Immersion Lithography Micro-Objectives

James Webb and Louis Denes
Corning Tropel Corporation, 60 O'Connor Rd, Fairport, NY 14450 (U.S.A.)
585-388-3500, webbj@corning.com, denesl@corning.com

ABSTRACT

The optical lithography community is quickly gaining confidence that immersion technology can further reduce critical dimensions based on theoretical models and high angle interference lithography techniques. The optical industry has responded by developing a new class of immersion lenses so that researchers can demonstrate practical imagery with lenses and immersion fluids with improved resolution. Corning Tropel has previously developed families of (dry) catadioptric objectives for industry researchers to help in the development phases of high resolution and inspection at wavelengths below 200 nm. They were designed for use with free running EXCIMER lasers for reduced cost and reduced sensitivity to environmental changes compared to monochromatic designs. New objectives based on the same design forms were developed for use with immersion fluids to extend the numerical aperture to values greater than 1.0 to help researchers extend the technology of small image formation. These objective designs will be described along with modeled performance and measured results.

Keywords: micro-objective, immersion, 157nm, 193nm, 248nm, achromatize, catadioptric, resist development, aerial image inspection, EXCIMER laser.

1. INTRODUCTION

A standard product line of lenses was modified by incorporating an additional element to be in contact with immersion fluid. This modification permits the migration of this product line from dry objectives to immersion objectives yielding numerical apertures greater than 1.0 and correspondingly higher resolution and depth of focus.

2. THE CATADIOPTRIC DESIGN FORM

The lens[1] shown in Figure 1 is a modification of a Schwarzschild objective that allows high numerical aperture wavefront correction with reduced central obscuration using all spherical surfaces. Light passes through the un-coated portion of the R1 surface of a Mangin mirror, then through refractive surfaces R2 and R3, reflecting off the R4 Mangin mirror surface portion of this three surface multifunction component. When the radius of R4 is less than R5, rays reflect back through R3 and R2 until reflected off the large reflective surface of R1. Then light refracts through R2 and R3 a third time with larger ray heights allowing light to refract through the transmissive portion of R5 above the obscuring surface of the R4 mirror. This arrangement eliminates the need for a supporting spider to hold the small primary mirror in an all-reflective objective[2]. This type of catadioptric objective provides a small central obscuration, typically less than 20% of the full numerical aperture.

The addition of refractive surfaces provide the variables needed to correct monochromatic aberrations at higher numerical apertures while introducing chromatic aberrations that require correction but limit the bandwidth of operation. Objectives of this form can be achromatized using a single material over the free-running spectrum of un-narrowed EXCIMER lasers at DUV and VUV (Nitrogen) wavelengths. Adding refractive components before, in between and after this double Mangin mirror cavity allow high numerical aperture solutions with long working distances.

Optical Microlithography XVII, edited by Bruce W. Smith, Proceedings of SPIE Vol. 5377
(SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.535358

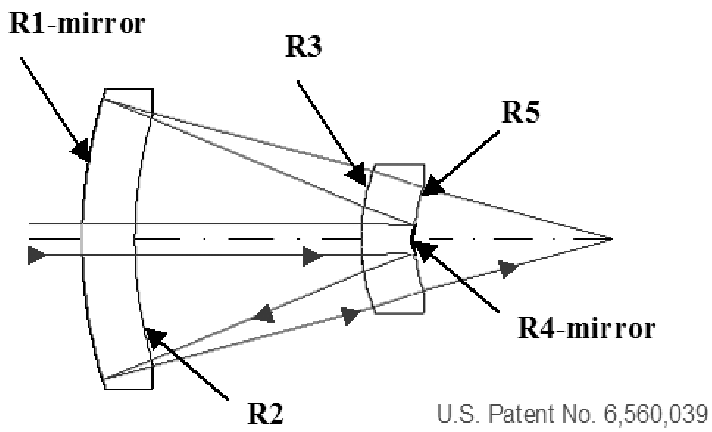


Figure 1 Catadioptric design form

3. μCAT® OBJECTIVE FAMILY

The lens in Figure 2 is an example of one such extension. This objective provides a 0.75 numerical aperture, covering 120 μm field of view, with 8 mm of working distance. Diffraction limited solutions[2] working at 248, 193 and 157 nm have been corrected for these laser sources over their free-running spectral bandwidth. The large working distance is useful in many applications. One such application is photomask inspection through a protective pellicle.

