White paper

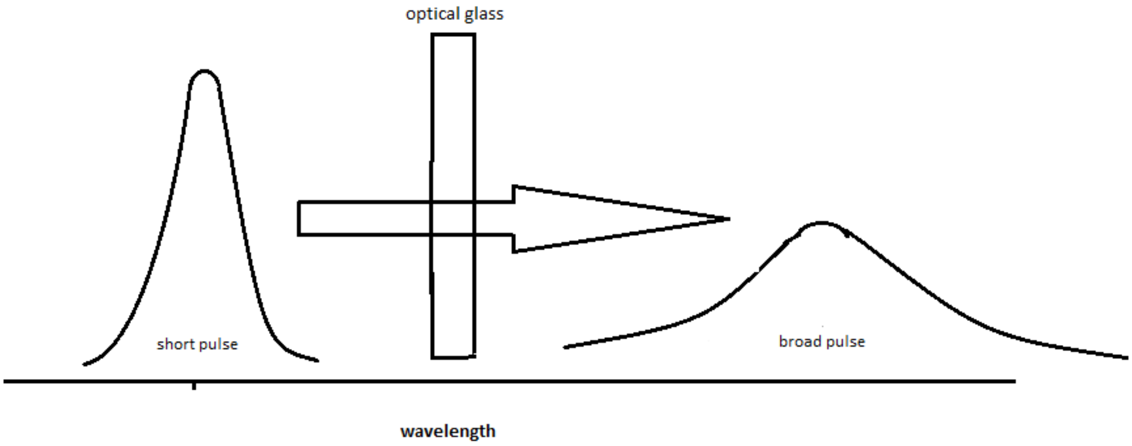
By Christian Dehnert

Color-corrected F-theta optics for femtosecond lasers

Analysis of why ultrashort pulse lasers distort the laser spot in F-theta lens. Advances in the development of short pulse and ultrashort pulse lasers has been amazingly rapid. Systems using picosecond and femtosecond lasers offer many advantages for industrial and scientific applications. Short pulse lasers offer high-precision machining and reduced heat-affected zone (HAZ) in many cases—resulting in no additional post processing clean-up work. This is called “cold ablation.”

Cold ablation occurs when the laser pulse time is shorter than the thermal diffusion time of the material. This prevents most of the heat from moving outside the pulse-affected material volume. Generally, the wavelength of the laser needs to be matched so it is best absorbed by the material. With femtosecond lasers, however, the wavelength of the laser is less critical to material absorption—allowing a broader range of materials to be processed using just one wavelength.

What is the optical challenge with short pulse lasers? As the pulse width of a laser decreases into the range of femtoseconds, a problem occurs in the optics in which a pulse spreads out in time as it passes through the optics (dispersive temporal broadening). For example, a 10-picosecond pulse at 1064 nm has a spectral width of about 0.25 nm, which results in essentially no pulse spreading. At the other extreme, a 50-femtosecond pulse at 1064 nm has a spectral width of about 60 nm, which results in a much broader spectral pulse. This means the wavelength of the pulse ranges from 1034 nm to 1094 nm. This is a problem for typical F-theta lenses, which are made of one glass type and designed for one specific wavelength, such as 1064, 532 or 355 nm.



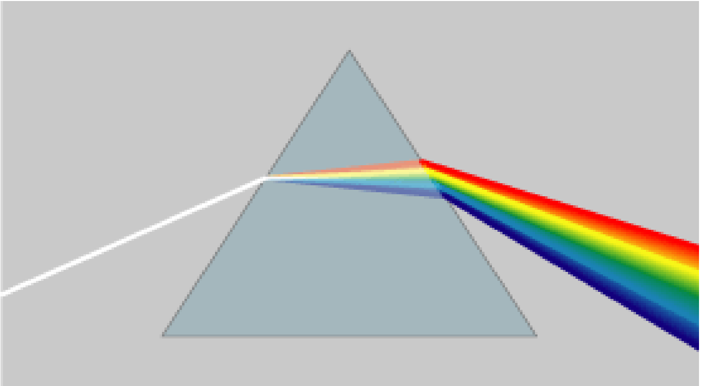
Three key issues need to be addressed with short pulse laser optics: dispersion, color correction, and ghost reflections.

