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Emily Finan
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Thomas D. Milster

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Optical design and system characterization of an imaging microscope at 121.6 nm

Weichuan Gao,^{a,*} Emily Finan,^a Geon-Hee Kim,^b Youngsik Kim,^a and Thomas D. Milster^a

^aUniversity of Arizona, College of Optical Sciences, Tucson, Arizona, United States

^bKorea Basic Science Institute, Division of Scientific Instrumentation, Daejeon, Republic of Korea

Abstract. We present the optical design and system characterization of an imaging microscope prototype at 121.6 nm. System engineering processes are demonstrated through the construction of a Schwarzschild microscope objective, including tolerance analysis, fabrication, alignment, and testing. Further improvements on the as-built system with a correction phase plate are proposed and analyzed. Finally, the microscope assembly and the imaging properties of the prototype are demonstrated. © 2018 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.57.3.035101]

Keywords: vacuum ultraviolet; Schwarzschild objective; alignment; phase plate; midspatial frequency error.

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1 Introduction

Research in optical microscopy is motivated by the desire to image ever smaller features. One obvious mechanism in pursuit of higher resolution is to reduce wavelength. Several extreme ultraviolet (EUV) microscopes at 13.5 nm and soft x-ray microscopes operating in the water window between 2.3 and 4.4 nm have been investigated.^{1–6} While such microscopes provide superior optical resolution, special sample preparation and complex imaging optics, i.e., Fresnel zone plates, glazing angle mirrors, or normal incidence mirrors with multilayer coatings, are required.⁶ Moreover, EUV and soft x-ray microscopes require a high-vacuum environment that encapsulates the optical system and sample.^{4,6}

The vacuum ultraviolet (VUV) Lyman- α line ($\lambda = 121.6$ nm) emission from atomic hydrogen is a promising short wavelength for microscopy, as it coincides with a transparent window in the air absorption spectrum.^{7–9} The transmission window provides flexibility in imaging samples and potentially eases system operation, as the object to be imaged can be outside the vacuum chamber. In this paper, we present the optical design and construction of a numerical aperture (NA) = 0.3 imaging microscope at $\lambda = 121.6$ nm. Details are provided for fabrication, testing, and alignment of a reflective microscope objective. Design of a phase plate for correction of residual wavefront aberration of the as-built system is proposed. Limitations and consequences of phase plate fabrication are analyzed. Optical performance of the final system is demonstrated with imaging experiments.

The availability of high-quality transmissive optical material in the VUV spectral range is extremely limited, where MgF₂ and LiF are the two materials most often used.^{7,10} However, the birefringence of MgF₂ is 4.44×10^{-3} at $\lambda = 121.6$ nm, which excludes MgF₂ for use in strongly focusing optical elements due to the excessive polarization aberration.¹¹ LiF is optically isotropic, but transmission of LiF in the VUV spectral range depends on the material

purity, growth process, polishing, storing and handling of the crystals, and is hard to maintain.¹² Thus, reflective mirrors are used as focusing elements in this system. MgF₂-coated aluminum obtains high reflectivity in the VUV band, which allows high throughput reflective optics as imaging components.¹³ A diamond turning process is used in fabricating the aluminum mirror substrate, as it offers comparable low-spatial frequency surface quality to the conventional polishing processes.^{14,15} It also allows straightforward implementation of freeform optics in the systems. Thus, this work is a test for evaluating direct diamond turning processes for VUV optical systems.

The prototype microscope system specification is summarized in Table 1. The microscope objective is designed for a moderate NA of 0.3, for which Rayleigh resolution is about 250 nm. This resolution is comparable with high-performance visible-light objective lenses. Transverse magnification of the microscope is $m_T = 53.5$. A Schwarzschild-type design with two spherical mirrors is used to provide diffraction-limited performance across the field of view.¹⁶ The objective-lens focal length is 10 mm, which is a compromise between overall system length and mirror size, where shorter systems require smaller mirrors that are more difficult to fabricate.

This paper describes details of the optical design, system engineering procedure, and challenges in constructing the imaging microscope prototype. Section 2 lists the detail on the optical design and tolerance analysis of the imaging system. Section 3 provides a discussion on system photon budget. Section 4 presents the fabrication, testing, and alignment of the microscope objective. Based on the as-built performance, Sec. 5 proposes the design of a phase plate to correct residual wavefront error of the as-built system, and performances of such correction plate designs are analyzed. Section 6 describes construction of the prototype microscope and discusses imaging results, and Sec. 7 lists the conclusions from this work.