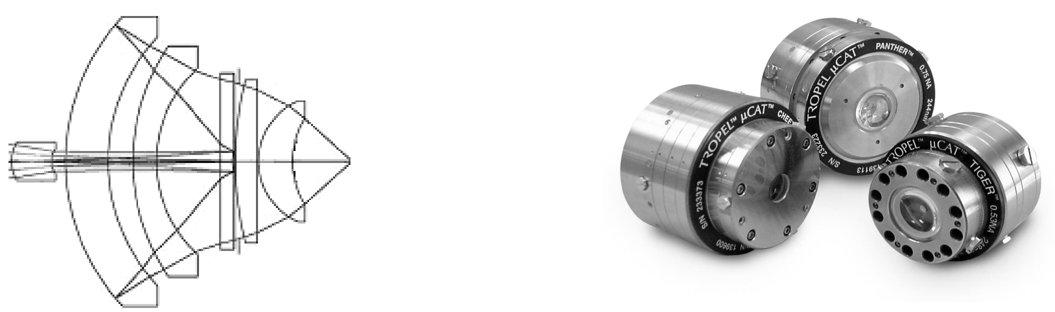


Figure 2 The μCat® Panther catadioptric objective

Corning Tropel has evolved this design form into a family of objectives ranging from 0.52 – 0.90 numerical aperture. This family carries the trademark name of μCat®.

4. AQUACAT™ WITH PLANO SURFACE INTERFACE

A fortuitous advantage of the long working distance is the large space made available to add an additional element that allows the light to couple into an immersion fluid, such as water. This increases the numerical aperture by changing the index n, of the image medium from air to water since NA=n*sin (θ). Two approaches are considered. The design shown in Figure 3 adds a convex-plano element. Even a small amount of refraction at each of the surfaces of this element introduces aberration.

