Multi-Element Lenses

CVI Multi-Element Lenses

A multi-element lens system is required when the aberrations of a singlet lens are too large to satisfy system requirements. CVI offers two and three element lenses for use at focal ratios where singlets fail due to spherical aberration. CVI multi-element lenses with diffraction limited *f*/numbers down to 3.3 are summarized in the table to the right.

Nomenclature

As with a singlet, the back focal distance **BFD** is the **signed distance** (distance noted with negative or positive value depending on whether it is positive or negative focal length) from the rear vertex to the back paraxial focal plane. This is shown in Figure 1 for a positive triplet.

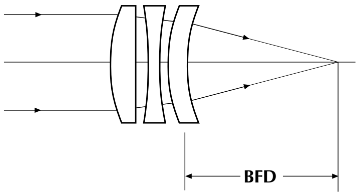


Figure 1.

For a negative lens, Figure 2, the BFD is negative and is calculated using the same rule. The BFD is the distance from the back vertex to the (virtual) back paraxial focal plane. We have put absolute value signs around the BFD in Figure 2 to emphasize this.

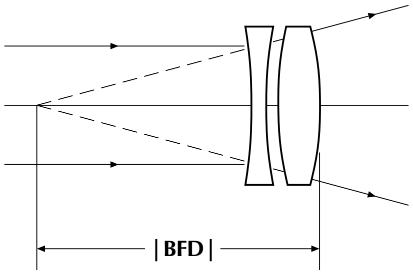


Figure 2.

Product Code		No. of Elements	*f*/#	Wavelength Range
	Monochromats			
LAP	Laser Aplanat (Positive)	2	5	420 - 2000nm
LAPQ	UV Laser Aplanat (Positive)	2	5	180 - 2200nm
LAN	Laser Aplanat (Negative)	2	5	420 - 2000nm
LANQ	UV Laser Aplanat (Negative)	2	5	180 - 2200nm
LAP + APM	Laser Aplanat + Aplanatic Meniscus	3	3.3	420 - 2000nm
LAPQ + APMQ	UV Laser Aplanat + UV Aplanatic Meniscus	3	3.3	180 - 2200nm
UVAP	UV Laser Aplanat	1	8-15	180 - 2200nm
		2	5-10	180 - 2200nm
		3	2.5	180 - 2200nm
	Achromats			
HAP	Nd:YAG / HeNe Achromat (Positive)	3	4	600 - 1300nm
HAN	Nd:YAG / HeNe Achromat (Negative)	3	4	600 - 1300nm
YAP	Nd:YAG / Doubled Nd:YAG Achromat (Positive)	3	4	532 - 1300nm
YAN	Nd:YAG / Doubled Nd:YAG Achromat (Negative)	3	4	532 - 1300nm
AAP	Aplanatic Achromat (Cemented)	2	4	400 - 750nm

The advantage of a consistent formalism is evident in the construction of a Galilean beam expander, Figure 3. Here, both the negative and positive elements will have a common focus as shown. To determine the spacing of the elements, distances strictly referenced to optical surfaces are required. The logical choice is to use the back focal distances: Thus we have

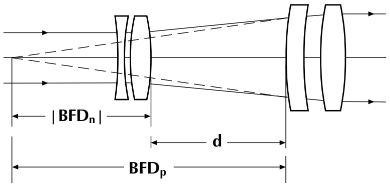


Figure 3.

$$d = BFD_p + BFD_n = |BFD_p| - |BFD_n|$$

The reader may notice that the equation above is actually not consistent with our definitions when the direction of the light rays is considered. Strictly speaking, it is the front focal distance of the positive element that is required in the formula above. However, it is customary to list the back focal distance of a lens as the distance from its last element to the focal plane when the lens is properly oriented for focusing a collimated beam from left to right. So, to design a system using lens tabulated values, keep in mind the orientation conventions used in the descriptions of the individual component lenses.

The working distance of elements in housings has been provided in the product tables. The working distance specifies the distance from the focal plane to a mechanical reference surface, here it is the housing edge closest to the focal plane. This is shown schematically in Figure 4 below:

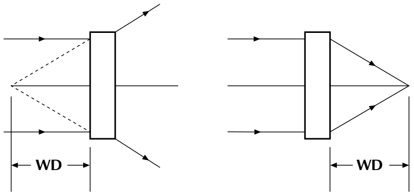


Figure 4.

