CVI Laser, LLC
Optical Components & Assemblies

Technical Reference
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Optics for Fiber Laser Applications

by Emily Kubacki and Lynore M Abbott, CVI Laser, LLC

Fiber lasers have found a processing and research niche where Nd:YAG lasers are too expensive or have beam properties which are undesirable (e.g. large M^2 values). Users of fiber lasers may be concerned with the interchangeability of their existing supply of optical components or how to specify new optics. This article addresses such areas of concern and highlights which characteristics should be specified particularly carefully.

Fiber lasers are gaining ground in a variety of applications such as drilling, welding, foil cutting, laser marking, and precise micro-machining. Research scientists are also finding them very useful as sources because of their small footprints and low M^2 values. The success of fiber lasers is based on their unique combination of beam characteristics unavailable from other sources in the same wavelength range: optional CW or pulsed operation, polarization control (random, linear or circular), narrow spectral bandwidth, and TEM_{00} M^2 values approaching 1. With such an improvement of M^2 over Nd:YAG lasers, significantly higher power densities can be realized. More tightly focused beams are possible, resulting in sharper images for marking and finer cuts for micromachining. Manufacturing working distances can also be increased. Thus, the marketplace is expecting to face a growing demand in dedicated optical components designed for fiber laser applications.

1 Effects of Beam Quality

The component selection process is heavily influenced by the high power densities achievable with fiber lasers. The optical cavity of a fiber laser is the fiber core which can be designed to minimize the number of modes, thus allowing manufacturers to commercially produce lasers with $M^2 = 1.05$. M^2 is the ratio of the laser beam's multimode diameter-divergence product to the ideal diffraction limited (TEM_{00}) beam diameter-divergence product:

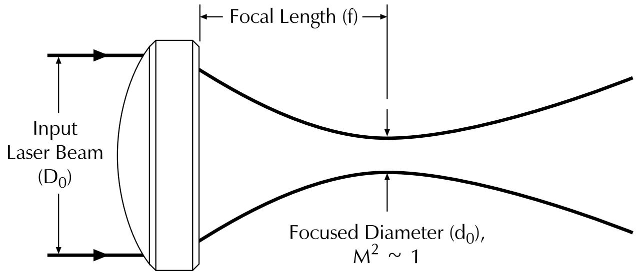

***Figure 1**: This figure details the variables used to calculate the focused beam diameter for a given lens focal length, wavelength, collimated beam diameter, and M^2 value. The theoretical limit of M^2 is 1*

$$M^2 = \frac{\pi}{\lambda} w_0\Theta_0 = \frac{\pi}{\lambda}\frac{d_0}{2}\frac{D_0}{2f} \qquad (1)$$

Where Θ_0 is the beam divergence in milliradians and w_0 is the width of the output beam waist (if the beam is circular, then w_0 can be replaced by the beam diameter d_0). Or for the achievable focal spot diameter d_0:

$$d_0 = \frac{M^2\,4\,\lambda f}{\pi D_0} \qquad (2)$$

Figure 1 illustrates the parameters used in equation (2). Fiber laser manufacturers typically provide a beam delivery head with a collimated output between 5mm and 20mm in diameter (D_0). Calculations show that a theoretical focal spot diameter d_0 of 10μm is achievable with a 19mm focal length lens. Therefore, for a 50W fiber laser at 1075nm, the focused beam packs tremendous optical power density

$$\frac{P}{A} = \frac{P}{\pi r^2} = \frac{50W}{\pi\,(5 \cdot 10^{-4}\ cm)^2} = 6.366 \cdot 10^7\,\frac{W}{cm^2} = 63.7\,\frac{MW}{cm^2} \qquad (3)$$

More combinations are given in **table 1**. While the beam steering optics may never see a perfectly focused spot, there is a safety factor that the design engineer will want to take into account; these high, diffraction limited power densities may impinge on optical elements during alignment.

