# *Maskless EUV Lithography*

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(Revised 6/27/2019. Full paper is in progress, will be submitted to JM$^3$.)

# Presentation Outline

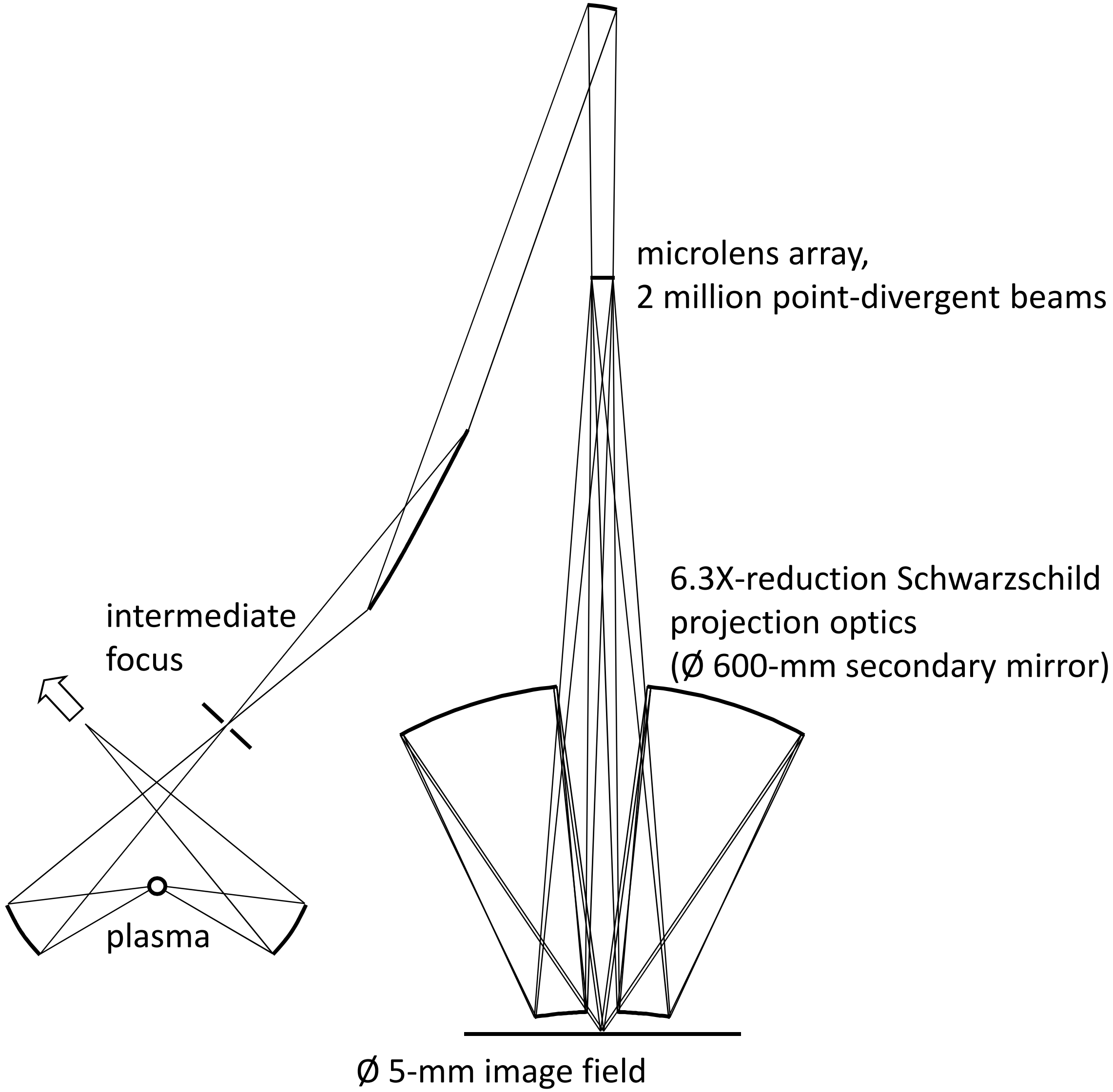
1. Target performance characteristics for Maskless EUV
2. System optics
3. EUV microlenses
4. Optical modulation
5. Scanning
6. Summary/Conclusions

# Performance Targets
# Maskless vs. Mask-Projection EUV

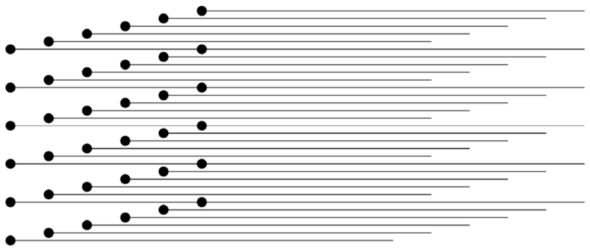
| | Mask-Projection (NXE) | Maskless | |
|---|---|---|---|
| Wavelength | 13.5 nm | 13.5 nm / 6.7 nm (maybe) | All design work to date has been at 13.5 nm, but the design might be adaptable to 6.7 nm. |
| NA | 0.33 / 0.55 | 0.55 | |
| Throughput | 125 wph, 300-mm | 6 hrs per 300-mm wafer<br>72 min per mask (132X104mm)<br>@ 8-nm grid step | - Pattern-dependent (e.g. use 16-by-8 nm grid for 8-nm HP lines → 3 hrs/wafer; use 4-by-4 nm grid for complex mask → 5 hrs/mask).<br>- Based on Adlyte "HPS" LPP product config with 24 kHz laser; throughput scales in proportion to laser rep rate. |
| Power | 250W @ IF, 2% band | 0.3W @ IF, 3% band | The Adlyte LPP produces much more power (e.g. 0.56W in a 0.2-Sr collection cone, 2% band @ IF; can be significantly more with increased Sr and 3% band). The power cannot be fully utilized because of etendu limitations, but the LPP power can be distributed to multiple scanners. The throughput target is per-scanner-module, could be several times higher per-source-module. |
| Exposure dose | 20 mJ/cm$^2$ | 200 mJ/cm$^2$ @ 8-nm grid | - The higher dose is due to higher optical efficiency (fewer mirrors) and probably also due to scan-reversal overhead in NXE.<br>- Pattern-dependent (e.g. up to 800 mJ/cm$^2$ @ 4-nm grid).<br>- **Advantage for Blue-X (6.7-nm wavelength): Efficiency.** |

# System optics

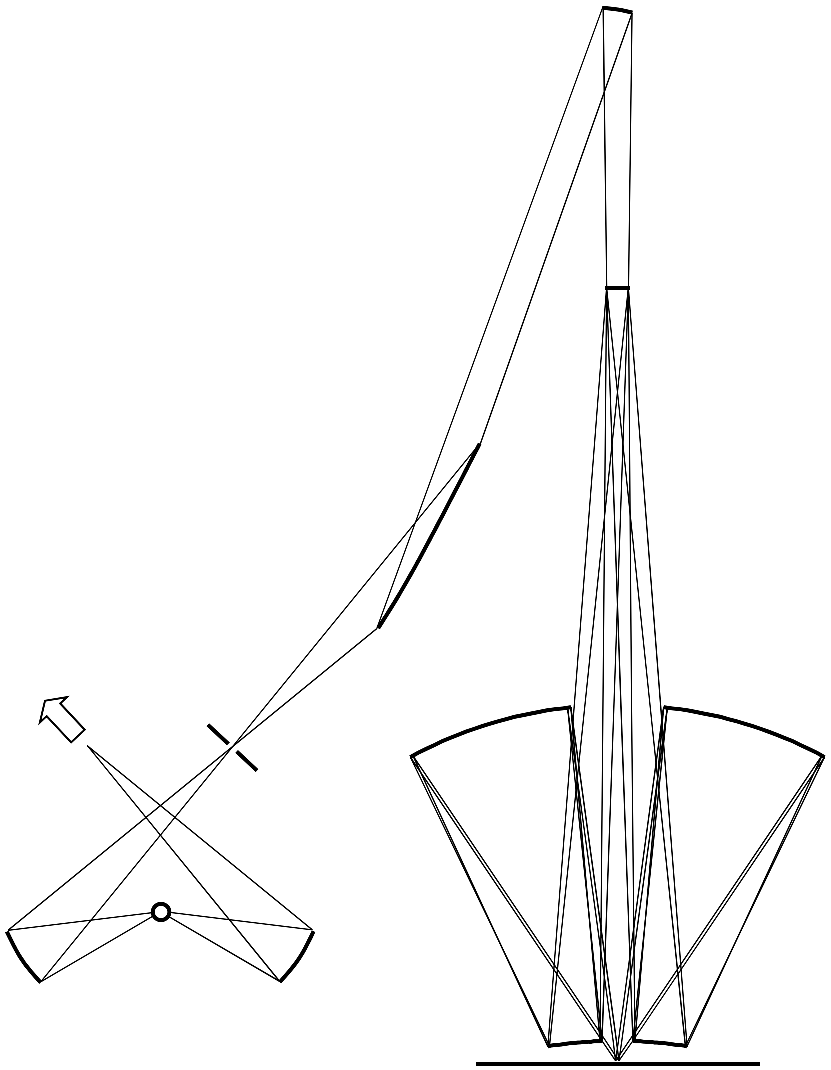
# Maskless Scanner Optics



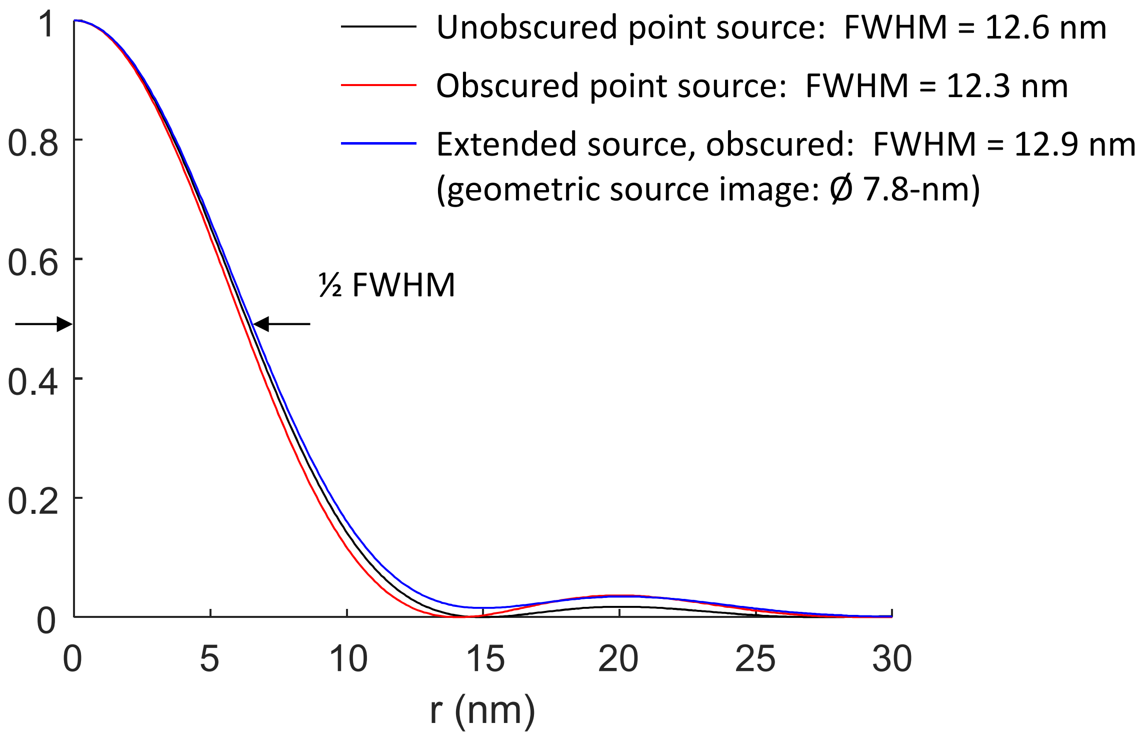

The wafer is scanned across the focal-point array as the points are modulated by MEMS shutters in the microlens array:



# The focus spots are diffraction-limited with a 12.9-nm FWHM.

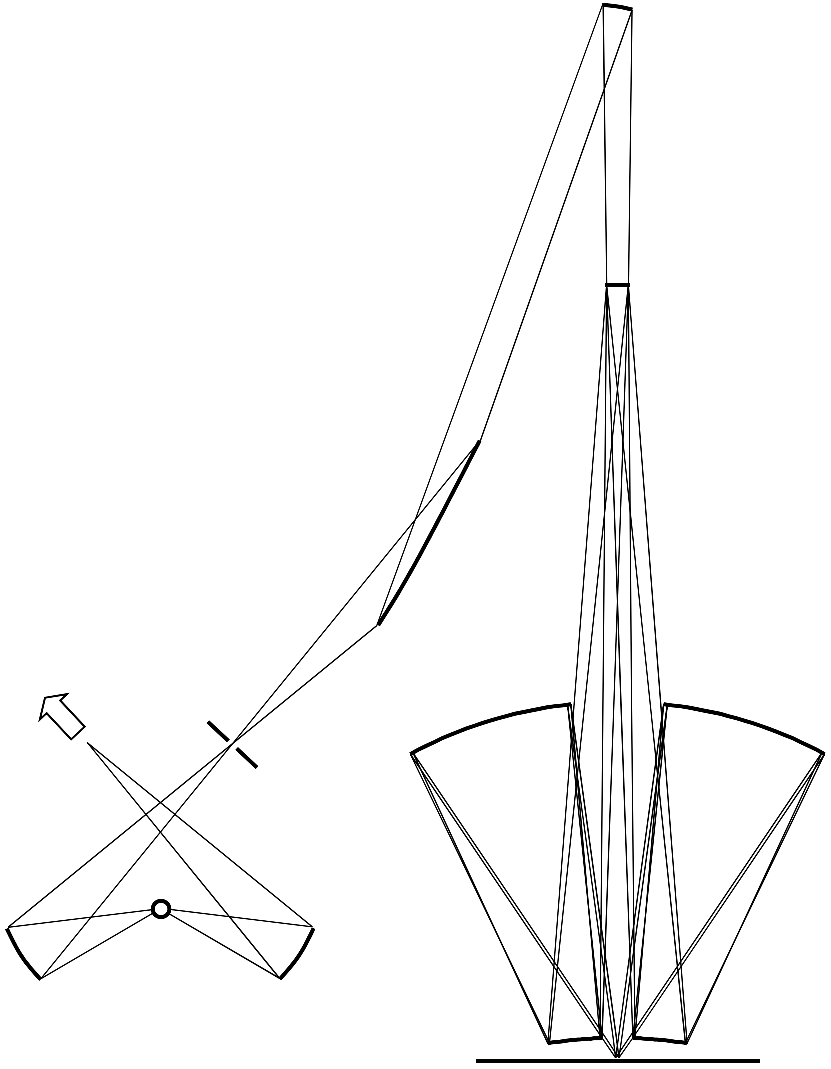


Diffraction PSF @ λ = 13.5 nm, NA = 0.55:

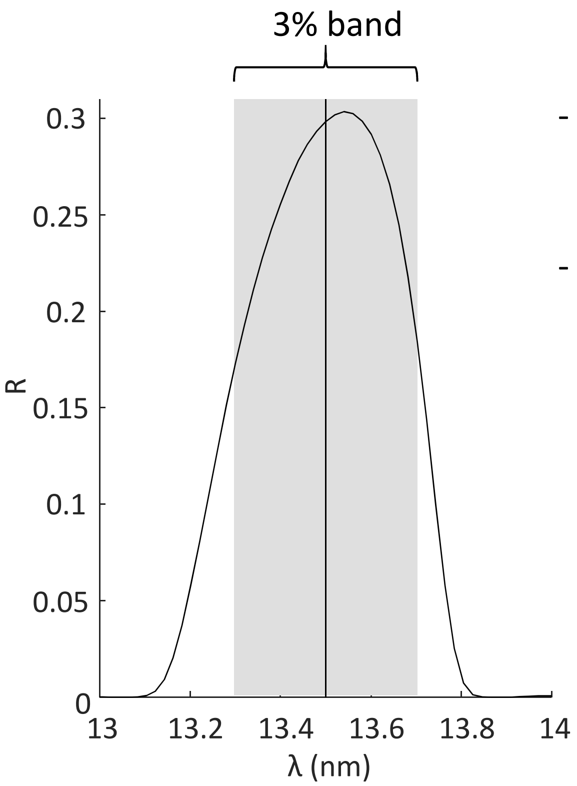



- The primary mirror's inner aperture is NA 0.132 (6% obscuration).
- Unlike mask-projection lithography, the diffraction tails do not interact coherently with nearby points, so their effect is relatively minimal.
- The extended source's geometric image size on the writing surface (Ø 7.8 nm) is determined to achieve the 200 mJ/cm$^2$ dose @ 8-nm grid step. The image size is controlled by an overfilled spatial filter aperture at the IF, which can be opened for higher power at the expense of lower resolution (e.g. doubling the power would increase the PSF FWHM by an additional 5%).

