Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

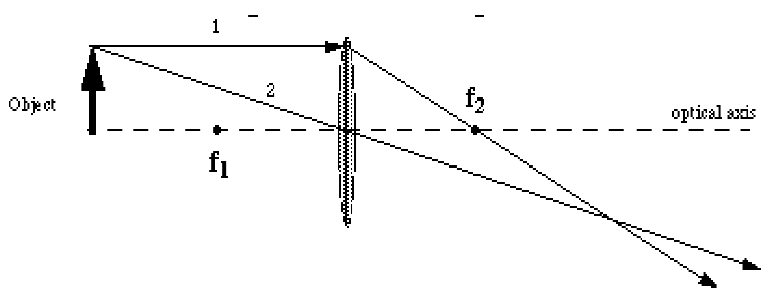
- **Aberrations: Non-Perfect Optical System**
  - **Point source image defects:**

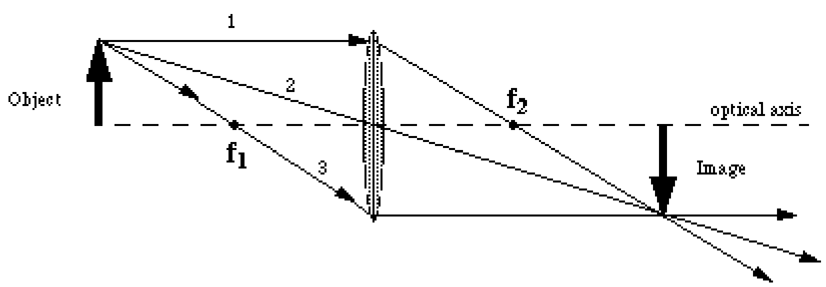
Ideal Coma Astigmatism Mixed

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- **Aberrations result from a Non-Perfect Optical System**
  - ***Definition of a perfect optical system:***
- **1. Every ray or a pencil of rays proceeding from a single object point must, after passing through the optical system converge to a single point of the image. There can be no difference between chief and marginal rays intersection in the image plane! Ray trace of simple converging lens: ray 1 = marginal ; ray 2 = chief; and ray 3 = focal**

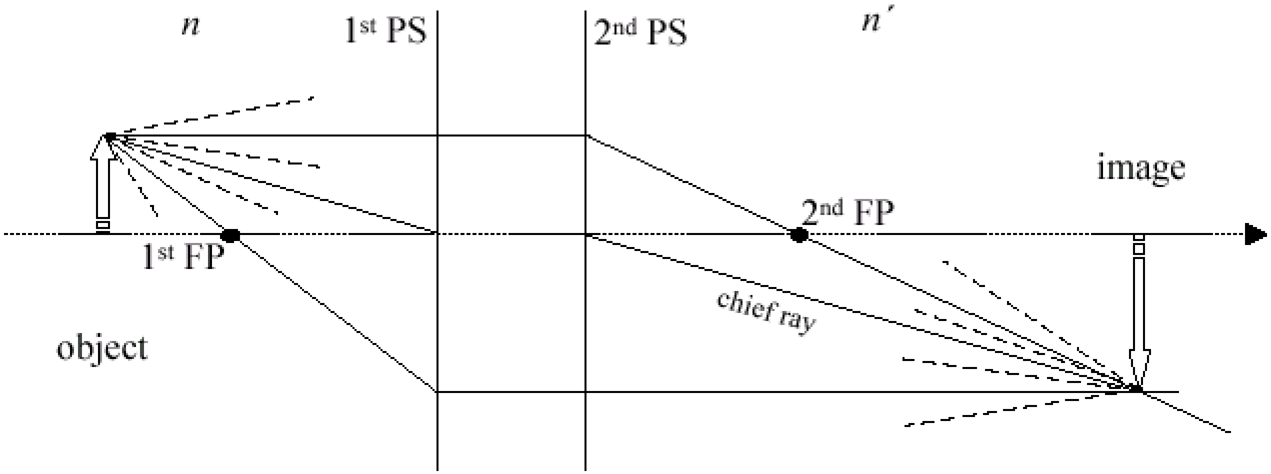




10. Imaging Aberrations, Defocus, and Zernike Polynomials

• Definition of a perfect optical system:

- **2. If the object is a plane surface perpendicular to the axis of the optical system, the image of any point on the object must also lie in a plane perpendicular to the axis.** ***This means that flat objects must be imaged as flat images and curved objects as curved images.***



- Image point is located at the common intersection of **all** rays which emanate from the corresponding object point
- The two rays passing through the two focal points and the chief ray can be ray-traced directly

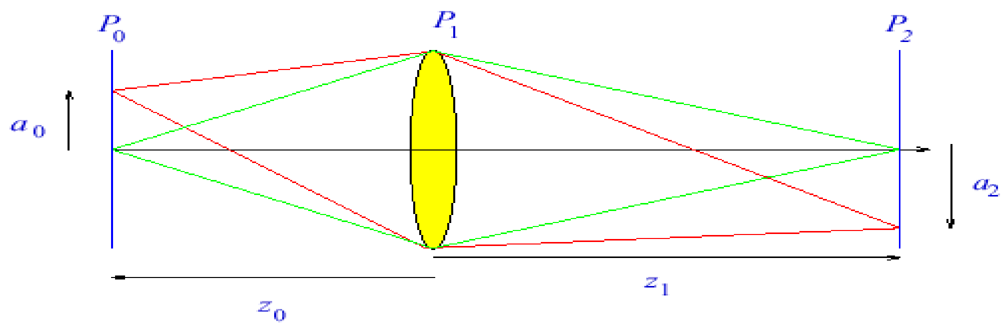
Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- **Definition of a perfect optical system:**

- **3. An image must be similar to the object whether it's linear dimensions are altered or not. This means that irregular magnification or minification cannot occur in various parts of the image relative to the object. IDEAL CASE BELOW:**

PSF moves linearly and does not change shape



System is said to be **Space Invariant**, and

$$a_2 = -\frac{z_1}{z_0} a_0 = -M a_0$$

Where $M = z_1/z_2$ is the magnification of the system.

- Ray tracing using monochromatic light with image and ***object located on the optical axis and paraxial rays (close to optic axis)*** typically meet this perfect image criteria.

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- **Aberrations results from:**
- ***1. Defects due to nature (design):***
- a. Dispersion: refractive index of galss varies with wavelength. (remember Shorter wavelength refracted more hence shorter focal length.)
- b. Spherical space of lens surfaces
- ***2. Defects due to fabrication:*** incorrect element spacing,tilted elements, rough glass surfaces, inhomogeneous glass (refractive index), glass stress, and incorrect element curvature or thickness.
- ***3. Defects due to application***: Thermal effects (lens heating), pressure changes, flare, and contamination (resist out-gassing or gas type change).

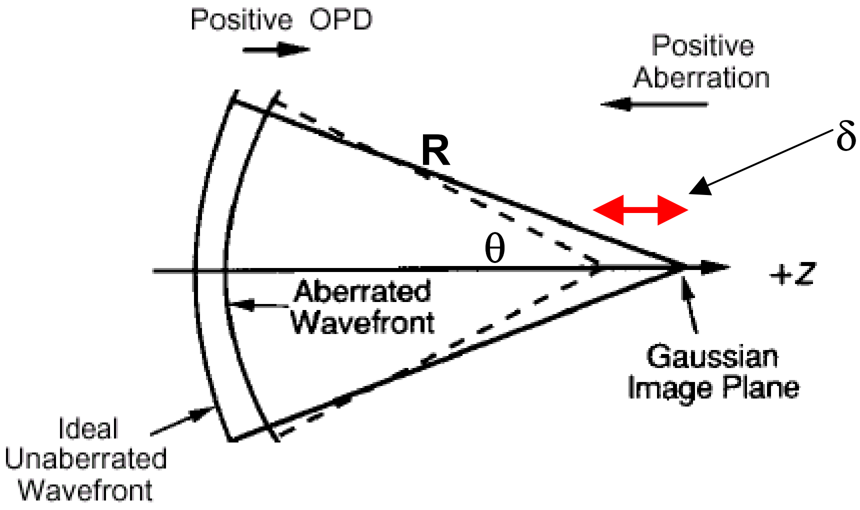
10. Imaging Aberrations, Defocus, and Zernike Polynomials

- Aberrations are defined as deviations in the image as a consequence of the light rays not obeying the 3 "perfect image" rules. The image location is not predicted by the classic ray trace procedure (applying Snells law at each surface). There is a ***wavefront deviation*** or optical path length difference (OPD) in the diffracted wavefronts forming the image
- **Aberration descriptions:** mathematically described as wavefront deviations: for **monochromatic aberrations**
- ***Zernike Polynominals:*** 37 terms from an infinite series; the magnitude of the coefficients (Z1 to Z37) values determine the aberrations in an optical system
- ***Seidel Aberrations:*** "3^{rd}" order approximation to Zernike terms
- Basic aberrations include: Defocus(Z4), Astigmatism(Z5 Z6); Coma (Z7 Z8) , Spherical (Z9) and **field curvature and distortion.**

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- **KEY ABERRATION IDEA: OPD = Optical path length difference between the wavefront emerging from the lens aperture and the ideal reference wavefront.(I.e. Perfect non-aberrated wavefront)**
  - ***Lens introduces a path length difference or phase shift!***



•***How this phase shift effects the image is the aberration!***

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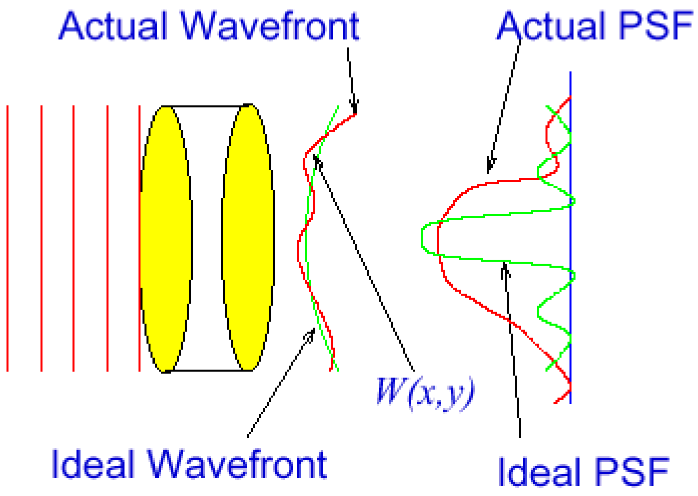
10. Imaging Aberrations, Defocus, and Zernike Polynomials

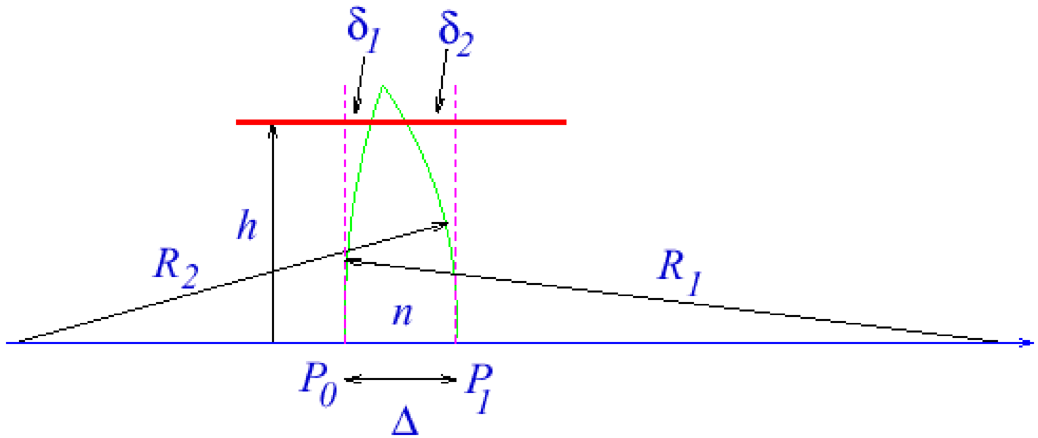
- **Aberrations exist due to the idea that the wavefront emerging from the *<u>lens aperture (exit pupil)</u>* is deformed in shape and causes an OPD between emerging wave and reference wave.**
- **Aberrations are measured in wavelength OPD units.**



Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- **Aberrations exist due to the idea wavefront being deformed in shape and causing an OPD between emerging wave and reference wave.**
- **Aberrations are measured in wavelength OPD units**
- ***Lens produces a path length difference or phase shift***
- ***Phase***



With **NO** lens, Phase Shift between , $P_0 \rightarrow P_1$ is

$$\Phi = \kappa\Delta \quad \text{where } \kappa = \frac{2\pi}{\lambda}$$ •Propagation constant in air

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- ***Phase function of lens: Φ= phase error***

with lens in place, at distance h from optical,

$$\Phi = \kappa \left(\underbrace{\delta_1 + \delta_2}_{\text{Air}} + n(\underbrace{\Delta - \delta_1 - \delta_2}_{\text{Glass}}) \right)$$

which can be arranged to give

$$\Phi = \kappa n \Delta - \kappa(n-1)(\delta_1 + \delta_2)$$

where δ_1 and δ_2 depend on h, the ray height.