Aplanat or Achromat?

An Aplanat lens is designed to be free of two monochromatic (**single wavelength**) wavefront errors called Spherical Aberration and Coma. Spherical Aberration is axially symmetric and occurs when rays from a point on the axis 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.

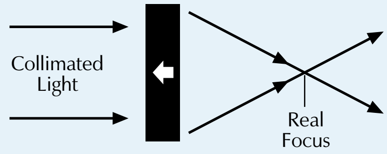
On the other hand, Achromatic lenses are corrected for Chromatic Aberration with respect to **two wavelengths** (normally blue and red). Chromatic aberration is produced by dispersion, or the variation of refractive index with wavelength, and causes different wavelengths to have different focal points. Using separate materials like crown glass and flint glass for the converging and diverging lens elements, the dispersion of each can be compensated for by the other thereby minimizing the total effect. In photography and precision micromachining, it is often crucial that the secondary spectrum or a third wavelength be color-corrected in addition to the blue (F-line) and red (C-line).

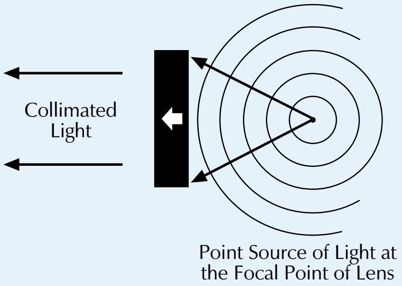
Neither crown nor flint glasses transmit well below 420nm so other materials are required for applications using broadband or multi-wavelength UV sources. there are few options available to optical designers, due to limitations in UV transmitting materials. Existing designs use fused silica glass for the positive element, and either UV grade calcium fluoride or lithium fluoride for the negative element. An UV achromat comprised of either of these material combinations can be optimized for a 200nm bandwidth centered around 300nm or 350nm depending on the application requirements.

Aplanat Marking Conventions

Positive Systems (Convergent)

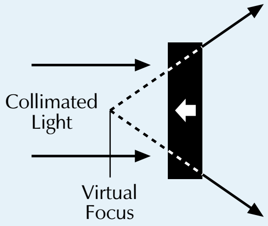
The arrow marking on the housing always points to the collimated light.

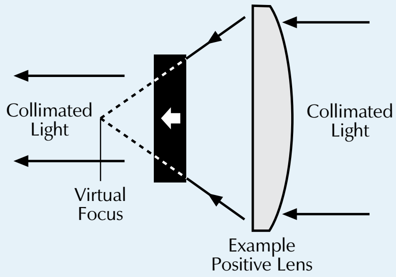




Negative Systems (Divergent)

The arrow marking on the housing always points to the collimated light.





UV achromats are ideally suited to broadband UV applications including photometric instrumentation and fluorescence analysis. They can also be used as UV focusing lenses in place of aplanat lenses in certain situations. Most commercially available UV aplanats are designed for 248nm. At other wavelengths, such as the laser diodes at 365nm (I line) and 405nm (H line) used in lithography exposure systems, more precise focal lengths may result from using an achromat in place of an aplanat which was designed for a different wavelength.

LAP/LAN Series Laser Aplanats

The **LAP**/**LAN** Series Laser Aplanats are air-spaced doublets designed to produce minimum focal spot size. An aplanat is a lens designed to minimize spherical aberration and coma. The **LAP**/**LAN** Series lenses exhibit essentially diffraction limited performance over their full *f*/5 apertures.

Use **LAP**/**LAN** doublets when the focal spot of a monochromatic laser must be an absolute minimum. Applications include nonlinear optics experiments, laser beam expanders and collimators, interferometers, beam handling systems, material ablation and cutting systems, power fiber optic interfacing, and other applications where lenses are used to focus collimated beams.