*Address all correspondence to: Weichuan Gao, E-mail: weichuan@optics.arizona.edu

Table 1 System specification.

Configuration	Schwarzchild
Wavelength	121.6 nm
Source spectrum FWHM	3 pm
Objective conjugate	Finite
Transverse magnification	53.5×
Field of view (object)	$\pm 50\ \mu\text{m}$
NA	0.3
Focal length	10 mm
Radius of primary mirror	36.780 mm
Radius of secondary mirror	12.668 mm
Mirror spacing	23.928 mm
Clear aperture of primary mirror	28.6 mm
Clear aperture of secondary mirror	6 mm
Central obscuration fraction	0.4
Total length	545 mm
Temperature	20°C
Pressure	100 mTorr

2 Prototype Optical Design

The prototype optical system layout is shown in Fig. 1. The concave primary mirror and convex secondary mirror are placed so that minimal spherical aberration, coma, and astigmatism are generated. Light from the source (High Brightness VUV Lamp, UV Solutions, Inc.) is reflected from a beam splitter (BS), which is a 2.5-mm-thick MgF_2 (VUVBS-45-1D, Acton Optics). After transmission through the objective lens, reflection from the object is collected by the objective lens, and the imaging path passes through BS and a narrowband VUV filter (FN122-N-.5D, Acton Optics) toward the camera (iKon-M SO, Andor). To maximize illumination efficiency, the spatially extended source is directly imaged onto the sample plane as critical illumination within a $100\text{-}\mu\text{m}$ -diameter area. Transmission through BS introduces a small amount of polarization aberration to the image formation, but the induced aberration for an unpolarized source from a 2.5-mm-thick c-cut MgF_2 plate oriented at 45 deg produces only a 0.06 reduction in Strehl ratio, which has negligible impact on system performance.

RMS wavefront error versus field height is shown in Fig. 2(a). Although the system exhibits plane symmetry due to the tilted BS, asymmetric wavefront perturbations are very small across the field. As shown in Fig. 2(b), a small amount of astigmatism is produced by the weak converging beam passing through the tilted BS. Figure 2(c) indicates that the designed system performance is well within the diffraction limit for the $\pm 50\text{-}\mu\text{m}$ field of view.

Tolerance analysis is performed with CODEVTM optical design software before defining fabrication specifications of

Fig. 1 Optical layout of the system. The incoming illumination path from the source is not shown. **Fig. 2** Optical performance: (a) RMS wavefront versus field, (b) spot diagram at center of field, and (c) spot diagram at periphery of the field. Black circles indicate the Airy disk size.

Fig. 3 Inverse sensitivity analysis of the objective lens assembly

Table 2 Fabrication and alignment tolerance analysis.

Tolerance parameter	Value
Radius of curvature	± 0.1 mm
Surface figure error	5-nm RMS
Mirror decentering	± 0.003 mm
Microroughness (RMS)	<2 nm
TIS	4.2% primary 3.8% secondary

the optical and mechanical components. Compensators include defocus, spacing between mirrors, clocking angle, and lateral displacement of the secondary mirror. Spacing among mirrors is adjusted with a precision metal spacer. The clocking angle between primary and secondary mirrors is optimized during the alignment process. The lateral displacement of the secondary mirror is achieved by precision adjustment screws.¹⁷ Errors in mirror radii are compensated with defocus and spacing between the two mirrors. The mirror wedge (usually interpreted as total indicator runout) and decentering, which are coupled for spherical-shape mirrors, are compensated with lateral displacement of the secondary mirror.¹⁸

Reflective elements used at 121.6 nm are extremely sensitive to residual surface figure errors from the fabrication process. For the tolerance analysis simulation, low-spatial frequency surface figure error is represented using astigmatic surface departure. As shown in Fig. 3, inverse sensitivities are analyzed for the as-built system with a 90% likelihood for diffraction-limited performance across the object field. Table 2 indicates the fabrication and alignment tolerances.