Dispersion

Dispersion in materials leads to a temporal broadening of the laser pulse by introducing a frequency-dependent delay of the different spectral components of the pulse. The higher the refractive index of a material, the higher the dispersion. The dispersion effect is greater for shorter wavelengths, and the significance of the impact depends on the pulse length and wavelength. For example, a 400-fs-long pulse with a central wavelength of 355 nm suffers a temporal broadening of approximately 0.3 fs while travelling through a 20-mm-thick fused silica window. The effect on temporal dispersion in F-Theta lenses is usually very small and not compensated for.

Color Correction: Why does a short pulse laser have color?

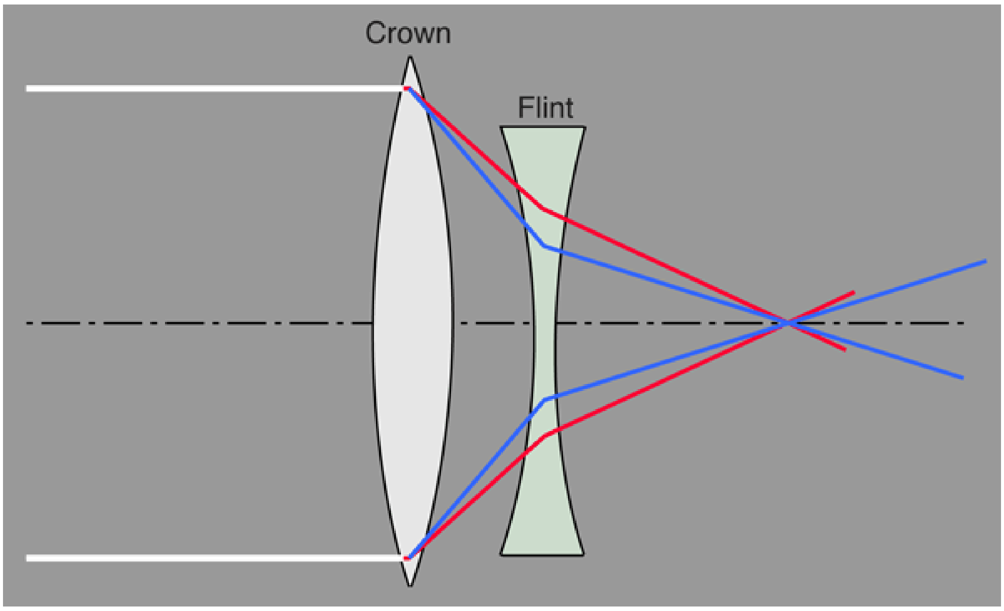
Using a prism, you can break up white sunlight into its different colors to see its visible spectrum with your eyes. If the lens is made of a single glass material, such as fused silica, it bends each wavelength a different amount as the index of refraction is wavelength dependent. Long wavelengths are bent less than short wavelengths.