For low energy pulsed fiber lasers and mid-range CW lasers (on the order of 1-5W average power), N-BK7 glass from Schott (www.schott.de) is a suitable and inexpensive substrate material for both reflective and transmissive optics where the energy at the optical surface is <50MW/cm². N-BK7 is a borosilicate crown optical glass with high homogeneity and high transmission in the visible and near-infrared. Anti-reflection (AR) coatings can be used on windows, lenses and partial reflectors to increase the overall transmission through the component. At these energies, either narrowband ("V"-coat) AR coatings or multi-layer broadband AR

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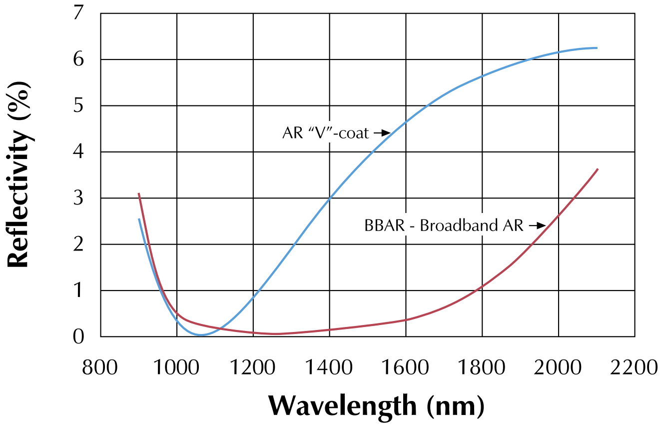
coatings can be used to reduce the per surface reflectivity from about 4% to <0.25% at a single wavelength or <0.5% over a bandwidth of 250-400nm for tunable laser systems (see **figure 2**).

Narrowband “V”-coats are multi-layer (typically two-layer) dielectric anti-reflection coatings that achieve theoretical minimum reflectance at a narrow band of wavelengths. Reflectance rises rapidly on either side of this minimum giving it a “V” shape in the reflectivity versus wavelength graph. U.S. manufacturers typically use the terminology “V-coat” or “laserline” to differentiate this coating from their broadband AR offerings.

Another material option for use with the 1-5W fiber lasers is N-SF11 glass from Schott which has a refractive index n = 1.754 at 1060 nm, higher than that of N-BK7 (1.507). This provides flexibility if a lens with a short focal length is required for the application. Because both N-SF11 and N-BK7 have thermal expansion coefficients in the $8x10^{-6}$/°C range, fused silica is the preferred choice of substrate material if thermal stability is important. Fused silica has a thermal expansion coefficient of only $0.57x10^{-6}$/°C, an order of magnitude more stable than the other optical materials.

***Figure 2**: Designed reflectivity of broadband (BBAR) and narrowband (“V”-coat) antireflection coatings. “V”-coats are better able to withstand high energies from fiber lasers emitting kilowatt power and higher*



Fiber laser manufacturers recommend fused silica for transmissive optics for use with fiber laser outputs greater than 50W. For example, Southampton Photonics, Inc. (www.spioptics.com) strongly recommends the use of fused silica for fiber laser applications because of its significantly higher laser damage threshold. It has similar transmissive properties to N-BK7 from 500-2000nm, but is more thermally stable and has higher damage threshold limits for both pulsed and CW systems. IPG Photonics (www.ipgphotonics.com) recommends IR grade fused silica for fiber lasers rated above 1kW. Again, AR coatings can be used to reduce surface reflections, but for higher energies it is best to use only multi-layer “V”-coat AR coatings, which withstand up to $1MW/cm^2$ or more.

CW Laser Power	10W	50W	100W	1000W
Focused spot size	10μm	10μm	10μm	10μm
Power Density at focused spot size	$12.7MW/cm^2$	$63.7MW/cm^2$	$127MW/cm^2$	$1.27GW/cm^2$
Max. focused spot diameter for a Power Density ≤$10MW/cm^2$	11μm	25μm	36μm	113μm

Table 1*: Sample calculations demonstrate the scaling of optical power densities for a focused beam based on a 19mm focal length lens and 10mm diameter collimated beam. Using equation 3, one can calculate the minimum beam diameter to stay below the $10MW/cm^2$ recommended limit for narrowband antireflection coatings*

