Optical Design Forms for DUV&VUV Microlithographic Processes

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ABSTRACT

Microlithographic objectives have been developed for deep ultraviolet and vacuum ultraviolet wavelengths used for printing and inspection applications related to microlithographic processes. Refractive and catadioptric design solutions using fused silica, calcium fluoride and other crystals are discussed. Several reflective and catadioptric design forms having central obscurations will be compared to refractive forms. Design complexity, performance and limitations are compared.

Keywords: Lenses, 248nm, 193nm, 157nm, refractive, reflective, chromatic, catadioptric, Newtonian, obscuration

1. INTRODUCTION

The microlithographic community has evolved through many generations of conventional refractive objective solutions for printing and inspection applications. Higher numerical apertures and shorter wavelengths have been used to meet imaging demands for printing and inspecting progressively smaller features. Refractive designs have become significantly more complex, requiring more glass path, larger diameters, more refractive surfaces while tolerances have simultaneously tightened for material homogeneity, birefringence, transmission, surface irregularity, axial thickness, radius of curvature, surface roughness, and optical coatings. At the shorter wavelengths, the reduced set of transmissive refractive materials present new challenges to optical designers and manufacturers. Shorter wavelengths dramatically reduce the number of useable glasses available for color correction. Catadioptric design forms offer an alternative to help reduce chromatic sensitivity. These solutions employing refractive and reflective elements, have much of the optical power contained in reflective components. Catadioptric forms provide design solutions that allow a continuation of performance improvement that otherwise would meet limitations that arise from materials, surface finishing and coating technology that makes it difficult to extend below 185 nm.

Tropel has developed catadioptric solutions that eliminate the need for line narrowing the laser source in many applications for deep ultraviolet and vacuum ultraviolet wavelengths that are used for printing and inspection at 248, 193 and 157 nm wavelengths. Single and two material refractive design examples are shown for comparison.

2. SINGLE MATERIAL REFRACTIVE DESIGNS

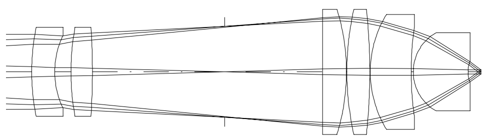
Material choices for designs below 300 nm wavelengths were initially limited to fused silica. Single material design solutions at 248 nm in combination with excimer lasers have become the standard for the industry. The dispersive properties restrict use at high numerical apertures unless used with line narrowed excimer lasers and frequency doubled or naturally narrow lines of ion lasers. The following expression computes the chromatic bandwidth assuming that the allowable degradation due to axial chromatic effects is within is one quarter of the Raleigh depth for a single material design:

$$BW_{FWHM} = \frac{(n-1)\lambda}{4f(1+m)(\delta n/\delta\lambda)NA^2} \tag{1}$$

where n is the index of refraction, λ is the central wavelength, f is the focal length, m is the magnification, $\delta n/\delta\lambda$ is the dispersion and NA is the numerical aperture[1]. Single material designs for DUV photolithography at high numerical aperture with large imagery fields have required the industry to develop expensive lasers with complex line narrowing packages.

3. SINGLE MATERIAL RESIST /PROCESS DEVELOPMENT OBJECTIVES

When shorter wavelengths are introduced to improve lithography resolution, the resist technology usually lags behind. This was the case in the transition from g-line lithography to i-line lithography. When 248 nm lithography was introduced, DUV resist technology required dramatic changes to the chemistry. Prior to the availability of commercial lithography tools, small field objectives were used for early resist development at universities and research labs. The objectives are designed with SiO_2 for use with excimer laser sources having variable aperture stops. At lower numerical aperture settings these objectives could print useful imagery for process development with un-narrowed and partially narrowed excimer sources. To fully utilize these designs at high numerical aperture settings required narrow bandwidths along with wavelength stabilization and tight controls of environmental factors such as temperature and barometric pressure. These are costly controls to implement on a small field evaluation tool.