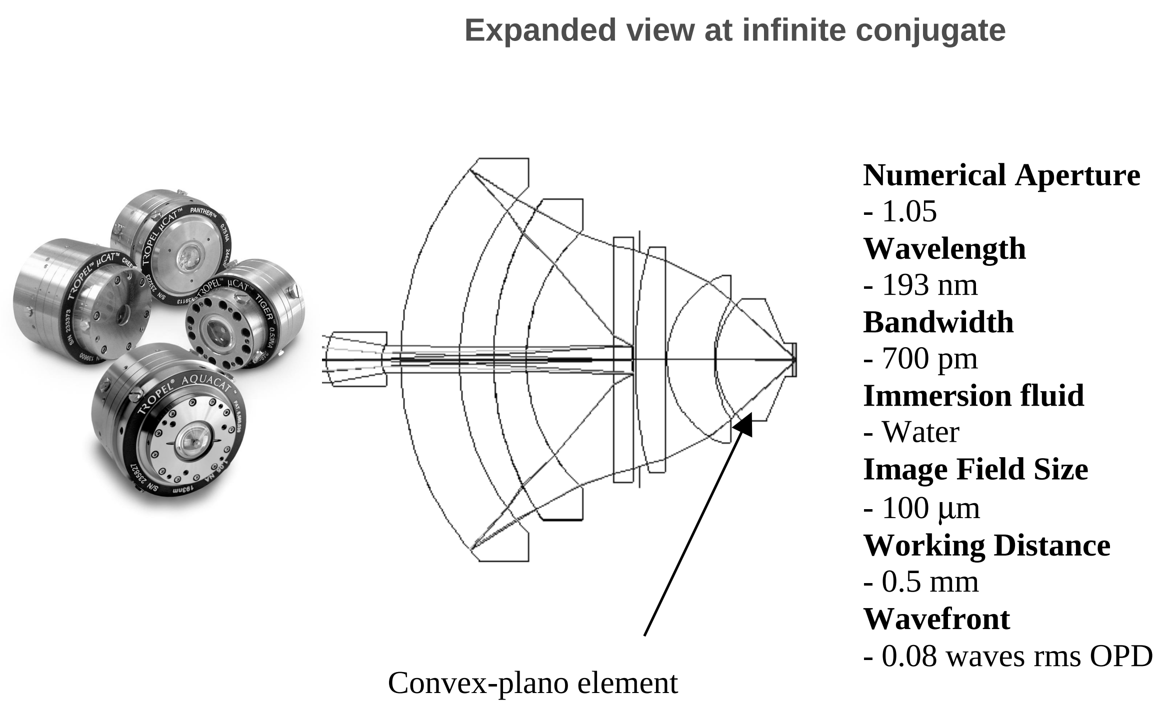


Figure 3 Immersion micro-objective with plano interface to fluid

Changing the curvatures of the elements after the stop in the lens compensates the aberrations over a 100 µm field of view (See Figure 4). The wavefront performance is limited by a tradeoff of field size and field curvature. The catadioptric objective easily corrects the 700 pm FWHM bandwidth of the EXCIMER laser source. Bandwidth is optimized over the range from 192.65 to 194 nm. The broad bandwidth achromatization using a single material provides other benefits. The objective has reduced sensitivity to environmental changes, such as temperature and barometric pressure and fluid index variations of +/- 0.0001 are easily tolerated.

The index of high purity water has been measured to be 1.436 at 193.3 nm wavelength[3]. The objective performance can be optimized at 1.05 numerical aperture using all spherical components and all elements that previously defined the Mangin cavity can be used without modification. This same objective design can be further extended in NA by aspherizing the convex-plano element. Alignment sensitivity is minimized by aspherizing the convex surface. The numerical aperture can be extended to 1.15 NA at the limiting apertures of the original design. Further extension of this design form is possible beyond 1.2 NA.

The first objective manufactured for 1.05 NA includes an additional element that provides a plano interface and 0.5 mm working distance in water.

An additional focusing lens is added in front to make this a finite conjugate objective with a 90X reduction ratio at a 210 mm track length (see Figure 5). For ease of alignment, the objective and tube lens combination is designed so that the entrance pupil is focused at the image plane before the objective is installed.

