Aplanats and Achromats

by Emily Kubacki, CVI Laser, LLC

The terminology used within the field of Optics can be confusing, but it is critical when searching for and specifying optical components. This is especially true for multi-element lenses; the two most basic of which are aplanats and achromats. Both lenses typically consist of two or three lens elements, respectively referred to as doublets or triplets. However, they are by definition two completely different lens types with different applications and different design criteria. Trying to substitute one for the other based solely on price or availability could produce disturbing results.

Aplanatic Lenses

An Aplanat lens (Fig 3) is designed to minimize two monochromatic (single wavelength) wavefront errors called Spherical Aberration and Coma. Spherical Aberration (Fig 1) 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 (Figure 2) 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. Often called "Fraunhofer" lenses after the 19th century optician and physicist Joseph von Fraunhofer, aplanats are used as microscope objective lenses and condenser lenses. In applications such as laser beam delivery systems, microchip production and narrow-

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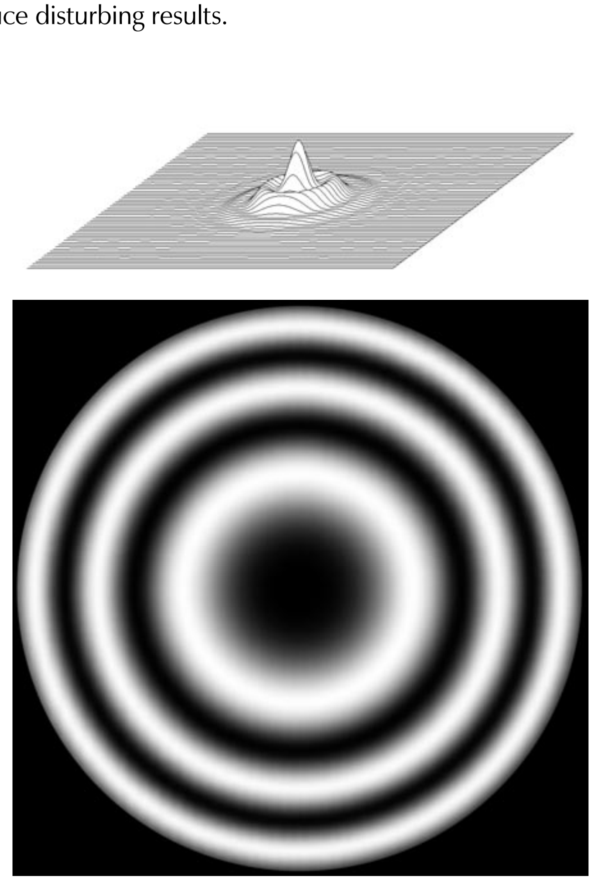

Figure 1. Uncorrected spherical aberrations lead to blurry focal spots. The top illustration shows the point-spread function of a lens with spherical aberration at marginal focus; the bottom is an interferogram of the same lens design.

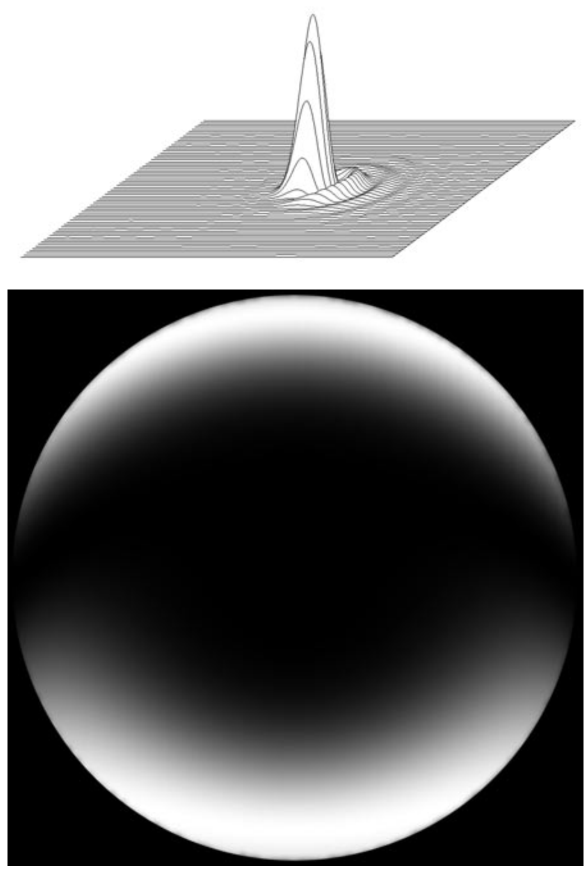

Figure 2. Uncorrected coma leads to irregularly shaped focus spots or a change in magnification with field angle. The top illustration is the point-spread function of a lens with coma; the bottom is a near-focus interferogram of the same lens design

band material processing, tight control of the image and/or focal spot size produced is critical to overall system performance and functionality.