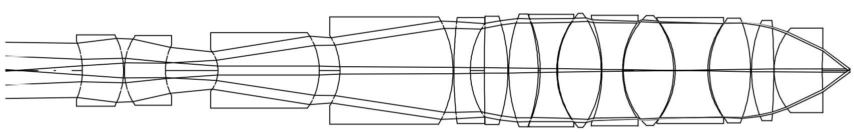


NA	0.6
Reduction	20X
Image Field	0.8 mm
Wavelength	248.4 nm
Bandwidth	10 pm
Track length	315 mm
Material	SiO

Figure 1. Single material small field projection optics for 248 nm resist evaluation

4. TWO MATERIAL DESIGN FORMS

Attempts to reduce chromatic aberrations have been made by introducing CaF_2 as a second material. Replacing positive "crown" elements with CaF_2 helps to reduce the chromatic sensitivity. Air spaced doublet combinations are required because at DUV wavelengths stable transmissive cements are not currently available. Reducing chromatic aberrations by the use of two suitable materials such as SiO_2 and CaF_2 requires increasing the number of elements and the overall length of the optical system as shown in figure 2 below.



NA	0.6
Reduction	20X
Image Field	0.8 mm
Wavelength	248.4 nm
Bandwidth	0.8 nm
Track length	315 mm
Materials	SiO_2/CaF_2

Figure 2. Two material small field projection optic for 248 nm

Increased power in both positive and negative elements is needed. Centering and alignment tolerances become prohibitive in this design approach with increasing numerical aperture. Surface tolerances become increasingly tighter with the increased number of surfaces. Polishing steeply curved CaF_2 surfaces to tighter tolerances requires deterministic polishing approaches**.** Additionally, the increased surface powers needed to achromatize give rise to large chromatic variations of aberrations, which also limit performance. Field size is usually limited by coma and lateral color, which are difficult to minimize due to a lack of symmetry about the stop which is needed to achieve telecentricity and lens reduction ratios not close to 1:1.

The overall increase in complexity necessary to achieve achromatization becomes even more challenging for shorter wavelength applications. At 157 nm wavelengths the crown material of choice remains CaF_2. Excimer grade SiO_2 does not transmit well enough at this wavelength to be considered. Currently a second "flint" material for achromatization has not been qualified for 157 nm applications. Some possible candidates are BaF_2 and SrF_2. The dispersion properties of these materials require even more complexity to achieve the same achromatic correction possible at longer wavelengths.

Alternative design approaches that offset this increased sensitivity at shorter wavelengths with reduced complexity are needed as we approach the shortest of wavelengths that will transmit through refractive materials. New design approaches are needed in the industry that will provide the continued transition to shorter DUV and VUV wavelengths, ideally with broader bandwidths, allowing utilization of less expensive un-narrowed excimer lasers and DUV lamps.

5. CATADIOPTRIC FORMS

Catadioptric design forms offer an alternative to reduce chromatic sensitivity with decreased overall complexity. These design forms have refractive elements with some or most of the power in reflective components. Single material catadioptric solutions having most of the power contained in the reflective components have reduced sensitivity to temperature, barometric pressure and are less sensitive to focus and magnification changes with wavelength[2].

In general, catadioptric forms have better chromatic wavefront correction using less optical material path and fewer refractive surfaces than comparable refractive designs. This is helpful as materials, surface finishing and coating technology are not easily extended below 185 nm. Continuing to increase performance at shorter wavelengths requires the use of high purity crystals which have been challenging to develop at high quality in volume. Special polishing and coating processes must be in place to help offset the effects of surface irregularities and roughness that induce flare and scattered light.

6. NEWTONIAN OBJECTIVES

A Newtonian objective form was developed for use with line narrowed mercury arc lamps and un-narrowed excimer laser sources in step and repeat cameras[3]. Single material designs are insensitive to environmental changes in temperature and barometric pressure. This form has enabled 193 nm and 157 nm resist technology development with nearly perfect aerial imagery [4,5]. This is accomplished with a combination of refractive elements and a double reflective Mangin mirror combination. The benefit and coaxial simplicity of these flat field designs is the ability to correct both design and manufacturing residual wavefront errors on a plano plate as part of a closed loop optimization process. The design nearly perfectly corrects the wavefront with an aspheric plate to >99% Strehl ratio. Strehl ratio is the intensity at the peak of the point image as a percentage of the peak of the aberration-free image with the same vignetting and obscuration. Measured wavefronts of actual assemblies have been corrected to >95% Strehl ratio.