# The microlenses are achromatized over a 3% wavelength band to achieve diffraction-limited performance.

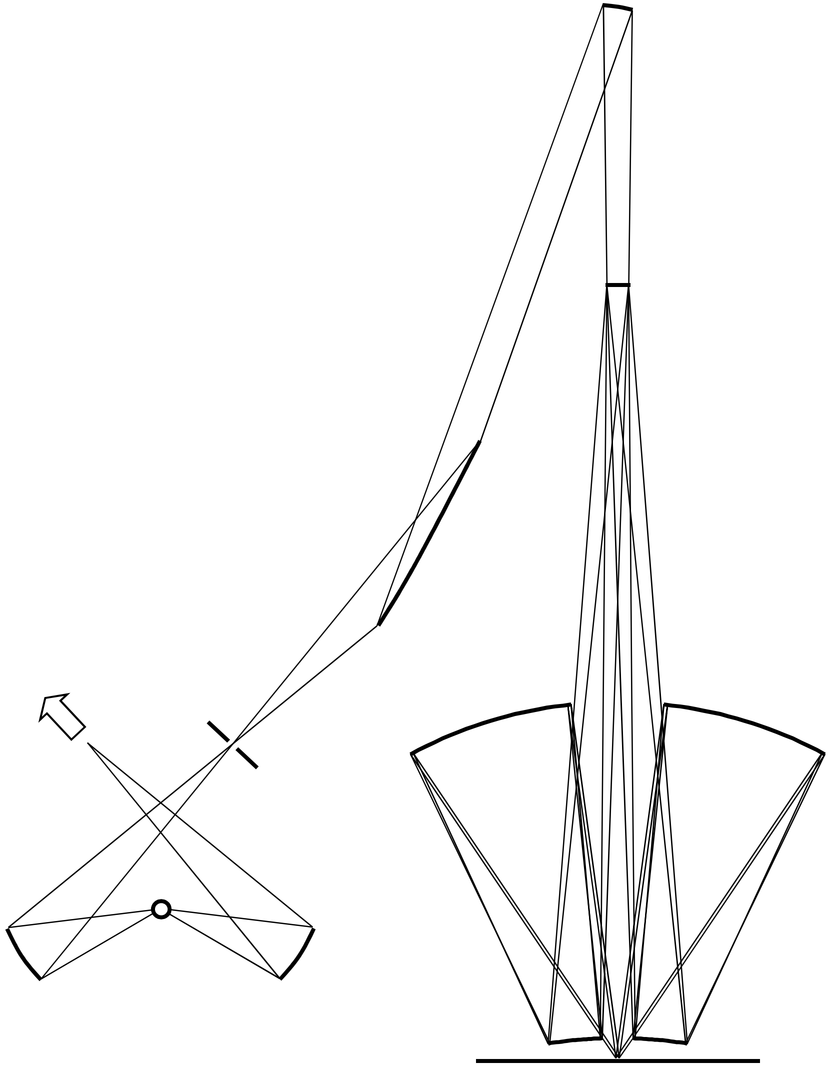


Compound reflectance of
4 near-normal-incidence mirrors:

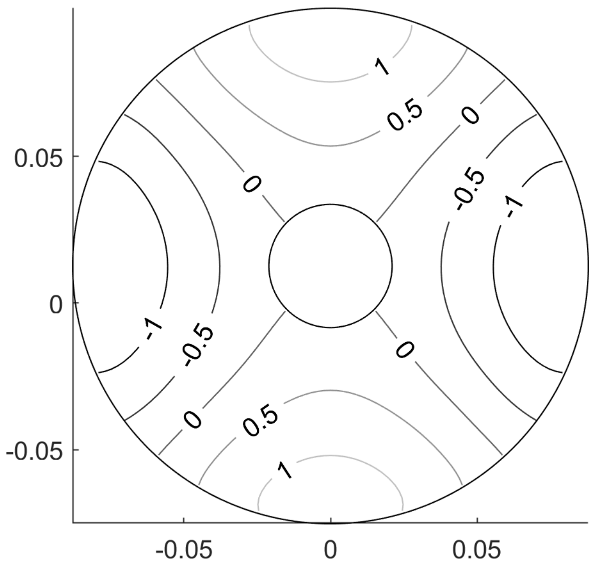



- The band is defined by 4 near-normal-incidence mirrors. (The grazing-incidence mirror and microlenses are not significantly band-limiting.)
- For Blue-X (6.7-nm wavelength) the band would be < 1%.

# The microlenses correct aberrations in the projection system – about 3 waves P-V over a 5-mm field.

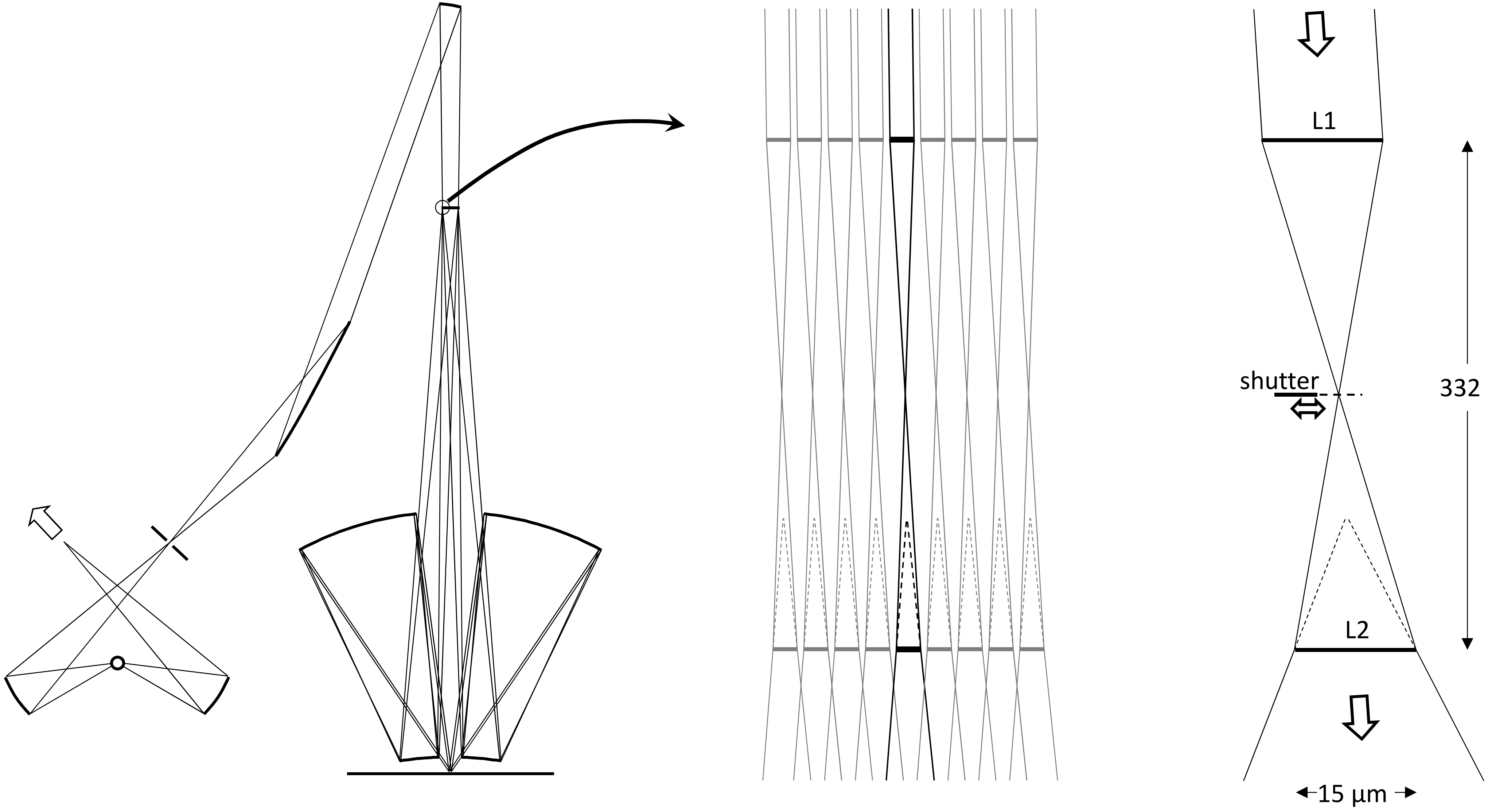


Projection optics phase aberration (wave asphericity in wave-cycle units) at edge of image field (5-mm diameter), plotted against ray direction cosines at object point:




The aberration plot is based on a reverse wave propagation from an image point at the periphery of the Ø 5-mm field back through the projection optics to the microlens array. The microlenses are designed to reproduce the exact same aberrated wavefront shape, which the projection optics will convert to a point-convergent spherical wave with zero aberration in the image space.

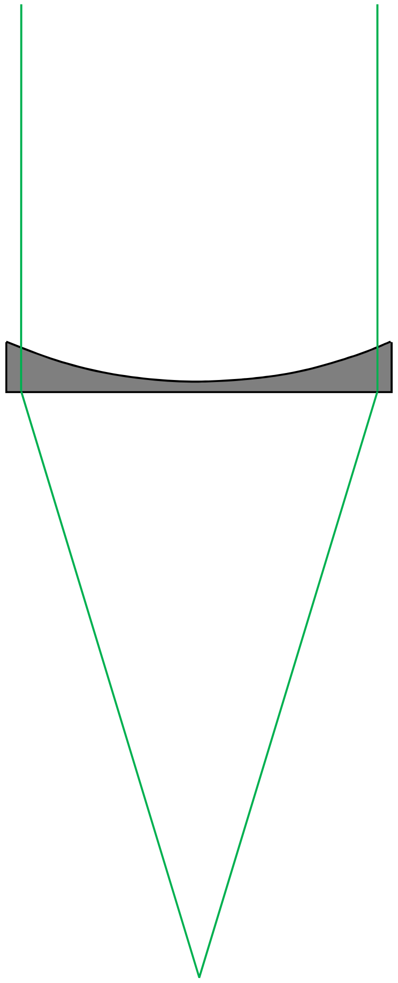
# The microlenses are Ø 15-µm, achromatic “Schupmann doublets” formed on a microchannel plate, 332-µm thick, with integrated MEMS shutters.



# EUV microlenses

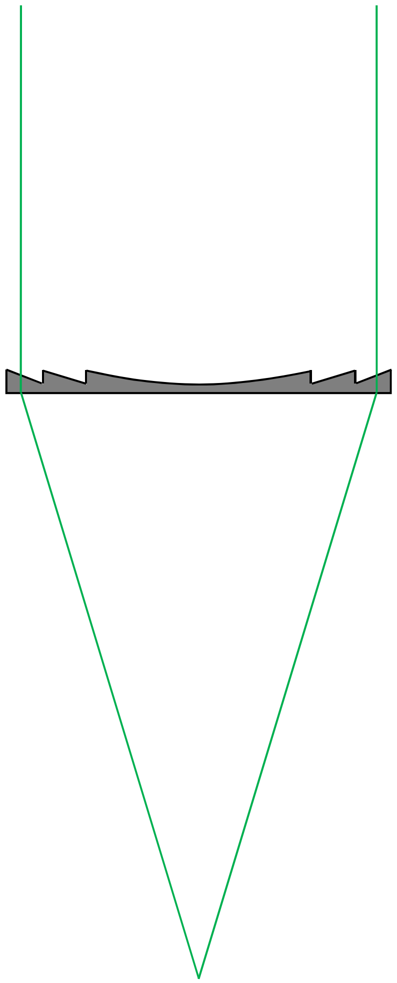
# Phase-Fresnel EUV lenses have good transmission efficiency (~50%)

A converging EUV lens (e.g. Mo) is meniscus because the refractive index is less than 1. But the lens transmittance would be unacceptably low for lenses of practical size.

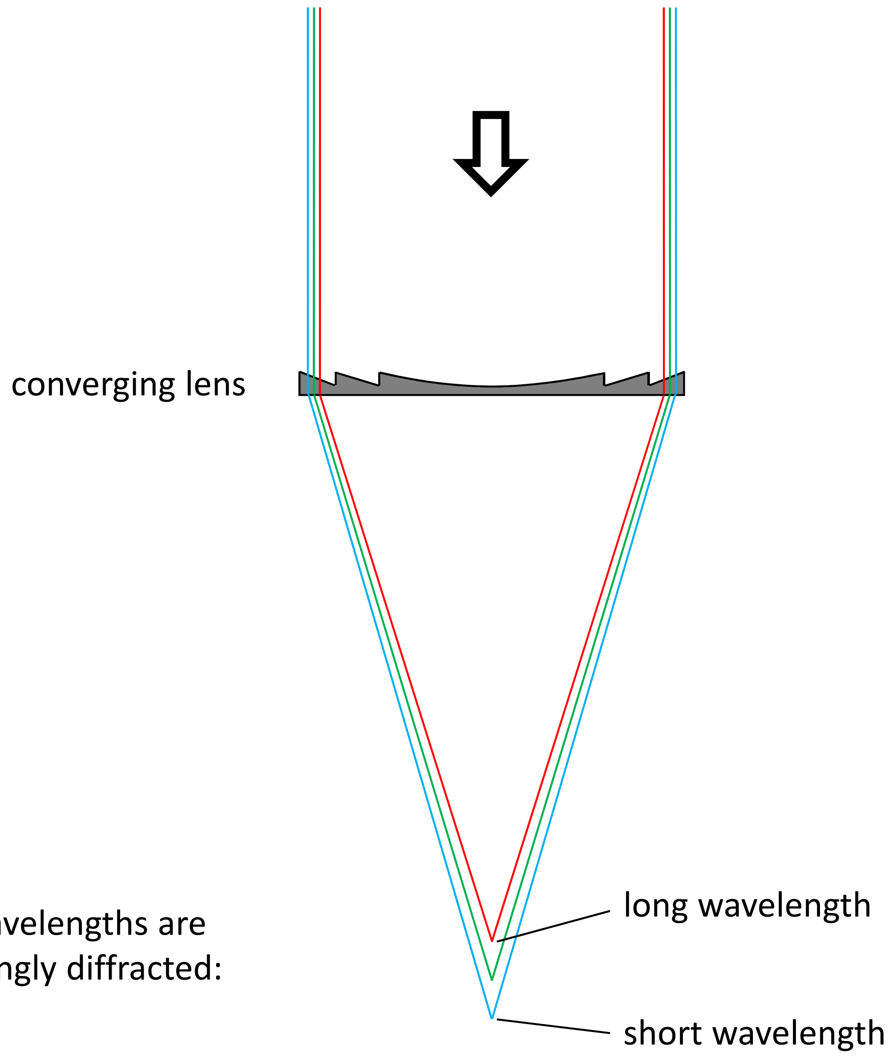


A “phase-Fresnel lens” is a Fresnel lens designed to preserve phase coherence across facet steps (at the design wavelength).