2 Lenses

In certain applications, such as imaging of optical traps, maintaining image quality throughout the beam path is critical. Although singlet lenses, in either fused silica or N-BK7 material, are suitable for simple beam steering applications, doublet or triplet aplanatic lenses may be more suitable in order to minimize transmitted wavefront errors. These lenses are designed to minimize two monochromatic wavefront errors called Spherical Aberration and Coma. Spherical Aberration is axially symmetric and occurs when collimated rays passing through the outer zones of the lens focus at a different distance from the lens than rays passing through the central zone. Coma is an off-axis non-symmetric wavefront distortion which increases linearly with field angle or distance from the principal axis. In combination, these aberrations distort the transmitted wavefront through the lens and cause the focal spot to become irregularly shaped and/or blurred.

Doublet and triplet lens designs can utilize the substrate materials previously listed or other materials, depending on the specific

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design criteria. They are optimized for a single wavelength and are usually air-spaced to minimize additional wavefront distortion induced by cement between the glass surfaces. Air-spacing the elements also allows for increased flexibility in design because adjacent surfaces do not have to have matching curvatures. Instead, each of the four to six surfaces can be optimized independently in order to best minimize coma and spherical aberrations through the complete lens assembly. Cemented lens assemblies should be avoided in order to maximize the overall damage threshold and lifetime of the component.

3 Narrow Spectral Bandwidth

The wavelength range of a fiber laser is determined by the manufacturer's pumping architecture and the dopants used in the active fiber laser cavity. Typical wavelength ranges are: 780-800nm for erbium doping, 1030-1120nm for ytterbium, 1530-1600nm for erbium-ytterbium, and 1800-2100nm for thulium.

The bandwidth of a fiber laser is typically defined by fiber Bragg gratings. The fiber laser manufacturers will specify a range, from which the end user can select a specific wavelength. The actual bandwidth of each laser is only 1-2nm. This could be an important detail when choosing components such as higher order waveplates which function properly only over a narrow bandwidth.

4 Polarization Optics

Bandwidth and energy density are the most important beam characteristics to know when choosing between various polarizers and waveplates. Polymer linear polarizers are not intended for use at energies greater than 1W/cm^2. Cemented cube polarizers are available in both narrow band and broadband designs but damage thresholds are limited by the internal epoxy. Although a few optical cements can reportedly withstand laser power densities of 500W/cm^2, fiber laser manufacturers recommend avoiding cemented optics for fiber lasers rated above 50W. Above this level, it is necessary to switch to an air-spaced or optically contacted polarizing cube design, which can typically handle more than 1 MW/cm^2 of CW laser light.

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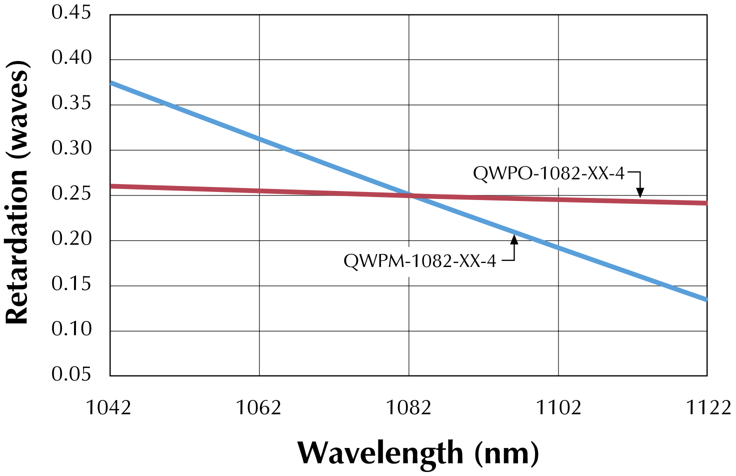

***Figure 3**: Graph relates retardation of a λ/4 zero order quartz waveplate (QWPO-1082-xx-4) to a λ/4 multiple order quartz waveplate (QWPM-1082-xx-4). Both are designed for use at 1082nm. Zero order waveplates as demonstrated above are more tolerant of wavelength or angle of incidence changes without significant degradation of performance*