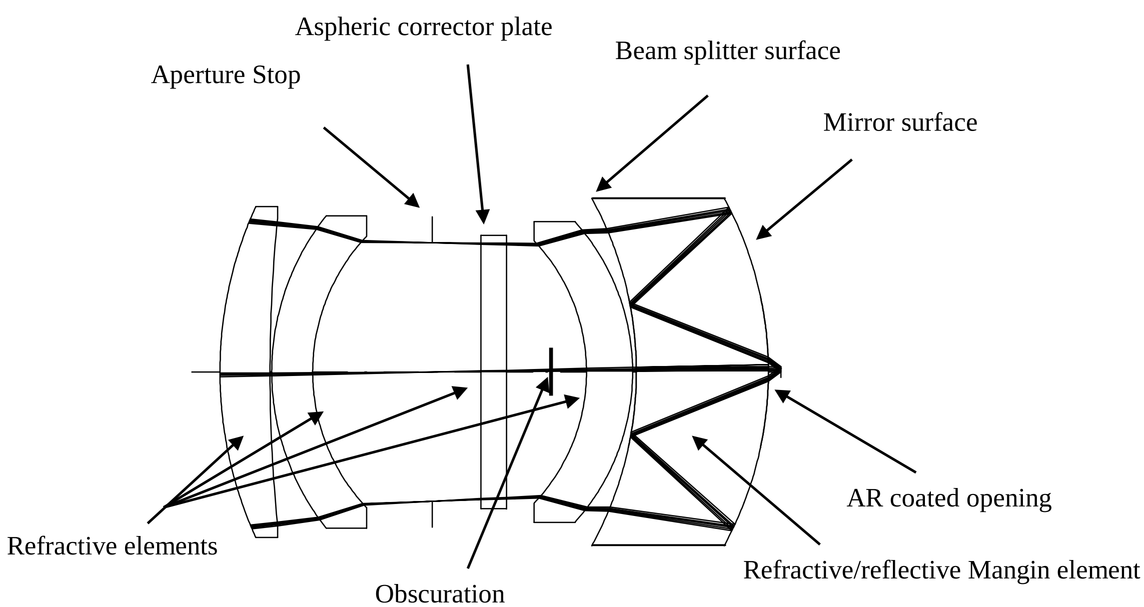
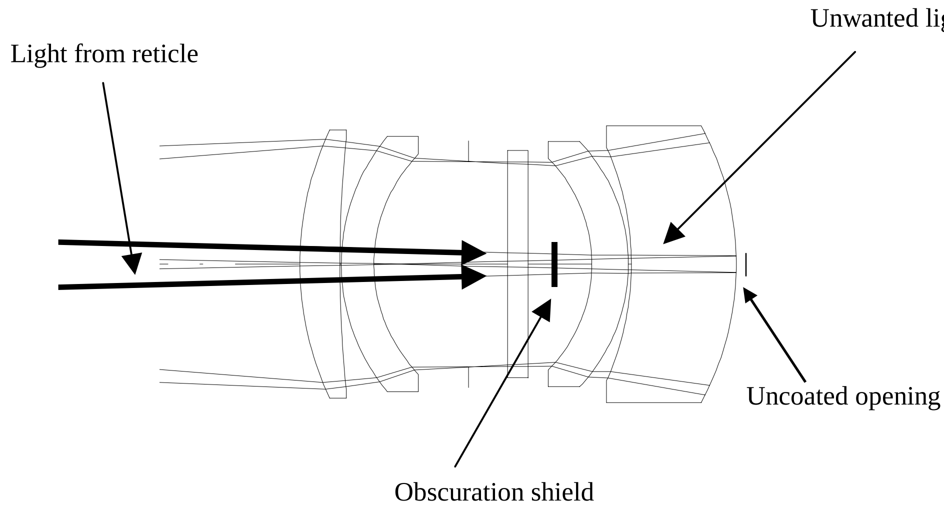


Figure 3. Major components in a small field Newtonian objective

The form is limited to short working distances and requires a central obscuration shield to prevent unwanted light from the reticle transmitting through the uncoated opening in the Mangin mirror to the image plane and exposing the wafer. The shield also helps to reduce some of the ghost image blur and flare light caused by multiple bounce reflections and scattered light from refractive surfaces that otherwise would reach the image plane. Flare in the image plane for 193 nm systems has been measured to be <1.5% and for 157 nm systems is <2.5%.



