7 x 10^{-7} MW = 870 mW (Theoretical Damage Threshold)

8.66×10^{-7} cm^2 x 250 kW/cm^2 = 2.1×10^{-4} kW = 210 mW (Practical Safe Level)

The effective area of a multimode (MM) fiber is defined by the core diameter, which is typically far larger than the MFD of an SM fiber. For optimal coupling, Thorlabs recommends focusing a beam to a spot roughly 70 - 80% of the core diameter. The larger effective area of MM fibers lowers the power density on the fiber end face, allowing higher optical powers (typically on the order of kilowatts) to be coupled into multimode fiber without damage.

Damage Mechanisms Related to Ferrule / Connector Termination

Fibers terminated with optical connectors have additional power handling considerations. Fiber is typically terminated using epoxy to bond the fiber to a ceramic or steel ferrule. When light is coupled into the fiber through a connector, light that does not enter the core and propagate down the fiber is scattered into the outer layers of the fiber, into the ferrule, and the epoxy used to hold the fiber in the ferrule. If the light is intense enough, it can burn the epoxy, causing it to vaporize and deposit a residue on the face of the connector. This results in localized absorption sites on the fiber end face that reduce coupling efficiency and increase scattering, causing further damage.



Click to Enlarge
Plot showing approximate input power that can be incident on a single mode silica optical fiber with a termination. Each line shows the estimated power level due to a specific damage mechanism. The maximum power handling is limited by the lowest power level from all relevant damage mechanisms (indicated by a solid line).

For several reasons, epoxy-related damage is dependent on the wavelength. In general, light scatters more strongly at short wavelengths than at longer wavelengths. Misalignment when coupling is also more likely due to the small MFD of short-wavelength SM fiber that also produces more scattered light.

To minimize the risk of burning the epoxy, fiber connectors can be constructed to have an epoxy-free air gap between the optical fiber and ferrule near the fiber end face. Our high-power multimode fiber patch cables use connectors with this design feature.

Determining Power Handling with Multiple Damage Mechanisms

When fiber cables or components have multiple avenues for damage (e.g., fiber patch cables), the maximum power handling is always limited by the lowest damage threshold that is relevant to the fiber component. In general, this represents the highest input power that can be incident on the patch cable end face and not the coupled output power.

As an illustrative example, the graph to the right shows an estimate of the power handling limitations of a single mode fiber patch cable due to damage to the fiber end face and damage via an optical connector. The total input power handling of a terminated fiber at a given wavelength is limited by the lower of the two limitations at any given wavelength (indicated by the solid lines). A single mode fiber operating at around 488 nm is primarily limited by damage to the fiber end face (blue solid line), but fibers operating at 1550 nm are limited by damage to the optical connector (red solid line).

In the case of a multimode fiber, the effective mode area is defined by the core diameter, which is larger than the effective mode area for SM fiber. This results in a lower power density on the fiber end face and allows higher optical powers (on the order of kilowatts) to be coupled into the fiber without damage (not shown in graph). However, the damage limit of the ferrule / connector termination remains unchanged and as a result, the maximum power handling for a multimode fiber is limited by the ferrule and connector termination.

Please note that these are rough estimates of power levels where damage is very unlikely with proper handling and alignment procedures. It is worth noting that optical fibers are frequently used at power levels above those described here. However, these applications typically require expert users and testing at lower powers first to minimize risk of damage. Even still, optical fiber components should be considered a consumable lab supply if used at high power levels.

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Bend Losses

Bend losses occur when a fiber is bent to a point where light traveling in the core is incident on the core/cladding interface at an angle higher than the critical angle, making total internal reflection impossible. Under these circumstances, light escapes the fiber, often in a localized area. The light escaping the fiber typically has a high power density, which burns the fiber coating as well as any surrounding furcation tubing.