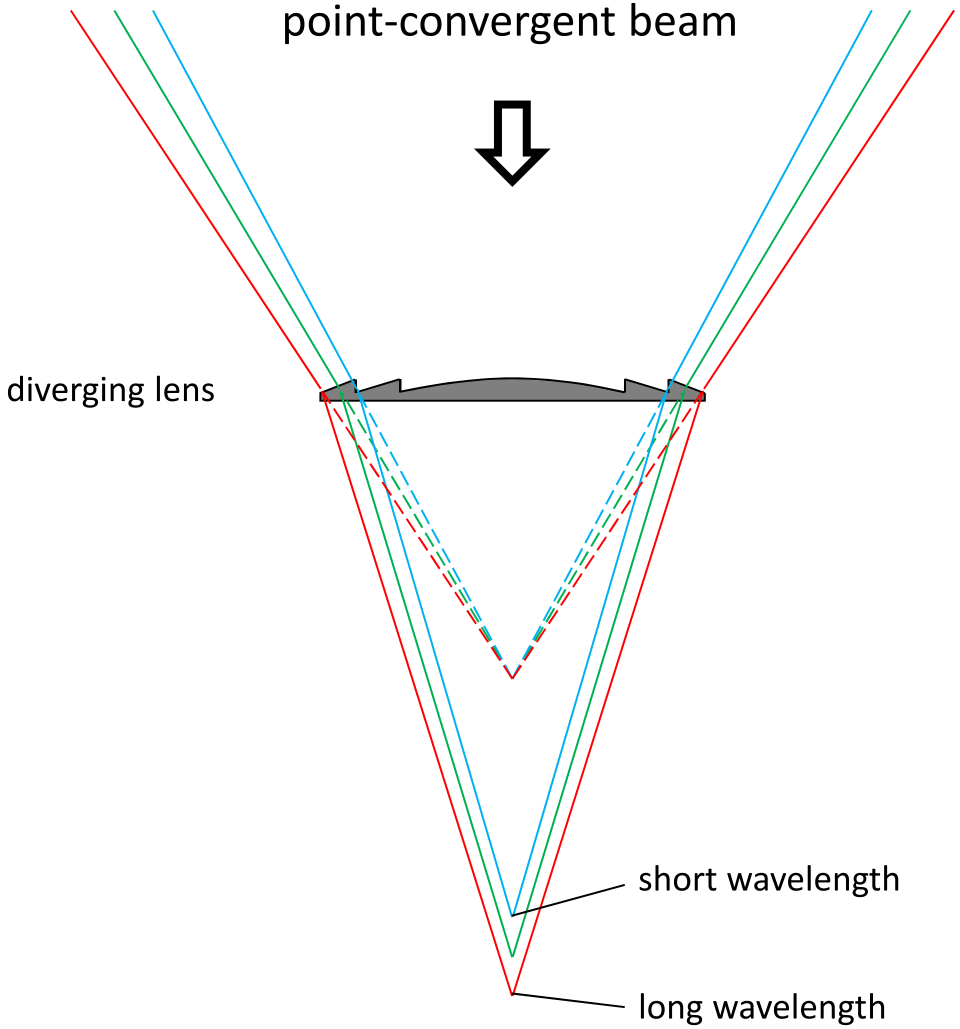
An EUV phase-Fresnel lens can have ~50% transmission efficiency over arbitrarily large apertures.



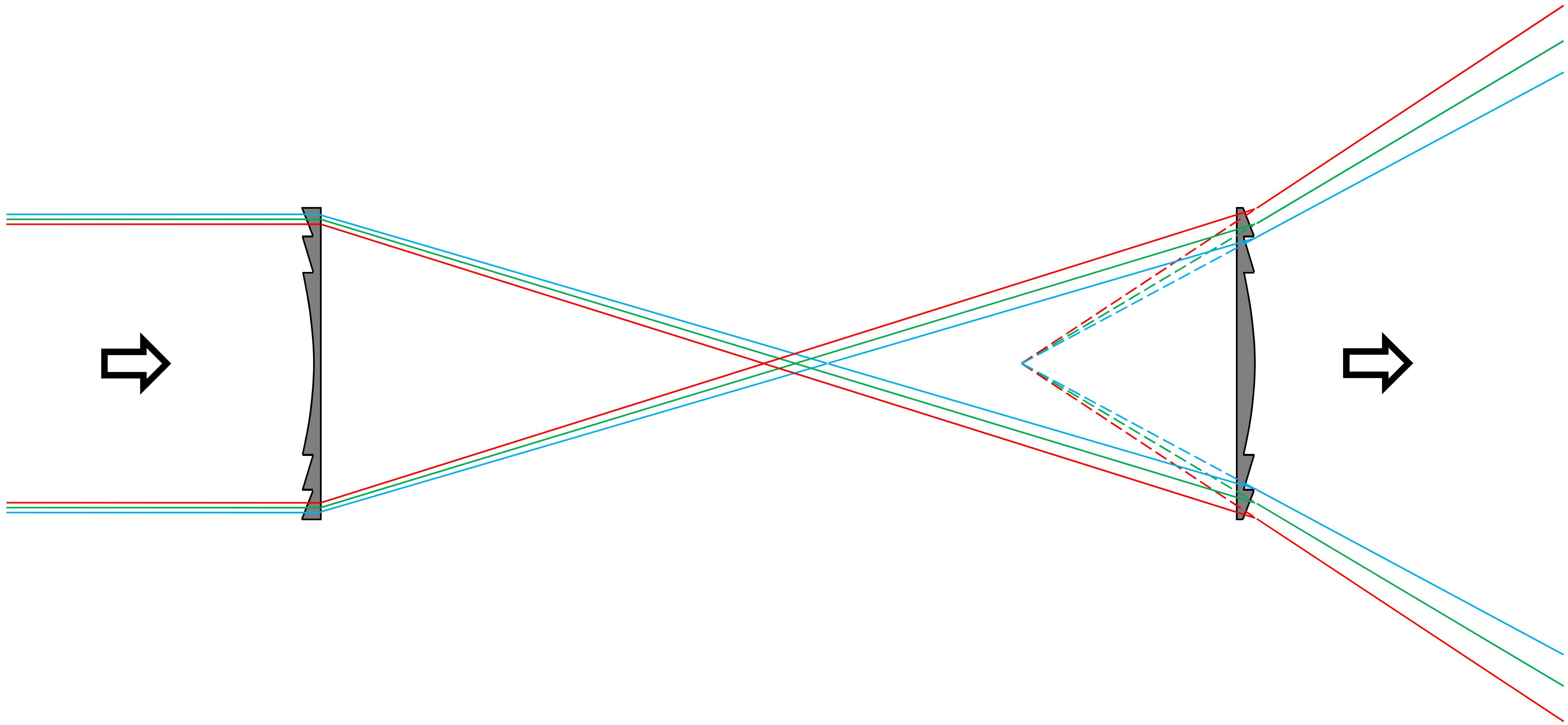
# Phase-Fresnel EUV lenses exhibit strong chromatic aberration.




Longer wavelengths are more strongly diffracted:



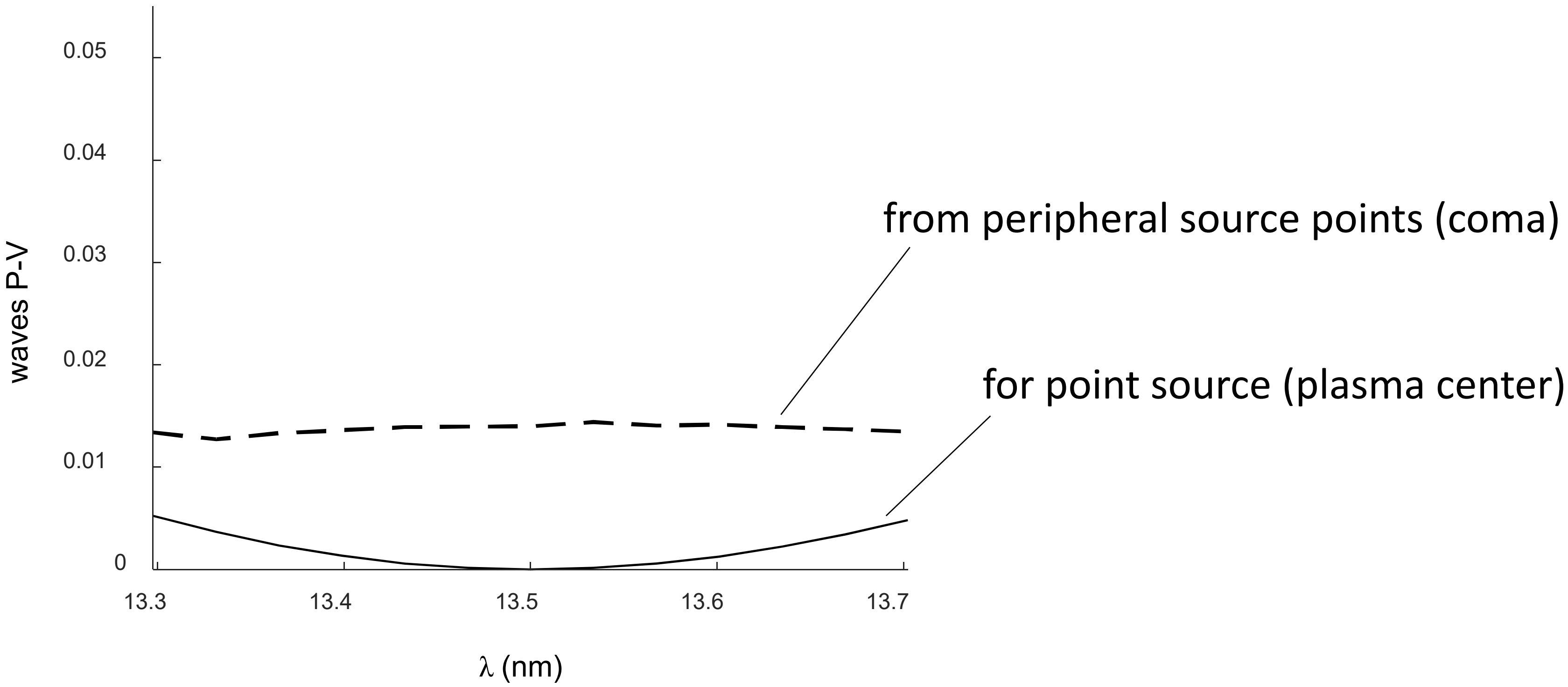
# Positive- and negative-power microlenses can be combined to achieve achromatic point-imaging performance. ("Schupmann Doublet")



# Point-imaging chromatic aberration can be <0.005 wave P-V over the 3% wavelength band.

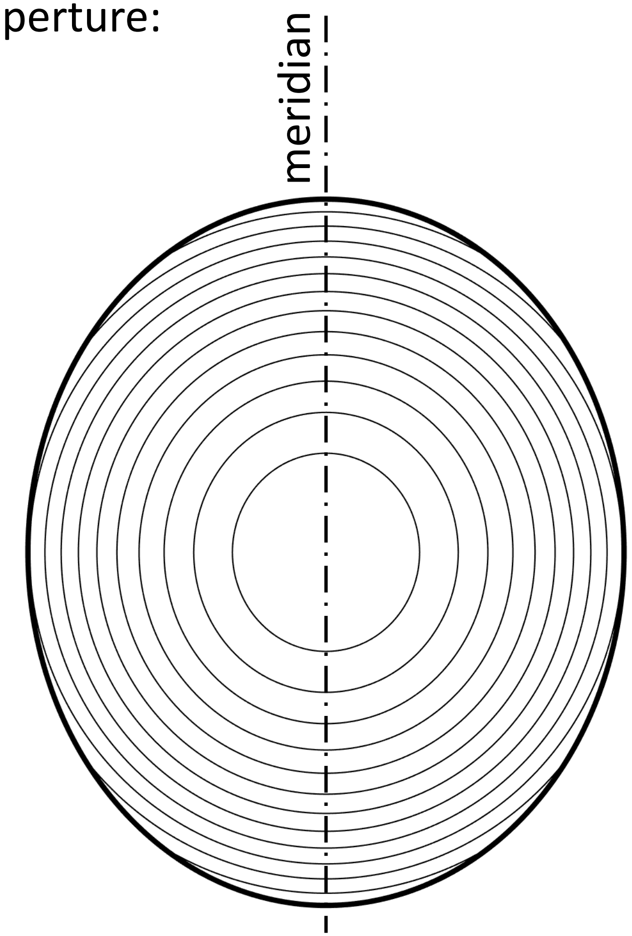
- Two lens elements have sufficient degrees of freedom to make the point-imaging aberration and its derivative with respect to wavelength both exactly zero at 13.5 nm.
- The calculated point-focus chromatic aberration is below 0.005 wave P-V over the full 3% band.
- For off-center source points at the edge of the source disk, there is > 0.01 wave of monochromatic aberration (coma).

Lens aberration versus wavelength at edge of image field:

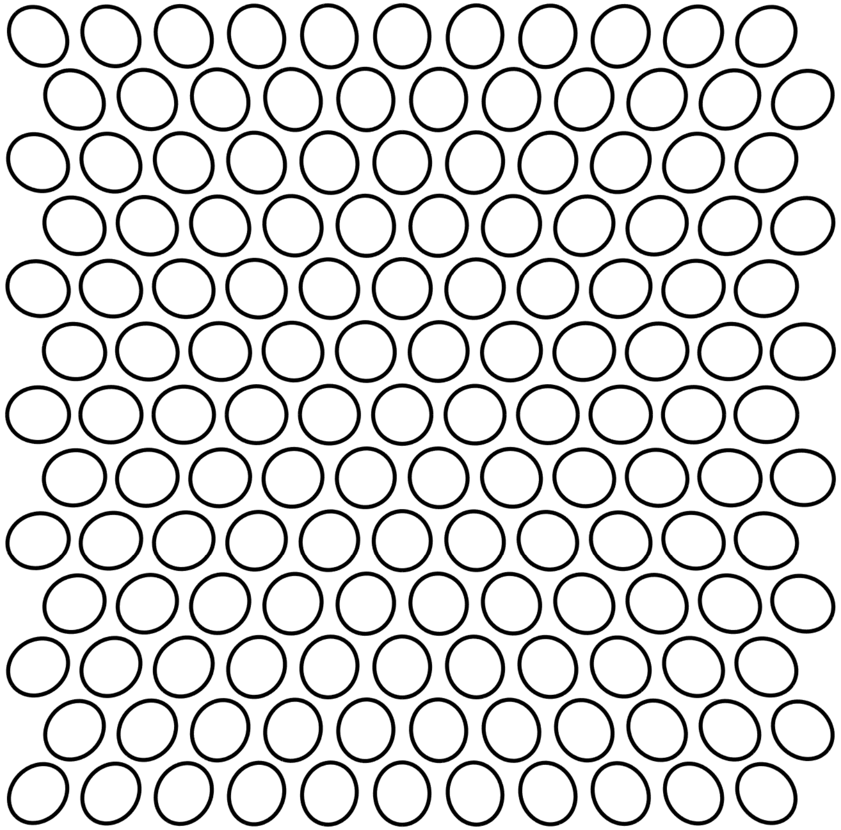


# L1 is elliptical, resulting in 15% fill-factor loss.

L1 aperture:

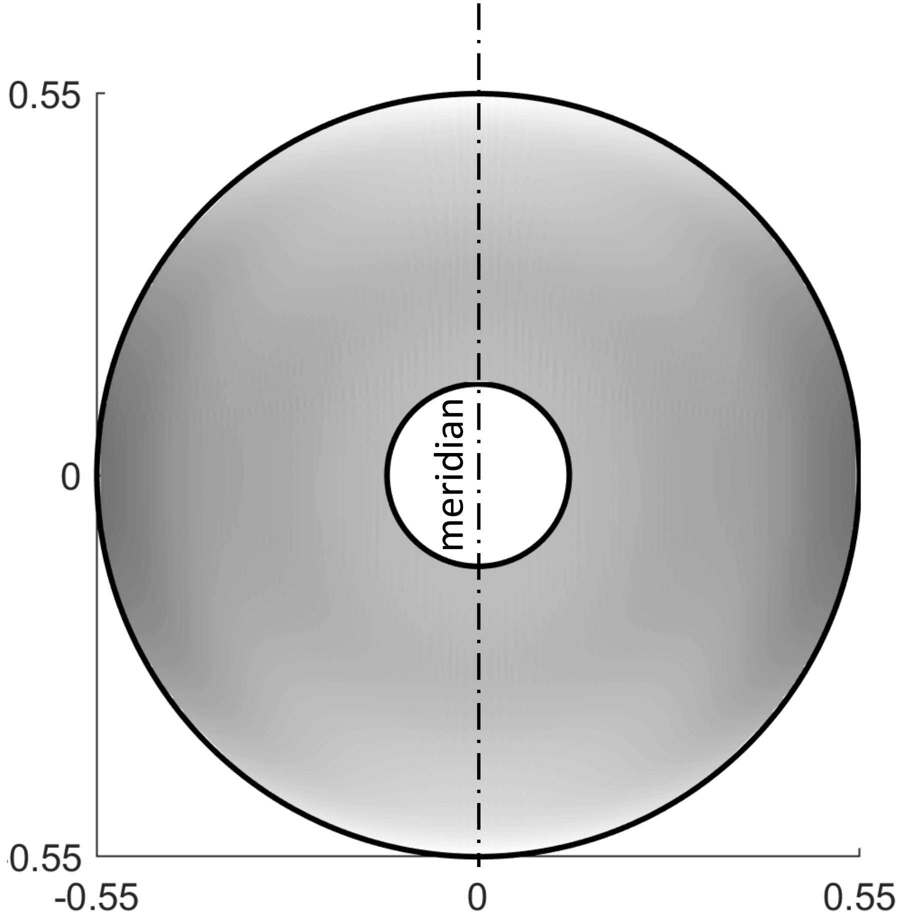



poor packing efficiency:

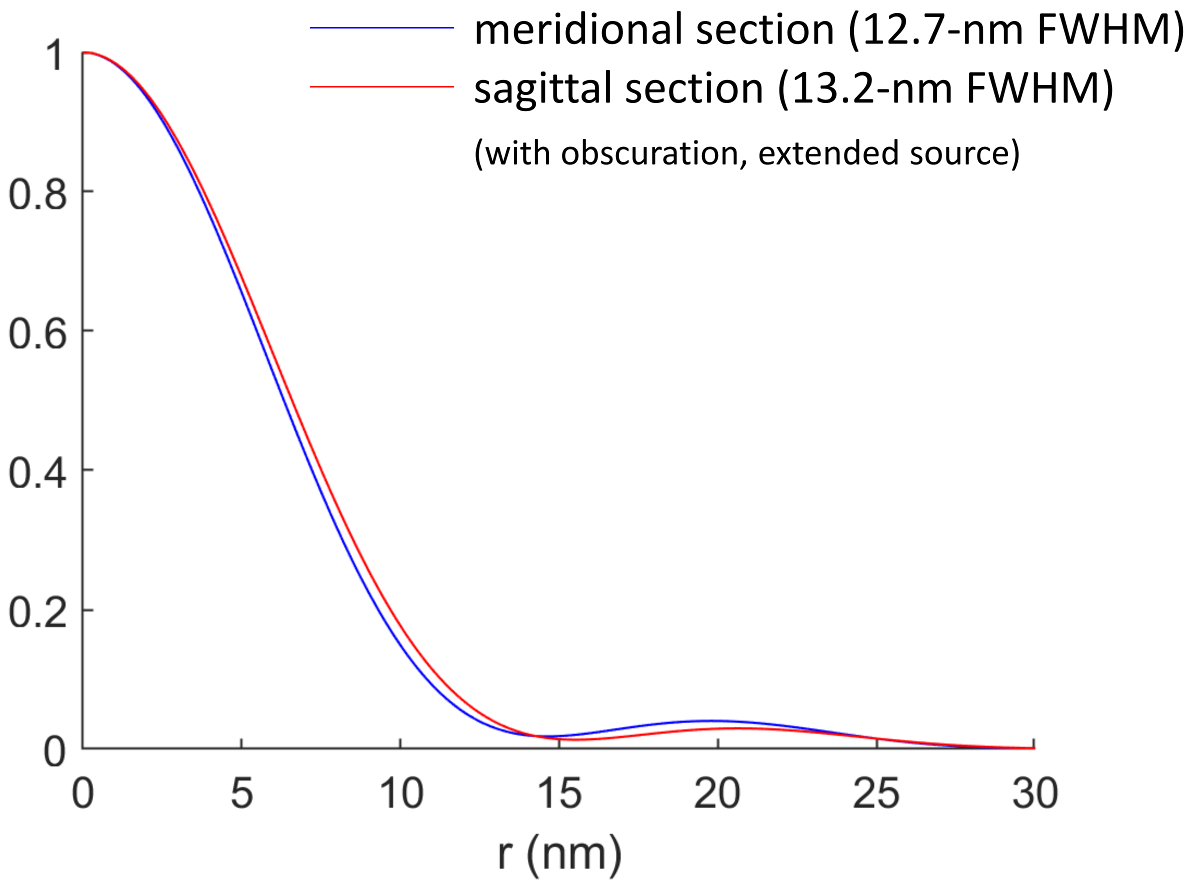


# The pupil illumination nonuniformity induces PSF asymmetry.

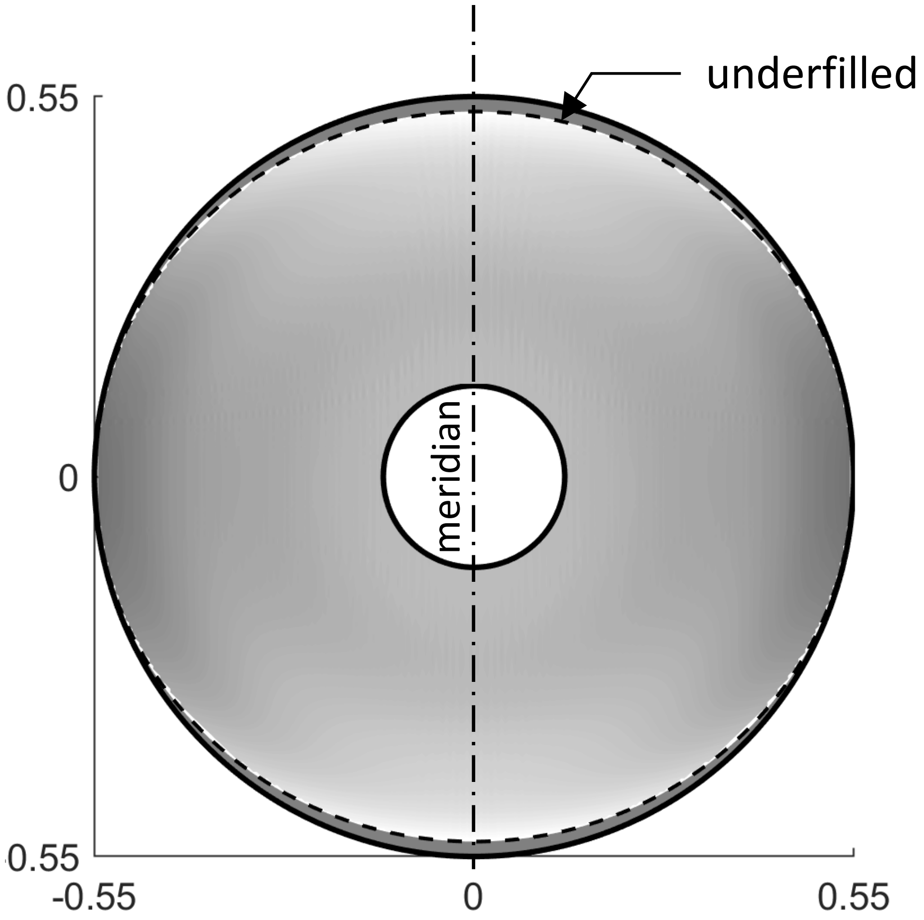
Exit pupil illumination (±38% variation from mean, plotted against direction cosines):

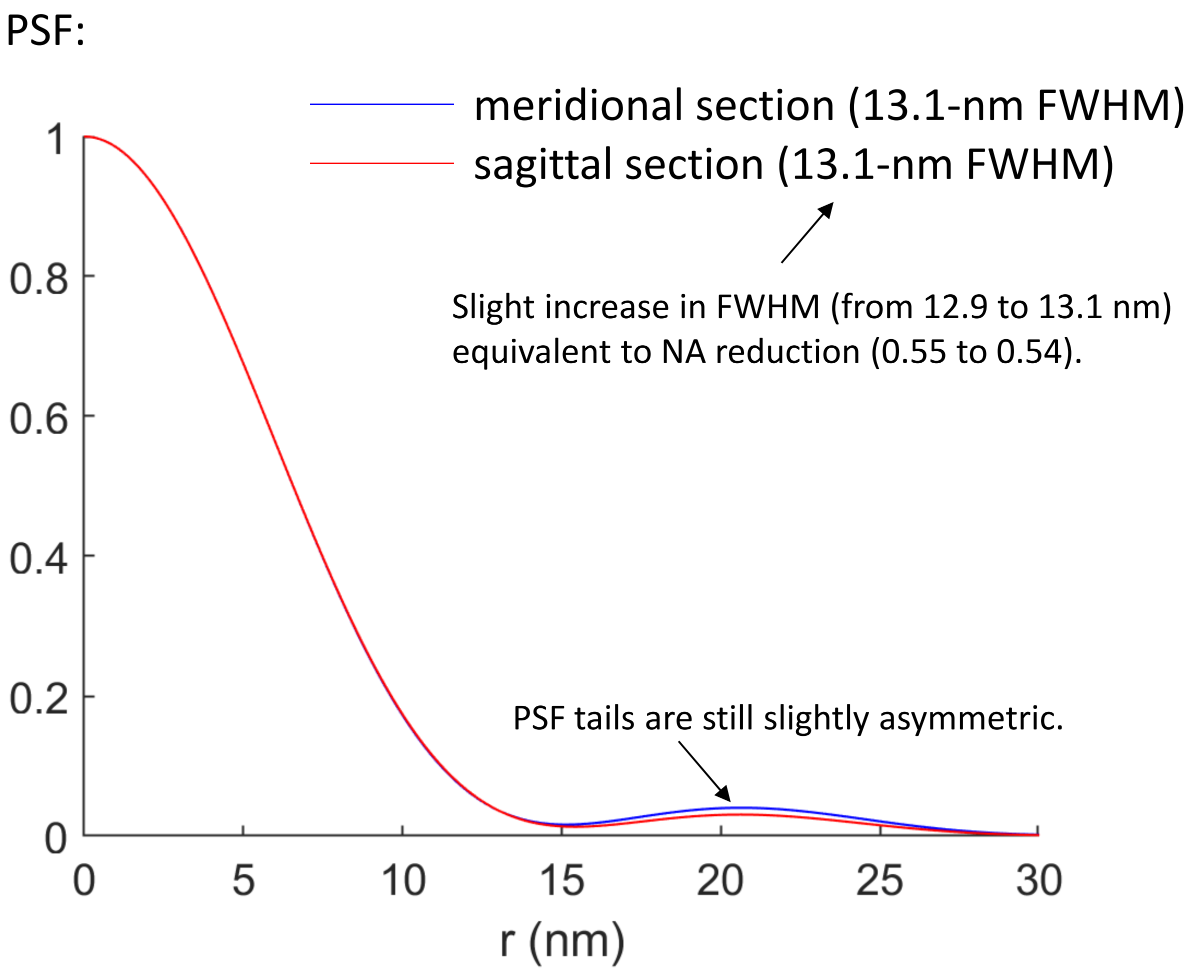



PSF:



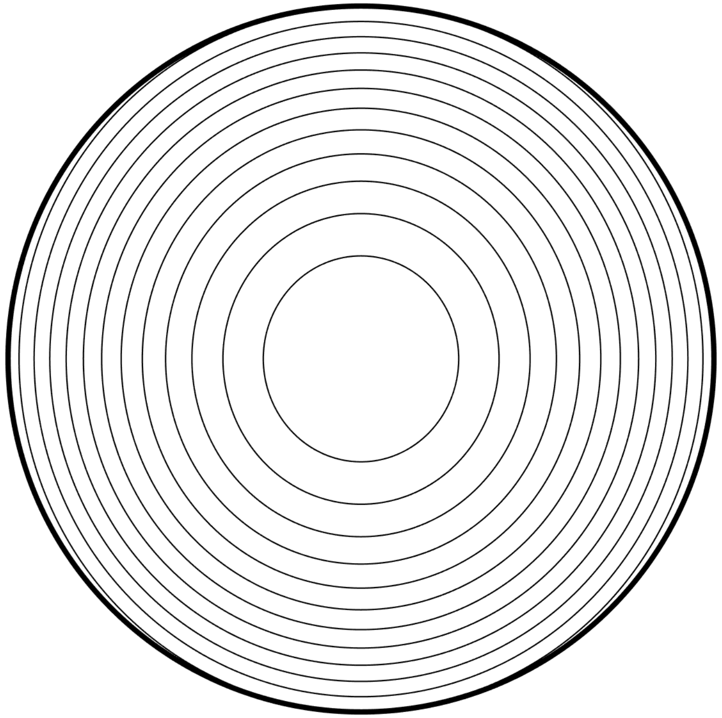
# The meridional pupil fill could be reduced to improve PSF symmetry.