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

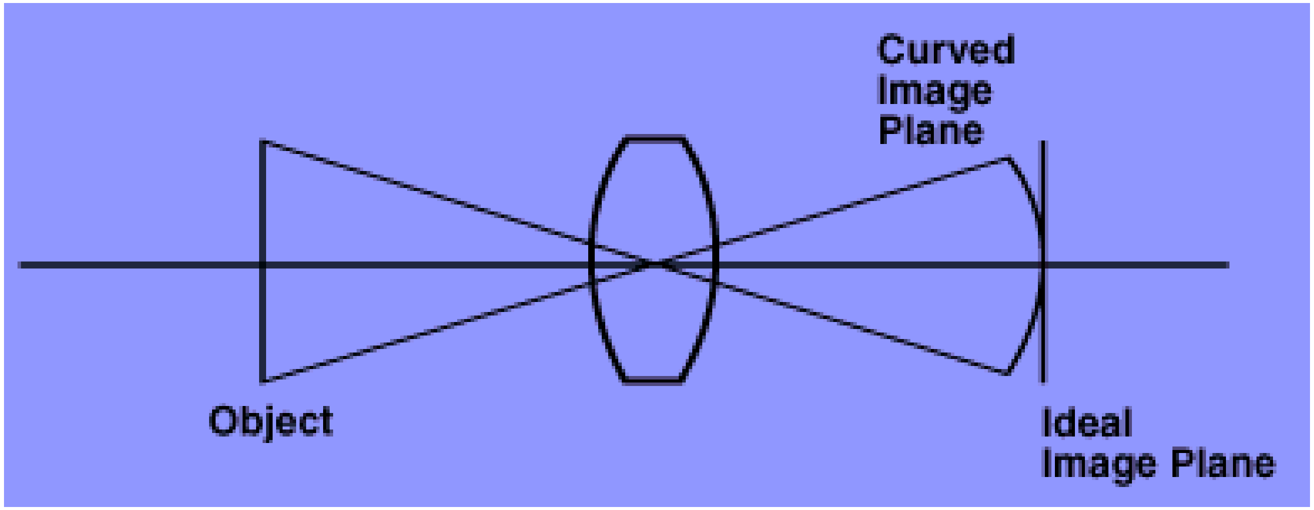
- Optical aberrations
- Monochromatic :Field Curvature, spherical, astigmatism, coma, distortion
- Polychromatic : Chromatic and lateral color

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

http://micro.magnet.fsu.edu/primer/anatomy/fieldcurvature.html

- Monochromatic :Field Curvature Aberration: Focus plane is curved.



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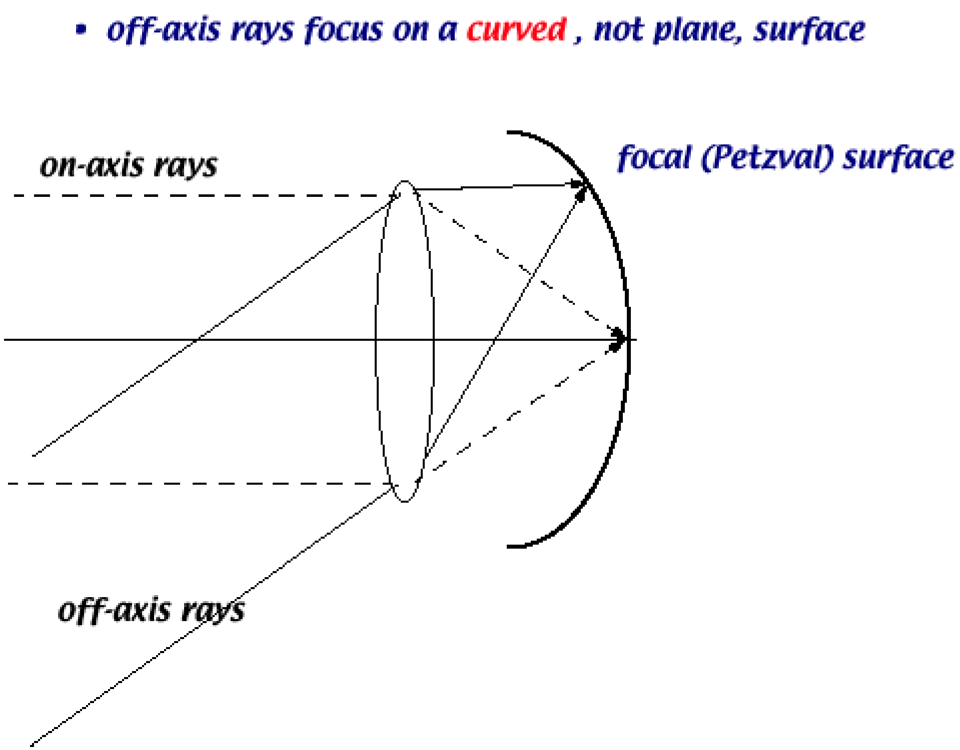
10. Imaging Aberrations, Defocus, and Zernike Polynomials

- Monochromatic :Field Curvature: Focus plane is curved. This natural curved focus plane is called Petzel surface.



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10. Imaging Aberrations, Defocus, and Zernike Polynomials

- Field Curvature:This image defect is the **natural result** of using lenses that have curved surfaces. When visible light is focused through a curved lens, the image plane produced by the lens will be curved. A simple lens focuses image points from an extended flat object, such as a specimen on a microscope slide, onto a spherical surface resembling a curved bowl. ***The nominal curvature of this surface is the reciprocal of the lens radius and is referred to as the Petzval Curvature of the lens.***

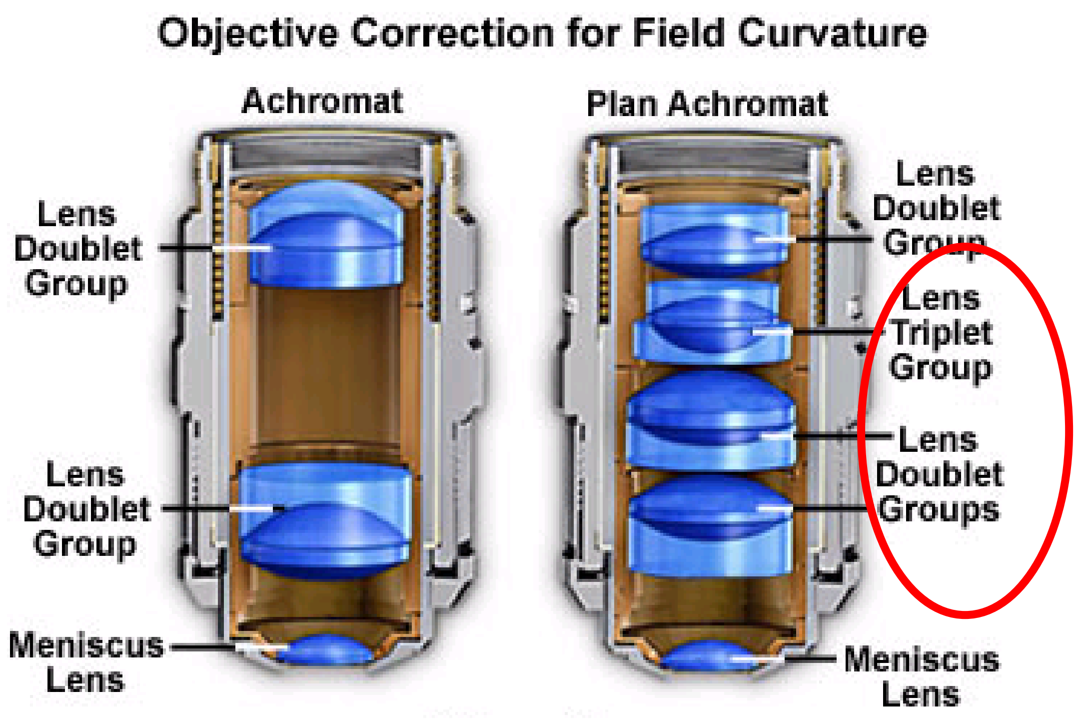
#	Aberration	Image Character	Wavelength	On axis and aperture A impact	Image Height Y off-axis Fct.	Total impact A - Y	Measurement	Microlithography Units spec modern Tool specs	Correction
1	Field Curvature	Petzval surface that is not flat plane	Monochromatic	OFF AXIS	Yes increases with the square of the image height Y	Y^2	Focal plane deviation across the field.	100nm	Spaced doublet; plan acrhomat

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

http://micro.magnet.fsu.edu/primer/anatomy/fieldcurvature.html

- Field Curvature: Correction for flat field

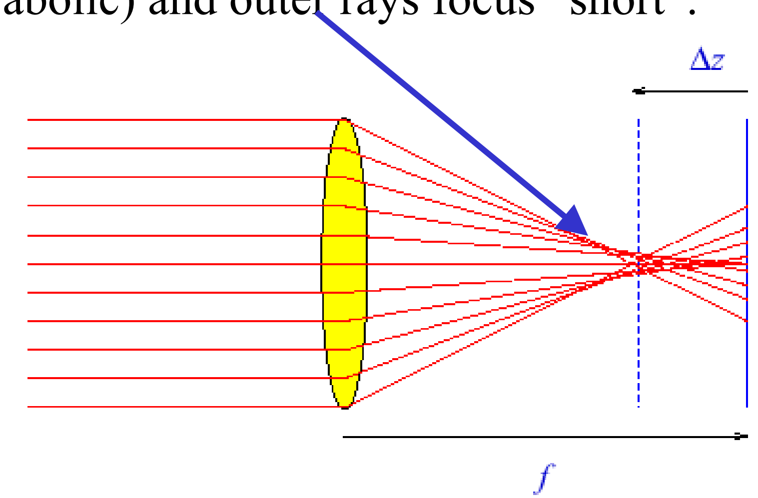


Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

http://micro.magnet.fsu.edu/primer/anatomy/aberrationhome.html

- Spherical: The most serious of the **monochromatic defects** that occurs with objectives, spherical aberration, causes the image to appear hazy or blurred and slightly out of focus. The effect of **spherical aberration manifests itself in two ways: the center remains more in focus than the edges of the image and the intensity of the edges falls relative to that of the center**. This defect appears in both on-axis and off-axis image points. ***Simple explanation***: lens is spherical (non parabolic) and outer rays focus "short".