193 nm Excimer Laser
- Free running un-narrowed spectrum

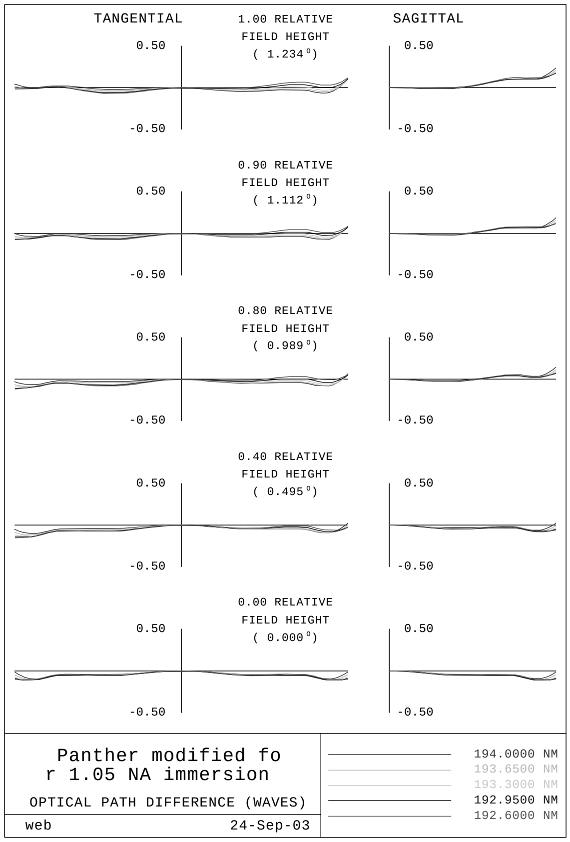


Figure 4 Optical path difference (OPD) - plano interface

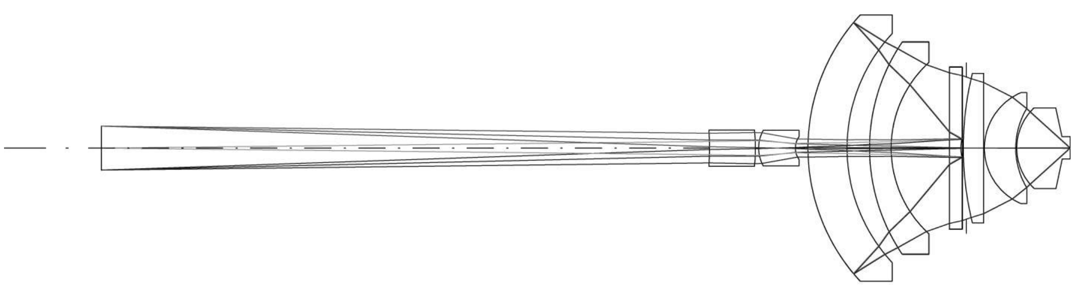


Figure 5 Finite conjugate AquaCat™

The objective is part of an optical system that includes a beam delivery and illumination system and is installed into a Micro-stepper[4]. See Figure 6. The system will be used to study resist image characteristics for hyper-NA using various illumination and polarization techniques.

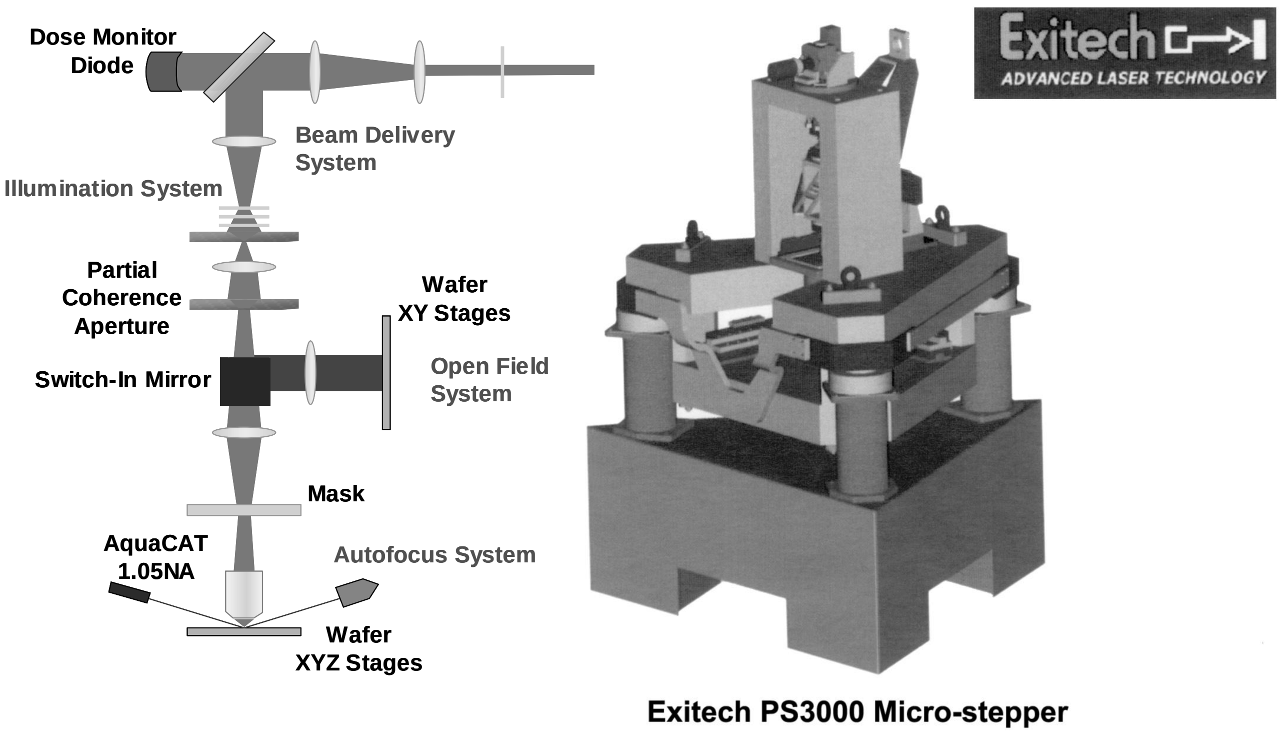


Figure 6 Exitech Micro-stepper

Collaborative experiments[4] were performed to determine the optimal element shape for immersion fluid retention. Several element styles were provided to Rochester Institute of Technology (RIT) researchers to determine the best shape for fluid adherence to the plano surface of the lens. The surface shape with sharp corners was chosen. See Figure 7.