A special category of optical fiber, called double-clad fiber, can reduce the risk of bend-loss damage by allowing the fiber's cladding (2nd layer) to also function as a waveguide in addition to the core. By making the critical angle of the cladding/coating interface higher than the critical angle of the core/clad interface, light that escapes the core is loosely confined within the cladding. It will then leak out over a distance of centimeters or meters instead of at one localized spot within the fiber, minimizing the risk of damage. Thorlabs manufactures and sells 0.22 NA double-clad multimode fiber, which boasts very high, megawatt range power handling.

Photodarkening

A second damage mechanism, called photodarkening or solarization, can occur in fibers used with ultraviolet or short-wavelength visible light, particularly those with germanium-doped cores. Fibers used at these wavelengths will experience increased attenuation over time. The mechanism that causes photodarkening is largely unknown, but several fiber designs have been developed to mitigate it. For example, fibers with a very low hydroxyl ion (OH) content have been found to resist photodarkening and using other dopants, such as fluorine, can also reduce photodarkening.

Even with the above strategies in place, all fibers eventually experience photodarkening when used with UV or short-wavelength light, and thus, fibers used at these wavelengths should be considered consumables.

Preparation and Handling of Optical Fibers

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These general cleaning and operation guidelines are recommended for all fiber optic products. Users should still follow specific guidelines for an individual product as outlined in the support documentation or manual. Damage threshold calculations only apply when all appropriate cleaning and handling procedures are followed.

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4. Users should use low power when aligning the system and optimizing coupling; this minimizes exposure of other parts of the fiber (other than the core) to light. Damage from scattered light can occur if a high power beam is focused on the cladding, coating, or connector.

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Optical fibers and fiber components should generally be operated within safe power level limits, but under ideal conditions (very good optical alignment and very clean optical end faces), the power handling of a fiber component may be increased. Users must verify the performance and stability of a fiber component within their system prior to increasing input or output power and follow all necessary safety and operation instructions. The tips below are useful suggestions when considering increasing optical power in an optical fiber or component.

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2. After connecting the fiber or component, the system should be tested and aligned using a light source at low power. The system power can be ramped up slowly to the desired output power while periodically verifying all components are properly aligned and that coupling efficiency is not changing with respect to optical launch power.

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4. Users should always choose the appropriate optical fiber for a given application. For example, large-mode-area fibers are a good alternative to standard single mode fibers in high-power applications as they provide good beam quality with a larger MFD, decreasing the power density on the air/fiber interface.

5. Step-index silica single mode fibers are normally not used for ultraviolet light or high-peak-power pulsed applications due to the high spatial power densities associated with these applications.

Part Number	Description	Price	Availability
SMF-28-J9	SMF-28 Ultra with Ø900 µm Jacket, Ø125 µm Cladding	$2.49 Per Meter	Today

		Volume Pricing Available	
SMF-28-100	100 m of SMF-28 Ultra with Ø900 µm Jacket, Ø125 µm Cladding	$57.08	Today
SMF-28-1000	1000 m of SMF-28 Ultra with Ø900 µm Jacket, Ø125 µm Cladding	$512.92	Today
CCC1310-J9	1260 - 1625 nm Low Bend Loss Fiber with Ø900 µm Jacket, Ø125 µm Cladding	$2.49 Volume Pricing Available	Today
1310BHP	Select Cut-Off Single Mode Fiber, 1310 - 1625 nm, Ø125 µm Cladding	$5.30 Per Meter Volume Pricing Available	Today
SM1550P	Customer Inspired! Single Mode Optical Fiber, 0.12 ± 0.02 NA, 1310 - 1550 nm, Polyimide Coating, Ø125 µm Cladding	$6.90 Per Meter Volume Pricing Available	Today
SM1250G80	Customer Inspired! Single Mode Optical Fiber, 0.11 - 0.13 NA, 1310 - 1550 nm, Ø80 µm Cladding	$5.08 Per Meter Volume Pricing Available	Today
1550BHP	Single Mode Optical Fiber, 1460 - 1620 nm, Ø125 µm Cladding	$5.30 Per Meter Volume Pricing Available	Today
SM1500G80	Customer Inspired! Single Mode Optical Fiber, 0.19 - 0.21 NA, 1520 - 1650 nm, Ø80 µm Cladding	$5.08 Per Meter Volume Pricing Available	Today
DCF4	Non-Zero Dispersion-Shifted Fiber, Dispersion: -4.0 ps/nm•km at 1550 nm	$3.98 Per Meter Volume Pricing Available	Today

