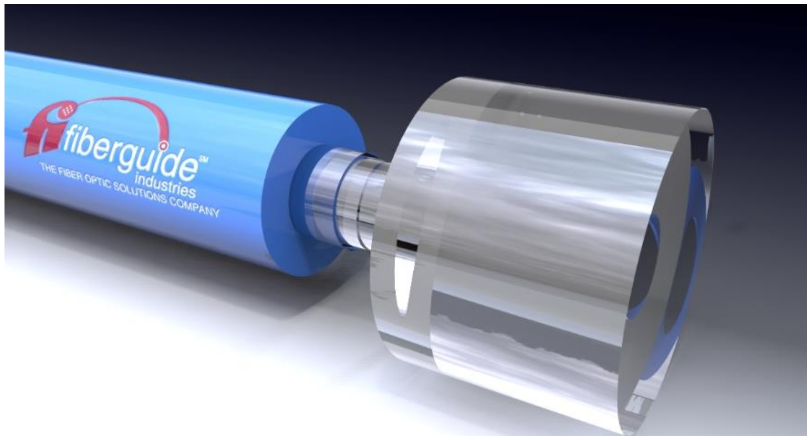
End Capped High Power Assemblies



Fiberguide's end capped fiber optic assemblies allow the user to achieve higher coupled power into a fiber core by reducing the power density at the air/ silica interface, commonly the point of laser damage. End cap diameters and lengths are offered for select numerical apertures and fiber cores size, but can be easily customized for a variety of fiber types and specialized applications.

GENERAL SPECIFICATIONS:

- Standard Fiber Type: Step Index Multimode Core Sizes, 50µm - 400µm
  Other fiber types (e.g., singlemode, graded index) available upon request.
- Wavelengths: 190nm – 1250nm (High OH) / 300nm – 2400nm (low OH)
- Standard Numerical Aperture: 0.20 or 0.22 Std
- Connector Options: High Power SMA, High Power FD-80
- Sheathing Options: PVC Coated Stainless Steel Monocoil, Bare Stainless Steel Monocoil
- Power Handling Capacity: Up to 3 kW, depending on fiber size and laser specifications
- Standard Temperature Range: -40°C to +100°C (-40°F to +212°F)

FEATURES & BENEFITS

- End capped assemblies allow for much higher transmitted powers by reducing the power density to a level below the damage threshold
- Shaped endcap tips can be tailored to specific laser launch conditions and applications
- Fiberguide's proprietary laser polishing process minimizes surface imperfections, and maximizes power handling
- High Power SMA and D-80 compatible connector options offer superior thermal management while minimizing connector stress for NA conservation
- Epoxy free cantilevered nose design (available in select versions) minimize laser and heat damage to surrounding materials

End Capped High Power Assemblies

SPECIFICATIONS:	
Optical Fiber Type	Step Index Multimode. (End Capping onto other fibers types available upon request)
Std Fiber Core Dia.	50µm to 400µm
Fiber Jacket Options	Nylon, Acrylate, Tezel, Polyimide
Numerical Aperture (NA)	0.20 ±0.02 (23° Full Acceptance Angle) 0.22 ±0.02 (25° Full Acceptance Angle)
Operating Wavelength (λ)	λ = 190nm - 1250nm (Ultraviolet - Visible) λ = 300nm - 2400nm (Visible - Infrared)
Typ Temperature Range	-40°C to 100°C / -40°F to 212°F (fiber coating dependent)

0.20 Numerical Aperture Fiber			
Fiber Core Size (µm)	Endcap Diameter (µm)	Nominal Endcap Length (mm)	Endcap Length Tolerance (µm)
100	300	0.57	± 16
200	600	1.13	± 23
300	900	1.70	± 34
400	1200	2.27	± 45

0.22 Numerical Aperture Fiber			
Fiber Core Size (µm)	Endcap Diameter (µm)	Nominal Endcap Length (mm)	Endcap Length Tolerance (µm)
100	300	0.52	± 15
200	600	1.03	± 21
300	900	1.55	± 31
400	1200	2.06	± 41

General Design Considerations and Guidelines

When selecting optical cable assemblies for power delivery systems, designers must consider the power limitations of the three main components of the cable assembly: the base material, the input connector, and the mode stripper (if applicable).