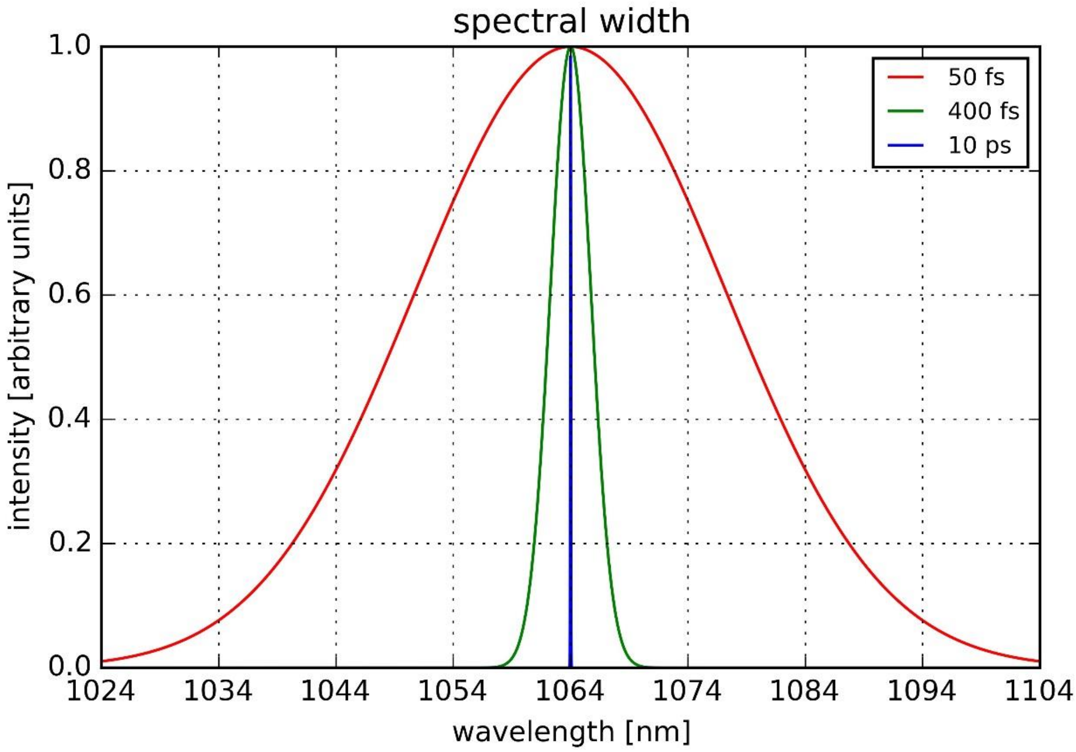
White light is split into its visible parts while passing through a prism.

Chromatic aberration, or chromatic distortion as it’s also known, is an optical phenomenon that occurs when a lens made of just one glass type can‘t bring all wavelengths of light to a single converging point.

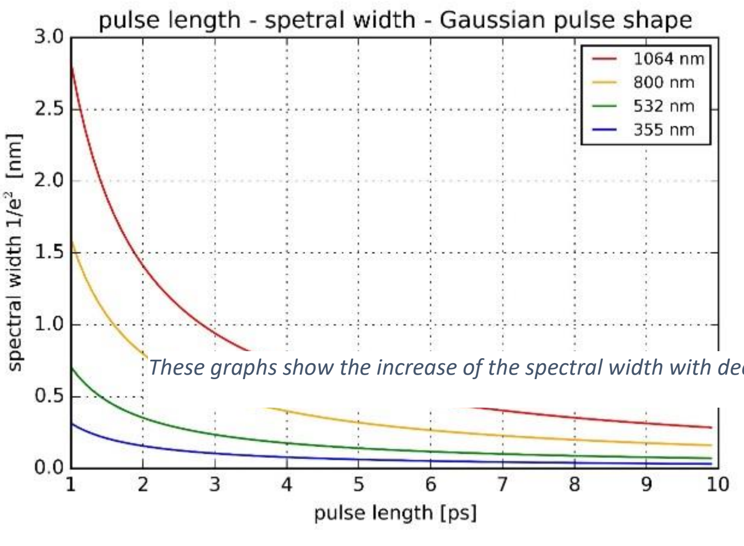
Most optical imaging lenses, which cover the human visible spectrum, correct this chromatic dispersion by combining various glass types with different indices of refraction so all colors focus at the same distance.