NA	0.60
Reduction	10X
Image Field	2.1 mm
Wavelength	248.4 nm
Bandwidth	6 nm
TCL	600 mm
Material	SiO2

Figure 4. Central obscuration shields image plane from unwanted light passing directly through opening

Because the lens incorporates a beamsplitter, light reflected from the beamsplitter and mirror surfaces must also be closely monitored as part of the design process. Stray light and ghost light analysis is used to track unwanted light and ensure the final design will prevent the unwanted light from exposing the wafer plane. The limitation in this design form is throughput. The beamsplitter limits the system transmission to <25%. The required central obscuration shields <2% of the pupil area and is typically <13% of the diameter of the pupil.

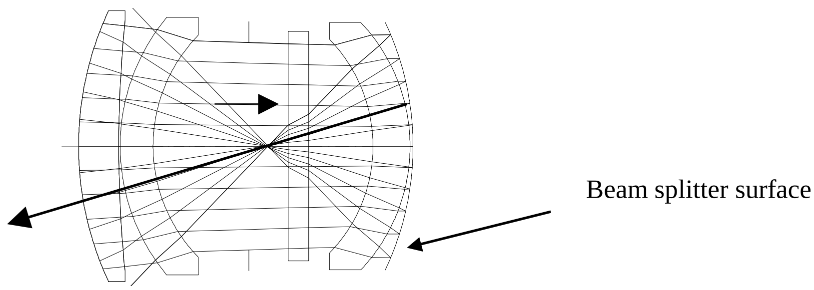
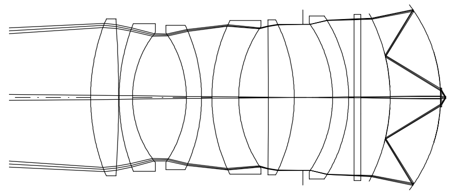


Figure 5. Reflected light off the beamsplitter travels away from the image plane

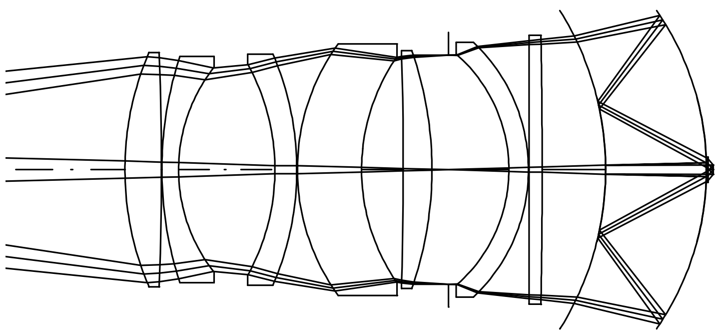
High performance Newtonian solutions are possible. Second generation catadioptric design solutions at 157 nm are being developed that have increased numerical aperture as lithographers push the limits of optical lithography at longer wavelengths further for resolving smaller geometries[6]. Several examples are shown in figures 6 and 7 that incorporate larger numerical apertures and larger image fields.



NA	0.85
Reduction	15X
Image Field	0.707 mm
Wavelength	157.63 nm
Bandwidth	120 pm
Track length	600 mm
Material	CaF2

Figure 6. Small field 0.85 NA Newtonian objective for 157 nm resist evaluation

Larger field solutions have been designed for device level process development.

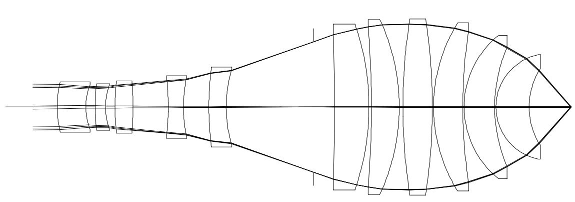


NA	0.75
Reduction	6X
Image Field	5.66 mm
Wavelength	157.63 nm
Bandwidth	120 pm
Track length	840 mm
Material	CaF2

Figure 7. Mid field 0.75 NA Newtonian objective for 157 nm device level process development

7. SINGLE MATERIAL LONG WORKING DISTANCE INSPECTION OBJECTIVES

Single material long working distance refractive designs are often required to inspect features printed on reticles through protective pellicles. A challenge to these types of objectives is the need for a working distance that is greater than their effective focal length. This requirement makes it necessary to place a telephoto group at the front of the lens to enlarge the input beam.