Figure 8 shows a sequence of photos where the element exhibits good wetting characteristics. A bead of water is contained by the sharp edges and the plano face of the fused silica element and is repelled off by the resist. Clearly the element is hydrophilic and the resist coated silicon wafer is hydrophobic.

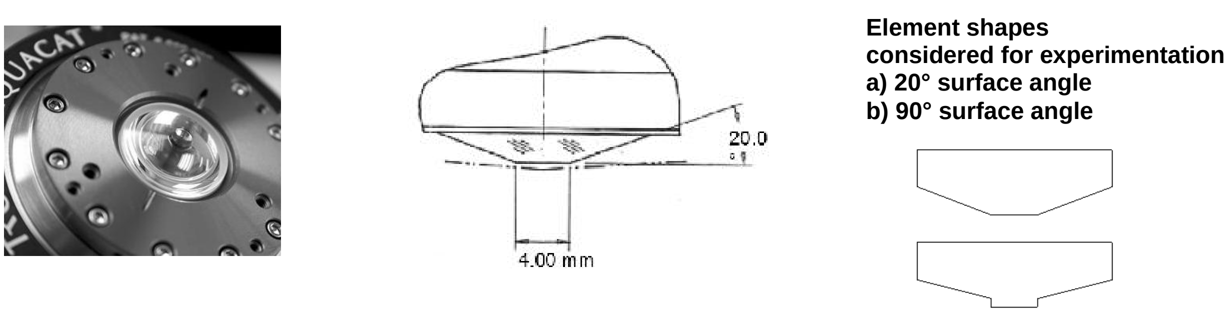


Figure 7 Element shapes considered for Immersion

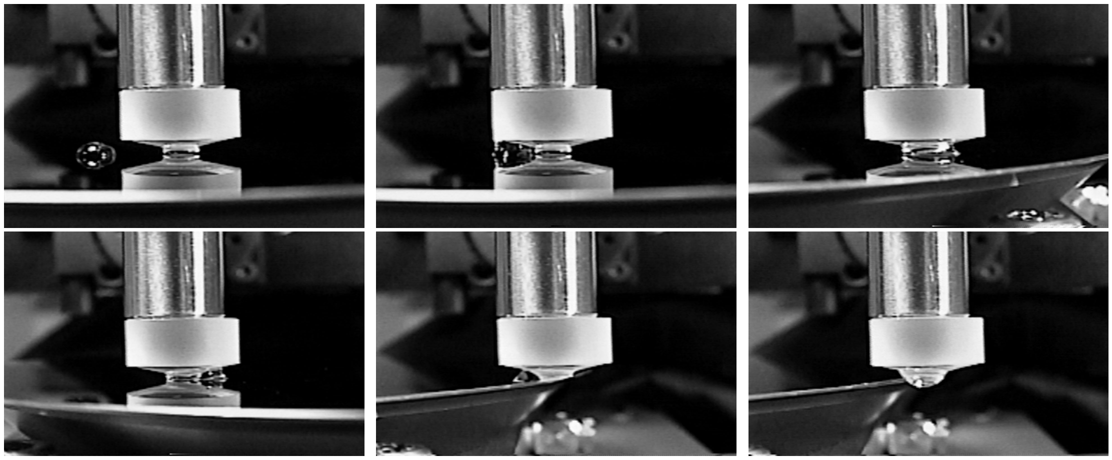
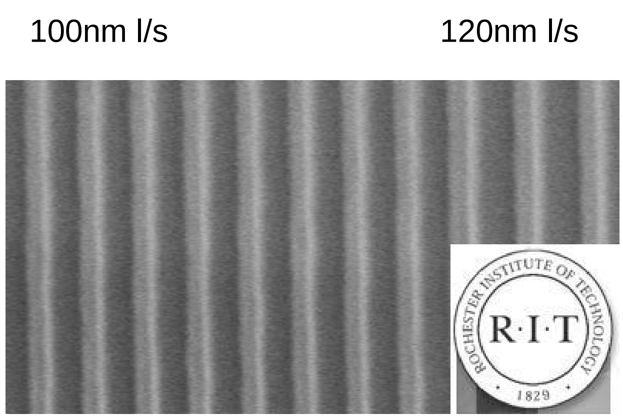