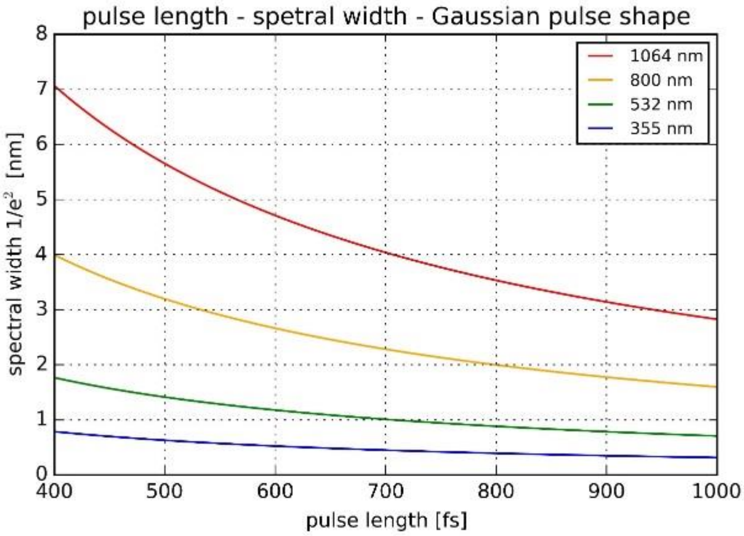
As the pulse width of a laser decreases into the range of femtoseconds (1 fs = 1 x 10^{-15} s), the pulse spreads out in frequency. This results in a “color” error in the lens, unless the lens is color corrected.

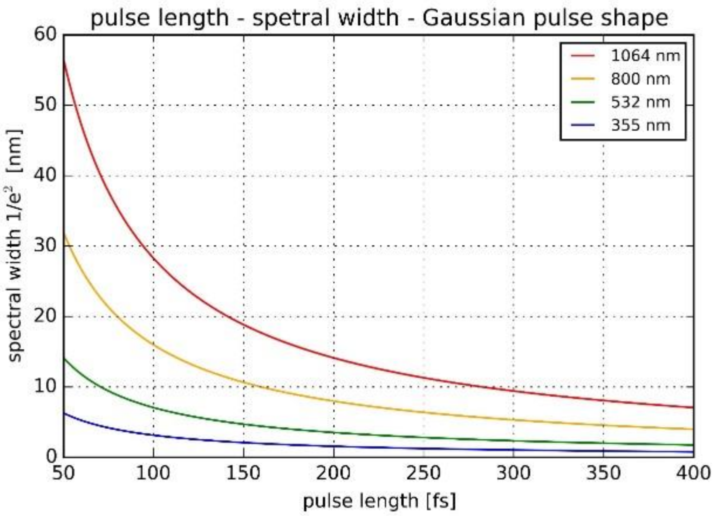


The shorter the pulse duration, the larger the spectral width of the pulse. It is most severe at longer wavelengths, and the following graphs show an increase of the spectral width with decreasing pulse length for different wavelengths. Note the steeper slope of the longer wavelengths. For pulse lengths in the picosecond regime, the spectral width is around one nanometer and below, and can usually be ignored. In that case, fused silica lenses that are corrected monochromatically can be used.



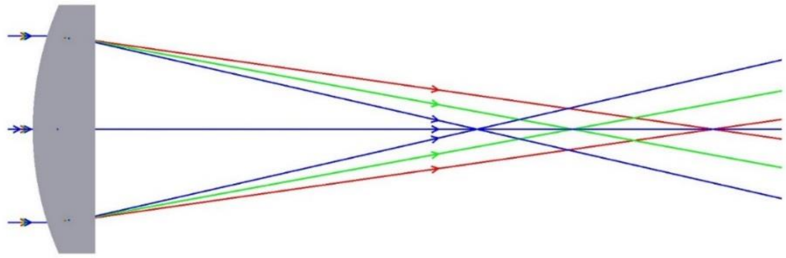
These graphs show the increase of the spectral width with decreasing pulse length