Single Mode Fiber: 1.7 to 2.3 µm

OVERVIEW

Features

- Shipped from Stock
- No Minimums
- Ge-Doped Silica Core, Pure Silica Cladding, and a UV Cured Acrylate Coating
- Large Core for Coupling 2 µm Light
- NA Compatible with Corning's SMF-28 Fiber
- Exceptional Core/Clad Concentricity Specifications
- Low Bend Losses (See *Specs* Tab)

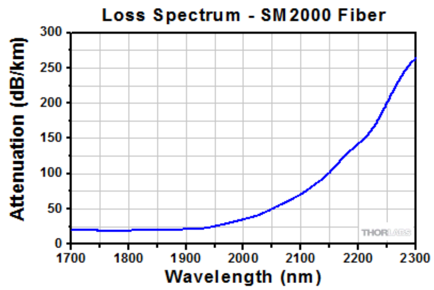
Stock Patch Cables Available with These Fibers	
SM2000 Fiber	More [+]

Custom cables are also available. Click here for details.

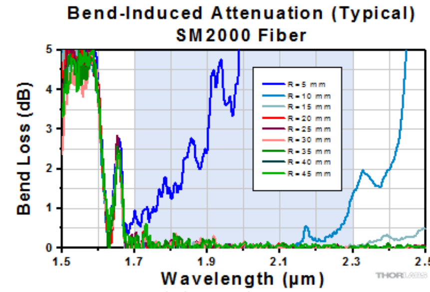
SPECS

Item #	Operating Wavelength	MFD	Core Diameter	Cladding Diameter	Buffer	Cut-Off Wavelength
SM2000	1700 - 2300 nm	13 ± 1 µm @ 1996 nm	11 ± 1 µm	125 ± 1 µm	245 ± 10 µm	1750 ± 50 nm

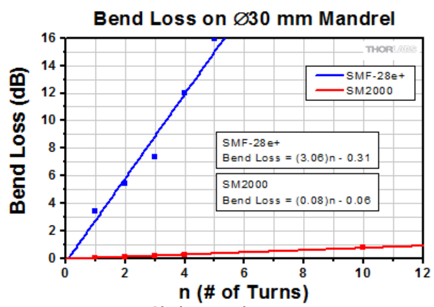
Item #	Cladding Noncircularity	Core-Clad Concentricity	Typical Attenuation	NA	Core Index	Cladding Index
SM2000	≤2%	<0.8 µm	2.3 µm: 250 dB/km (0.25 dB/m) 1.9 µm: 20 dB/km (0.02 dB/m)	0.12 ± 0.01	2 µm: 1.4436	2 µm: 1.4381



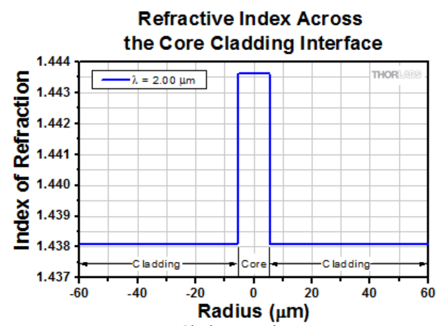
Click to Enlarge
Click for Raw Data
This plot contains the measured attenuation for our SM2000 fiber across the single mode wavelength range (1700 nm - 2300 nm).



Click to Enlarge
Click for Raw Data
This plot contains the measured attenuation for a single loop of our single mode SM2000 fiber at nine different bend radii. The shaded region in the plot denotes the single mode wavelength range (1.7 - 2.3 µm).



Click to Enlarge
Using a 1996 nm source and a Ø30 mm mandrel, the bend losses (dB) of the SM2000 and SMF-28e+ fibers were measured for each turn of the fiber around the mandrel. Based on the measurement, the loss/turn of the SM2000 fiber is ~0.08 dB. For the SMF-28e+ fiber, the loss/turn is ~3 dB. The SM2000 fiber is much less sensitive to bending than SMF-28e+ fiber.