Figure 8 Element shapes considered for Immersion

Corning Tropel is working jointly on this program with RIT and Exitech Ltd. to establish RIT as a technology center for immersion research. Early results on the tool have shown that it is possible to resolve 100 nm lines and spaces without illumination or polarization enhancement techniques. (See Figure 9)



100nm l/s, binary mask, 0.7 sigma, TOK ILP-03 resist, Brewer ARC29A, TSP-03 topcoat

Figure 9 binary mask images of equal lines and spaces

5. AQUACAT™ WITH CONCAVE SURFACE INTERFACE

RIT[4] has demonstrated that it is possible to further increase the numerical aperture by using alternative transmissive immersion fluids with higher index of refraction at 193 nm using Smith-Talbot interference lithography[4]. Resist images smaller than 40 nm have been formed.

To explore the full advantage of fluids with higher indices, a variation of the AquaCat™ design allows the last surface to curve to a concave shape. Although the index difference between fused silica and water is small compared to and air, even small index mismatches can introduce large aberrations. When the rays exiting the last surface of the lens are precisely normal to the surface (see Figure 10) then refraction and hence aberrations are absent. This is strictly true on axis, but is tolerable within the wavefront specification over a restricted field of view.

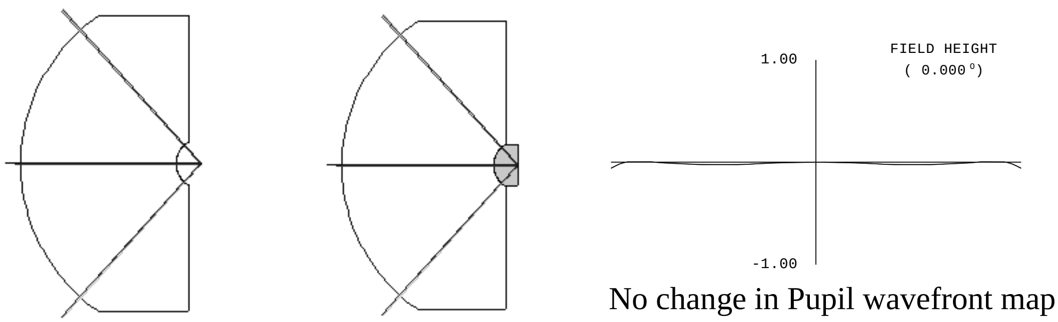


Figure 10 The concave surface normal to exiting rays does not refract

A 193 nm immersion design with the index fluid varying over a range from 1.44-1.74 is shown in Figure 11. A Panther MicroCat™ objective is used with an additional element as shown. This element is *nearly* concentric to reduce ghost reflections and balance correction over an 80 μm field of view.