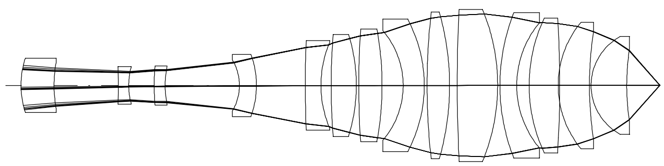
NA	0.75
Image Field	0.2 mm
Wavelength	248.4 nm
Bandwidth	2 pm
Working Dist.	9 mm
EFL	8 mm
Material	SiO_2

Figure 8. Long working distance objective for reticle inspection at 248 nm

The lens performance therefore behaves as if it had a longer focal length, and as a result, all aberrations, including chromatic aberrations, scale up in accordance with the telephoto ratio. The effective focal length in equation (1) is thus larger, which reduces the bandwidth.

8. TWO MATERIAL LONG WORKING DISTANCE OBJECTIVE FORM

Attempts to increase the bandwidth of chromatic correction for this design form were made by introducing CaF_2 as a second material. Again cemented doublet combinations are not considered and positive “crown” elements are replaced with CaF_2 which helps to reduce the chromatic sensitivity. Chromatic improvements are still not adequate for un-narrowed excimer lasers or the less expensive broad -band emission sources. This form effectively has both the limitations of the two material refractive form mentioned in section 4 and the limitation of the single material long working distance form discussed in section 7.



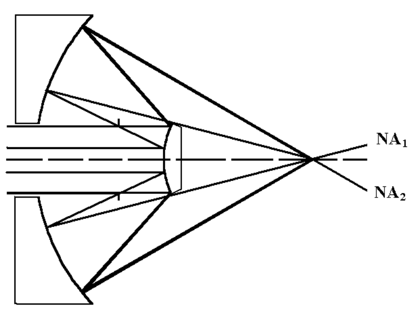
NA	0.75
Image Field	0.2 mm
Wavelength	248.4 nm
Bandwidth	15 pm
Working Dist.	9 mm
EFL	8 mm
Materials	SiO_2/CaF_2

Figure 9. 0.75 NA long working distance objective for reticle inspection at 248 nm

9. SCHWARZSCHILD OBJECTIVE

The Schwarzschild objective is an all-reflective objective that provides both long working distance and broad of chromatic correction, but the form has some serious limitations for most lithographic printing and inspection applications. Near the concentric condition the aberrations are minimized, but the central obscuration is large, typically >30% of the diameter. A thin spider structure is necessary to support the small primary convex mirror and adds to the obscuration in the pupil and adds diffraction spikes. A reduction of the central obscuration can only be achieved at the expense of large amounts of spherical and severe off axis aberrations being introduced.

With the very limited degrees of freedom, extending the design to higher NA (>0.60) requires at least one mirror to be aspheric to correct spherical aberration. With both mirror surfaces aspheric, off axis aberrations can also be corrected, but this form has a very limited field of view due to field curvature. Alternative design approaches are required.

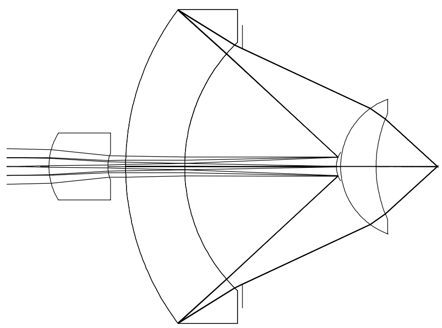


NA	0.5
Image Field	0.100 mm
Wavelength	248 nm
Bandwidth	Polychromatic
Working Dist.	10 mm
EFL	6 mm
Material	ULE/Reflection

Figure 10. Long working distance two mirror reflective objective

Design forms having central obscurations block some of the light that forms the imaging cone. The percent of the numerical aperture that is missing (NA_1/NA_2*100), where $\sin(\theta) = NA$, is calculated by determining the limiting aperture angle, (NA_1) that passes without obstruction, divided by the full numerical aperture (NA_2), as shown in figure 10.