Depending on the overall design criteria, doublet and triplet aplanatic lens designs can utilize all the same substrate material or different materials. 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. The air-space can then be treated like an additional lens element in order to better reduce coma and spherical aberrations through the complete lens assembly. Although the original Fraunhofer doublet was designed with a narrow air-gap, other designs utilize a wide gap, a narrow gap with the edges of the lens actually touching (called a contact doublet) or a bonded assembly. The benefits of a bonded assembly are increased mechanical strength, greater durability, and increased overall transmission as a result of fewer surface reflections which are produced by external surfaces.

Aplanat lenses designed using only UV or excimer grades of fused silica glass are commonly used as excimer laser focusing lenses, but are also suitable for high energy 1064nm Nd:YAG laser beam steering applications. Fused silica glass is

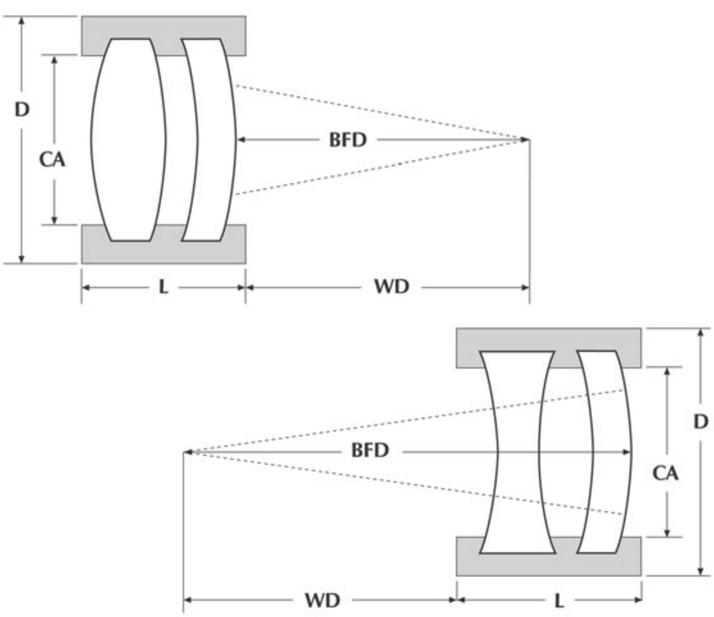

Figure 3. Positive (top) and negative (bottom) aplanat doublets correct for spherical and coma aberrations.

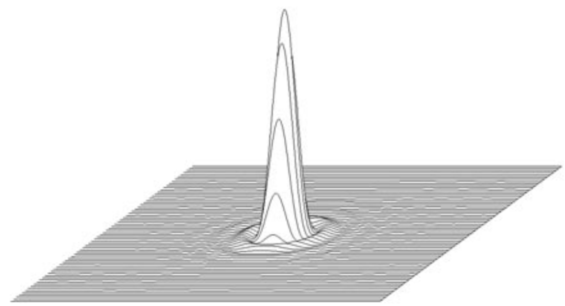

Figure 4. This point-spread function depicts a diffraction-limited lens.

an amorphous form of silicon dioxide and has very high laser damage thresholds as well as high transmittance throughout the UV, visible and near-infrared wavelength regions. With high-energy antireflection coatings applied, an air-spaced fused silica doublet lens will transmit greater than 98-99% of the incoming light while still withstanding more than 30J/cm² of pulsed light at 1064nm.

Aplanatic Meniscus Lenses

Aplanatic meniscus lenses shorten the focal length of the laser aplanat while minimizing aberrations inherent in the aplanat.

The best aplanat and meniscus lens combination is an f/3.3 focal system made up of reasonably priced standard components.

The aplanatic meniscus 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:

$$f_{combination} = \frac{f_{initial}}{n}$$

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

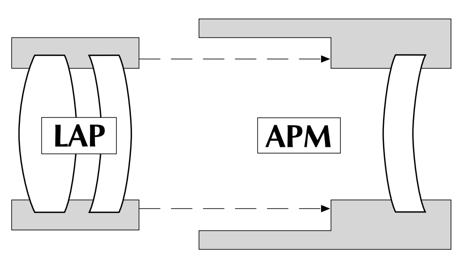

Figure 5. The LAP Series Aplanatic lens is inserted into the housing of the APM Series companion meniscus lens.

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lens must be properly spaced from its companion laser aplanat. Therefore, aplanatic meniscus and aplanatic lenses are used in pairs, Figure 5. CVI provides each aplanatic meniscus lens pre-mounted in a housing that assures proper spacing and orientation with its paired aplanatic lens. Aplanatic meniscus 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.

Achromatic Lenses

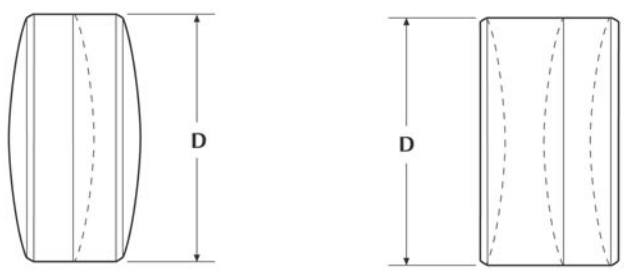

Figure 6. Positive and negative achromat doublets correct for chromatic aberrations

On the other hand, achromatic lenses are designed for broadband applications including astronomical telescopes, color photomicrography, plasma spectroscopy and biomedical instrumentation. They must consist of two or more lens elements composed of discrete glass materials and 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. By using separate substrate materials like crown glass and flint glass for the converging (positive) and diverging (negative) lens elements, the dispersion of each can be compensated for by the other thereby minimizing the total effect. Whether the overall lens assembly is converging or diverging depends on which lens element has the greater power. In a typical achromat, the positive element is constructed from crown glass and is plano-convex or biconvex in shape; the negative element is made of flint glass and is usually meniscus, or crescent shaped.