The first consideration is the base material, more specifically the base material interface. Fiberguide's high power assemblies are built with our Step Index Multimode fiber. This fiber has a pure fused silica core and fluorine doped cladding. The fused silica is extremely high purity and, as a result, can handle enormous amounts of optical energy. The challenge, however, is getting the optical energy into the fused silica, and this is governed by the air-silica interface that exists at the input connector. Fiberguide uses a proprietary laser polishing technique to maximize the amount of power that this interface can handle.

The failure mode for Continuous Wave (CW) Lasers is thermal, caused by microscopic irregularities in the air-silica interface absorbing the laser's energy. For Pulsed Lasers, the failure mode can either be thermal or a dielectric breakdown at the atomic level, depending on the laser's characteristics. In either case, there is a maximum power per unit of area, referred to as the damage threshold, that can be coupled into the assembly. This is expressed in W/cm^2 (irradiance) for CW lasers and J/cm^2 (fluence) for Pulsed Lasers. The reason for this difference is that Pulsed Lasers operate as a series of repeating energy bursts, or pulses. The duration of the pulses and their repetition rate determine the Peak Power and Average Power for the laser. Since a Joule (J) is the amount of energy required to produce one Watt (W) of power for one second, this unit of measure is used to remove the time factor so comparisons can be easily made.

Determining if a laser will damage a fiber involves calculating the irradiance or fluence for the laser by dividing the CW Power, or the Energy per Pulse, by the area of the beam where it makes contact with the fiber. This value must be adjusted to compensate for wavelength in a CW laser, and wavelength and pulse duration in a Pulsed Laser. If the adjusted value is below the damage threshold, the beam size and fiber size are suitable for the laser. If the adjusted value exceeds the damage threshold, the beam size and / or the fiber size should be increased until the irradiance or fluence is below the damage threshold. The charts and tables on the following pages show maximum irradiance and fluence values for various fiber core sizes by wavelength for CW lasers, and by wavelength and pulse duration for Pulsed Lasers.

The power handling capabilities for the other two main cable assembly components - the input connector and a mode stripper, if applicable, must also be examined. The failure mode on these is always thermal and there are detailed sections on each of these components in the following pages.

End Capped High Power Assemblies

Table 1: Background & Assumptions

CW Air-Silica Fused Interface Damage Threshold	~1.5 MW/cm^2 (CW Laser @ λ: 1064nm) Damage Threshold is λ dependent, and behaves relatively linearly in the range from 190nm - 2400nm with the shorter wavelengths being more destructive.
Pulsed Air-Fused Silica Interface Damage Threshold	~16.0 J/cm^2 (Pulsed Laser @ λ: 1064nm and τ: 1ns) Damage Threshold is λ dependent, and behaves relatively linearly in the range from 190nm - 2400nm with the shorter wavelengths being more destructive. Damage Threshold is τ dependent, and scales with the square root of the pulse duration from 10ps to 1µs with the shorter pulse durations being more destructive. NOTE: The CW and Pulsed Air-Fused Silica Interface Damage Thresholds above have been adjusted to compensate for the peak intensity in the Gaussian Beam Profile.
Spot Size Diameter	≤ 85% of the Fiber Core Diameter
Alignment & Beam Waist	X & Y Alignment within ± 5% of the core diameter / Z Position beyond source beam waist
Numerical Aperture (NA)	Fiber NA ≥ Source NA + 10%
Beam Shape & Quality	The spatial profile and quality of the beam will greatly affect high power performance. This analysis assumes a Gaussian Beam where the peak fluence is given by "2 E/p*(W_o)^2", meaning that the peak power is approximately double the 1/e^2 specified power.
Connector Polish, End Face, & Flatness	The connector end face must be factory laser polished to reduce microscopic inclusions and be cleaned prior to use. The end face must also be flat, <10% of the core diameter peak to valley, so it doesn't act like a lens and focus the laser energy inside the fiber.
AR Coating	When AR Coatings are applied to optical fibers, the coating may become the limiting factor to power handling capability, so it is important to check the specifics of the selected coating. For high power applications, AR coating is typically not recommended.

Please Note: This information provided is designed to help guide product selection, because each optical system is unique, Fiberguide strongly recommends thorough testing before committing to system critical components.

Maximum CW Power Level Table:

The following table shows CW Power Maximums. For fiber sizes ≤ 400µm, the air-silica interface damage threshold is more commonly the limiting factor for the assembly. For larger core sizes, the connector power limits typically govern the overall power handling capabilities of the assembly. Please note that In order to illustrate the dependency of damage threshold on wavelength, the table shows power levels that are far beyond what is possible / currently available for some wavelengths.