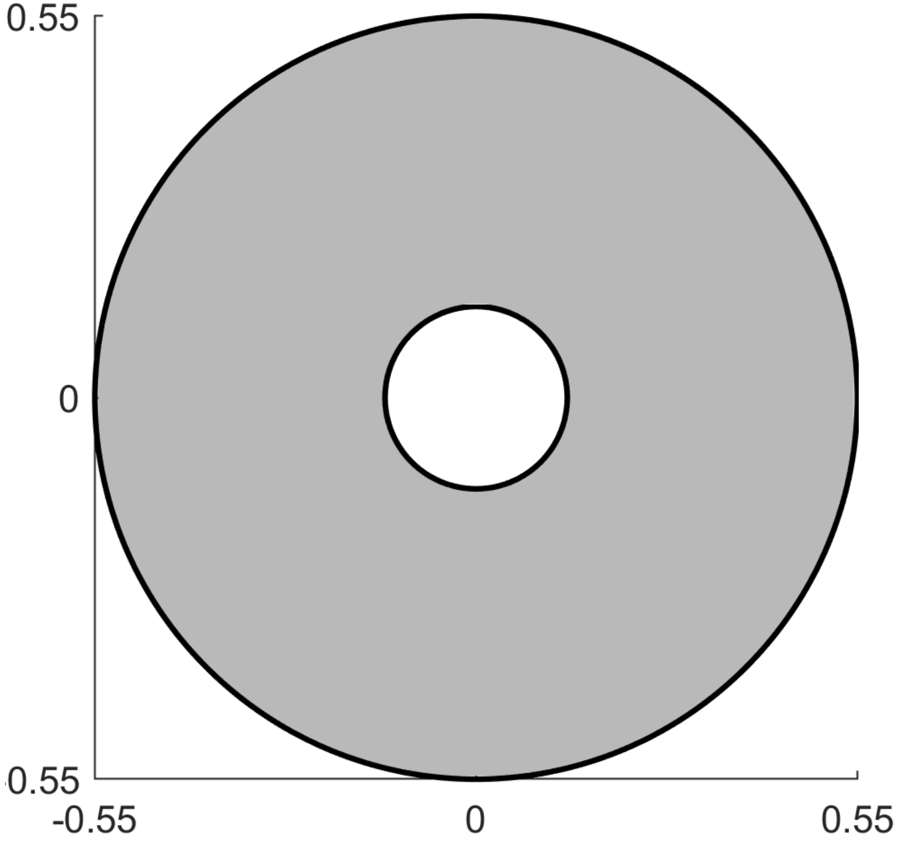



# Alternative approach: Constrain the design to make L1 circular and pupil illumination uniform.

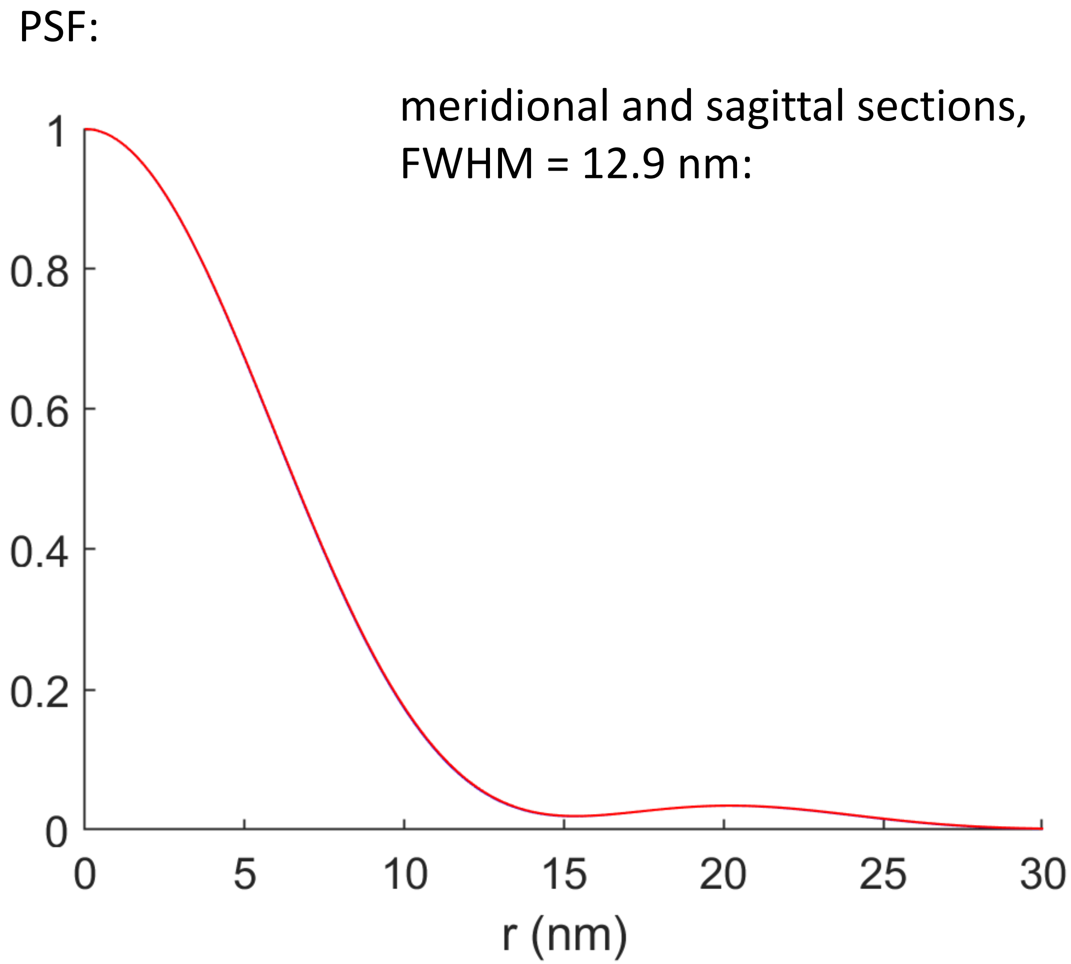
L1 aperture (circular, good fill factor):



Exit pupil illumination (uniform):

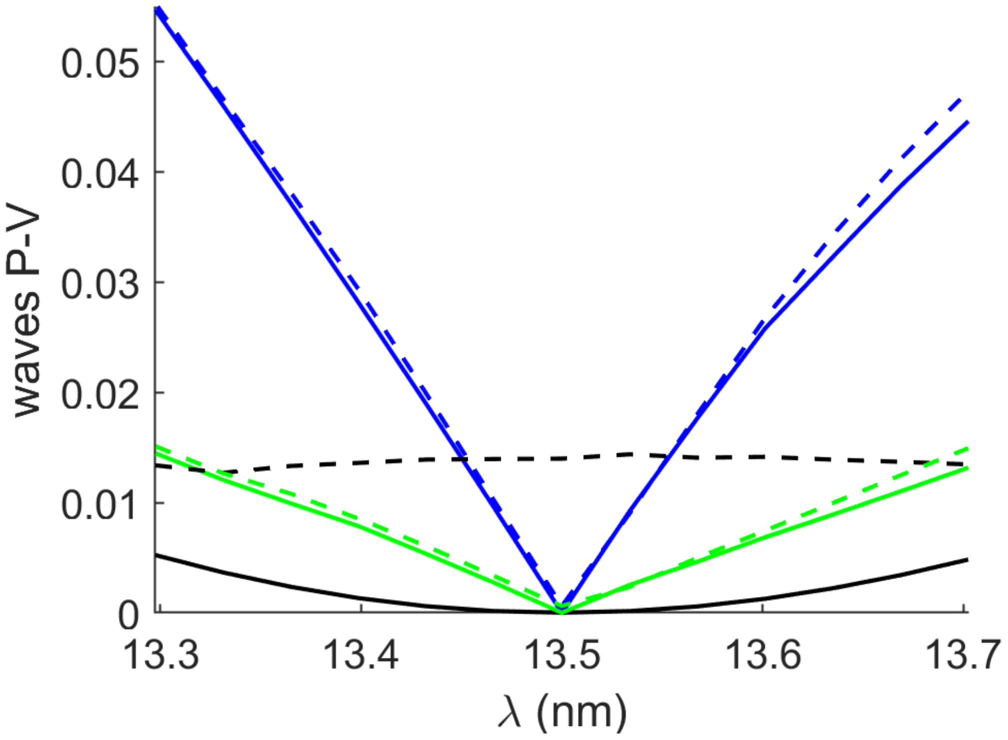


# The constrained lens design makes the PSF symmetric.



# The constrained design's aberration is < 0.05 wave P-V over the 3% wavelength band.

Lens aberration versus wavelength
at edge of image field:

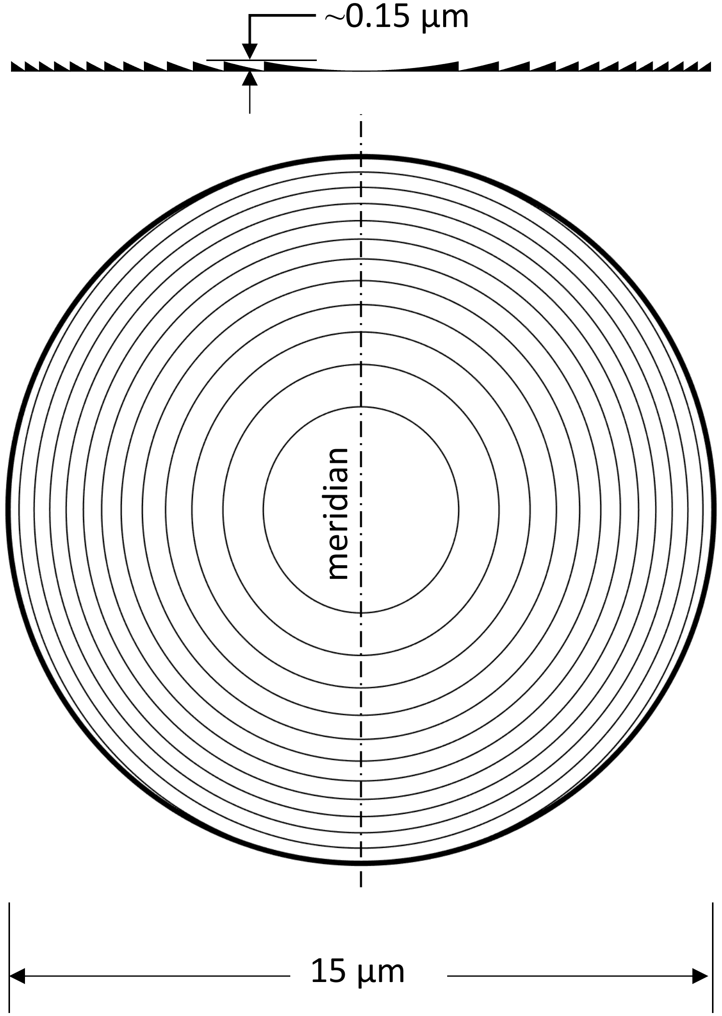



unconstrained design:
point source
extended source
circular L1 shape, uniform pupil illumination:
point source
extended source
unconstrained L1 shape, uniform pupil illumination:
point source
extended source

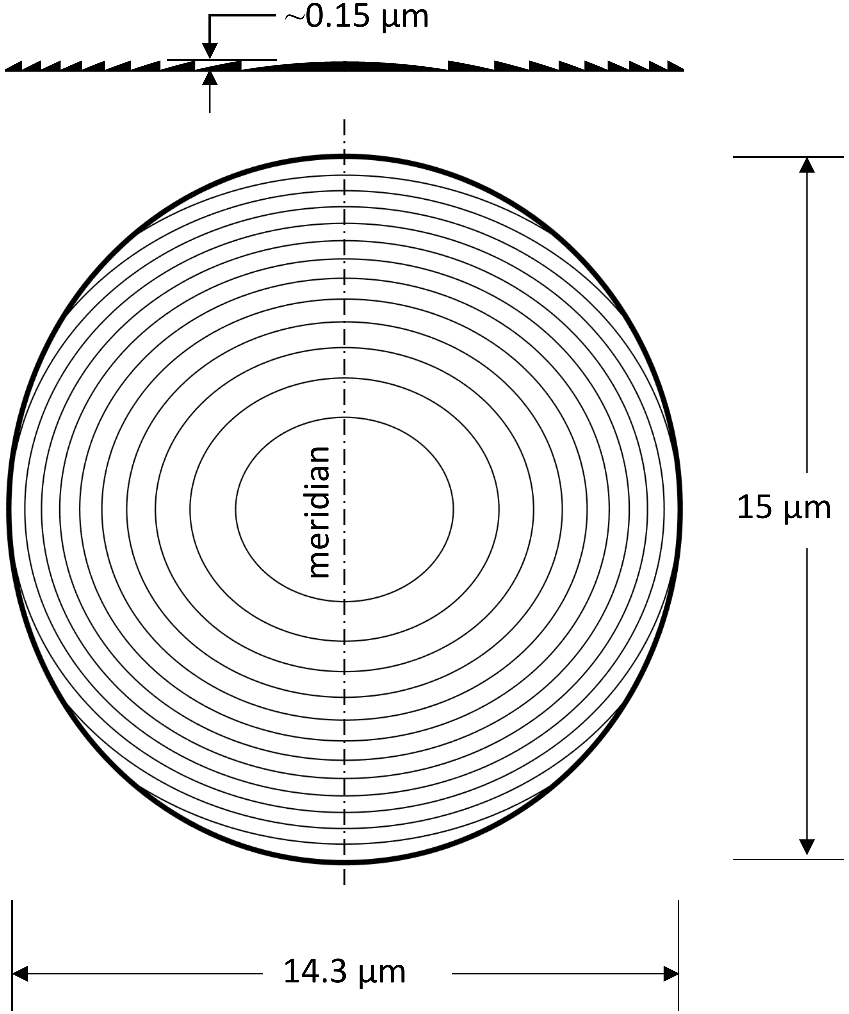
- The pupil illumination constraint enforces the Abbe sine condition, so coma aberration is eliminated and the lens achieves zero-aberration geometric imaging over the full source disk at wavelength 13.5 nm.
- The 0.05-wave P-V aberration at the band limits is ~0.01-wave RMS.
- For Blue-X (6.7-nm wavelength) the wavelength window would be much narrower and the chromatic aberration would be much less.
- With the last design option (unconstrained L1 shape, uniform pupil illumination) the L1 ellipticity would result in about 12% fill-factor efficiency loss.

# L1 and L2 have 13 phase zones over a 15 µm aperture, profile height ~0.15 µm.

L1 design (circular):

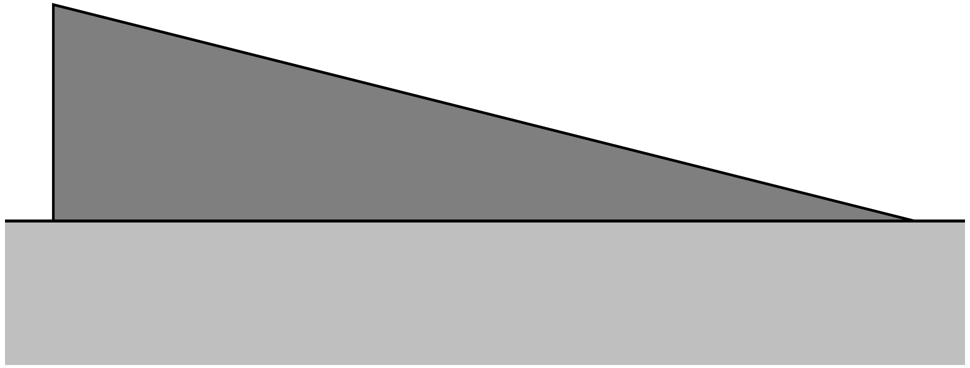



L2 design:

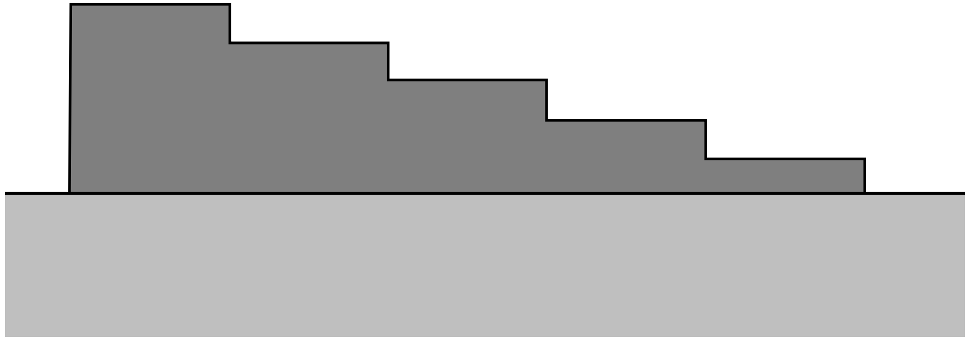


# The Fresnel facets' sawtooth profile can be approximated by a staircase structure.

Ideal profile, grayscale-patterned:

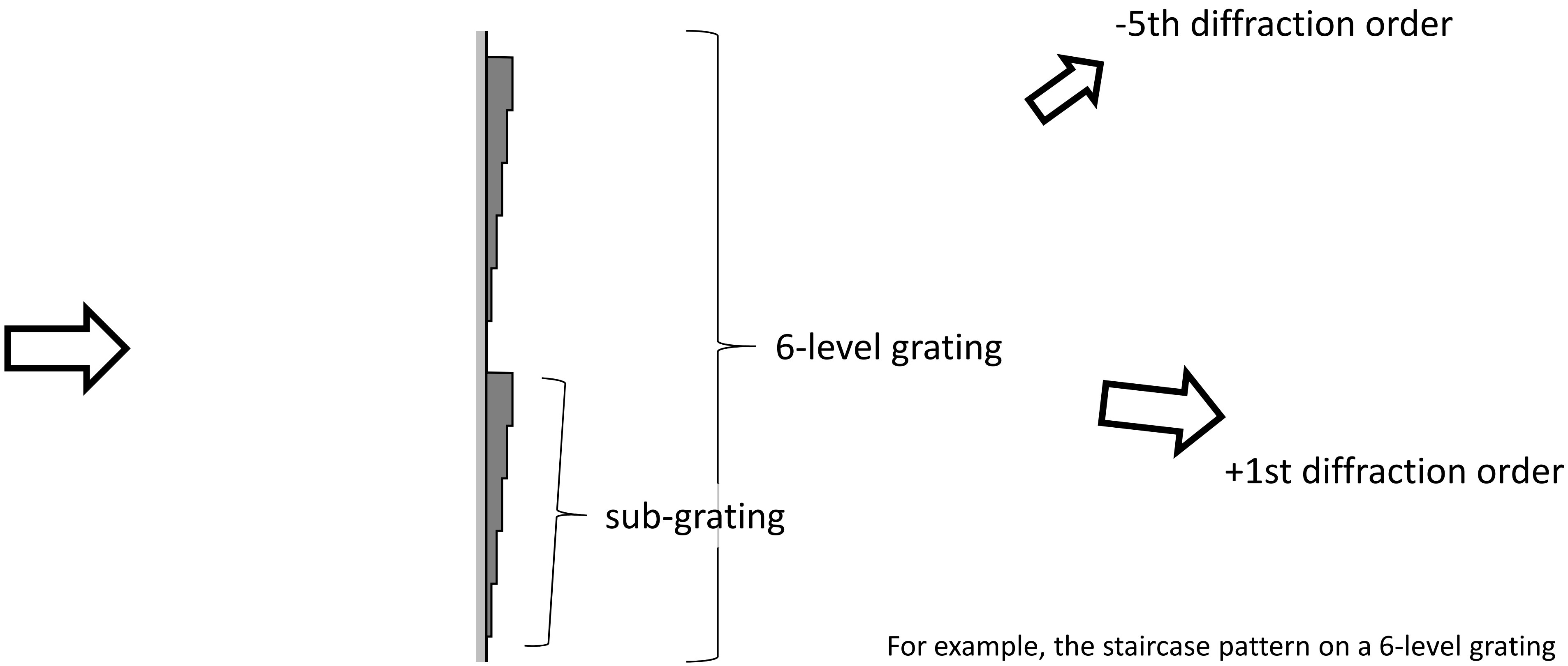


Standard deposition/etch process:



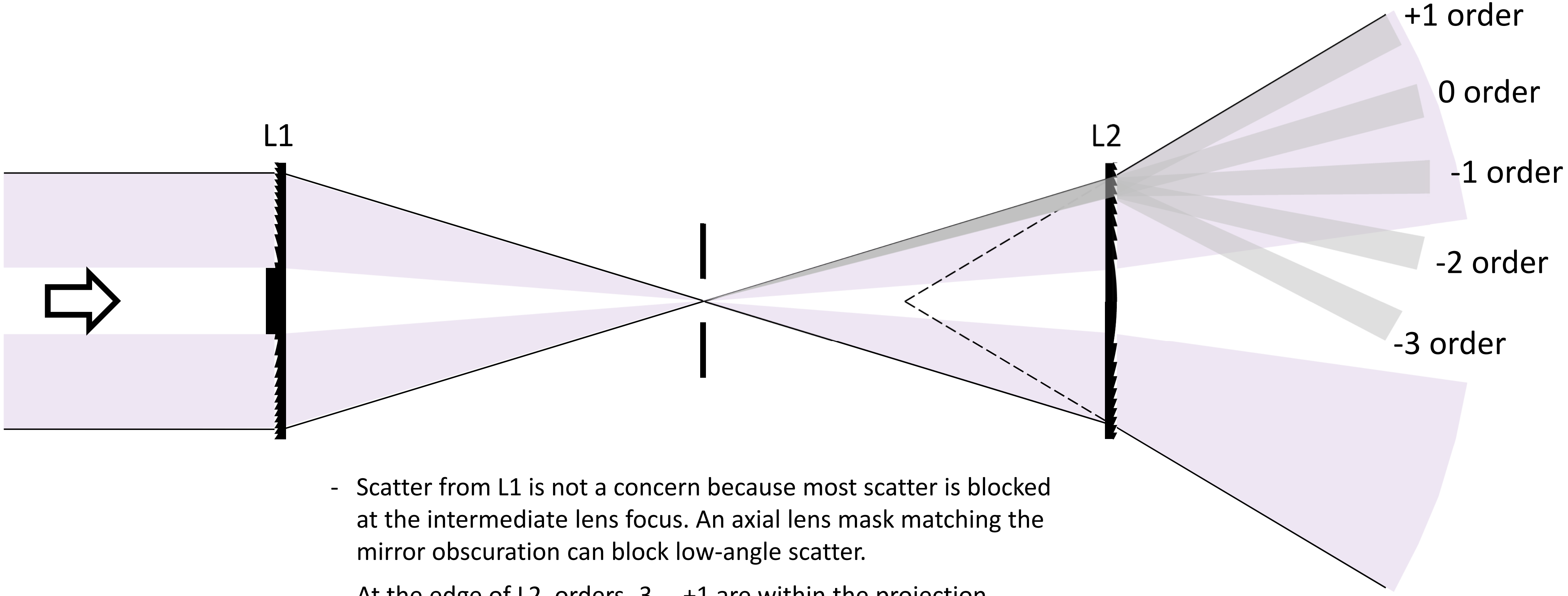
- The multilevel depo/etch process does not rely on litho to control depth dimensions.
- Depth tolerances are loose compared to EUV reflection masks because the optical materials have very low refractive index contrast and operate in transmission mode.
- Litho tolerances (edge placement) would probably be comparable to a 6X-reduction EUV mask.
- Point defects are not critical because the defects are not in focus at the writing surface.

# A staircase grating generates an extraneous diffraction order of significant amplitude.



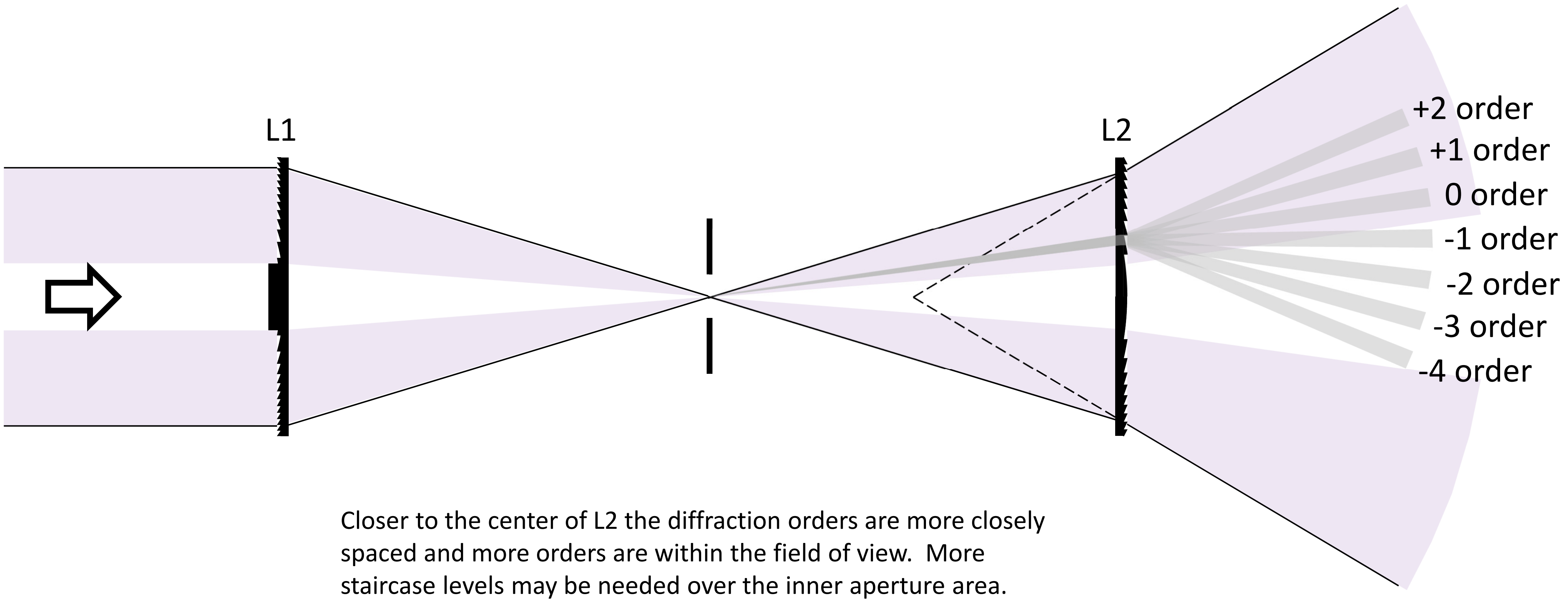

For example, the staircase pattern on a 6-level grating diverts a few percent of the transmitted energy from the +1 diffraction order into the -5 order.

# Multiple diffraction orders from L2 are within the projection system's field of view.



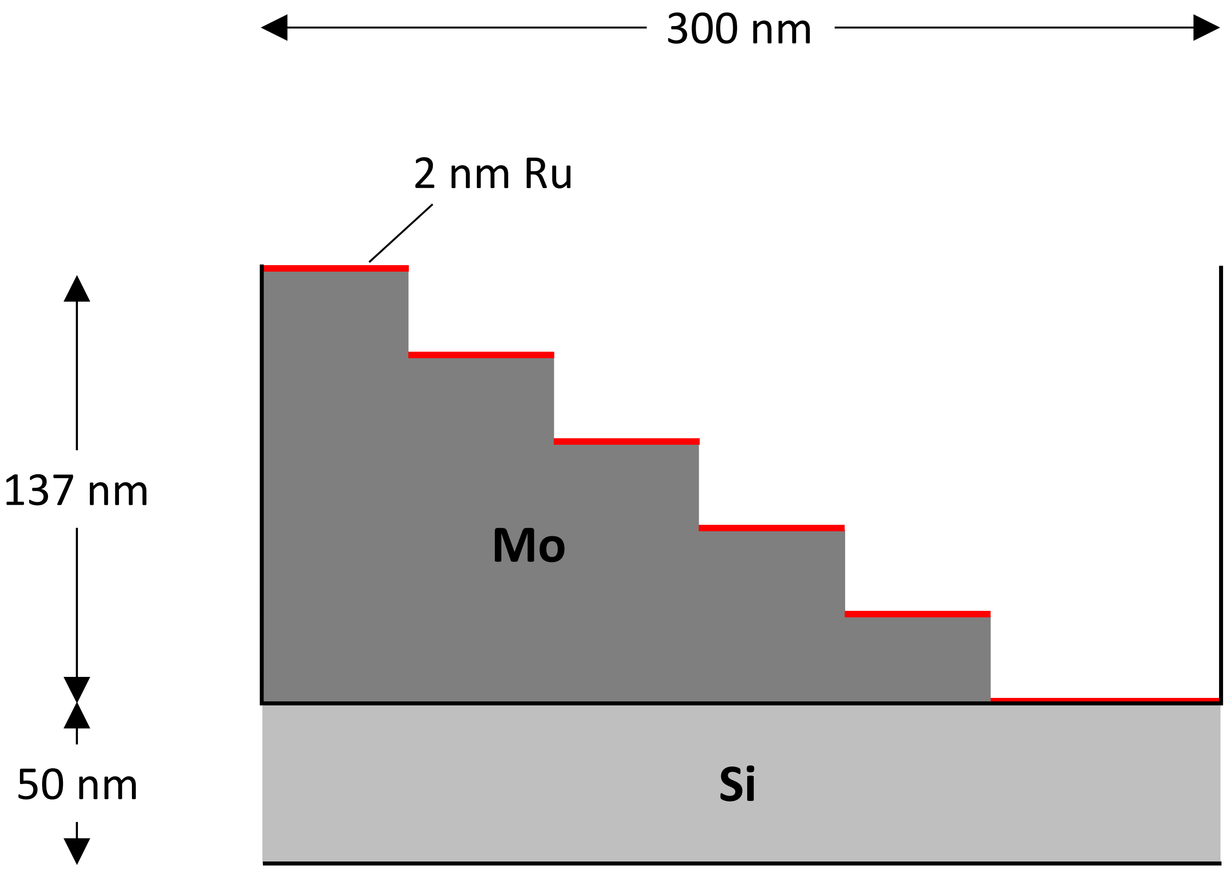

- Scatter from L1 is not a concern because most scatter is blocked at the intermediate lens focus. An axial lens mask matching the mirror obscuration can block low-angle scatter.
- At the edge of L2, orders -3 … +1 are within the projection system's field of view.
- If a 4-level structure is used then the staircase pattern will create a diffraction spike in order -3. At least five levels should be used.

# Multiple diffraction orders from L2 are within the projection system's field of view.




Closer to the center of L2 the diffraction orders are more closely spaced and more orders are within the field of view. More staircase levels may be needed over the inner aperture area.

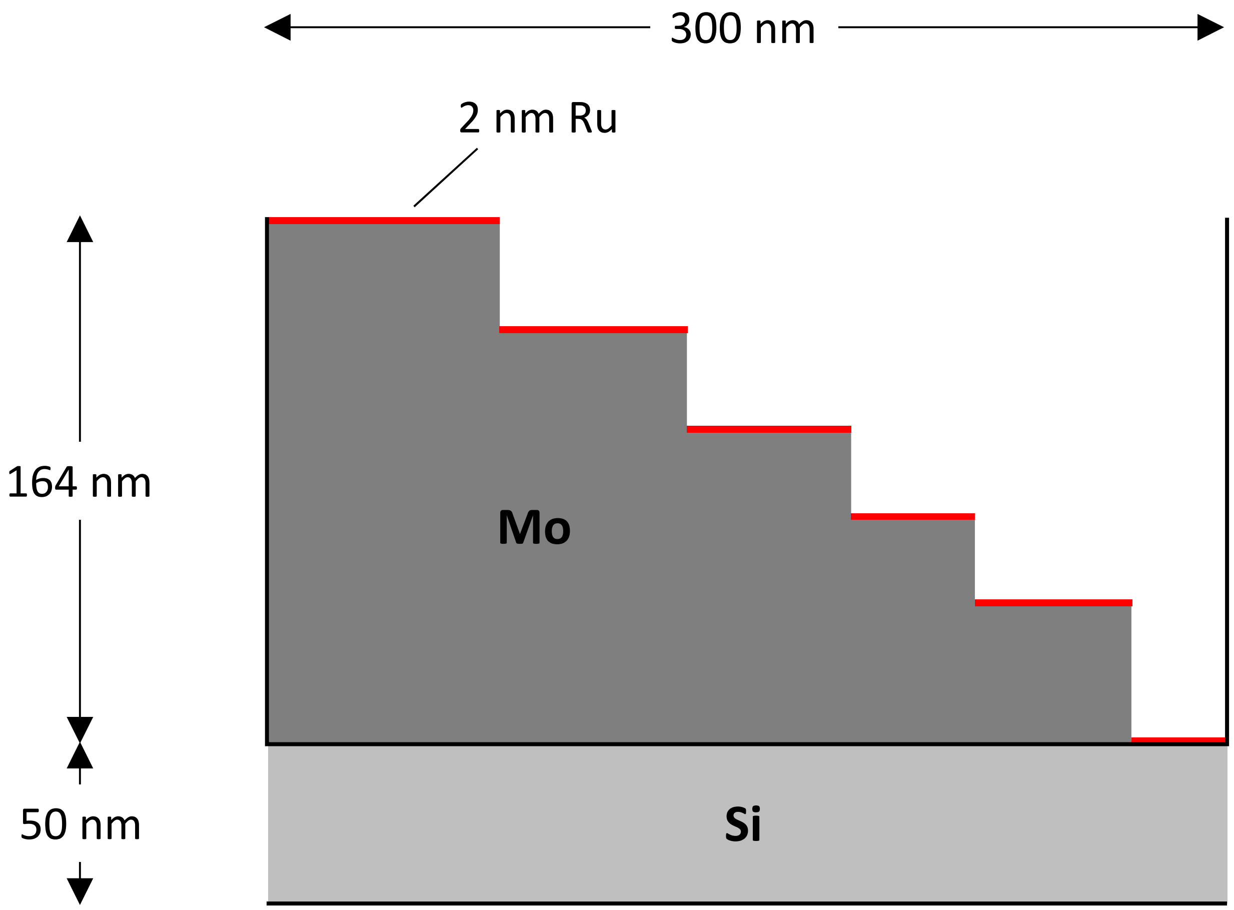
# An efficiency-optimized EUV transmission grating will exhibit significant scatter into extraneous orders.




| Order | Efficiency |
|---:|---:|
| -3 | 1.6% |
| -2 | 1.8% |
| -1 | 2.1% |
| 0 | 2.8% |
| +1 | 49% |

This type of structure could work for L1, but the scatter into extraneous orders might be too high for L2.