Color Correction

In imaging 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). An apochromatic lens which minimizes both Spherical aberration

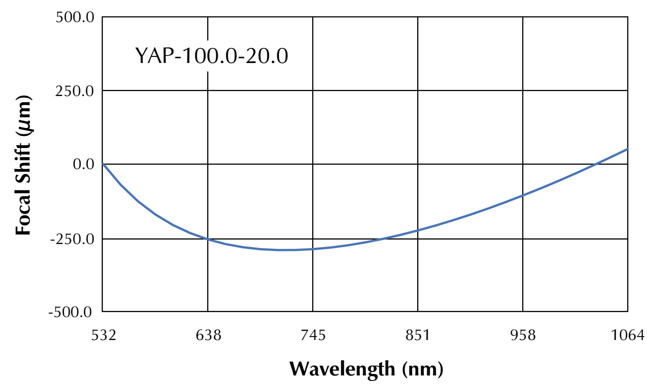

Figure 7. This focal shift plot shows that this achromat designed for use at 532nm and 1064nm has the same focal point at those wavelengths. It also shows how far from ideal the lens will perform if used with other than the design wavelength.

and Chromatic aberration at three wavelengths is used to accomplish this. Apochromatic lenses are more expensive than ordinary achromats because they are typically made from more exotic glass materials which cost more and are more difficult to process than standard crown and flint glasses.

Doublet and triplet achromatic lens designs can be optimized for broad wavelength regions (usually visible 400-700nm) or for two distinct wavelengths (1064nm & 532nm for example) depending on the application. For dual wavelength beam steering applications, alignment of near infrared lasers and diodes is made easier with the use of a visible HeNe or doubled Nd:YAG laser beam which follows the same optical path. In addition, although achromatic doublets are usually cemented, they can be air-spaced to increase damage threshold and to reduce transmitted wavefront distortion through the assembly. As with aplanats, air-spacing the components allows for more flexibility in the design which in turn leads to even better color correction. Because they are not symmetric in either design or function, however, achromatic lenses will exhibit significant wavefront distortions if not oriented correctly.

Neither crown nor flint glasses transmit well below 420nm so other materials are required for applications using broadband or multi-wavelength UV sources. Due to limitations in UV transmitting materials, however, there are few options available to optical designers. 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.

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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.

There are two important points to remember regarding achromatic lenses. First, they must consist of at least two different glass types or materials in order to compensate for the inherent dispersion properties of each. Second, they correct for a multiple wavelength aberration and are not the conventional choice for applications using a single narrowband wavelength, such as precision ultra-violet (UV) microlithography or nearfield optical recording.

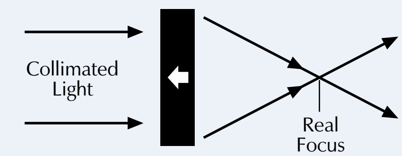
Summary

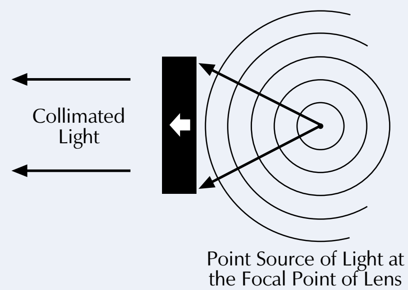
In summary, aplanat lenses are designed to produce the minimum focal spot size at a particular wavelength by eliminating Coma and Spherical aberrations. They are usually air-spaced, and can have two, three or four lens elements made from one or more glass materials. In contrast, an achromat can be cemented or air-spaced, is used for multiple wavelengths, and must be made from at least two different types of glass. Achromats and apochromats can be corrected for other variations besides Chromatic aberration, but are primarily intended to focus two or three wavelengths at the same point in the image plane.

CVI Aplanat Marking Conventions

Positive Systems (Convergent)

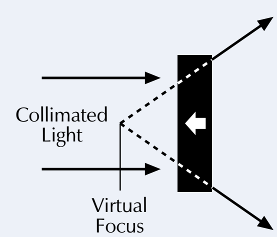
The arrow marking on the housing always points to the collimated light.

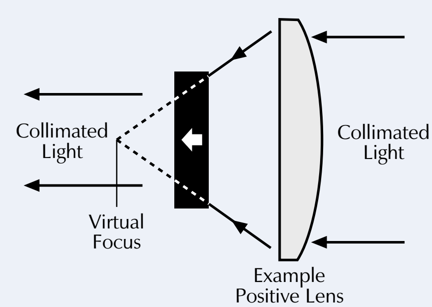




Negative Systems (Divergent)

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





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