3 Photon Budget Analysis

A simple radiometric analysis is carried out to determine photon efficiency of the optical system. A 50% transmission efficiency is assumed for the MgF_2 lens (LA6006, Thorlabs) that is used to collimate the diverging beam from the VUV

lamp. BS is specified to have 25% transmission and 32% reflectance. Assuming the illumination beam is uniform and matches the entrance pupil of the objective, the central obscuration fraction is 0.4, which provides 84% transmission. Mirrors and testing samples are coated using an in-house coating chamber, for which 20% reflectance was measured in a separate experiment. With the EPI configuration, transmission efficiencies from the source to the object and from the object to the detector are about 0.54% and about 0.84%, respectively. In the optical system design, critical illumination and transverse magnification adjustment are used to partially address this low-efficiency issue. The VUV lamp is specified to emit a beam with a 3-deg to 5-deg divergence angle with about 10 mW/pulse and 1-kHz repetition rate. Assuming the source emission has a 4-deg diverging angle, the beam after the collimating lens has a diameter of 6.3 mm. The transmission loss through the smaller 6-mm entrance pupil is about 10%. The resulting illumination onto the object is about $48.6 \mu\text{W}/\text{pulse}$. A highly reflective mirror sample offers 20% reflectance. The narrowband VUV filter has 15% transmission, and the CCD detector has a quantum efficiency of about 3% at $\lambda = 121.6$ nm. Therefore, imaging from a highly reflective mirror sample produces 2.25×10^{11} detected photons per second across the imaging area in the detector with a 5.4-mm-diameter circle. With 13- μm pixel pitch, the detected photon flux is 1.66×10^6 /pixel/s. Signal-to-noise ratio calculated under current experimental condition with typical integration time (160 s) and binning factor (4×4) is 1.6×10^5 .

4 Fabrication, Testing, and Alignment

The fine-grain-sized RSA-6061 aluminum alloy primary mirror and secondary mirror are fabricated with direct diamond turning (Nanotech 450 UPL). Figure 4 shows the surface figure of the fabricated mirrors tested with a laser Fizeau interferometer (Zygo Verifire ATZ). The primary and secondary mirrors have RMS surface figure errors of 0.028λ and 0.011λ , respectively, at 633 nm, which translate to 17.7 and 7.0 nm in RMS surface height variation, respectively, as listed in Table 3. Cylindrical power polarities observed on the surfaces suggest that the clocking angle between the primary and secondary mirrors can be used to improve system performance. The radii and diameter of mirrors are measured with a contact surface profilometer (Form Talysurf Series 2, Taylor Hobson) and a coordinate measuring machine (CONTURA G2, Carl Zeiss). Radii of the mirrors are fabricated within specification, but the surface figure error and microroughness listed in Table 3 are out of specification. The figure error on the primary mirror (17.7-nm RMS) is more than three times the specification value (5-nm RMS) and results in significant degradation in image quality. Surface microroughness is limited by the diamond turning fabrication process and the substrate material properties.^{14,15} The 2-nm specification in Table 2 introduces transmission loss through 4.2% scattering on the primary mirror and 3.8% on the secondary mirror as defined by total integrated scatter (TIS).^{17,19} Further analyses for the bidirectional reflectance distribution function (BRDF) of the mirror surface are necessary if the nonspecular angle-dependent reflectance change contributes to the image artifacts.²⁰ As the current system performance is primarily limited by the surface figure errors, BRDF analysis is not performed in this

Fig. 4 Surface figure of (a) primary mirror and (b) secondary mirror.

Table 3 Measurements of mirror fabrication.

Parameter	Measurement	
	Primary	Secondary
Radius of curvature	+0.09 mm ☺	+0.01 mm ☺
Surface figure error	17.7-nm RMS ☹	7.0-nm RMS ☺
Microroughness (RMS)	2.15 nm ☺	3.23 nm ☺
TIS	4.8% ☺	9.7% ☺

work. As shown in Fig. 5, the surface microroughness data (2.15 and 3.23 nm) as measured with an optical surface profilometer (NT 9800, Veeco) are larger than the specification. Table 3 lists the calculated TIS, along with mechanical parameters compared with nominal design values from Sec. 2.

Fabrication of the mirror cell, as shown in Fig. 6, proceeds by assembling the mirrors sequentially. The primary mirror is fixed using urethane (D-50, Hardman) through six glue channels on the primary mirror cell. The primary mirror cell is roughly centered and fixed in the objective barrel using four adjustment screws (100 threads/in.). Spacing between primary and secondary mirrors is optimized using

measured data, and a metal spacer is prepared with the desired thickness. The secondary mirror is mounted on the spider, and the spider is mounted on the secondary mirror cell. Alignment features are marked on the mirror cells to indicate the correct clocking orientation, so that clocking angle among the mirrors can be optimized.