10. LONG WORKING DISTANCE µCAT™



NA	0.75
Image Field	0.120 mm
Wavelength	248 nm
Bandwidth	6 nm
Working Dist.	8 mm
EFL	2.4 mm
Material	SiO2

Figure 11. Long working distance high NA catadioptric objective with low % obscuration

The µCAT™ design makes use of a "floating" primary mirror. In the Schwarzschild design the primary mirror is typically held in place with mechanical struts or "spiders". Eliminating these struts reduces unwanted diffraction effects and scattered light.

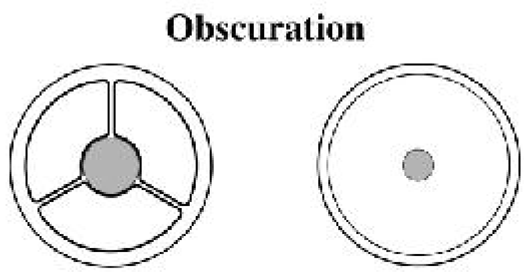


Figure 12. Comparing pupil and obscuration of Schwarschild and µCAT designs

This design form was developed to provide a family of long working distance single material catadioptric design solutions for broader chromatic correction than single and two material all refractive designs. The form is similar to a Schwarschild objective, having a central obscuration, but incorporates additional refractive surfaces and reflective Mangin mirror surface that facilitates correction of aberrations at high numerical aperture. This restricts the wavelength band for chromatic correction to <10 nm, but a major benefit of the form is the ability to correct numerical apertures >0.65 with a relatively small central obscuration, typically <15%. A field flattener is added to increase the FOV. These single material solutions are insensitive to temperature and pressure changes. Solutions covering the individual wavelengths of 266, 257, 248 and 244 nm have been designed using excimer grade SiO_2. Chromatically corrected solutions have also been designed for un-narrowed excimer lasers at 248 or 193 nm using SiO_2 and at 157 nm using CaF_2.

As shown in Figure 13 below, with incoherent illumination, designs with a central obscuration <15% of the diameter have much less performance impact on mid frequency MTF when compared to Schwarschild forms with obscurations > 30%.

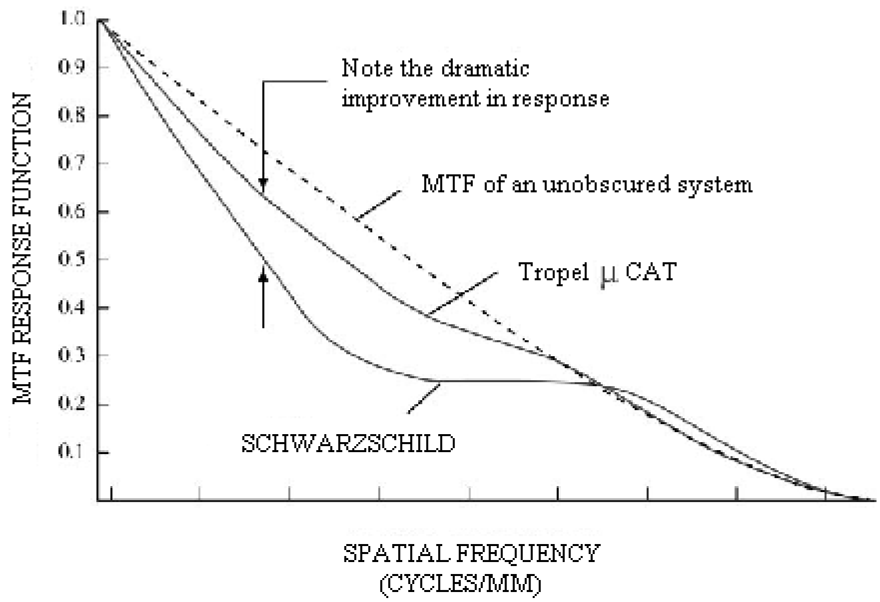


Figure 13. Best focus MTF Curve showing effect of central obscuration on the response function