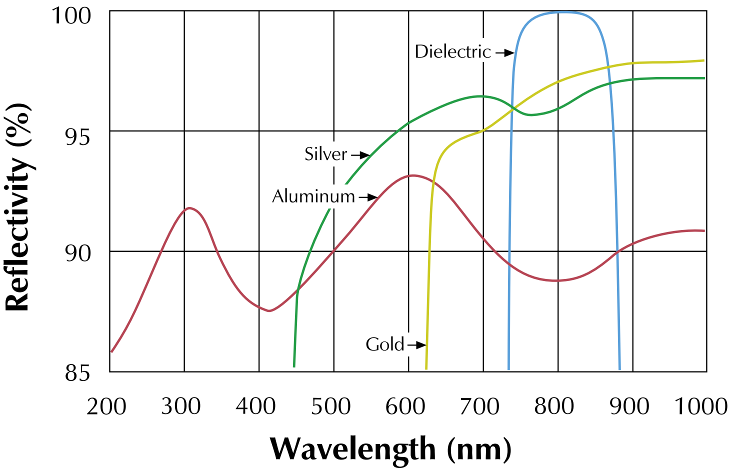

***Figure 4**: Gold, silver, and aluminum coatings provide broadband performance. Dielectric coatings, in comparison, achieve higher reflectivity over a narrower bandwidth and incident angle*

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For a multiple order crystal quartz waveplate near 1mm thickness, 2nm variation in wavelength can make the difference between an excellent waveplate and an unacceptable part. A 1mm thick $\lambda/4$ waveplate designed for 1082nm would actually be a 0.23λ waveplate at 1084nm, or $\lambda/50$ off. Alternatively, a compound zero order waveplate designed for the same two wavelengths would change retardation between the two by $<\lambda/1000$ waves, which is well within typical measurement limits. Zero order waveplates work very well over ± 40-70nm from the design wavelength, and are well suited for tunable laser systems as well as those with laser line bandwidths of >1nm (see **figure 3**).

5 Mirrors

Standard components - i.e. existing coating designs - for other laser lines may not match up well enough to the new fiber laser wavelengths and powers for optimal performance. For very low energy systems, protected metal mirror coatings such as gold, aluminum and silver may be suitable choices for certain applications where 100% reflectivity is not required. They are readily available and inexpensive. However, even with the protective layers, metal coatings are soft and will eventually get scratched or corroded if not properly handled.

Alternatively, multilayer dielectric mirrors are hard-coated, durable, and highly reflective at either normal incidence or 45° (see **figure 4**). They have damage thresholds exceeding 20J/cm^2 in 10-20ns pulsed systems and so should not degrade or incur damage when used in either pulsed or CW fiber laser setups. Although not particularly broadband, a dielectric standard mirror designed for 1064nm Nd:YAG systems will still reflect >99% at 1075nm or 1080nm.

6 Conclusion

CVI has introduced a new line of mirrors specifically designed for use with fiber laser systems. Additionally, CVI has added the most common fiber laser wavelengths to the existing product lines including AR coatings for transmissive optics, such as waveplates, lenses, and windows, as well as reflective coatings for beamsplitters, partial reflectors, output couplers, and mirrors.

Fiber laser manufacturers continue to push the limits of their technology, increasing the CW-power and pulsed energy commercially available. The excellent beam quality coupled with the higher energies will continue to place increasing demands on the optical components used in these systems. Key specifications for these components will include substrate material, damage threshold and surface quality.

Literature references:

[1] Bill Shiner, Fiber Frenzy, Laser Focus World, June 2004

[2] Carlos Roundy, Propagation Factor quantifies laser beam performance, Laser Focus World, December 1999, pp. 119-122

[3] Oliver Graydon, Pumping up the Power, Opto & Laser Europe, June/July 2003

[4] Mikhail Zervas et al., Single and few-moded high power fibre lasers for industrial applications, Advanced Laser Applications Technology Conference, November 2004

[5] Ping Xie et al., Tunable Blue, Green, Orange, and Red Upconversion Fiber Lasers, Industrial Quarterly – Los Alamos National Labs Highlights, Winter/Spring 1995, www.de.afrl.af.mil/APT/iq3-2.lanl.html

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