The first step in the fine alignment of the objective lens is achieved with a custom point source microscope (PSM) on a lens centering station.^{21–23} Position of a reference point on the PSM CCD sensor is first determined by a retroreflector. The optical axis of the PSM is then aligned with the rotation axis of an air bearing. Then, the center of curvature of the primary mirror is reimaged to the reference point on the CCD. After inserting the spacer and the secondary mirror subgroup, centration of the secondary mirror is adjusted by six fine adjustment screws (254 threads/in.) until the focus of the two-mirror system is also reimaged to the reference point on the CCD. Alignment on the lens centering station is followed by fine-tuning wavefront performance with a laser Fizeau interferometer. A collimated beam from a transmission flat passes through the objective lens and focuses at the center of curvature of the reference sphere. The retroreflected rays from the reference sphere pass through the objective again to interfere with the plane wavefront reflected from the transmission flat. Final alignment is done by slightly rotating the angle of the secondary mirror and fine-tuning the adjustment screws until the RMS wavefront error is minimized.

Fig. 5 Surface roughness of (a) primary mirror and (b) secondary mirror.

Fig. 6 Optomechanical design of the objective lens.

Since the infinite conjugate arrangement used during testing with the Fizeau interferometer is different from what is used in the application, the calculated change in spherical aberration is subtracted from the interferometric testing result. The resulting transmission wavefront from the two-mirror system is shown in Fig. 7. Cylindrical power from the primary mirror is the main residual wavefront error. Results from the reoptimized model, which incorporate surface measurements, and the as-built system show good agreement. In the reoptimized model, the simulated single-pass transmission wavefront has a $P - V$ of 151 nm at $\lambda = 633$ nm, which translates to 1.24 waves at the 121.6-nm application wavelength. In the as-built system, the experimental transmission wavefront has a $P - V$ of 210 nm at $\lambda = 633$ nm, which translates to 1.6 waves at $\lambda = 121.6$ nm. Compared with the nominal system design point spread function (PSF), which has a Strehl ratio of 0.955, both the reoptimized model and the as-built system fail to focus the energy inside a tightly localized region. The PSFs of the reoptimized model and the as-built system have a Strehl

ratios of 0.138 and 0.117, respectively, at $\lambda = 121.6$ nm. Although this objective lens would perform well for visible wavelengths, it does not meet design expectations for hydrogen Lyman- α (HLA) applications.

5 Design of a Phase Corrector

Although resurfacing the mirror substrates to improve the surface figure might be possible, experiments show that better results are difficult to achieve with direct diamond turning. An alternative for improving imaging performance and improving the signal-to-noise ratio is to add a phase corrector designed with an MgF_2 material pattern deposited on 0.5-mm-thick MgF_2 plane parallel plate. The optimal position of the phase corrector is at the pupil or toward the high magnification end of the system, so that the chief ray height is minimized on the plate and field-independent correction is achieved. Placing the corrector inside the focusing cone is prohibited for this system, because the MgF_2 birefringence generates significant polarization aberrations. Due to the nature of the mechanical design, as shown in Fig. 6, the

Fig. 7 Transmission wavefront (in waves, $\lambda = 121.6$ nm) and PSF of (a) and (d) the nominal design, (b) and (e) the reoptimized model, and (c) and (f) the as-built system, respectively.

Fig. 8 Simulation results for the correction plate designs: (a), (b), and (c) are 4-level corrector; (d), (e), and (f) are 8-level correctors; (a) and (d) phase corrector; (b) and (e) residual wavefront error (in waves, $\lambda = 121.6$ nm); (c) and (f) on-axis PSF of the corrected system.

only mechanically accessible area for the corrector is beyond the objective barrel.²⁴ Since the phase correction is optimized for on-axis wavefront performance, off-axis rays carry undesired phase perturbations. In the simulation, the corrector plate preserves good wavefront correction over a field of view of ± 10 μm in the object plane, which is a factor of 5 reductions compared with the designed field of view.

The phase corrector is designed with 4- and 8-level approximations to the ideal continuous phase function. Phase corrector design, residual wavefront errors after the correction, on-axis PSFs, and encircled energy plots are shown in Figs. 8 and 9.