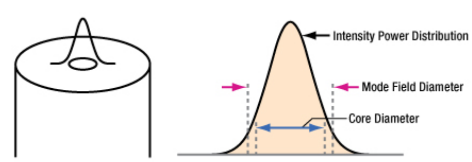


Click to Enlarge

MFD DEFINITION

Definition of the Mode Field Diameter

The mode field diameter (MFD) is one measure of the beam width of light propagating in a single mode fiber. It is a function of wavelength, core radius, and the refractive indices of the core and cladding. While much of the light in an optical fiber is trapped within the fiber core, a small fraction propagates in the cladding. The light can be approximated as a Gaussian power distribution as shown to the right, where the MFD is the diameter at which the optical power is reduced to $1/e^2$ from its peak level.



Click to Enlarge
The left image shows the intensity profile of the beam propagated through the fiber overlaid on the fiber itself. The right image shows the standard intensity profile of the beam propagated through the fiber with the MFD and core diameter called out.

Measurement of MFD

The measurement of MFD is accomplished by the Variable Aperture Method in the Far Field (VAMFF). An aperture is placed in the far field of the fiber output, and the intensity is measured. As successively smaller apertures are placed in the beam, the intensity levels are measured for each aperture; the data can then be plotted as power vs. the sine of the aperture half-angle (or the numerical aperture for an SM fiber).

The MFD is then determined using Petermann's second definition, which is a mathematical model that does not assume a specific shape of power distribution. The MFD in the near field can be determined from this far-field measurement using the Hankel Transform.

DAMAGE THRESHOLD

Laser-Induced Damage in Silica Optical Fibers

The following tutorial details damage mechanisms relevant to unterminated (bare) fiber,

Quick Links
Damage at the Air / Glass Interface

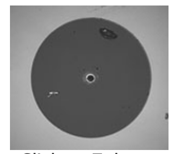
terminated optical fiber, and other fiber components from laser light sources. These mechanisms include damage that occurs at the air / glass interface (when free-space coupling or when using connectors) and in the optical fiber itself. A fiber component, such as a bare fiber, patch cable, or fused coupler, may have multiple potential avenues for damage (e.g., connectors, fiber end faces, and the device itself). The maximum power that a fiber can handle will always be limited by the lowest limit of any of these damage mechanisms.

Intrinsic Damage Threshold
Preparation and Handling of Optical Fibers

While the damage threshold can be estimated using scaling relations and general rules, absolute damage thresholds in optical fibers are very application dependent and user specific. Users can use this guide to estimate a safe power level that minimizes the risk of damage. Following all appropriate preparation and handling guidelines, users should be able to operate a fiber component up to the specified maximum power level; if no maximum is specified for a component, users should abide by the "practical safe level" described below for safe operation of the component. Factors that can reduce power handling and cause damage to a fiber component include, but are not limited to, misalignment during fiber coupling, contamination of the fiber end face, or imperfections in the fiber itself. For further discussion about an optical fiber's power handling abilities for a specific application, please contact Thorlabs' Tech Support.

Damage at the Air / Glass Interface

There are several potential damage mechanisms that can occur at the air / glass interface. Light is incident on this interface when free-space coupling or when two fibers are mated using optical connectors. High-intensity light can damage the end face leading to reduced power handling and permanent damage to the fiber. For fibers terminated with optical connectors where the connectors are fixed to the fiber ends using epoxy, the heat generated by high-intensity light can burn the epoxy and leave residues on the fiber facet directly in the beam path.


Click to Enlarge
Damaged Fiber End


Click to Enlarge
Undamaged Fiber End

Damage Mechanisms on the Bare Fiber End Face

Damage mechanisms on a fiber end face can be modeled similarly to bulk optics, and industry-standard damage thresholds for UV Fused Silica substrates can be applied to silica-based fiber. However, unlike bulk optics, the relevant surface areas and beam diameters involved at the air / glass interface of an optical fiber are very small, particularly for coupling into single mode (SM) fiber. therefore, for a given power density, the power incident on the fiber needs to be lower for a smaller beam diameter.