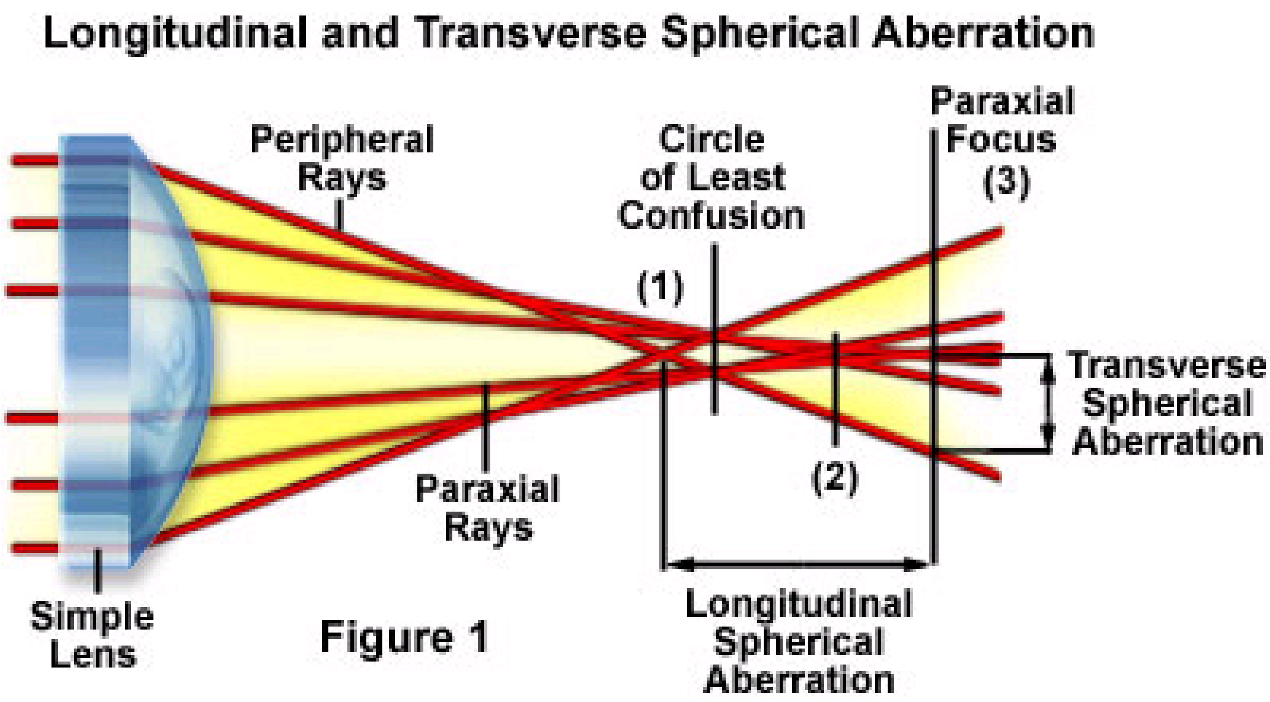


Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

http://micro.magnet.fsu.edu/primer/java/aberrations/spherical/index.html

- Spherical: measured as LSA and TSA



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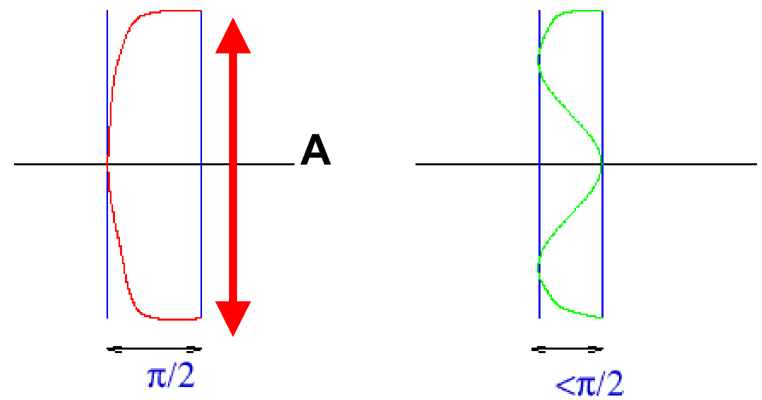
10. Imaging Aberrations, Defocus, and Zernike Polynomials

- Spherical:

Able to "cancel" some of the Spherical Aberration with defocus

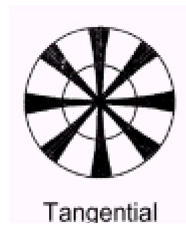


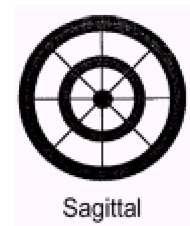
#	Aberration	Image Character	Wavelength	On axis and aperture A impact	Image Height Y off-axis Fct.	Total impact A - Y	Measurement	Microlithography Units spec modern Tool specs	Correction
2	Spherical	variation in focal plane with radial beam position	Monochromatic	ON AXIS					Bending , high index aspheerics, gradient index, doublet
	LSA			Increases as square of aperture diameter		A^2			
	TSA			Increases as cube of aperture diameter		A^3			

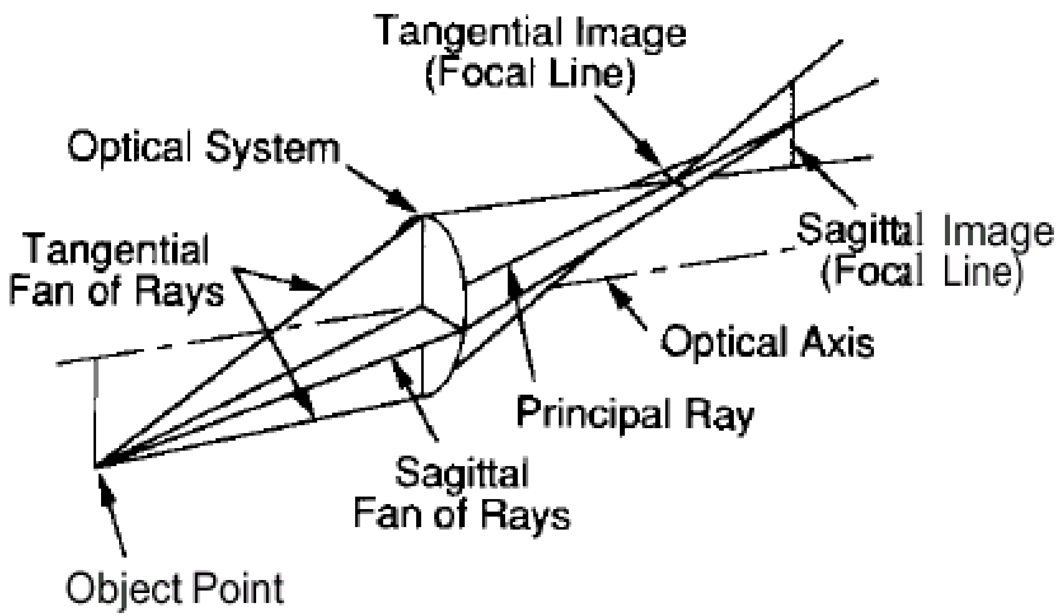
10. Imaging Aberrations, Defocus, and Zernike Polynomials

Modern Optical Engineering; Warren Smith ISBN 0-07-059174-1 McGraw-Hill

- Astigmatism: vertical and horizontal objects have different foci due to lens curvature





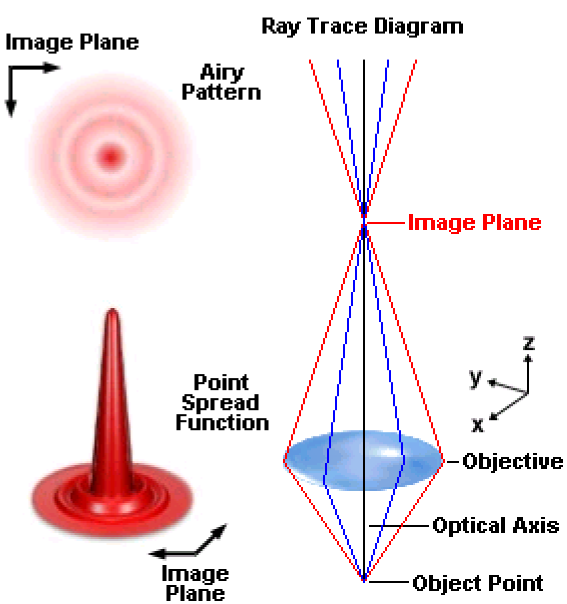


Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

http://micro.magnet.fsu.edu/primer/anatomy/aberrationhome.html

- Astigmatism: vertical and horizontal objects have ***different foci due to lens curvature: Common fabrication error to make surfaces slightly cylindrical instead of perfectly spherical. In which case orthogonal wavefronts leaving the surface will have different radii***



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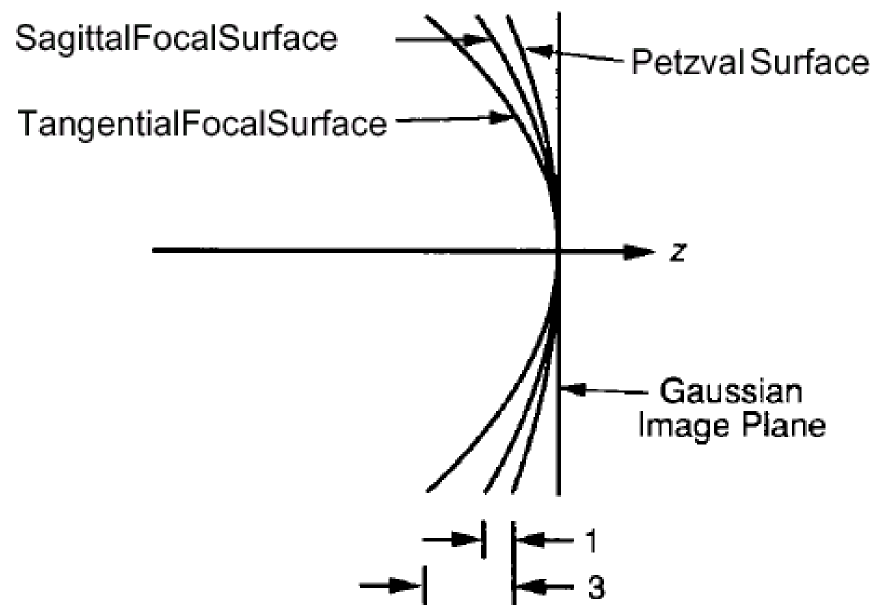
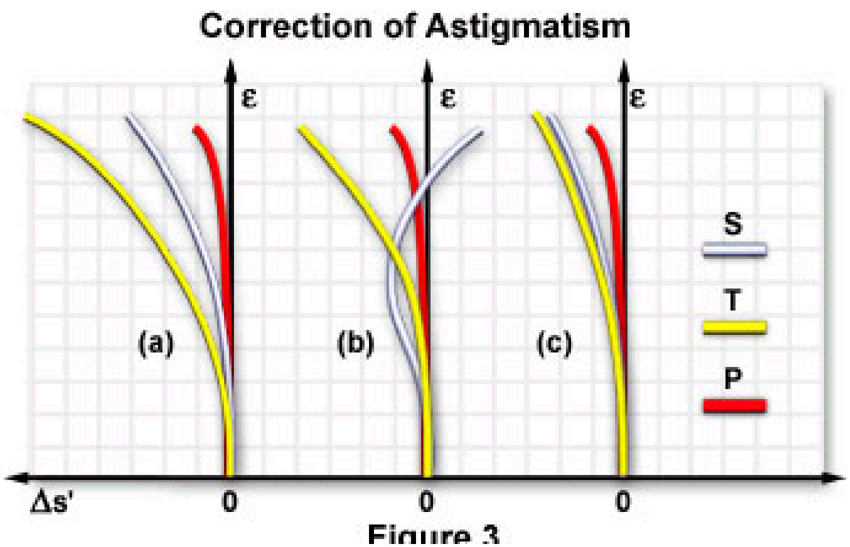


Basic Optics : Microlithography

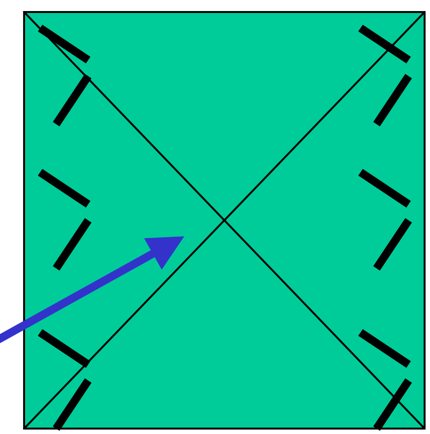
10. Imaging Aberrations, Defocus, and Zernike Polynomials

http://micro.magnet.fsu.edu/primer/anatomy/aberrationhome.html

- ***Astigmatism:*** Complete removal of astigmatism is difficult, but can occur in optical systems when the two curves, **S** and **T**, become flatter and coincide (Figure 3(c)), and the image is then formed in a region near the ***Petzval surface*** (**P**)