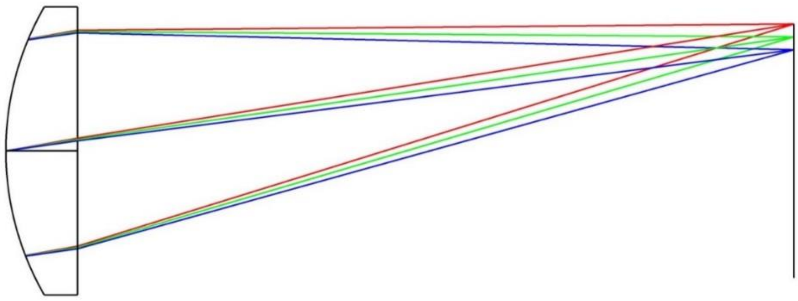
Below 400 fs, spectral broadening increases rapidly.

Due to the spectral broadening, color errors occur when the beam passes through optics. Wavelengths are focused to different locations along the propagation direction (axial chromatic focal shift) and lateral to it (lateral chromatic color aberration). The following drawing illustrates the axial chromatic focal shift. Green rays represent the central wavelength, and wavelengths shorter or longer than the central wavelength have different focal planes.



Color focal shift along the optical axis (not corrected for color).

The amount of the lateral color error is dependent on the focal length and the wavelength. Image height is proportional to the field angle (field height ≈ focal length times field angle), so the field height is different for different wavelengths.



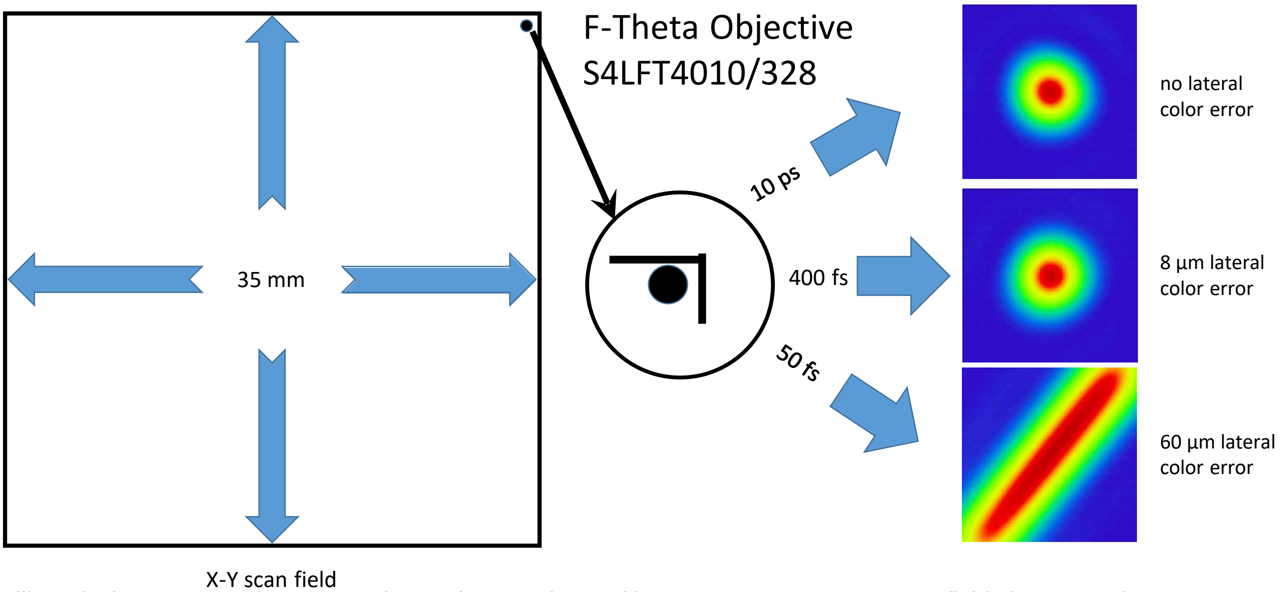
Lateral focus shift, single lens (not corrected for color)

Most optical imaging lenses that cover the human visible spectrum, such as binocular or machine vision imaging lens, correct color errors by combining various glass types with different index of refractions and different Abbe numbers. The Abbe number is a measure of the material's dispersion, i.e. of the variation of the refractive index versus wavelength.