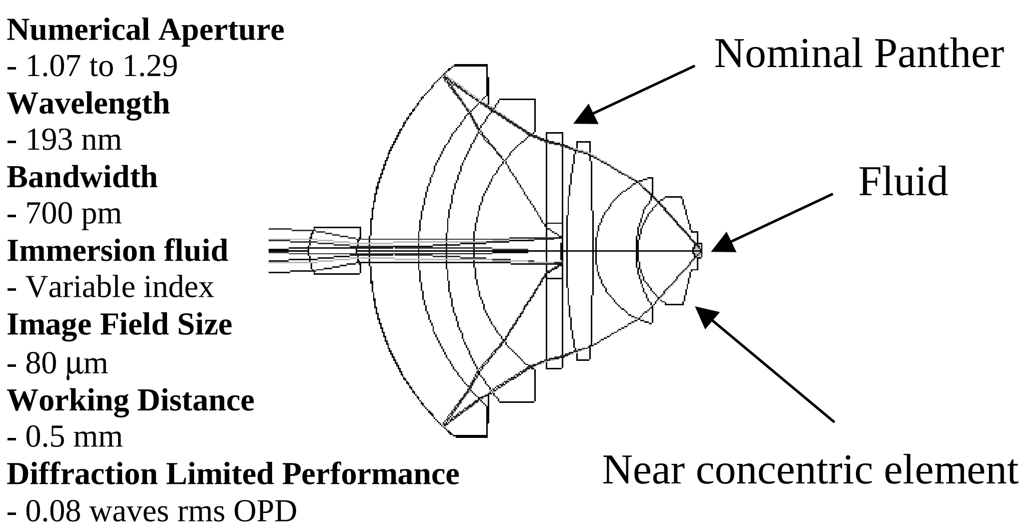


Figure 11 Immersion micro-objective with concave surface interface to fluid

In this design, the index can vary and the numerical aperture of the lens is proportional to the index of the fluid as shown in Figure 12. Correction is preserved over the range of index. The numerical aperture and thereby the resolution will both increase if a fluid can be found with high transmission at 193 nm.

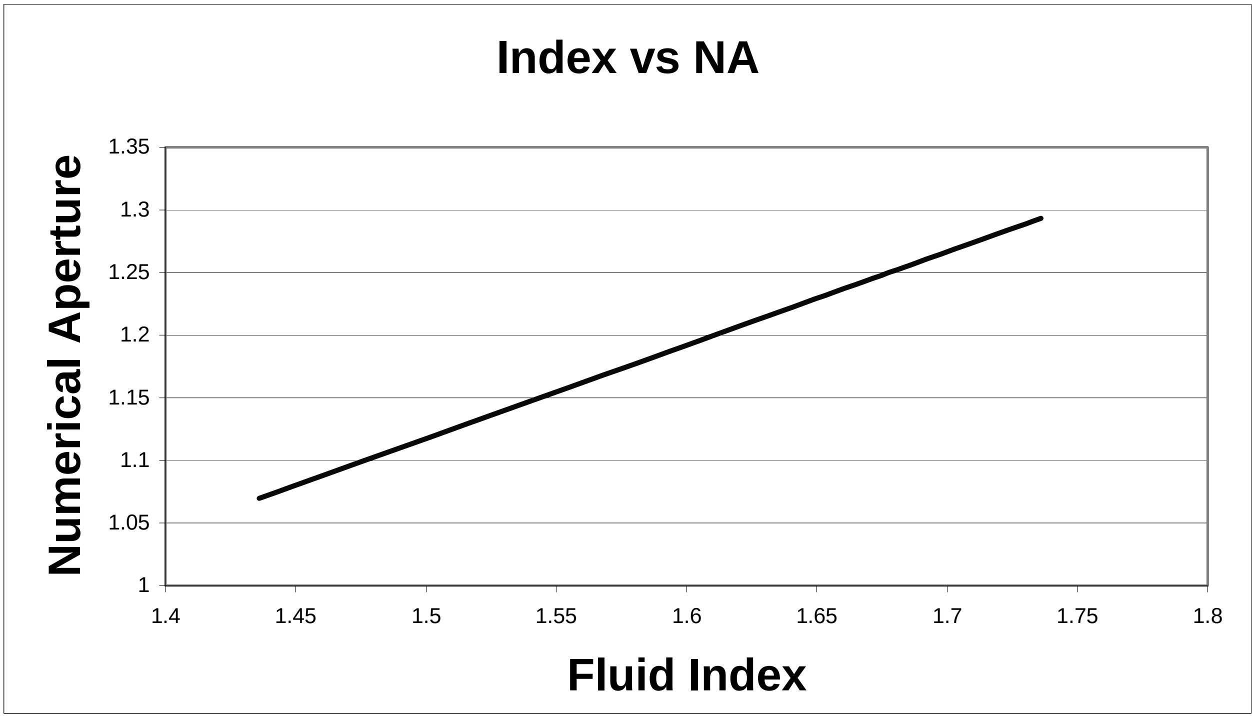
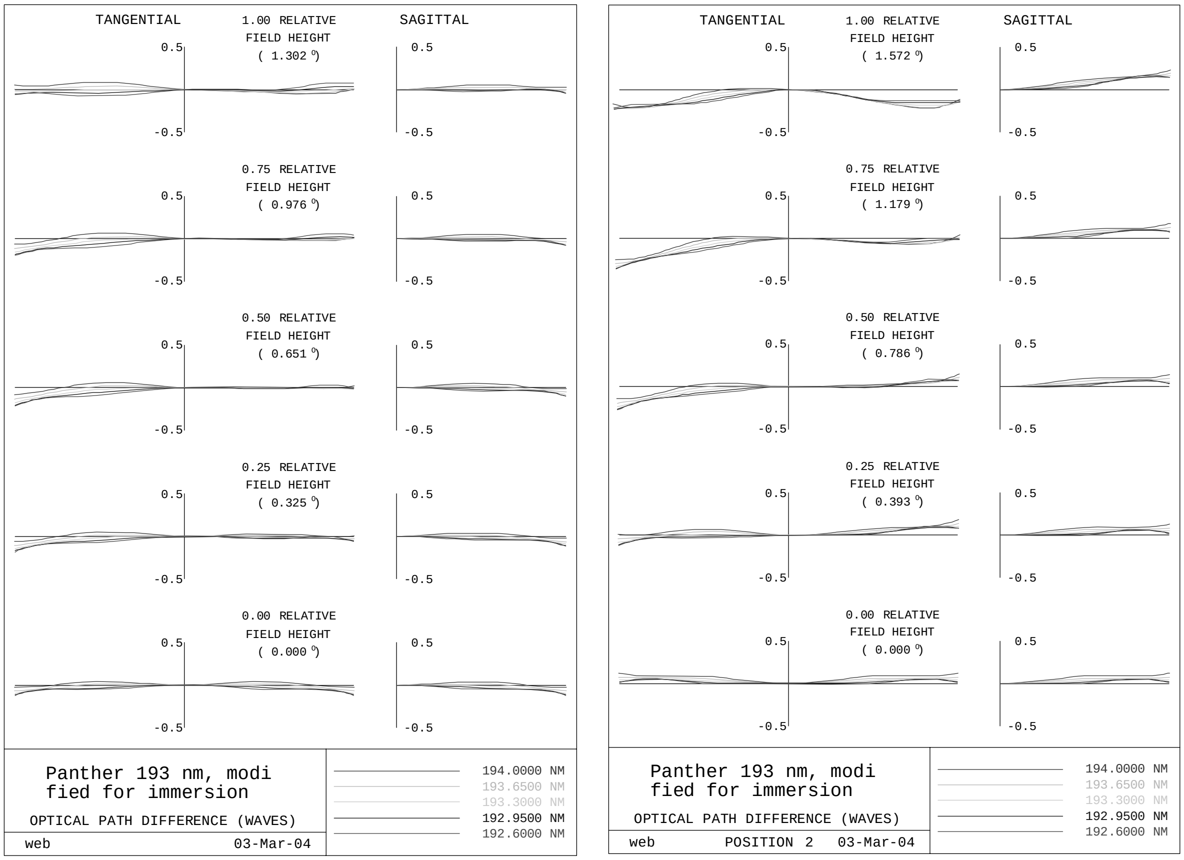