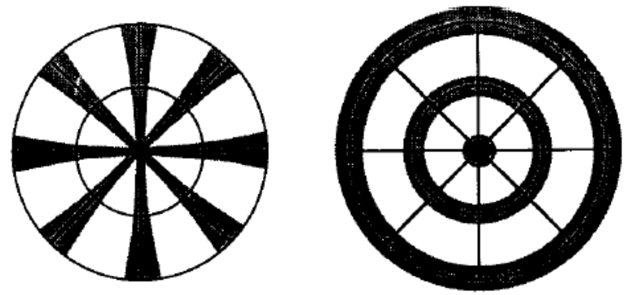
Focal plane moving from "on-axis" = 0



Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- ***Astigmatism:***

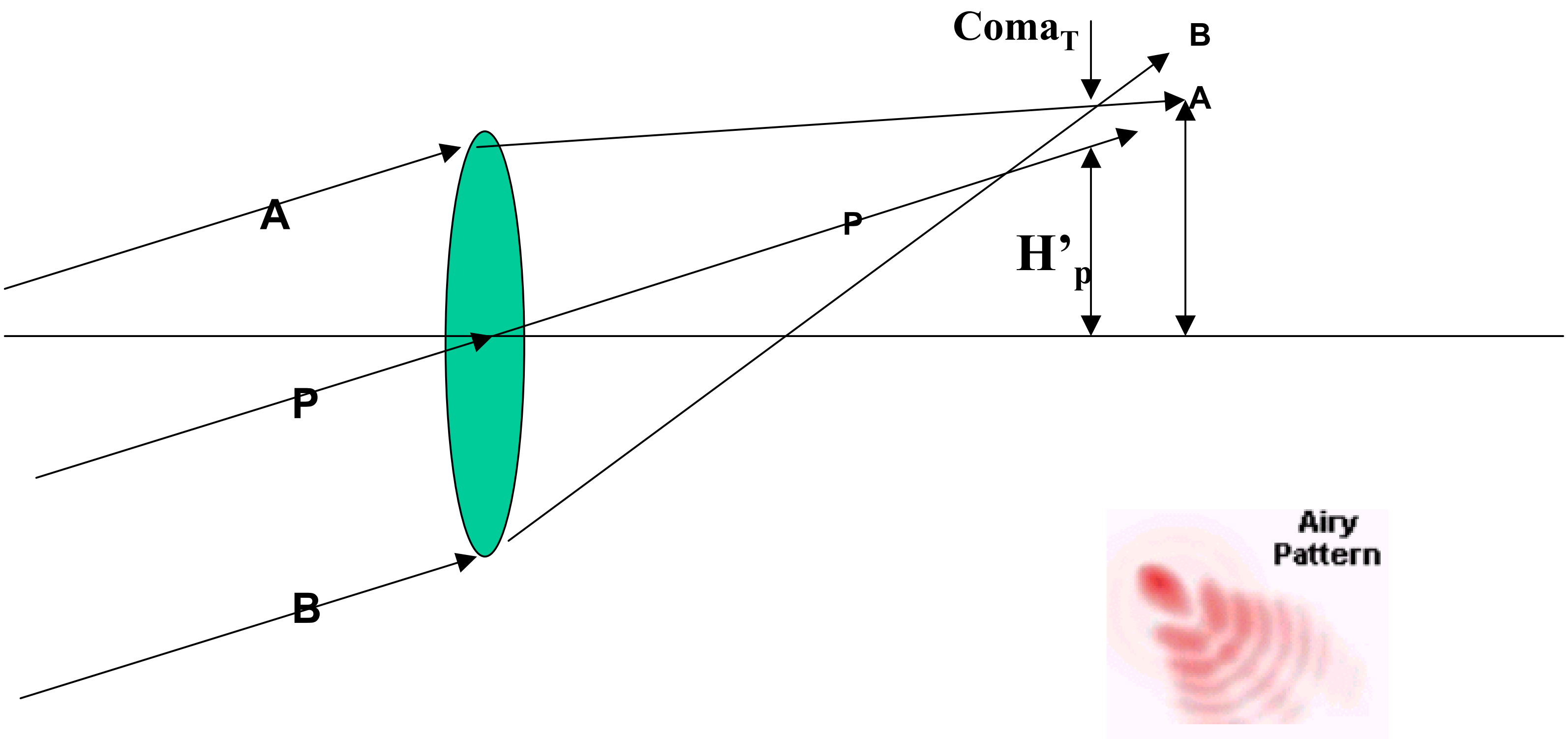


#	Aberration	Image Character	Wavelength	On axis and aperture A impact	Image Height Y off-axis Fct.	Total impact A - Y	Measurement	Microlithography Units spec modern Tool specs	Correction
3	Astigmatism	Rays in different planes do not have common foci	Monochromatic	**OFF AXIS**	Yes increases with the square of the image height Y	Y^2	V focus - H focus across the field	**50 nm**	**Bending (spherical lens) ;Spaced doublet with stop**

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- Coma: ***Also called off-axis spherical aberration :***off axis singular object point imaging as multiple points
- **Tangential Coma of the lens** $\mathbf{Coma_T = H''_{AB} - H'_p}$



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10. Imaging Aberrations, Defocus, and Zernike Polynomials

- Coma: Comatic aberrations are similar to spherical aberrations, but they are mainly encountered with off-axis light fluxes and are most severe when the microscope is out of alignment. When these aberrations occur, the image of a point is focused at sequentially differing heights producing a series of asymmetrical spot shapes of increasing size that result in a comet-like (hence, the term coma; Figure 1) shape to the Airy pattern.

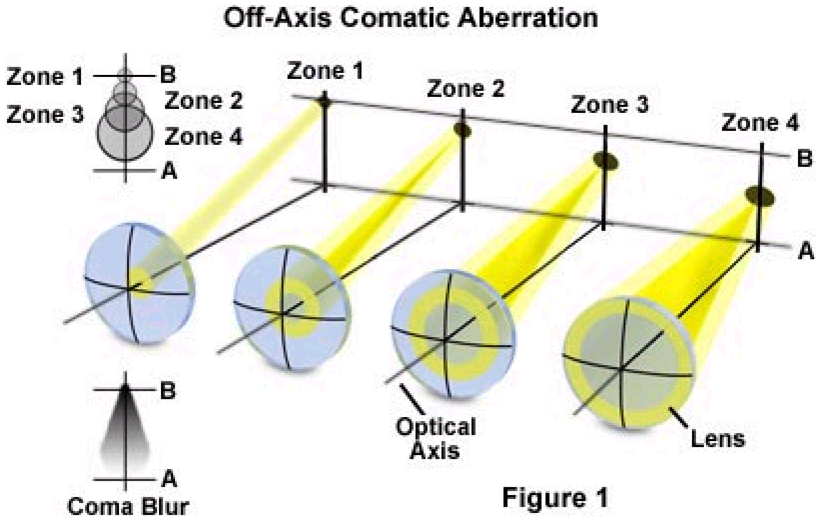
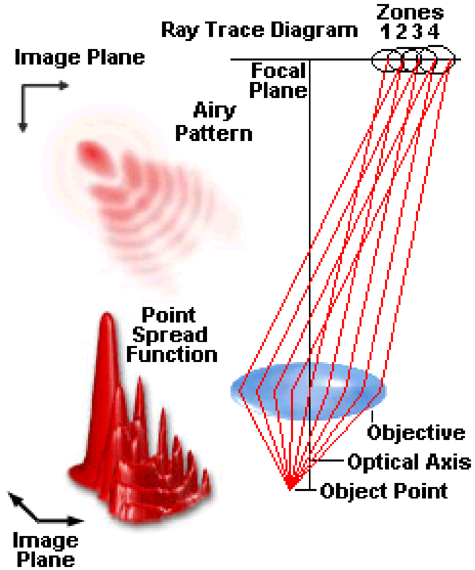


Figure 1



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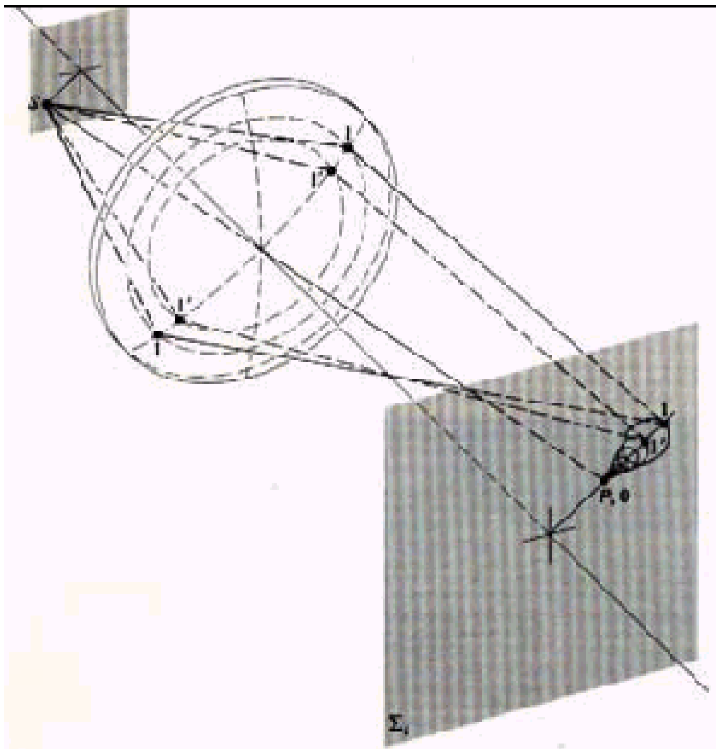
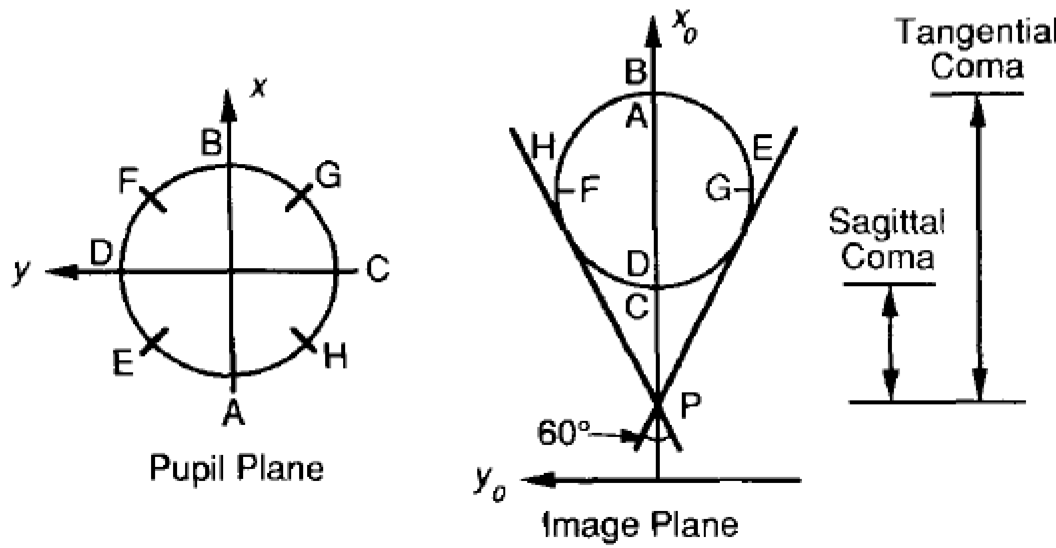
10. Imaging Aberrations, Defocus, and Zernike Polynomials

- Image with coma (x_o plane):





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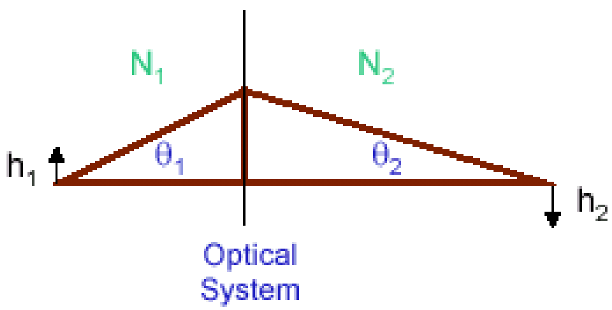
10. Imaging Aberrations, Defocus, and Zernike Polynomials

- **<u>Coma can be corrected by using a combination of lenses that are positioned symmetrically around a central stop.</u>** In order to completely eliminate coma, the **Abbe sine condition** must be fulfilled**:**

$$N_1 h_1 \sin \theta_1 = N_2 h_2 \sin \theta_2$$



•The magintude of Coma, like spherical aberration, is heavily dependent upon the shape of the lens. A strongly concave positive meniscus lens will demonstrate substantial negative comatic aberration, whereas plano-convex and bi-convex lenses produce comas that range from slightly negative to zero. Objects imaged through the convex side of a plano-convex lens or a convex meniscus lens will have a positive coma.