NA 0.6 λ=248.4 nm 1:1

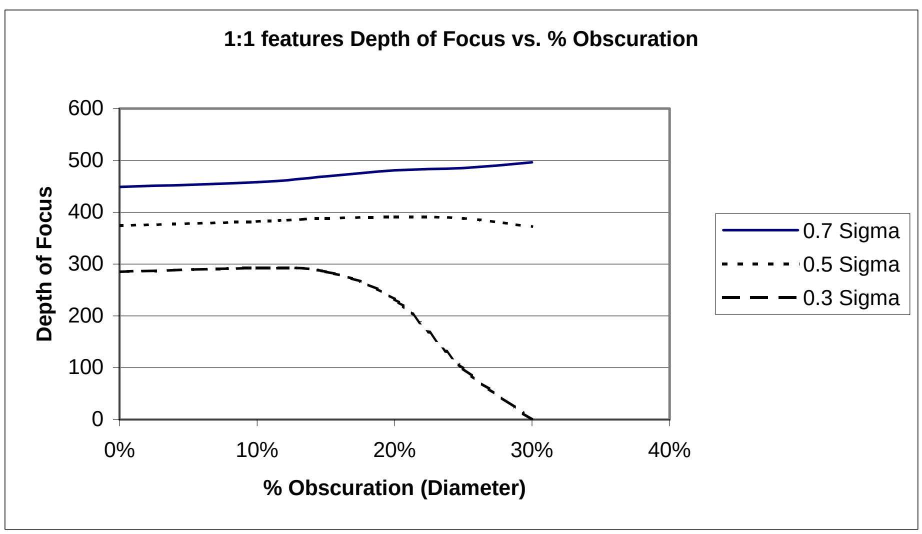


Figure 14. Effect that central obscuration has on partial coherent depth of focus for different pupil fill

Catadioptric designs with a central obscuration have different performance characteristics when used with partial coherent illumination[7]. Central obscurations have negligible effect on depth of focus with large pupil fill (sigma >0.5). When using partial coherent illumination for small pupil fill (sigma <0.3) the useable depth of focus can be dramatically effected with increasing obscurations as shown in Figure 14.

11. REDUCING CHROMATIC ABERRATION

A single material all refractive objective design has uncorrected longitudinal chromatic aberration, where shorter wavelengths will focus shorter than longer wavelengths. A method of evaluating chromatic lens performance is to plot the optical path difference over the pupil of the lens at different wavelengths. The horizontal axis represents the radial coordinate in the pupil of the lens at best focus on axis. The vertical axis shows chromatic variation of focus and spherical aberration in waves. Perfect wavefronts in focus are straight lines parallel to the horizontal axis. The larger the wavefront error the larger the optical path difference and thus the larger the image blur. A two material refractive objective design can reduce the amount of longitudinal chromatic variation of aberrations. The single material catadioptric design reduces the longitudinal chromatic aberrations to nearly zero over a narrow bandwidth range in Figure 15.

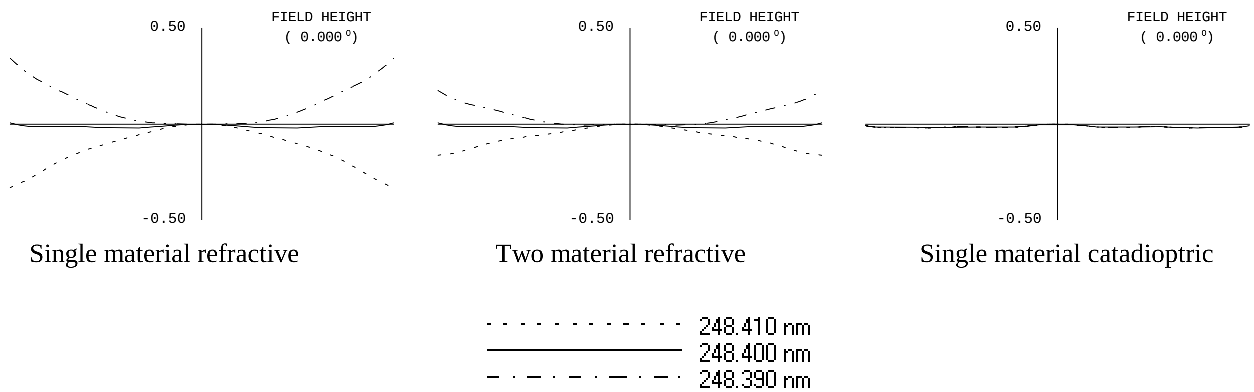


Figure 15. Comparing 0.75 NA design amounts of chromatic optical path difference (OPD) for narrow bandwidth

Chromatic correction can be increased in two material refractive designs by adding increased complexity. The chromatic correction of catadioptric design forms can be increased significantly when most or all of the power is in the mirrors. Examples of designs with differing complexity and spherochromatic correction are shown in figure 16.