The $P - V$ of the as-built transmission wavefront is 210 nm without correction, which is greater than one wavelength at $\lambda = 121.6$ nm, so a wrapped phase design is also considered with a maximum thickness corresponding to one wavelength of optical path difference. The wrapped phase

plate designs and the simulated performance are shown in Fig. 10. Strehl ratios and RMS wavefront errors of corrector-plate designs are compared with the ideal continuous phase function in Table 4.

The residual wavefront error after applying the phase corrector resembles midspatial frequency (MSF) errors.^{25–28} The step height of the phase plate is on the order of several tens of nanometers, which is comparable with the depth of the high-spatial frequency tooling marks generated from a single-point diamond turning machine, as shown in Fig. 5. It is known that MSF errors decrease low-spatial frequency contrast and broaden the system PSF. Effects on tangential and sagittal MTF of the on-axis field and image simulations are shown in Fig. 11. From the MTF plots, the 8-level wrapped corrector offers the best correction followed by the 8-level, the 4-level wrapped, and the 4-level correctors. With the 8-level wrapped corrector, 42.2% of the energy is focused

Fig. 9 Encircled energy with different system configurations at the image plane.

Fig. 10 Simulation results for the 2π wrapped correction plate designs: (a), (b), and (c) are 4-level wrapped corrector; (d), (e), and (f) are 8-level wrapped correctors; (a) and (c) phase corrector, (b) and (e) residual wavefront error (in waves, $\lambda = 121.6$ nm); (c) and (f) on-axis PSF of the corrected system.

Table 4 Summary of the correction phase plate designs.

Phase plate	Step height (nm)	Residual RMS wavefront error (nm)	Strehl ratio of on-axis PSF
None	—	—	0.117
4-level	80	22.5	0.531
8-level	40	11.4	0.757
4-level wrapped	48	13.9	0.640
8-level wrapped	24	6.9	0.850

within the Airy disk diameter as indicated by the encircled energy plot in Fig. 9. With the 8-level, the 4-level wrapped, and the 4-level correctors, 37.8%, 32.0%, and 27.2% of the energies are focused within the Airy disk diameter, respectively. During fabrication, fiducial markers can be fabricated with the phase pattern onto the substrate for alignment.

Tolerance analysis of the phase corrector is accomplished with a sensitivity test considering fabrication and alignment tolerances. Fabrication tolerances are the errors generated during fabrication and measurement processes, including scaling error and height error. Alignment tolerances are the errors generated during the alignment process, including centration error, tilt error, and error in the clocking angle. The tolerances of the five parameters are simulated individually, and the resulting Strehl ratios are compared with the unperturbed systems with the 8-level and the 8-level wrapped phase correctors, as shown in Table 5.

Scaling error is defined as errors in the transverse dimension. This error is the difference between the simulated pixel size and the actual pixel size of the fabrication tool. Linear scale errors cause the fabricated phase corrector size to be different from the simulation size, which is a nonunity scaling factor. From Table 5, the scaling factor error has a high sensitivity, which indicates that the transverse dimensions should be consistent throughout the measurement and fabrication process within $\pm 3\%$ accuracy.

Height error is defined as errors in the depth dimension. This error is primarily generated from the fabrication process. It can be minimized by calibrating the deposition rate for each step. The system performance with $\pm 10\%$ height error indicates a relatively low sensitivity on the control of the depth dimension, which simplifies the fabrication process.

The centration, tilting, and clocking angle errors all come from the alignment process. Simulations show that alignment marks and adjustment mechanisms are needed to precisely control the phase plate position.

6 Imaging System Characterization

The imaging microscope is contained in a housing made from off-the-shelf vacuum components. As shown in Fig. 12, the illumination path is reflected from BS. The imaging path passes through BS toward the camera. Two sets of filters are mounted in the imaging path, where certain bands of wavelengths are selected by moving the filters with a linear motion vacuum manipulator. One filter includes a narrowband VUV filter and the other filter includes the same narrowband VUV filter and a sapphire window (AQSP1230OW, eSource Optics). The filter with a sapphire window blocks wavelengths < 150 nm. The Lyman- α image

Fig. 11 Tangential and sagittal MTF of the corrected system and image simulation. (a) and (e) 4-level, (b) and (f) 8-level, (c) and (g) 4-level wrapped, and (d) and (h) 8-level wrapped.