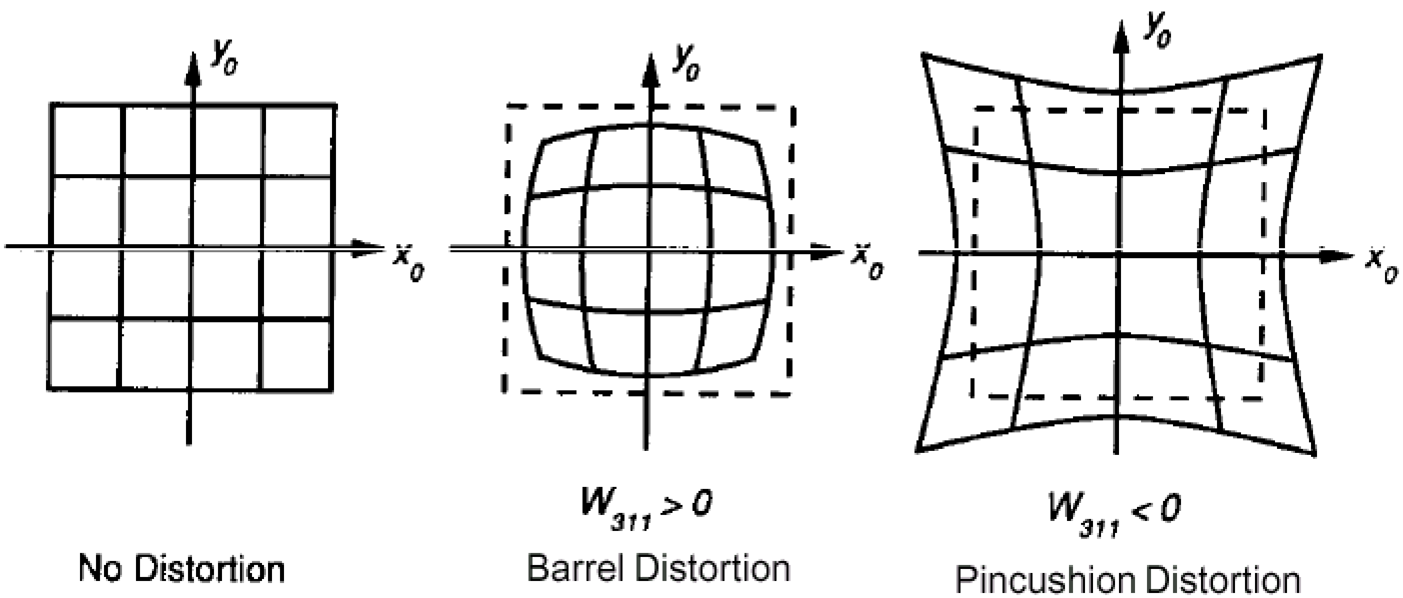
#	Aberration	Image Character	Wavelength	On axis and aperture A impact	Image Height Y off-axis Fct.	Total impact A - Y	Measurement	Microlithography Units spec modern Tool specs	Correction
4	Coma	Variation in magnification with aperture (distance from optical axis	Monochromatic	**OFF AXIS** Increases as square of aperture diameter	Yes increases linearly with the image height Y	A^2Y	left right linewidth deltas	**50 nm**	**Bending ,spaced doublet with central stop**

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

http://micro.magnet.fsu.edu/primer/java/aberrations/distortion/index.html

- Distortion : ***off axis non-uniform magnifcation*** error across image field. Results in image placement errors.



Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

http://micro.magnet.fsu.edu/primer/java/aberrations/distortion/index.html

- Distortion : The origin of geometrical distortion lies in a difference between the transverse magnification of a lens and the off-axis image distance. When this distance deviates from that predicted by paraxial theory for constant transverse magnification, distortion can arise due to differences in focal lengths and magnifications through various parts of the lens. In the absence of other aberrations, geometric distortion is manifested by a mis-shaped image, even though each image point is in sharp focus, as discussed above. Quantitatively, distortion can be described by the following equation:

  - **$DM = (M_l - M)/M$**

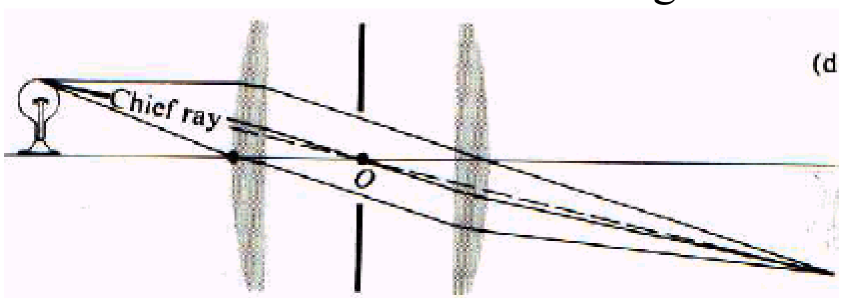
- where M is the axial lateral magnification and M(l) is the off-axis magnification at the image plane. If the lateral magnification increases proportionally with the off-axis distance of the object, distortion is positive, producing a pincushion effect (Figure 1). In this instance, each image point is displaced radially outward from the center, with the peripheral image points being displaced the greatest distance. Alternatively, when magnification is decreased with the off-axis object distance, distortion is negative and a barrel aberration is observed. Barrel distortion corresponds to a situation where the transverse magnification decreases with axial distance and each image point moves radially towards the center of the image.

10. Imaging Aberrations, Defocus, and Zernike Polynomials

http://micro.magnet.fsu.edu/primer/java/aberrations/distortion/index.html

• Distortion :

- Correction:
- Spaced doublet with central stop
- Also corrects Coma and astigmatism



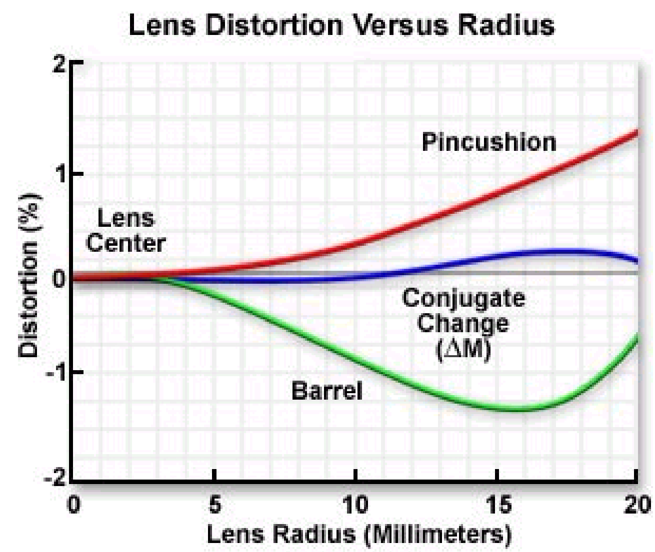


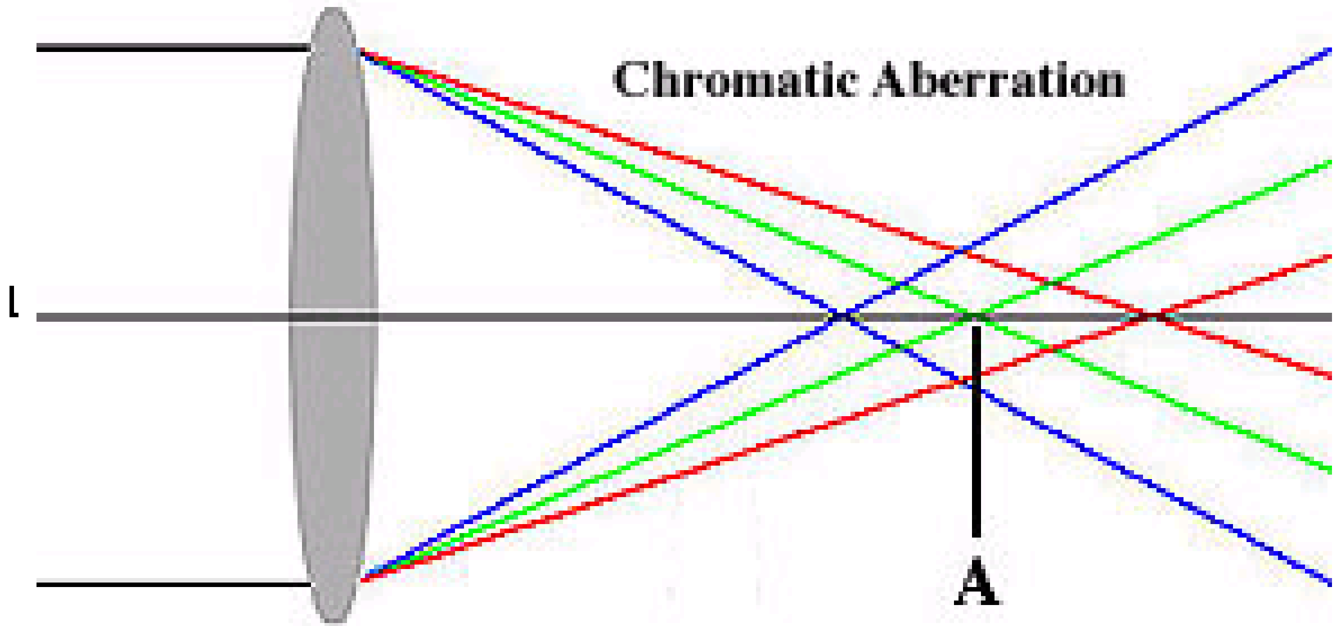
Figure 1

#	Aberration	Image Character	Wavelength	On axis and aperture A impact	Image Height Y off-axis Fct.	Total impact A - Y	Measurement	Microlithography Units spec modern Tool specs	Correction
5	Distortion	Radial displacement of off-axis points causing a field magnification error	Monochromatic	OFF AXIS	Yes increases with the cube of the image height Y	Y^3	Registration errors	Maximum error 20 nm	Spaced doublet with stop

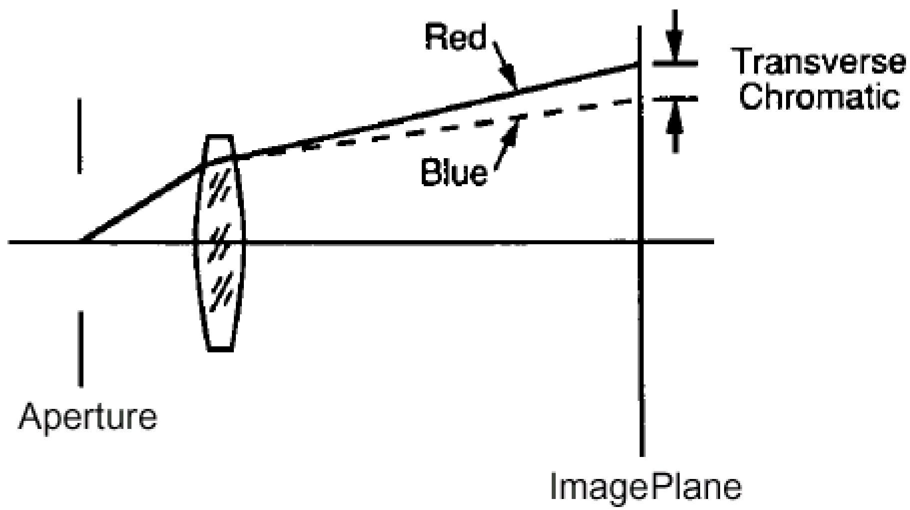
Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- Polychromatic : Chromatic(result of dispersion i.e lens is like a prism)

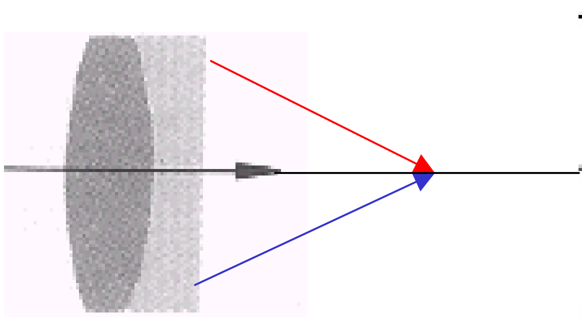


- Polychromatic : Lateral of traverse Chromatic aberration (Magnification changing with wavelength.)

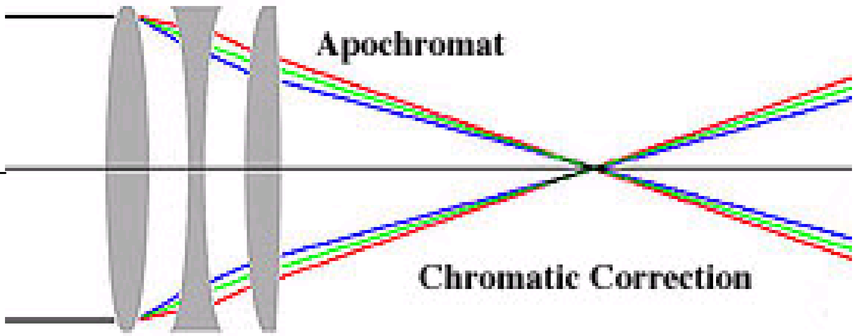


10. Imaging Aberrations, Defocus, and Zernike Polynomials

- Polychromatic : Chromatic correction Achromatic lens
- Doublet



Power, Shape and index of each lens cancel the aberration of the other.