Figure 5 shows the construction of the **LAP** Series positive lenses; identical definitions apply to the **LAN** Series negative lenses. Both elements are fabricated from SF11 glass and are

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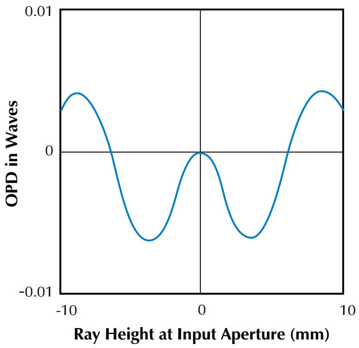

Figure 6. LAP-100.0-20.0 with BFD = 93.20mm and λ = 488nm

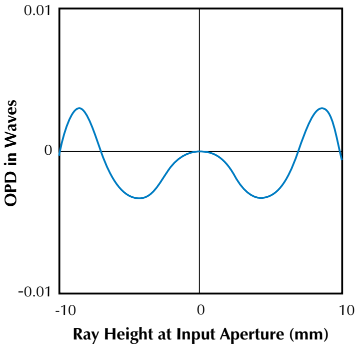

Figure 7. LAP-100.0-20.0 with BFD = 96.53mm and λ = 633nm

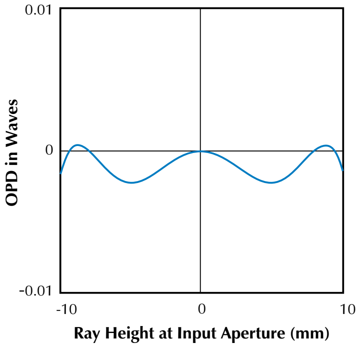

Figure 8. LAP-100.0-20.0 with BFD = 99.71mm and λ = 1064nm

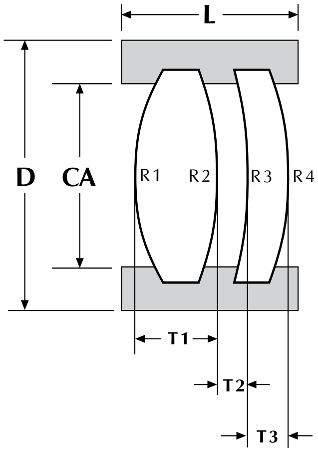

Figure 5. Laser Aplanat

antireflection coated with hard, damage resistant coatings. Lens design prescriptions are available in many of the commercially available optical design software packages to facilitate computer analysis, such as ZEMAX.

Figures 6 through 8 show the degree of design correction that has been achieved for **LAP-100-20**. The peak-to-valley wavefront distortion is shown on the axis at three wavelengths. The X-axes span the ± 10mm clear aperture for rays above and below the optical axis. Note that for each wavelength, the lens has been refocused to find the focal plane where the optical path difference (OPD) spread is a minimum. The BFD of this focal plane is given.

The graphs show that the theoretical deviation from a perfect spherical wavefront centered on the point of best focus is negligible. CVI guarantees less than λ/4 peak-to-valley wavefront distortion for all elements of the **LAP**/**LAN** Series. This means that the energy falling within a theoretical circle co-incident with the minimum of the first dark ring of the Airy diffraction pattern will contain at least 80% of the energy contained in the corresponding region of an ideal diffraction pattern.

The **LAP** Series positive aplanats have relative apertures of $f/5$. If you require a smaller spot size, add an **APM** Series aplanatic meniscus lens to shorten the focal length by a factor of 0.67 to create a combined system of $f/3.3$ relative aperture.

LAPQ and **LANQ** are positive and negative diffraction limited aplanats optimized for 248 nm. The "Q" designates UV grade fused quartz used in place of SF11.

APM Series Aplanatic Meniscus Lenses

The CVI **APM** or **APMQ** Series aplanatic meniscus lenses shorten the focal length of the **LAP** or **LAPQ** Series positive laser aplanats while maintaining the minimization of the aberrations inherent in the **LAP** or **LAPQ** Series lenses. An **LAP**/**APM** or **LAPQ**/**APMQ** combination is an $f/3.3$ focal system made up of reasonably priced standard components.

The **APM** lens acts to shorten the combined focal length of the system without introducing additional coma or spherical aberration. The resulting focal length obtained is always:

$$f_{\text{combination}} = \frac{f_{\text{initial}}}{\eta}$$

where η is the index of refraction of the meniscus element. To introduce no spherical aberration or coma, the **APM** lens design must be matched to the spherical wavefront generated by the preceding **LAP** lens. This requirement determines the front and back radii and center thickness of the meniscus lens.