The table to the right lists two thresholds for optical power densities: a theoretical damage threshold and a "practical safe level". In general, the theoretical damage threshold represents the estimated maximum power density that can be incident on the fiber end face without risking damage with very good fiber end face and coupling conditions. The "practical safe level" power density represents minimal risk of fiber damage. Operating a fiber or component beyond the practical safe level is possible, but users must follow the appropriate handling instructions and verify performance at low powers prior to use.

Estimated Optical Power Densities on Air / Glass Interface[a]

Type	Theoretical Damage Threshold[b]	Practical Safe Level[c]
CW (Average Power)	~1 MW/cm^2	~250 kW/cm^2
10 ns Pulsed (Peak Power)	~5 GW/cm^2	~1 GW/cm^2

a. All values are specified for unterminated (bare) silica fiber and apply for free space coupling into a clean fiber end face.
b. This is an estimated maximum power density that can be incident on a fiber end face without risking damage. Verification of the performance and reliability of fiber components in the system before operating at high power must be done by the user, as it is highly system dependent.
c. This is the estimated safe optical power density that can be incident on a fiber end face without damaging the fiber under most operating conditions.

Calculating the Effective Area for Single Mode and Multimode Fibers

The effective area for single mode (SM) fiber is defined by the mode field diameter (MFD), which is the cross-sectional area through which light propagates in the fiber; this area includes the fiber core and also a portion of the cladding. To achieve good efficiency when coupling into a single mode fiber, the diameter of the input beam must match the MFD of the fiber.

As an example, SM400 single mode fiber has a mode field diameter (MFD) of ~Ø3 µm operating at 400 nm, while the MFD for SMF-28 Ultra single mode fiber operating at 1550 nm is Ø10.5 µm. The effective area for these fibers can be calculated as follows:

SM400 Fiber: Area = Pi x $(MFD/2)^2$ = Pi x $(1.5\ \mu m)^2$ = 7.07 μm^2 = 7.07 x 10^{-8} cm^2

SMF-28 Ultra Fiber: Area = Pi x $(MFD/2)^2$ = Pi x $(5.25\ \mu m)^2$ = 86.6 μm^2 = 8.66 x 10^{-7} cm^2

To estimate the power level that a fiber facet can handle, the power density is multiplied by the effective area. Please note that this calculation assumes a uniform intensity profile, but most laser beams exhibit a Gaussian-like shape within single mode fiber, resulting in a higher power density at the center of the beam compared to the edges. Therefore, these calculations will slightly overestimate the power corresponding to the damage threshold or the practical safe level. Using the estimated power densities assuming a CW light source, we can determine the corresponding power levels as:

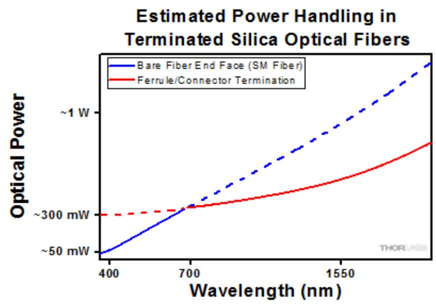
SM400 Fiber: 7.07×10^{-8} cm^2 x 1 MW/cm^2 = 7.1×10^{-8} MW = 71 mW (Theoretical Damage Threshold)
7.07×10^{-8} cm^2 x 250 kW/cm^2 = 1.8×10^{-5} kW = 18 mW (Practical Safe Level)

SMF-28 Ultra Fiber: 8.66×10^{-7} cm^2 x 1 MW/cm^2 = 8.7×10^{-7} MW = 870 mW (Theoretical Damage Threshold)
8.66×10^{-7} cm^2 x 250 kW/cm^2 = 2.1×10^{-4} kW = 210 mW (Practical Safe Level)

The effective area of a multimode (MM) fiber is defined by the core diameter, which is typically far larger than the MFD of an SM fiber. For optimal coupling, Thorlabs recommends focusing a beam to a spot roughly 70 - 80% of the core diameter. The larger effective area of MM fibers lowers the power density on the fiber end face, allowing higher optical powers (typically on the order of kilowatts) to be coupled into multimode fiber without damage.