#	Aberration	Image Character	Wavelength	On axis and aperture A impact	Image Height Y off-axis Fct.	Total impact A - Y	Measurement	Microlithography Units spec modern Tool specs	Correction
6	Chromatic	on and off axis image blur	Polychromatic	ON AXIS Lateral OFF AXIS			red - blue focal plane	modern exposure tool bandwidth - 0.5 pm!	Achromatic lens (refractive index deltas to cancel dispersive powers)

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- **Chromatic aberration effects:**

http://www.finle.com/product_information/publications/SPIE2000Cymer.pdf

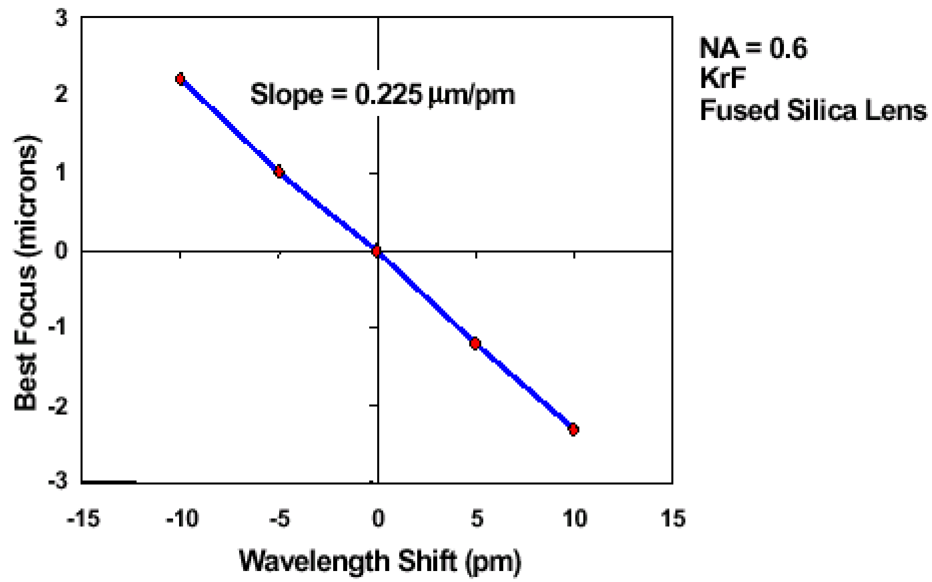


Figure 1. Measurement of best focus as a function of central wavelength shows a linear relationship with a slope of 0.225 µm/pm for this 0.6 NA projection lens.

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- **Chromatic : Wavelength on exposure tools are not pure monochromatic: hence >> multiple wavelengths exist!**
- **From :** http://www.finle.com/product_information/publications/SPIE2000Cymer.pdf

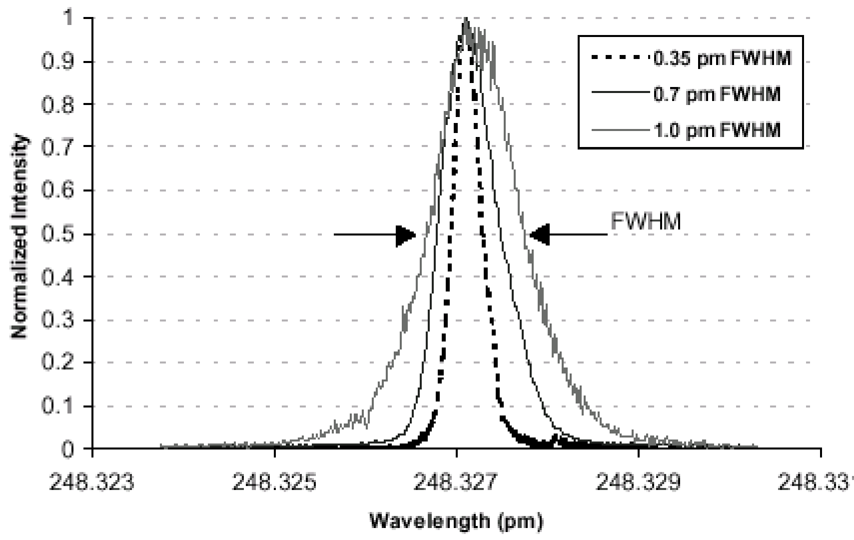


Figure 2. Examples of different KrF excimer laser spectra.

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- **Chromatic : Focus dependence on wavelength: Using Zernike Z4 Focus (Note this reference uses calls it Z3.)**
- **From :** http://www.finle.com/product information/publications/SPIE2000Cymer.pdf

As an example, the response of wavelength as a focus shift can be modeled using the third fringe Zernike polynomial term (see reference 4 for a complete description of the Zernike polynomial used here). The coefficient of this Zernike term Z_3 can be related to a focus shift $\Delta\delta$ by

$$Z_3 = \Delta\delta \frac{NA^2}{4\lambda_o} = (slope)\Delta\lambda \frac{NA^2}{4\lambda_o} \qquad (1)$$

where λ_0 is the central wavelength of the illumination spectrum. Thus, if the focus shift as a function of wavelength is known, a value of Z_3 for each wavelength in the illumination spectrum can be computed from the equation (1).

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- **Chromatic : Focus dependence on wavelength:**
- **From :** http://www.finle.com/product_information/publications/SPIE2000Cymer.pdf

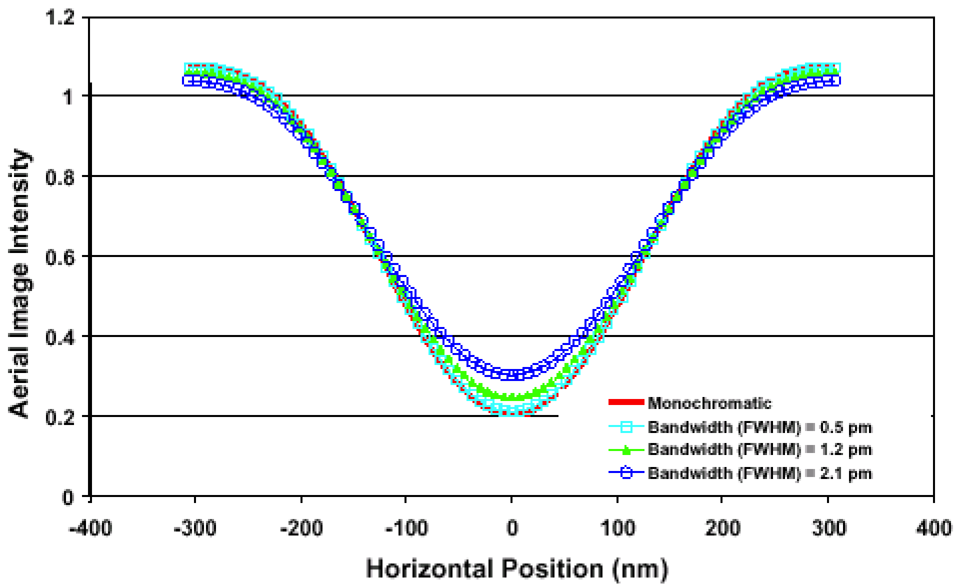


Figure 3. Degradation of the aerial image of a 180 nm line (500 nm pitch) with increasing laser bandwidth for a chromatic aberration response of 0.225 µm/pm.

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- **Chromatic : Process latitude dependence on excimer laser bandwidth wavelength:**
- **From :** http://www.finle.com/product_information/publications/SPIE2000Cymer.pdf

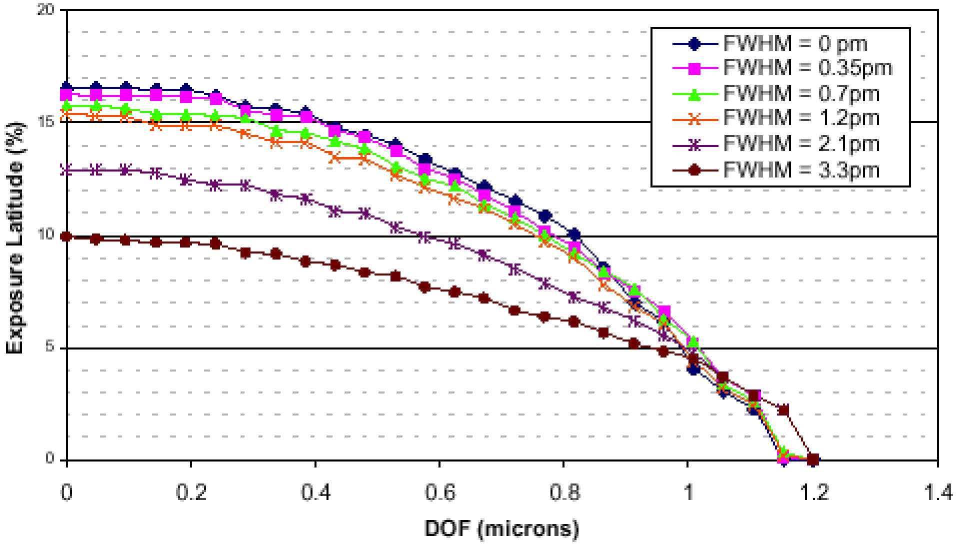


Figure 5. Sensitivity of the focus-exposure process window to laser bandwidth. Numerical aperture of the lens is set at 0.6 and partial coherence factor σ at 0.75.

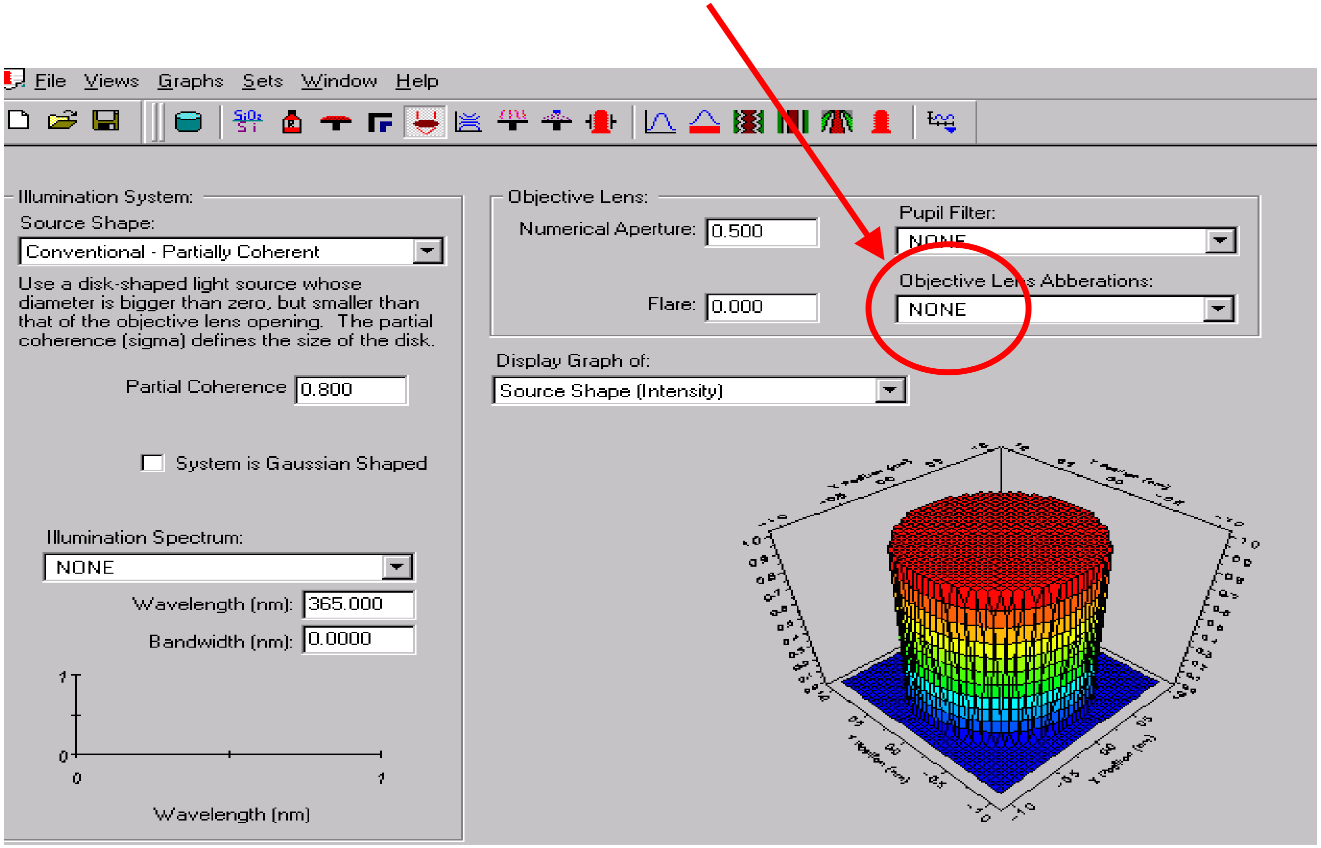
Basic Optics : Microlithography

Imaging Aberrations: Summary

#	Aberration	Image Character	Wavelength	On axis and aperture A impact	Image Height Y off-axis Fct.	Total impact A - Y	Measurement	Microlithography Units spec modern Tool specs	Correction
1	**Field Curvature**	Petzval surface that is not flat plane	Monochromatic	**OFF AXIS**	Yes increases with the square of the image height Y	**Y^2**	Focal plane deviation across the field.	0.2um	Spaced doublet; plan acrhomat
2	**Spherical**	variation in focal plane with radial beam position	Monochromatic	**ON AXIS**					Bending , high index aspheerics, gradient index, doublet
	LSA			Increases as square of aperture diameter		**A^2**			
	TSA			Increases as cube of aperture diameter		**A^3**			
3	**Astigmatism**	Rays in different planes do not have common foci	Monochromatic	**OFF AXIS**	Yes increases with the square of the image height Y	**Y^2**	V focus - H focus across the field	0.10 um	Spaced doublet with stop
4	**Coma**	Variation in magnification with aperture (distance from optical axis	Monochromatic	**OFF AXIS** Increases as square of aperture diameter	Yes increases linearly with the image height Y	**A^2Y**	left right linewidth deltas	0.05um	Bending ,spaced doublet with central stop
5	**Distortion**	Radial displacement of off-axis points causing a field magnification error	Monochromatic	**OFF AXIS**	Yes increases with the cube of the image height Y	**Y^3**	Registration errors	Maximum error 20 nm	Spaced doublet with stop
6	**Chromatic**	on and off axis image blur	Polychromatic	**ON AXIS Lateral OFF AXIS**			red - blue focal plane	modern exposure tool bandwidth - 0.5 pm!	Achromatic lens (refractive index deltas to cancel dispersive powers)