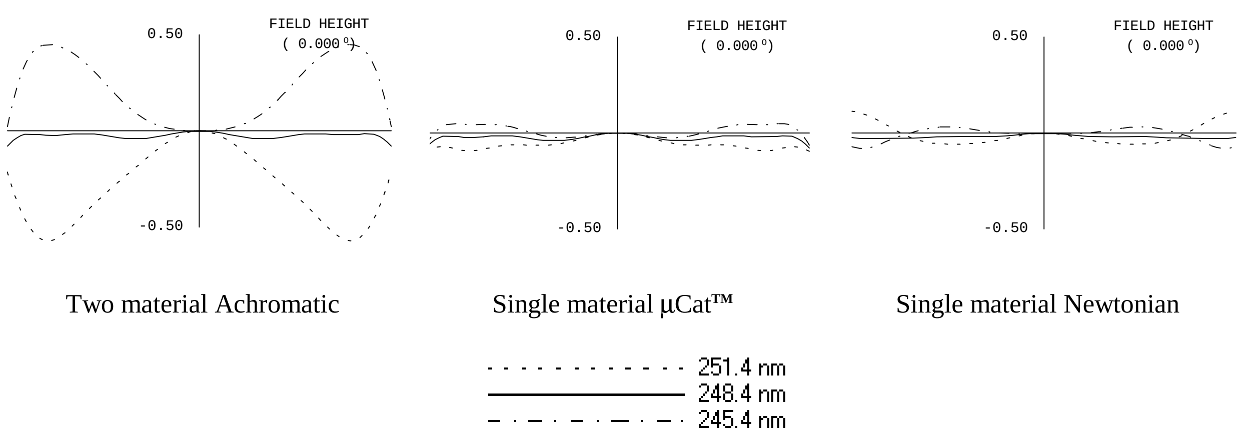


Figure 16. Comparing 0.6 NA design amounts of Spherochromatic optical path difference (OPD) for broad bandwidth

12. SUMMARY

It is often difficult to make comparisons between objective design forms with different focal lengths. It is often more useful to make comparison at a fixed numerical aperture, wavelength and working distance. Table 1 compares three objectives with greater than 1 mm working distance. Compared to a single material refractive design, a two material objective corrects chromatic aberration for a source with more than ten times the bandwidth. The Newtonian objective form provides more than three orders of magnitude greater chromatic bandwidth than the single material refractive design making possible the use of lamp sources.

λ=248.4 nm

Type	Single material	Two material	Newtonian
EFL	**14 mm**	**15 mm**	**25 mm**
Bandwidth @ 0.60 NA	**0.011 nm**	**0.8 nm**	**6 nm**
Bandwidth @ 0.75 NA	**0.008 nm**	**--**	**4 nm**

Table 1. Short working distance objectives chromatic bandwidth comparisons

In Table 2 three lens types are compared, each having greater than 8 mm working distance. Modest improvement in bandwidth are achieved when SiO_2 and CaF_2 are used. Approximately 10X improvement is achieved. The μCat design form corrects 1000x greater chromatic bandwidth than the single material telephoto refractive design after scaling for focal length.

λ=248.4 nm

Type	Mono	Two material	μCat ™
EFL (mm)	**8 mm**	**8 mm**	**2.66 mm**
Bandwidth @ 0.60 NA	**0.002 nm**	**0.018 nm**	**10 nm**
Bandwidth @ 0.75 NA	**0.0015 nm**	**0.014 nm**	**6 nm**

Table 2. Long working distance objectives chromatic bandwidth comparisons

The two catadioptric forms have much better chromatic correction than any all refractive design of reasonable complexity. There is minor compromise in performance due to the central obscuration, but there are significant benefits. The reduction in complexity allows continued usage at even shorter wavelengths. There are many new markets where catadioptric design forms can provide a significant cost benefit because an inexpensive broader band light sources can be used.

ACKNOWLEDGEMENTS

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