Figure 11 Fluid index vs. numerical aperture

The design wavefront at the extremes of probable index variation are examined. The two graphs (See Figure 12) show how the wavefronts vary as a function of field for these two extreme cases. Wavefront errors less than 0.08 waves rms optical path difference (OPD) can be achieved within the range of 1.44-1.74 indices over an 80 μm field of view.

193 nm EXCIMER Laser
- Free running un-narrowed spectrum



NA= 1.07, n=1.44 **NA=1.29, n=1.74**

Figure 12 AquaCat™ design wavefronts with varying index

6. CONCLUSIONS

New design solutions for immersion lithography research have been developed based on μCat® Panther objectives. Corning Tropel has manufactured and delivered a 1.05 NA 193 nm objective as part of a collaborative effort with RIT and Exitech Ltd. to demonstrate hyper NA imaging in resist. Variations of mask, illumination and polarization will be explored using this platform.

Imaging characteristics of different immersion fluids can be studied over a range of numerical apertures with this flexible design approach.

7. ACKNOWLEDGEMENTS

The authors would like to thank Bruce Smith, RIT; Malcolm Gower and Julian Cashmore, Exitech Ltd.; Dave Young, John Bruning, Lisa Rich and the litho team from Corning Tropel for their help in completing this manuscript.

8. REFERENCES

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