10. Imaging Aberrations, Defocus, and Zernike Polynomials

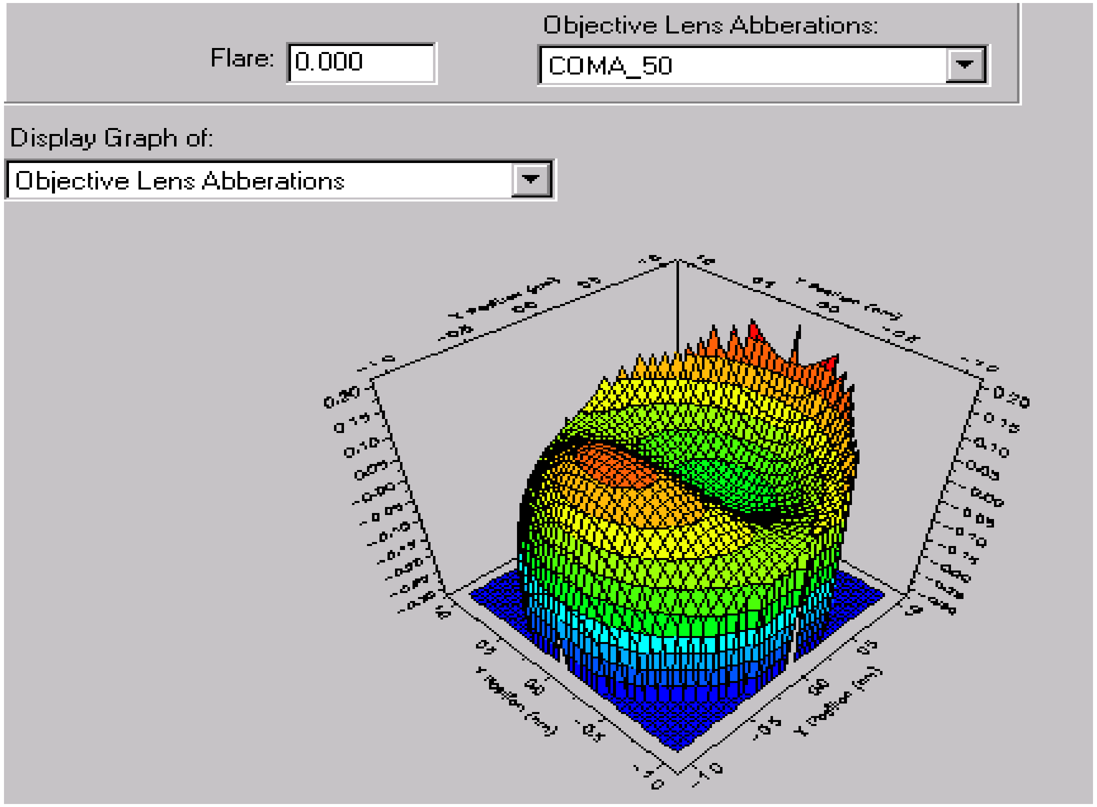
- **Typical wavefront shapes at the entrance pupil for the primary aberrations. This can be observed in Prolith by inputting various aberrations**
  - **No Aberrations : wavefront shape**
- **Can model in Prolith with Zernike input files lists magnitudes fro the 37 terms**



Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

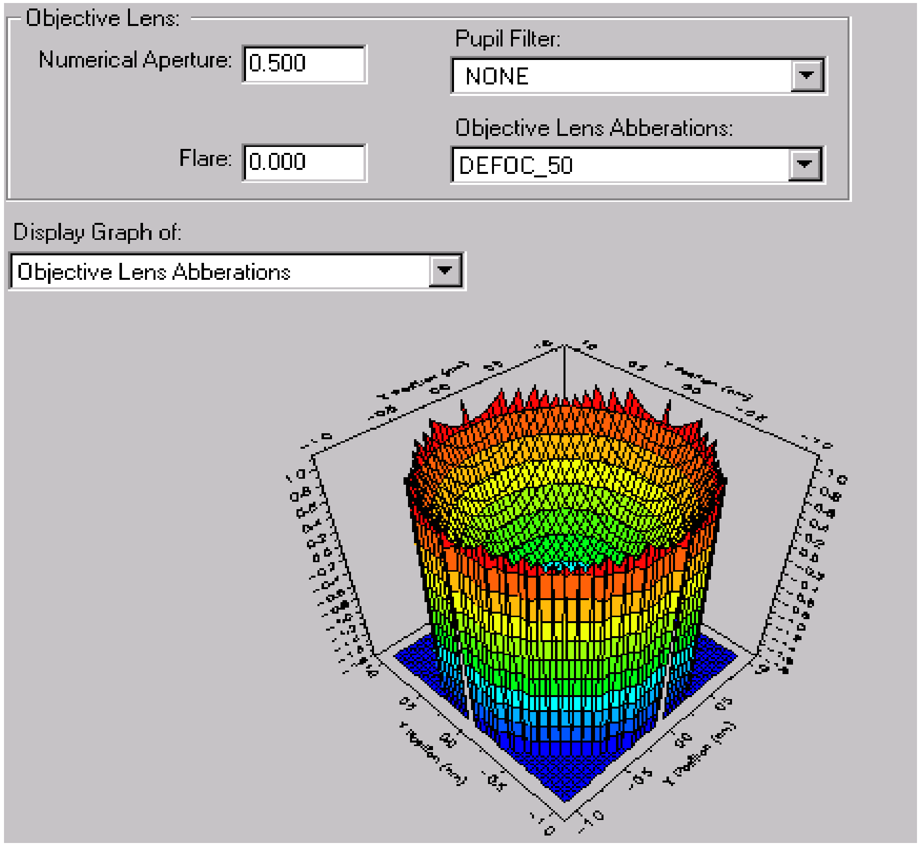
Prolith : coma wavefront errors Z7 Z8



Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

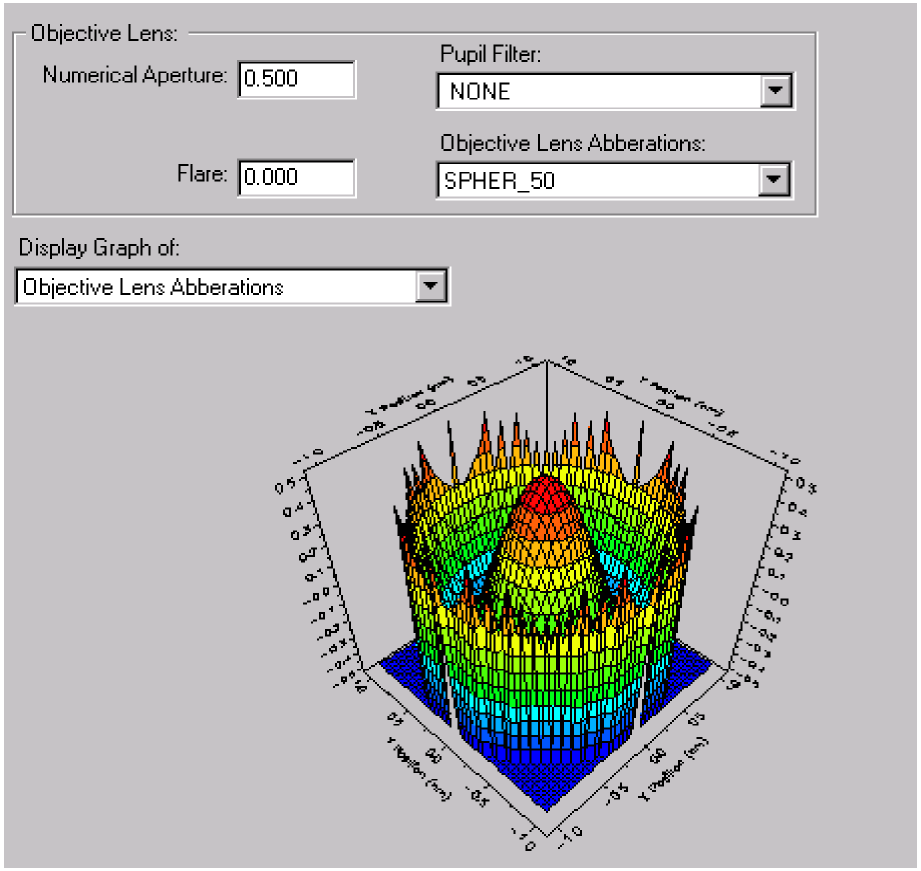
Prolith : defocus wavefront errors Z4



Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

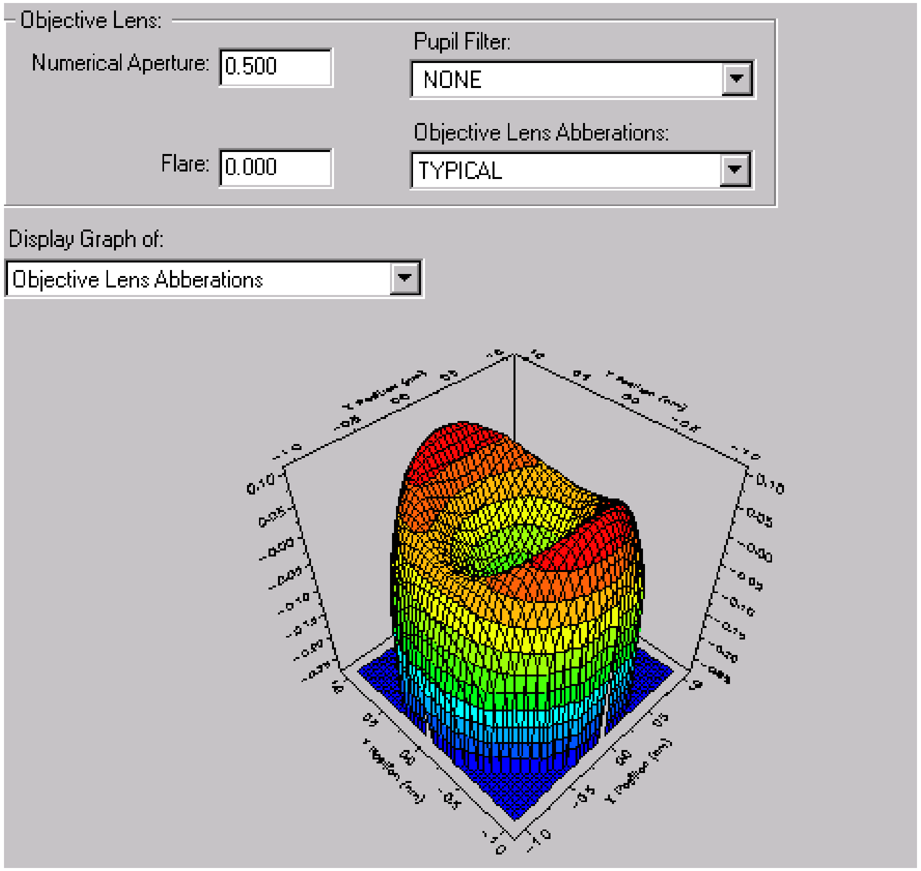
Prolith : Spherical wavefront errors Z9



Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

Prolith :multiple aberrations wavefront errors



Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- **The shape of these wavefronts is very complex. To analyze these and potentially correct the errors it is useful to fit the wavefront to a polynomial with each term (coefficient) representing a specific aberration. Two common Polynomials models (page 219 of text):**

- **SEIDEL**: 1856 Philip Ludwig von Seidel in Germany (3rd order approximation to Zernike terms with power laws for variations across the pupil field.