Table 2: CW Power Maximums for End capped Fiber Core Sizes 100µm - 400µm with λ: 193nm - 2100nm

Fiber Core Size (µm)	Wavelength							
	193nm	405nm	532nm	808nm	980nm	1064nm	1900nm	2100nm
100	45	96	129	195	234	255	456	489
200	186	490	510	777	942	1020	1824	2016
300	417	876	1149	1742	2108	2286	4104	4536
400	741	1554	2043	3102	3762	4086	7296	8064

Pulsed Lasers

When determining power limits for cable assemblies coupled to Pulsed Lasers, the Pulse Duration (τ) dictates which calculations are used. For Pulse Durations greater than 1 microsecond: 1µs (10^{-6} s), the failure mode is thermal, and the CW calculations / charts alone are used. In this case, the Laser's Average Power = Energy Per Pulse (J) x Pulse Frequency (Hz), is used in place of the CW power. For Pulse Durations smaller than 10 picoseconds: 10ps (10^{-11} s), the failure mode is 2^{nd} order, non-linear phenomenon, such as Stimulated Brillion Scattering (SBS) or Stimulated Raman Scattering (SRS), which are always present in optical fiber and become dominant actors at very short pulse durations. In these cases, thorough testing of various beam and / or fiber sizes is the best way to determine what is appropriate.

For pulse durations between 10ps and 1µs, the failure mode tends to be a dielectric breakdown at the atomic level, and the Energy Per Pulse and the Fiber Size are the key factors in determining power maximums. To determine if a fiber size is suitable, the Energy per Pulse must be divided by the area of the beam where it makes contact with the fiber and the resulting number compared to the air-silica damage threshold. This is straightforward if the laser characteristics those of the damage threshold, and an additional step is required if they do not.

In cases where the wavelength and/or pulse duration of the laser are different than those of the damage threshold (λ: 1064nm and τ: 1ns), Table 3 (next page) is used to determine the correction factor. The Energy Per Pulse of the laser is then multiplied by the correction factor to calculate the Equivalent Energy Per Pulse at λ: 1064nm and τ: 1ns. These are derived by scaling wavelength in a linear fashion where the shorter wavelengths are more destructive, and by scaling pulse duration in a square root fashion where the shorter pulses are more destructive.

Pulsed Lasers (cont'd)

Once the Equivalent Energy per Pulse at λ: 1064nm and τ: 1ns is known, Table 4 (next page) can be used to determine which fiber size(s) can potentially be used. These maximums are based on the assumptions stated in Table 1 in the previous section.

The final step for Pulsed Lasers is to also check the Laser's Average Power using the CW calculations / chart to take the duty cycle into consideration, where Average Power = Energy Per Pulse (J) x Pulse Frequency (Hz). All potential fiber sizes from the previous step must be evaluated to ensure they pass both criteria. These are ultimately the fiber sizes that can be used with a given Pulsed Laser Source.

Table 3: Correction Factors used to Convert Energy Per Pulse to Equivalent Energy Per Pulse at λ: 1064nm and τ: 1ns

	Wavelength (nm)							
(Sec)	λ: 193nm	λ: 405nm	λ: 532nm	λ: 808nm	λ: 980nm	λ: 1064nm	λ: 1900nm	λ: 2100nm
10ps	55.13	26.27	20.00	13.17	10.86	10.00	5.60	5.07
50ps	24.65	11.75	8.94	5.89	4.86	4.47	2.50	2.27
100ps	17.43	8.31	6.32	4.16	3.43	3.16	1.77	1.60
500ps	7.80	3.72	2.83	1.86	1.54	1.41	0.79	0.72
1ns	5.51	2.63	2.00	1.32	1.09	1.00	0.56	0.51
5ns	2.47	1.17	0.89	0.59	0.49	0.45	0.25	0.23
10ns	1.74	0.83	0.632	0.42	0.34	0.32	0.18	0.16
50ns	0.78	0.37	0.28	0.19	0.15	0.14	0.08	0.07
100ns	0.55	0.26	0.20	0.13	0.11	0.10	0.06	0.05
500ns	0.25	0.12	0.09	0.06	0.05	0.04	0.03	0.02
1µs	0.17	0.08	0.06	0.04	0.03	0.03	0.02	0.02

Table 4: End Capped Maximum Energy Per Pulse (mJ) at λ: 1064nm and τ: 1ns

	Fiber Core Diameter			
	100µm	200µm	300 µm	400 µm
Maximum Equivalent Energy Per Pulse (mJ)	2.7	10.8	24.3	43.5