Damage Mechanisms Related to Ferrule / Connector Termination

Fibers terminated with optical connectors have additional power handling considerations. Fiber is typically terminated using epoxy to bond the fiber to a ceramic or steel ferrule. When light is coupled into the fiber through a connector, light that does not enter the core and propagate down the fiber is scattered into the outer layers of the fiber, into the ferrule, and the epoxy used to hold the fiber in the ferrule. If the light is intense enough, it can burn the epoxy, causing it to vaporize and deposit a residue on the face of the connector. This results in localized absorption sites on the fiber end face that reduce coupling efficiency and increase scattering, causing further damage.



Click to Enlarge
Plot showing approximate input power that can be incident on a single mode silica optical fiber with a termination. Each line shows the estimated power level due to a specific damage mechanism. The maximum power handling is limited by the lowest power level from all relevant damage mechanisms (indicated by a solid line).

For several reasons, epoxy-related damage is dependent on the wavelength. In general, light scatters more strongly at short wavelengths than at longer wavelengths. Misalignment when coupling is also more likely due to the small MFD of short-wavelength SM fiber that also produces more scattered light.

To minimize the risk of burning the epoxy, fiber connectors can be constructed to have an epoxy-free air gap between the optical fiber and ferrule near the fiber end face. Our high-power multimode fiber patch cables use connectors with this design feature.

Determining Power Handling with Multiple Damage Mechanisms

When fiber cables or components have multiple avenues for damage (e.g., fiber patch cables), the maximum power handling is always limited by the lowest damage threshold that is relevant to the fiber component. In general, this represents the highest input power that can be incident on the patch cable end face and not the coupled output power.

As an illustrative example, the graph to the right shows an estimate of the power handling limitations of a single mode fiber patch cable due to damage to the fiber end face and damage via an optical connector. The total input power handling of a terminated fiber at a given wavelength is limited by the lower of the two limitations at any given wavelength (indicated by the solid lines). A single mode fiber operating at around 488 nm is primarily limited by damage to the fiber end face (blue solid line), but fibers operating at 1550 nm are limited by damage to the optical connector (red solid line).

In the case of a multimode fiber, the effective mode area is defined by the core diameter, which is larger than the effective mode area for SM fiber. This results in a lower power density on the fiber end face and allows higher optical powers (on the order of kilowatts) to be coupled into the fiber without damage (not shown in graph). However, the damage limit of the ferrule / connector termination remains unchanged and as a result, the maximum power handling for a multimode fiber is limited by the ferrule and connector termination.

Please note that these are rough estimates of power levels where damage is very unlikely with proper handling and alignment procedures. It is worth noting that optical fibers are frequently used at power levels above those described here. However, these applications typically require expert users and testing at lower powers first to minimize risk of damage. Even still, optical fiber components should be considered a consumable lab supply if used at high power levels.

Intrinsic Damage Threshold

In addition to damage mechanisms at the air / glass interface, optical fibers also display power handling limitations due to damage mechanisms within the optical fiber itself. These limitations will affect all fiber components as they are intrinsic to the fiber itself. Two categories of damage within the fiber are damage from bend losses and damage from photodarkening.

Bend Losses

Bend losses occur when a fiber is bent to a point where light traveling in the core is incident on the core/cladding interface at an angle higher than the critical angle, making total internal reflection impossible. Under these circumstances, light escapes the fiber, often in a localized area. The light escaping the fiber typically has a high power density, which burns the fiber coating as well as any surrounding furcation tubing.