# The grating can be optimized to suppress extraneous orders, at the expense of somewhat lower efficiency.

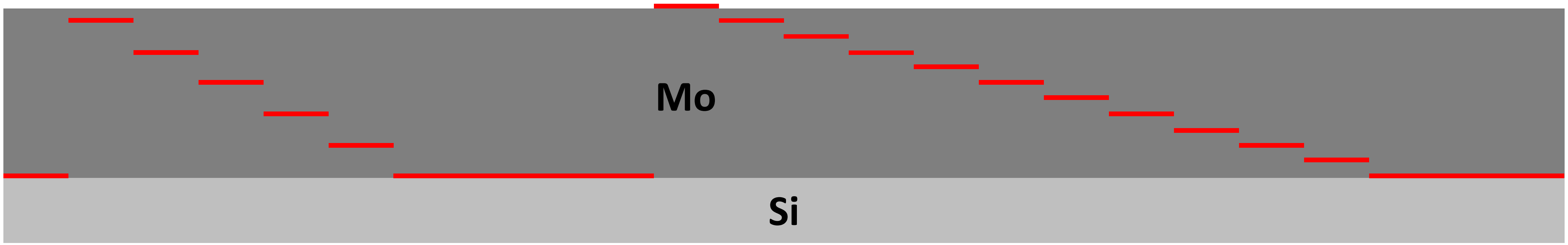



| Order | Efficiency |
|---|---|
| -3 | 0.12% |
| -2 | 0.16% |
| -1 | 0.15% |
| 0 | 0.02% |
| +1 | 42% |

This structure is optimized ***not*** for maximum efficiency, but for maximum contrast between the +1 and extraneous orders. This type of design would be suitable for L2.

# The phase-Fresnel lenses can be made using patterned Ru etch-stop layers embedded in Mo.

after Mo/Ru depositions & Ru patterning, before Mo etch:




The Mo depositions are ~10-15 nm. The Ru depositions are ~2 nm (somewhat thinner at the bottom and thicker at the top) and are lithographically patterned.

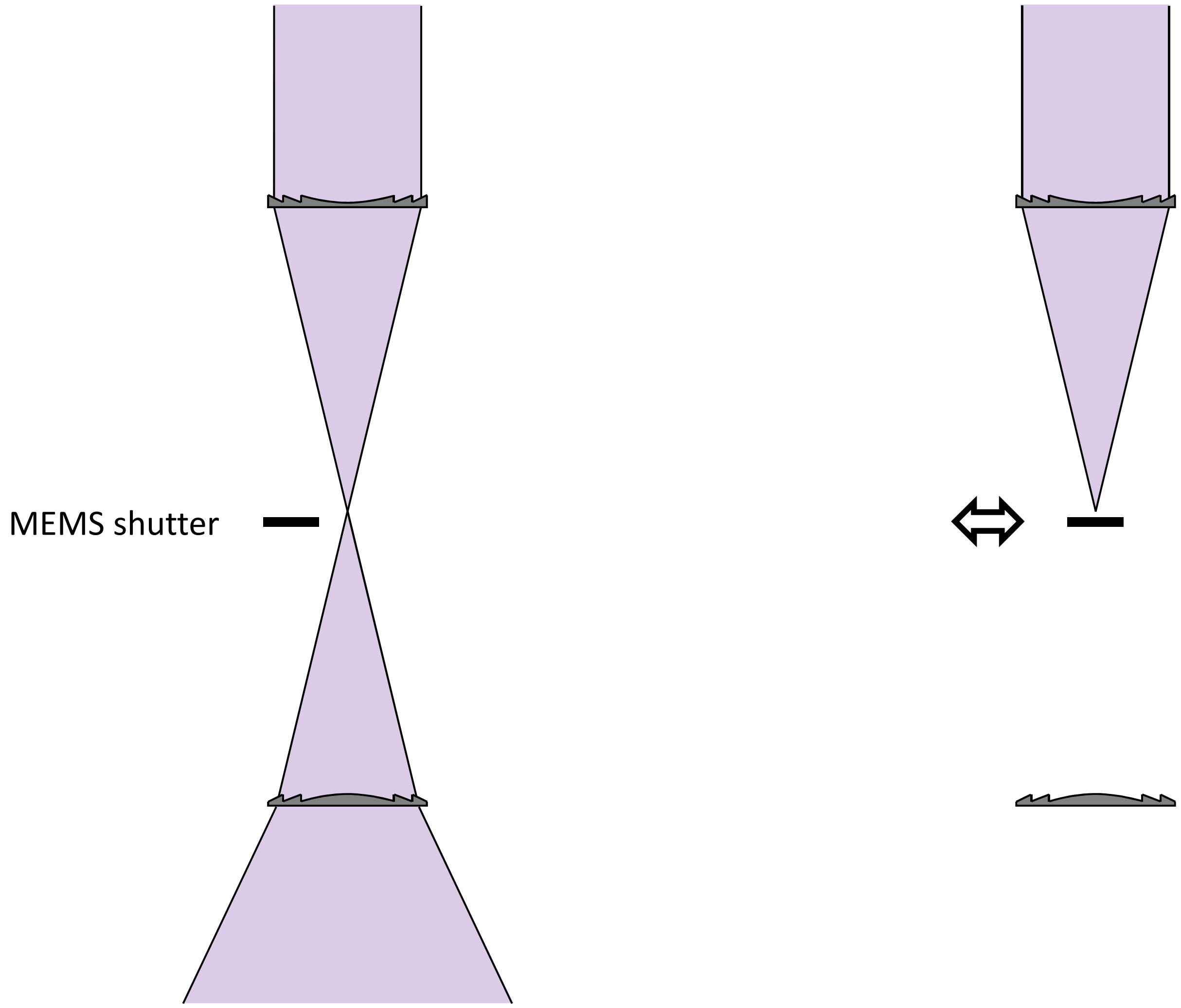
after Mo etch down to Ru etch stop:

6-layer, short-period structure (near lens edge)

12-layer, long-period structure (near lens center)

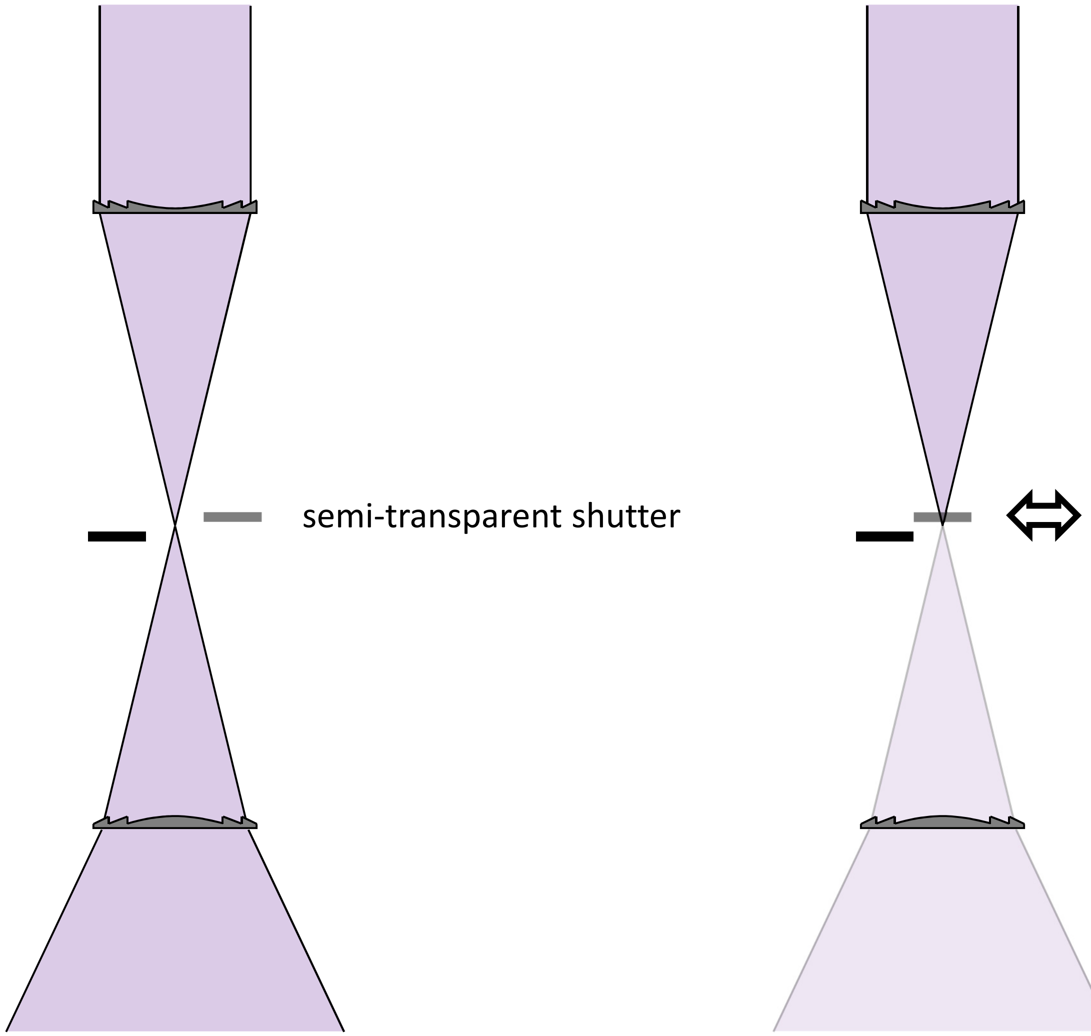
# Optical modulation

# First modulation option: MEMS shutters at intermediate lens foci



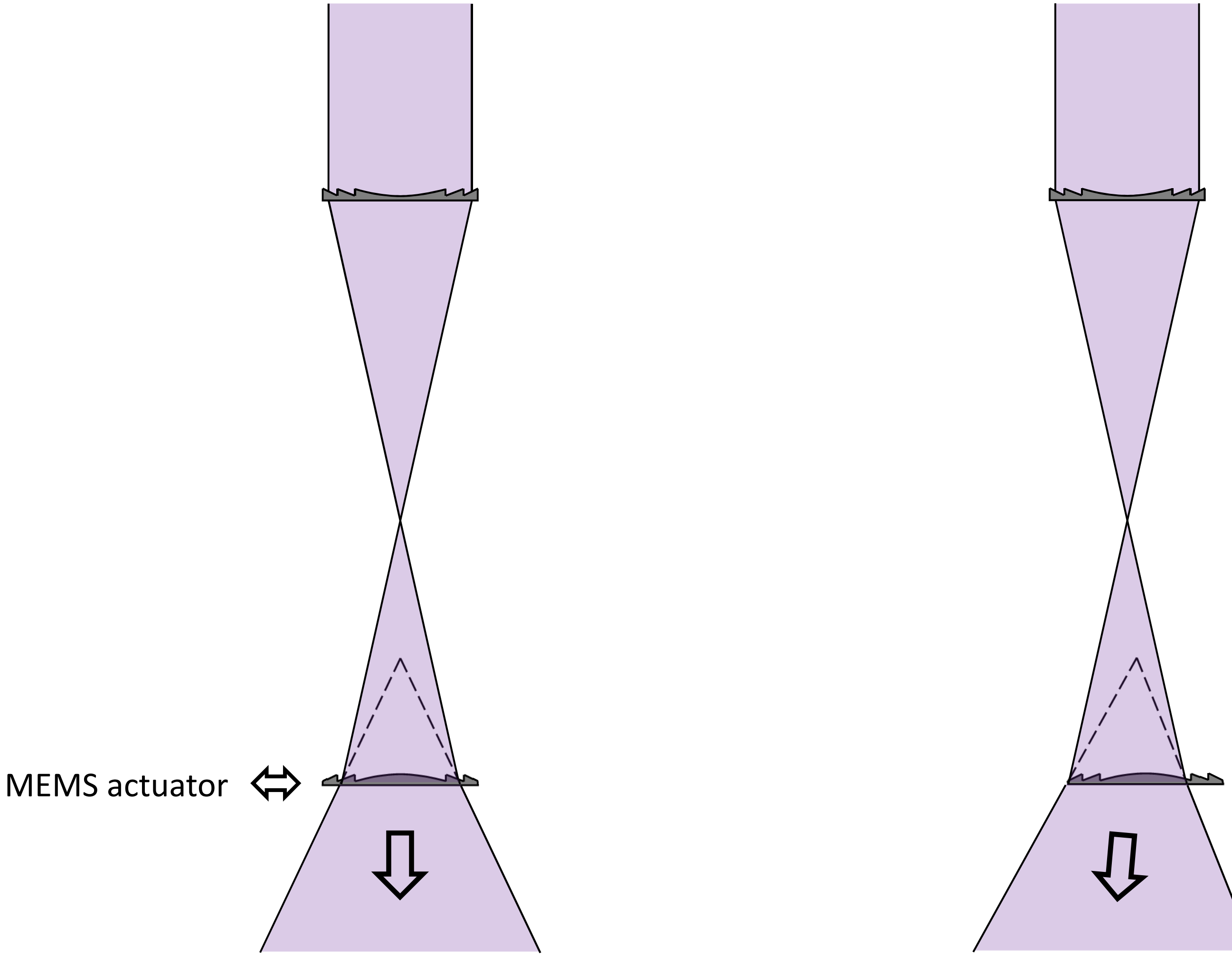

- The shutter stroke is < 1μm.
- The switching rate is 24 kHz.
- Each shutter and associated MEMS/electronics must fit within a 250 μm$^2$ footprint.

# Second modulation option: Additional semitransparent shutter(s) for gray level control



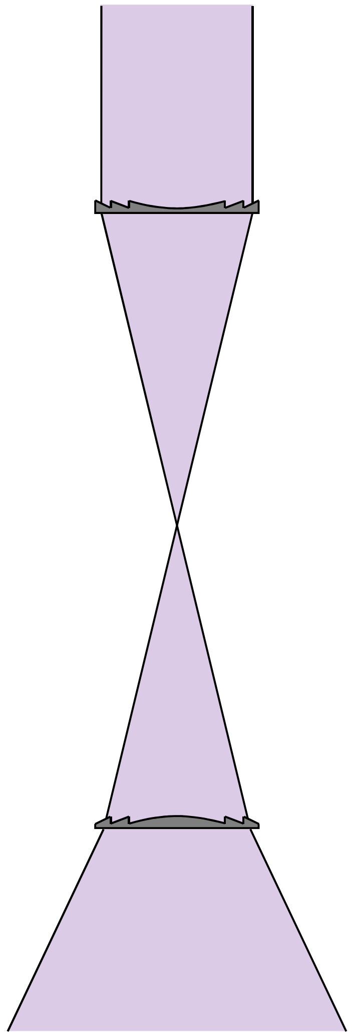

The exposure gray level can be controlled using halftone printing with a dense grid. But direct gray level control could achieve the same result with a sparser print grid, at higher throughput.