In typical laser lenses, the optical system is optimized for a single wavelength. With a very narrow bandwidth laser (single wavelength laser), the lens will focus at just one point. This is essentially also true for nanosecond and picosecond pulse lasers. In the picosecond second region, the spectral spread is very small—on the order of a few nanometers or less. This results in essentially no wavelengths that are out of focus, both in Z and laterally in the X & Y scan field. In this case, fused silica lenses designed for a single wavelength and corrected monochromatically can be used.

To illustrate the bandwidth impact on the performance of a scan lens, the Sill Optics telecentric F-theta lens S4LFT4010/328 was analyzed. It has a focal length of 100 mm and can be used with a 10-mm input beam ($1/e^2$, vignette at $1/e^2$). The maximum field size is 35 mm x 35 mm. It is designed for one wavelength only at 1064 nm.

The following pictures are images of the spot in the corner of the scan field where the color errors are at their maximum.



Sill Optics' S4LFT4010/328 monochromatic scan lens with a 35 mm x 35-mm scan field demonstrating spot performance in the corner of the scan field at 10-ps, 400-fs and 50-fs pulse widths. The spot is extremely distorted at 50 fs.

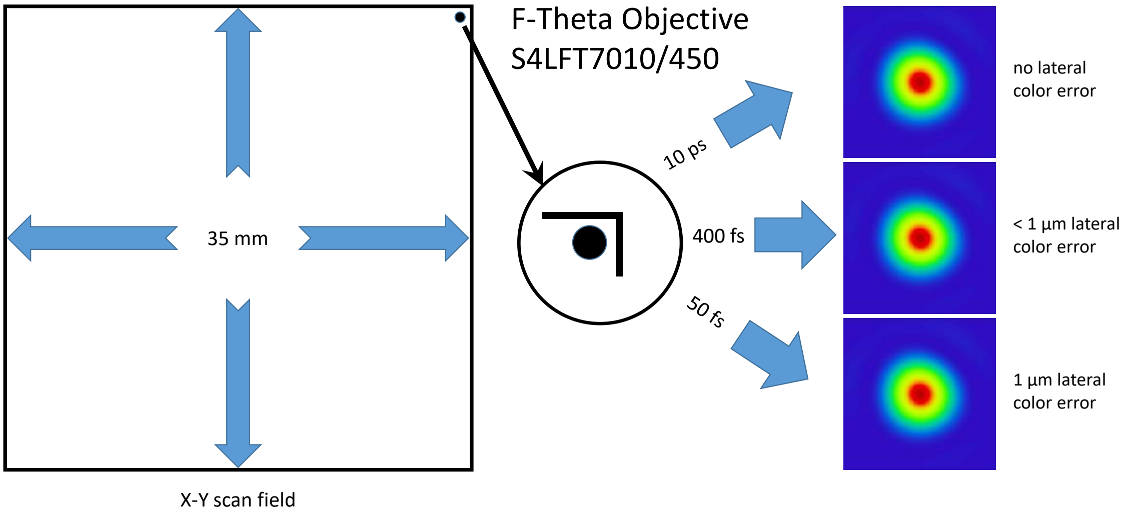
The wide spectral bandwidth of short pulse lasers results in color errors both within and transverse (scan length) to the propagation direction (focal length). The resulting spot will be distorted from the lateral focus shift and blurred from the focus shift along the optical axis, which decreases the energy intensity by increasing the spot shape. This negatively affects process performance.

At 400 fs, the spot shape is essentially the same as for a 10-ps or longer pulse. The lateral color error is small in respect to the spot size. And the image size of the Huygens PSF (point spread function) plot is 40 µm, the lateral color error is approx. 8 µm.