A special category of optical fiber, called double-clad fiber, can reduce the risk of bend-loss damage by allowing the fiber's cladding (2nd layer) to also function as a waveguide in addition to the core. By making the critical angle of the cladding/coating interface higher than the critical angle of the core/clad interface, light that escapes the core is loosely confined within the cladding. It will then leak out over a distance of centimeters or meters instead of at one localized spot within the fiber, minimizing the risk of damage. Thorlabs manufactures and sells 0.22 NA double-clad multimode fiber, which boasts very high, megawatt range power handling.

Photodarkening

A second damage mechanism, called photodarkening or solarization, can occur in fibers used with ultraviolet or short-wavelength visible light, particularly those with germanium-doped cores. Fibers used at these wavelengths will experience increased attenuation over time. The mechanism that causes photodarkening is largely unknown, but several fiber designs have been developed to mitigate it. For example, fibers with a very low hydroxyl ion (OH) content have been found to resist photodarkening and using other dopants, such as fluorine, can also reduce photodarkening.

Even with the above strategies in place, all fibers eventually experience photodarkening when used with UV or short-wavelength light, and thus, fibers used at these wavelengths should be considered consumables.

Preparation and Handling of Optical Fibers

General Cleaning and Operation Guidelines

These general cleaning and operation guidelines are recommended for all fiber optic products. Users should still follow specific guidelines for an individual product as outlined in the support documentation or manual. Damage threshold calculations only apply when all appropriate cleaning and handling procedures are followed.

1. All light sources should be turned off prior to installing or integrating optical fibers (terminated or bare). This ensures that focused beams of light are not incident on fragile parts of the connector or fiber, which can possibly cause damage.

2. The power-handling capability of an optical fiber is directly linked to the quality of the fiber/connector end face. Always inspect the fiber end prior to connecting the fiber to an optical system. The fiber end face should be clean and clear of dirt and other contaminants that can cause scattering of coupled light. Bare fiber should be cleaved prior to use and users should inspect the fiber end to ensure a good quality cleave is achieved.

3. If an optical fiber is to be spliced into the optical system, users should first verify that the splice is of good quality at a low optical power prior to high-power use. Poor splice quality may increase light scattering at the splice interface, which can be a source of fiber damage.

4. Users should use low power when aligning the system and optimizing coupling; this minimizes exposure of other parts of the fiber (other than the core) to light. Damage from scattered light can occur if a high power beam is focused on the cladding, coating, or connector.

Tips for Using Fiber at Higher Optical Power

Optical fibers and fiber components should generally be operated within safe power level limits, but under ideal conditions (very good optical alignment and very clean optical end faces), the power handling of a fiber component may be increased. Users must verify the performance and stability of a fiber component within their system prior to increasing input or output power and follow all necessary safety and operation instructions. The tips below are useful suggestions when considering increasing optical power in an optical fiber or component.

1. Splicing a fiber component into a system using a fiber splicer can increase power handling as it minimizes possibility of air/fiber interface damage. Users should follow all appropriate guidelines to prepare and make a high-quality fiber splice. Poor splices can lead to scattering or regions of highly localized heat at the splice interface that can damage the fiber.

2. After connecting the fiber or component, the system should be tested and aligned using a light source at low power. The system power can be ramped up slowly to the desired output power while periodically verifying all components are properly aligned and that coupling efficiency is not changing with respect to optical launch power.

3. Bend losses that result from sharply bending a fiber can cause light to leak from the fiber in the stressed area. When operating at high power, the localized heating that can occur when a large amount of light escapes a small localized area (the stressed region) can damage the fiber. Avoid disturbing or accidently bending fibers during operation to minimize bend losses.

4. Users should always choose the appropriate optical fiber for a given application. For example, large-mode-area fibers are a good alternative to standard single mode fibers in high-power applications as they provide good beam quality with a larger MFD, decreasing the power density on the air/fiber interface.

5. Step-index silica single mode fibers are normally not used for ultraviolet light or high-peak-power pulsed applications due to the high spatial power densities associated with these applications.

Part Number	Description	Price	Availability
SM2000	Customer Inspired! Single Mode Optical Fiber, 1.7-2.3 µm, Ø125 µm Cladding	$16.34 Per Meter Volume Pricing Available	5-8 Days