# Third modulation option:
# Lateral lens translation for beam steering




- A 125-nm lens translation will displace the focus spot by 10 nm on the wafer (and would induce only 0.03 wave P-V aberration).
- Enables beam positioning on a nm-scale address grid, even when scanning with a relatively coarse grid step.
- Could be useful, e.g., for accurate edge placement, for printing curvilinear resolution-enhancement features on masks, or for offsetting thermal drift and calibrated alignment errors.

# Fourth modulation option: None of the above. The power is modulated at the source.

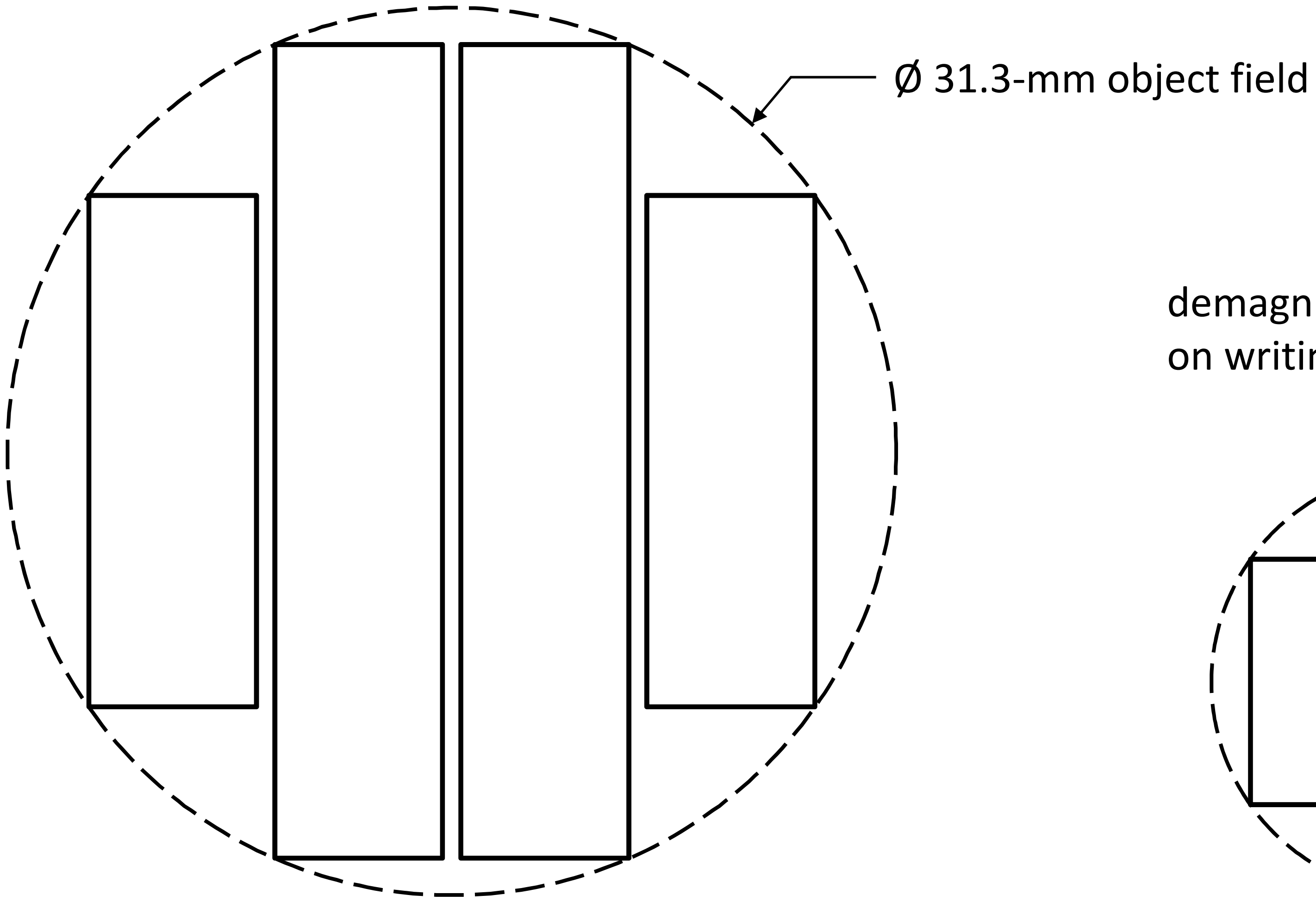


- All microlens channels write identical patterns.
- Could be useful for printing regular line or point arrays (e.g. quantum dots, photonic crystals, nanosieve membranes, …).
- If the source can be modulated at the 24 kHz frame rate, then any periodic pattern can be printed with a periodicity matching the demagnified lens period (~2.5 µm).

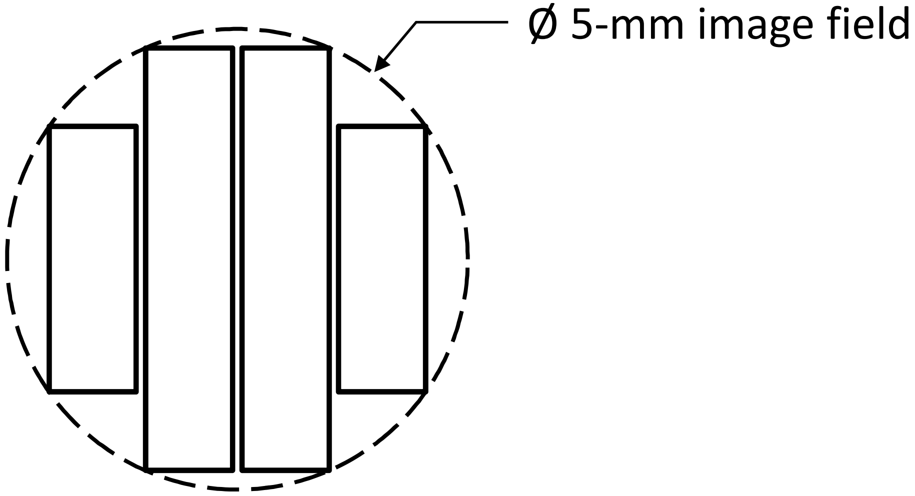
# Scanning

# The microlens array is partitioned into four subarrays.

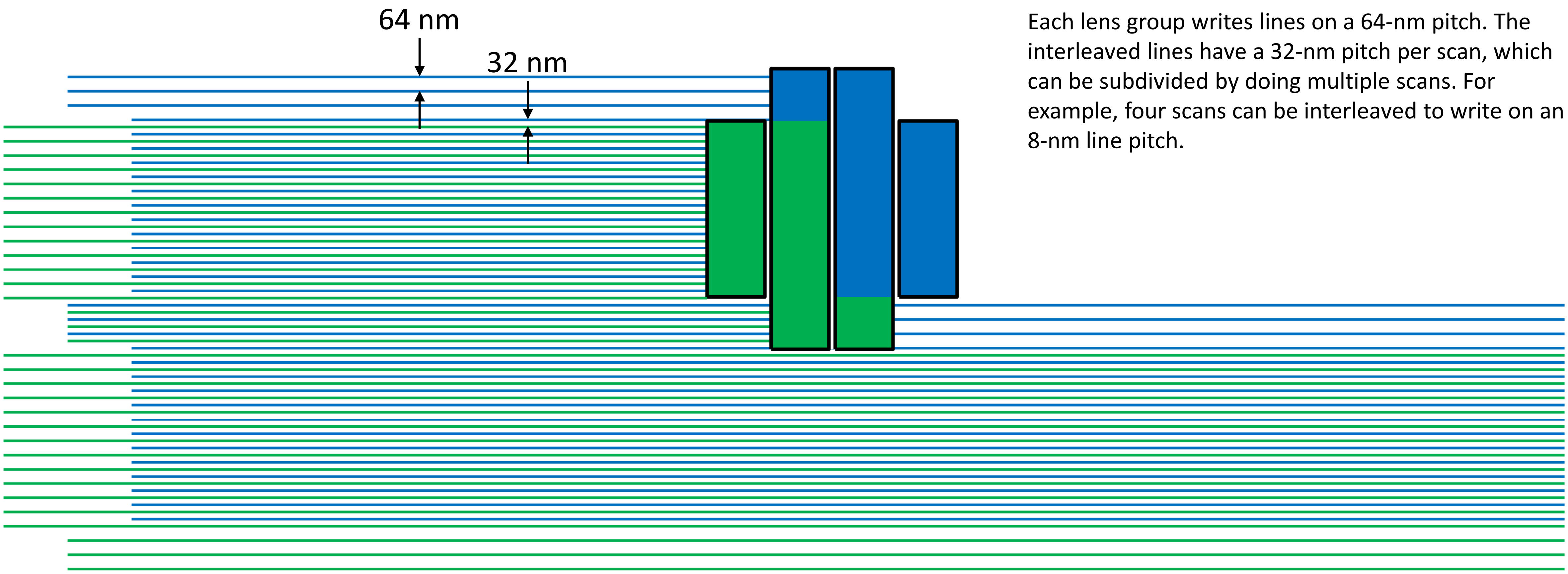
array geometry:




demagnified array footprint
on writing surface:



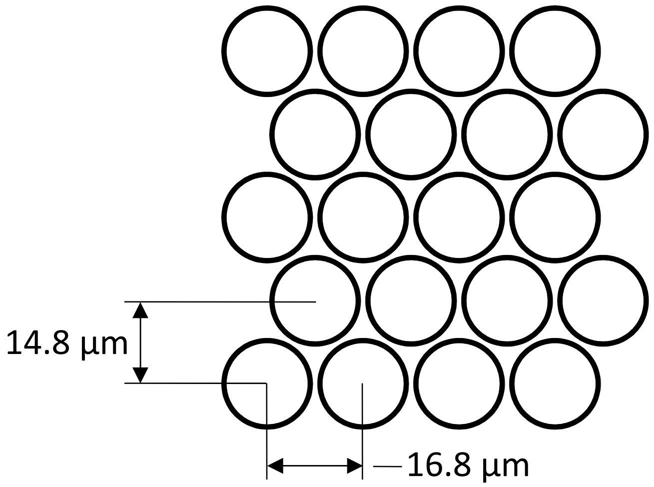
# The microlenses are separated into two groups, which write separate, interleaved raster lines.



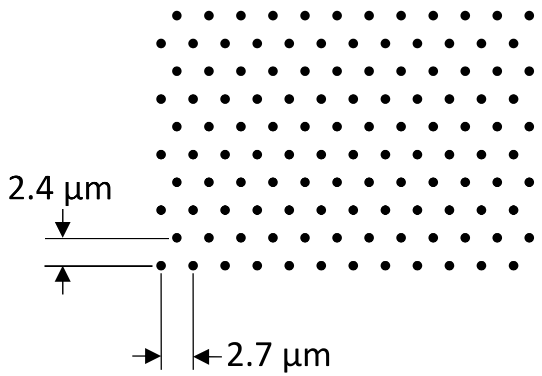

Each lens group writes lines on a 64-nm pitch. The interleaved lines have a 32-nm pitch per scan, which can be subdivided by doing multiple scans. For example, four scans can be interleaved to write on an 8-nm line pitch.

# The microlens apertures are arranged in a hexagonal honeycomb array.

aperture layout:

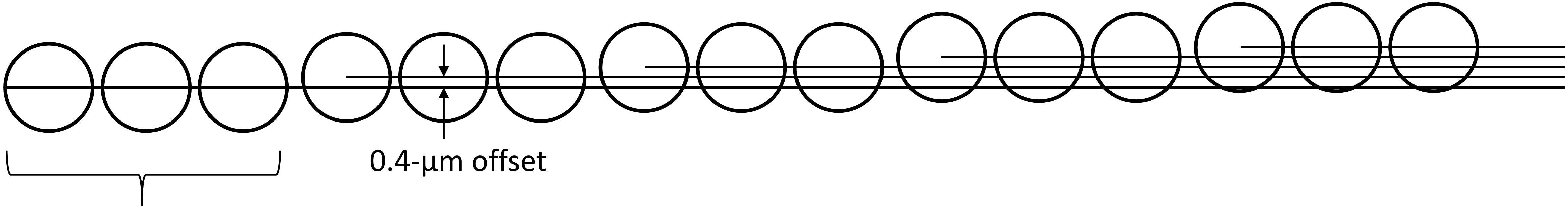



focus-spot pattern
on image plane:



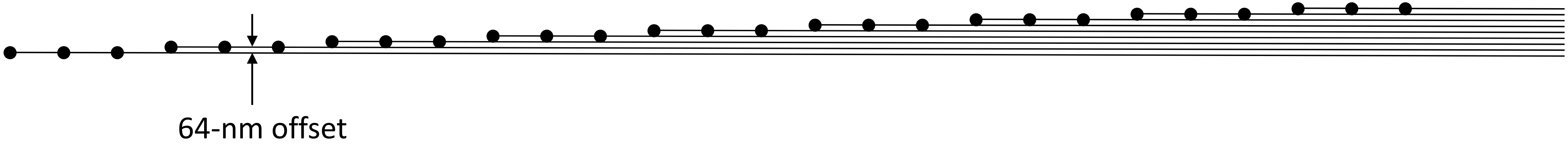
# Each lens row is partitioned into echelon subrows covering different raster lines.

aperture layout:



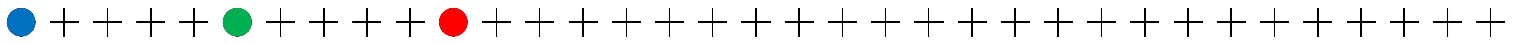

19 lenses per subrow
(illustrated as 3)

focus-spot pattern
on image plane:

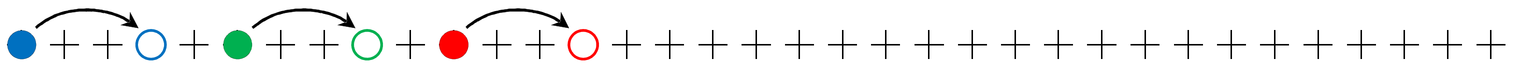


# The lenses in each subrow write interleaved dot patterns on the print grid, on one raster line.

After first pulse: +'s are grid points on the wafer, colored dots represent lens foci (5 grid steps per focus interval).



After second pulse:  The wafer scans left-to-right, 3 grid steps per pulse. Open O's are exposed grid points (centroids of overlapping point-spread functions).



After many pulses:  The scanned grid points are all exposed – no gaps or double exposures.  If the grid step is less than the 12-nm optical resolution limit then the overlapping PSF's sum to an isolated line image with straight exposure contours.

- N = number of lenses per subrow = 3 (illustrated), 19 (actual).
- Grid step = (focus interval) / M with M = 5  (illustrated), 336 (actual, for 8-nm grid step).
- Limitation:  M and N must be relatively prime (i.e., M cannot be a multiple of 19).
- Number of grid steps per pulse = N.  (Scan speed = 3.6 mm/sec with an 8-nm grid step.)

# Summary/Conclusions

Maskless EUVL at 13.5 nm, 0.55 NA could be implemented with existing technology infrastructure, and relative to HVM mask-projection EUVL would have:

- ~100X lower throughput, but …
- ~100X lower power requirement,
- ~10X higher exposure dose,
- ~1000X lower scan velocity and acceleration,
- Maskless capability

For Blue-X (6.7-nm , 0.55-NA) Maskless EUVL could overcome some critical feasibility limitations of HVM mask-projection lithography including:

- Power (~10X reduced ML mirror bandwidth at 6.7 nm vs 13.5 nm)
- Stochastics (2X smaller dimensions with 2X higher photon energy)
- Mask 3-D effects (with ~200 ML bilayers)