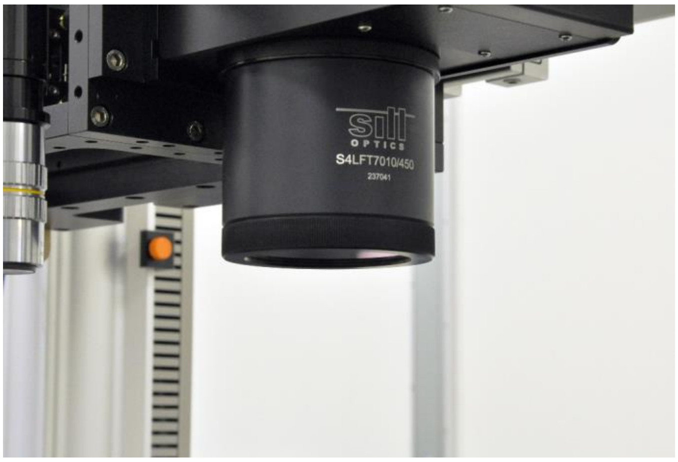
At 50 fs, the lateral color error is approx. 60 µm and the aberrations are very large.

Sill Optics has introduced a color-corrected telecentric F-Theta lens with a focal length of 100 mm and a maximum field size of 35 mm x 35 mm. The unique feature of this lens is the color correction from 1.0 µm to 1.1 µm, i.e. for a 100-nm wide spectrum. For a 10-mm beam the lens is diffraction limited (the maximum theoretical resolution possible). This F-Theta lens is available under part number S4LFT7010/450.

The lateral color error in the field corner is below 1 µm by nominal design, which results in a very round non-aberrated spot.



Additional aberrations occur if beam expanders or other transmissive optics are used that are not color corrected. The lateral color error remains constant, but the chromatic focal shift, i.e. the extension of the spot shape along the propagation axis, increases. This decreases the power density in the focal spot and decreases the probability of nonlinear effects, which are desirable if femtosecond lasers are used.



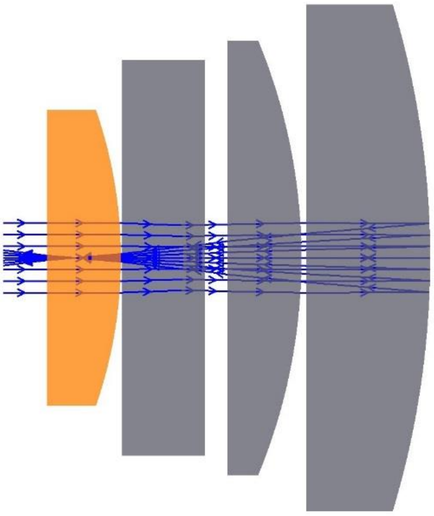
Short pulse lens S4LFT7010/450

Complementary with this new scan lens, Sill Optics introduced a beam expander that is usable with this color-corrected F-Theta lens. It is color corrected from 1.0 µm to 1.1 µm. The expander is diffraction-limited for a 10-mm beam (double $1/e^2$ diameter). This 3x expander joins our standard series, with 85-mm total length, and has identical mechanical interfaces. It will be available as part number S6ASS4803/450.

Ghost Reflections

Ghost or “back” reflections occur when a portion of laser light is reflected back from a lens surface to a previous lens element.

Lens surfaces will typically reflect back about 2 to 4% of the light energy on each surface. Laser lenses are therefore coated with an antireflective coating that transitions the light from the index of refraction of the air to the refractive index of the bulk material of the lens. This reduces the back reflection from each surface to about 0.2%. While 0.2% seems like a small amount, in a pulsed laser the peak power of the ghost spot can exceed the damage threshold of the coating or the bulk material.



Back reflection on the outer surface of the fourth lens element forms a focus in first lens element.

Most scan lens have between four to six lens elements. The solution is to design the lens so no back reflections or ghosts occur on any of the lens elements or on the scan mirrors if placed at the recommended distances. This is accomplished by using an appropriate adapter ring.

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