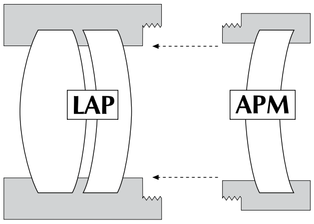

Figure 9. The APM meniscus lens is inserted into the housing of the LAP companion lens.

Also, the **APM** lens must be properly spaced from its companion laser aplanat. Therefore, **APM** and **LAP** lenses are used in pairs, Figure 9. CVI provides each **APM** lens pre-mounted in a housing that assures proper spacing and orientation with its paired **LAP** lens. **APM** lenses can be ordered with their companion laser aplanats or separately. This gives you the ability to change the focal length of an existing system at a later time.

UVAP UV and Excimer Laser Focusing Lenses

CVI designed the **UVAP** Series to focus large aperture excimer beams and for general purpose ultraviolet focusing applications. The **UVAP** Series has optimum correction of spherical aberration and coma in a lens transmitting to 200nm. Choose lenses from this series whenever your application requires ultraviolet diffraction limited performance at modest f/numbers. Lenses from the **UVAP** Series can satisfy many requirements in photoablation, microlithography, and image relay applications without the need for expensive custom designs.

YAG/HeNe Achromats

These air-spaced triplets have the same focal length at 1064nm and 633nm. They can be used to focus a YAG beam and HeNe beam to align to the same point. They can also be used to form beam expanders that collimate YAG and HeNe beams at the same lens spacing.

These lenses are corrected for spherical aberration at 1064nm and 633nm and for coma at 1064nm (see Figure 10). Because they are air-spaced, they can be used in high power YAG applications. The coatings are designed to give reflection losses of less than 0.5% per surface at both 1064nm and 633nm. Uncoated reflections can be as much as 4% per surface on BK7 elements and 8% per surface on SF11 elements.

To compare the performance of these lenses with that of telescope objectives, one can ray-trace representative telescopes consisting of two CVI cemented aplanats and two high power achromats. The high power achromats offer better wavefront quality and achromatization at two useful laser wavelengths. The inner surfaces are air-spaced and coated with high efficiency anti-reflection coatings and are suitable for high power applications that would cause telescope objectives to fail.

YAG/Doubled YAG Achromats

These lenses are similar to the **HAP/HAN** Series except they are achromatized for 1064nm and 532nm. They are air-spaced and all surfaces are coated with double-V AR coatings that have anti-reflection of less than 0.6% per surface at both 1064nm and 532nm. These lenses can be used to focus YAG and doubled YAG beams simultaneously or to form a beam expander that is concurrently collimated for YAG and doubled YAG.

A cross section of the **YAP-100.0-20.0** is shown in Figure 11. Figure 12 shows the OPD fans for this lens at the best common focus. Both wavelengths are theoretically less than $\lambda/20$ peak-to-valley transmitted wavefront distortion. These lenses are diffraction limited at 1064nm and 532nm.

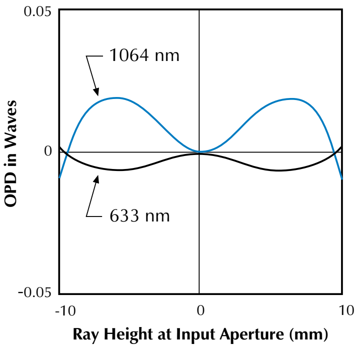

Figure 10. HAP-100.0-20.0 OPD fan

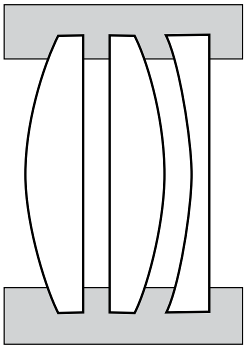

Figure 11. YAP-100.0-20.0

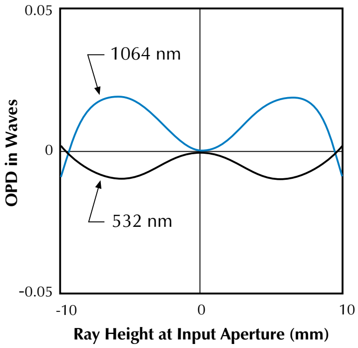

Figure 12. YAP-100.0-20.0 OPD fan