Table 5 Summary of tolerance analysis.

System perturbation	Tolerance	Strehl ratio (8-level)	Strehl ratio (8-level wrapped)
Nominal	—	0.757	0.850
Scaling	+3%	0.415	0.473
	−3%	0.544	0.600
Height	+10%	0.680	0.791
	−10%	0.750	0.826
Centration	+X50 μm	0.620	0.730
	+X100 μm	0.413	0.513
Tilt	+5 deg	0.490	0.458
Clocking (around z-axis)	+5 deg	0.670	0.781
	−5 deg	0.658	0.772

is then calculated by subtracting the two images obtained through each filter set.

A high-reflectance tribar sample is used as the imaging target. Preliminary imaging tests are shown in Fig. 13. The tribar structure is fabricated with 1- μm -height photoresist coated with aluminum. Measured contrast is generated from the high-reflectance sample from the phase shift at the edges of the structure. The noisy HLA image and cross section indicate that the signal-to-noise ratio is not

Fig. 12 The image path CAD model of HLA microscope.

as high as the calculation in Sec. 3. The light source output is sensitive to the gas mixture flowing into the lamp and is likely to be one of the reasons for the increased noise, where the output power is much less than the specification. Fabrication errors also contribute to the degradation of the image quality, as discussed in Sec. 5. The camera is designed for higher energy photon detection and has much lower quantum efficiency at the HLA-VUV wavelength. In addition, the camera exhibits a fixed pattern noise due to ice formation in a previous experiment. Quantifying the contrast by $\frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$, across a field of view of 50 μm , the 3-edge cross section of the HLA image has an average contrast of 0.76, which is higher than the average image contrast of 0.58 from the 50 $\times$ standard microscope.

Fig. 13 Tribar images with (a) the VUV microscope (160-s exposure, 4×4 binning) and (b) a standard microscope (50 $\times$).

7 Conclusion/Discussion

This paper demonstrates the optical design and system characterization of a prototype imaging microscope at 121.6 nm. Optical design, fabrication, alignment, and testing of a reflective Schwarzschild microscope objective are discussed. Due to fabrication defects of the primary mirror, the as-built optics fail to deliver diffraction-limited performance as designed. Implementation of a phase correction plate is thus proposed to correct the as-built system. To maintain the manufacturability, a multiple-level approximation is applied in the design of the correction phase plate. The discrete steps in the residual wavefront error in the corrected system resemble the MSF errors from tool marks. Their effect on the system transfer function and the PSF is simulated with optical design software. The sensitivity study on the correction phase plate corresponding to different perturbations provides insights into the mechanical design of the phase corrector mount and tooling. Also, it guides the alignment procedure with emphasis on placing higher priority in tighter tolerances.

The imaging experiment demonstrates the potential of the HLA microscope. To further improve the image quality, better quality optical components and a higher intensity source are critical and will be included in our future work.

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Weichuan Gao is a PhD candidate at the College of Optical Science, the University of Arizona. His primary research involves the development of optical design methods and aberration theory.

Emily Finan is pursuing his PhD at the College of Optical Sciences, the University of Arizona. With a background in physics from the University of Tennessee, her current research in optical engineering focuses on the design, implementation, and testing of adaptive optics systems.

Geon-Hee Kim received his PhD in mechanical engineering at Chungnam National University in 2003. He joined as a principal researcher fellow at Optical Instrumentation Research Center, Korea Basic Science Institute (KBSI) in 1993. His current research interests focus on the areas of biomechanics, optical devices, and ultra precision manufacturing.

Youngsik Kim is currently working for the College of Optical Sciences, the University of Arizona. For the past over 20 years, he

has published over 20 articles in scientific publications and over 135 patents relating to imaging science, spectroscopy, photonics, optical engineering, optical inspection, illumination, optical data storage, microscopy, lithography, camera lens, display, interferometry and diffraction, through Philips Electronics and LG Electronics he worked prior to the university.

Thomas D. Milster graduated with a BS degree in electrical engineering at the University of Missouri-Rolla in 1981 and his PhD in optical sciences from the University of Arizona in 1987. He worked for IBM Corporation and then joined the University of Arizona in 1989. He teaches physical optics and has active research programs in microscopy, lithography, diffractive optics, and data storage. He is a fellow of the SPIE and the Optical Society of America.