- **Zernike Polynomials:** (can be cartesian (X,Y) or polar (R,q) . They apply to a wavefront at a single point. To map the entire field the polynomial needs to be calculated at multiple points. Each term represents individually the best least squares fit of the data. This means to remove for eaxmple focus shift or coma from the wavefront, one just sets those terms to zero (Z4 for focus, Z8,Z9,Z14,Z15, Z23,Z24,Z34, and Z35 for XY coma). There are 37 terms. **Need to watch order and notation of coefficients when obtaining values!!**

- **SEIDEL's five aberrations**
- The five (5) monochromatic aberrations analyzed by SEIDEL in Germany, in 1856 :
  1.) spherical aberration
  2.) coma
  3.) astigmatism
  4.) curvature of field
  5.) distortion

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

http://www.iue.tuwien.ac.at/publications/PhD%20Theses/kirchauer/node57.html

Seidel Aberrations

- The derivations of the previous equations for the object, image and focal distances assumed **$n_1\theta_1 = n_2\theta_2$.** However, Snell's Law is exact; the inclusion of higher orders of the sine expansion produces slight alterations to the predictions of first-order theory. Adding the next non-zero term yields the approximation

  - $$\sin = \theta - \theta^3/3!,$$

- which is used to define the third-order, or Seidel, aberrations. Aberrations refer to the difference in behavior of a real ray compared to an ideal ray. Wavefront error and transverse ray error are two methods of describing an aberration. Commonly used to describe the results of interferometric tests, the wavefront error compares the actual wavefront to a perfect, spherical wave converging to the focal point. Alternately, the **transverse ray** error is defined by the blur at the image plane for a specified object point and relates easily to geometric tests.

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

Seidel Aberration Coefficients

WAVEFRONT ABERRATION COEFFICIENTS AND RELATIONSHIP TO SEIDEL ABERRATIONS

Wavefront Aberration Coefficient	Seidel Aberration Coefficient	Functional Form	Name
W_{200}		x_0^2	piston
W_{111}		$x_0 \rho \cos\theta$	tilt
W_{020}		ρ^2	focus
W_{040}	$= \frac{1}{8} S_{I}$	ρ^4	spherical
W_{131}	$= \frac{1}{2} S_{II}$	$x_0 \rho^3 \cos\theta$	coma
W_{222}	$= \frac{1}{2} S_{III}$	$x_0^2 \rho^2 \cos^2\theta$	astigmatism
W_{220}	$= \frac{1}{4}(S_{III} + S_{IV})$	$x_0^2 \rho^2$	field curvature
W_{311}	$= \frac{1}{2} S_{V}$	$x_0^3 \rho \cos\theta$	distortion

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

Seidel Aberrations : Seidel Wavefront error equation
ΔW = wavefront error deviation from perfect wavefront

In polar coordinates: $x = \rho\cos\theta$ and $y = \rho\sin\theta.$

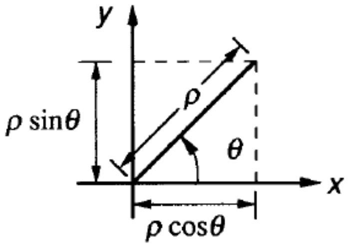
$$W(x_0, \rho, \theta) = W_{200}x_0^2 + W_{111}x_0\rho\cos\theta + W_{020}\rho^2 + W_{040}\rho^4 + W_{131}x_0\rho^3\cos\theta + W_{222}x_0^2\rho^2\cos^2\theta + W_{220}x_0^2\rho^2 + W_{311}x_0^3\rho\cos\theta;$$

3rd order is the highest

X_o = image point

Seidel aberration coefficients S,:

$$W(x_0, \rho, \theta) = \tfrac{1}{8}S_I\rho^4 + \tfrac{1}{2}S_{II}x_0\rho^3\cos\theta + \tfrac{1}{2}S_{III}x_0^2\rho^2\cos^2\theta + \tfrac{1}{4}(S_{III} + S_{IV})x_0^2\rho^2 + \tfrac{1}{2}S_V x_0^3\rho\cos\theta.$$



Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

Seidel Aberrations : Seidel Wavefront error equation

ΔW = wavefront error deviation from perfect wavefront

Seidel Aberrations

A. Spherical Aberration $(\Delta W = W_{040}\rho^4 = W_{040}(x^2 + y^2)^2)$

B. Coma $(\Delta W = W_{131}x_0\rho^3\cos\theta = W_{131}x_0x(x^2 + y^2))$

C. Astigmatism $(\Delta W = W_{222}x_0^2\rho^2\cos^2\theta = W_{222}x_0^2x^2)$

D. Field Curvature $(\Delta W = W_{220}x_0^2\rho^2 = W_{220}x_0^2(x^2 + y^2))$

E. Distortion $(\Delta W = W_{311}x_0^3\rho\cos\theta = W_{311}x_0^3x)$

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

T.A. Brunner.
Impact of Lens Aberrations on Optical Lithography.

IBM J.Res.Dev., 41(1/2):57-67, January/March 1997.

- Imaging consequences of first **11** Zernike polynomials
- ***Note different Zernike terminology***

	(b, c)	Name	Imaging consequence
Z1	**(0, 0)**	Piston	None
Z2 Z3	**(1, ± 1)**	Lateral translation	Shift of image, independent of pattern
Z4	**(2, 0)**	Defocus	Image degradation
Z5 Z6	**(2, ± 2)**	Astigmatism (hor./vert. or ± 45°)	Orientation dependent shift of focus
Z7 Z8	**(3, ± 1)**	Lateral coma	Image asymmetry and pattern dependent shift of image
Z10 Z11	**(3, ± 3)**	Three-leaf clover (rotated 30°)	Imaging anomalies with threefold symmetry
Z9	**(4, 0)**	Third-order spherical	Pattern dependent focus shift

Basic Optics : Microlithography

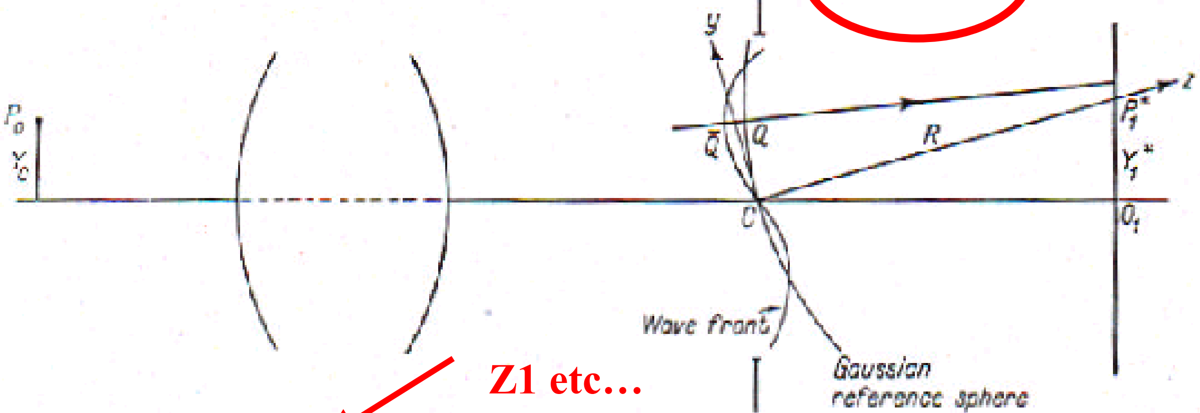
10. Imaging Aberrations

Phase error W(pθ) for terminlogy used here:

$P(\rho,\theta) = P_i(\rho,\theta)\exp(i\,k\,W(\rho,\theta))$ $k=2\pi/\lambda$

$P(\rho,\theta)$ = generalized pupil function, $P_i(\rho,\theta)$ = ideal pupil function

$k\,W(\rho,\theta))$ = effective phase error, $W(\rho,\theta))$ = wave aberration



Z1 etc…

$$W(\rho,\theta) = a_{W(\rho,\theta)=0} + a_1 2\rho\cos\theta + a_2 2\rho\sin\theta + a_3\sqrt{3}\,(2\rho^2-1) + a_4\sqrt{6}\,\rho^2\sin 2\theta + a_5\sqrt{6}\,\cos 2\theta +$$
$$a_6\sqrt{8}\,(3\rho^3-2)\sin\theta + a_7\sqrt{8}\,(3\rho^3-2)\cos\theta + a_8\sqrt{8}\,\rho^3\sin 3\theta + a_9\sqrt{8}\,\rho^3\cos 3\theta \;+\; \cdots\cdots$$

where: $\rho = \sqrt{x^2+y^2}$ $\theta = \tan^{-1}\frac{x}{y}$ are pupil coordinates.

Ref1: Principles of Optics, M. Born and E. Wolf, Sixth Edition, Pergamon Press, pp 460-490.
Ref2: J. Kirk, SPIE vol. 4000, pp 2-8.

Basic Optics : Microlithography

10. Imaging Aberrations Fringe Zernike Polynomials

$$\Phi_n^m(\rho, \theta) = c_{nm}\epsilon_m \sqrt{2(n+1)} R_n^m(\rho) \cos m\theta \ ,$$

which represents a term in the expansion of the aberration function in terms of a complete set of *Zernike circle polynomials*,[1] which are orthonormal over a unit circular pupil, where n and m are positive integers (including zero), $n - m \geq 0$ and even. The radial polynomial

$$R_n^m(\rho) = \sum_{s=0}^{(n-m)/2} \frac{(-1)^s \ (n-s)!}{s![(n+m)/2-s]![(n-m)/2-s]!} \rho^{n-2s}$$

is a polynomial of degree n in ρ containing terms in ρ^n, ρ^{n-2}, ..., and ρ^m. The quantity

$$\epsilon_m = 1/\sqrt{2}, m = 0$$

$$= 1 \quad , m \neq 0 \ .$$

Unless $n = m = 0$, the coefficient c_{nm} represents the standard deviation of the aberration across the pupil, i.e.,

$$c_{nm} = \sigma_\Phi \ .$$

The orthonormality of the Zernike polynomials implies that

$$\int_0^1 \int_0^{2\pi} \Phi_n^m(\rho,\theta)\Phi_{n'}^{m'}(\rho,\theta)\rho d\rho d\theta \Big/ \int_0^1 \int_0^{2\pi} \rho d\rho d\theta = c_{nm}^2 \delta_{nn'}\delta_{mm'} \ ,$$

where δ_{ij} is a Kronecker delta.

Ref: V. Mahajan, Aberration theory made simple, volTT6, SPIE press.

10. Imaging Aberrations Fringe Zernike Polynomials:

The common ordering of ordering of the Zernike coefficients is the "fringe" set from the University of Arizona. It is a subset of 37 terms from the infinite series.. **Note some references start Z1 as X Tilt!**

See page 224 of book Table 2 for the standard order. Fringe Zernike Polynomials:

Z1: Piston: Normalization term no effect (some references Z0)
Z2: X Tilt
Z3: Y Tilt
Z4: Defocus
Z5: 3rd order Astigmatism 0 – 90°
Z6: 3rd order Astigmatism 45 – 135°
Z7: X coma
Z8: Y coma
Z9: Spherical
Z10: 3-leaf Clover
Z11: 3-leaf Clover

10. Imaging Aberrations Zernike Polynomials:

Zernike Polynomials:Another ordering method you might see:

ZERNIKE RADIAL POLYNOMIALS

n	m	No.	Polynomial
0	0	0	1
1	1	1	$\rho \cos \theta'$
		2	$\rho \sin \theta'$
	0	3	$2\rho^2 - 1$
2	2	4	$\rho^2 \cos 2\theta'$
		5	$\rho^2 \sin 2\theta'$
	1	6	$(3\rho^2 - 2)\rho \cos \theta'$
		7	$(3\rho^2 - 2)\rho \sin \theta'$
	0	8	$6\rho^4 - 6\rho^2 + 1$
3	3	9	$\rho^3 \cos 3\theta'$
		10	$\rho^3 \sin 3\theta'$
	2	11	$(4\rho^2 - 3)\rho^2 \cos 2\theta'$
		12	$(4\rho^2 - 3)\rho^2 \sin 2\theta'$
	1	13	$(10\rho^4 - 12\rho^2 + 3)\rho \cos \theta'$
		14	$(10\rho^4 - 12\rho^2 + 3)\rho \sin \theta'$
	0	15	$20\rho^6 - 30\rho^4 + 12\rho^2 - 1$

10. Imaging Aberrations Zernike Polynomials:

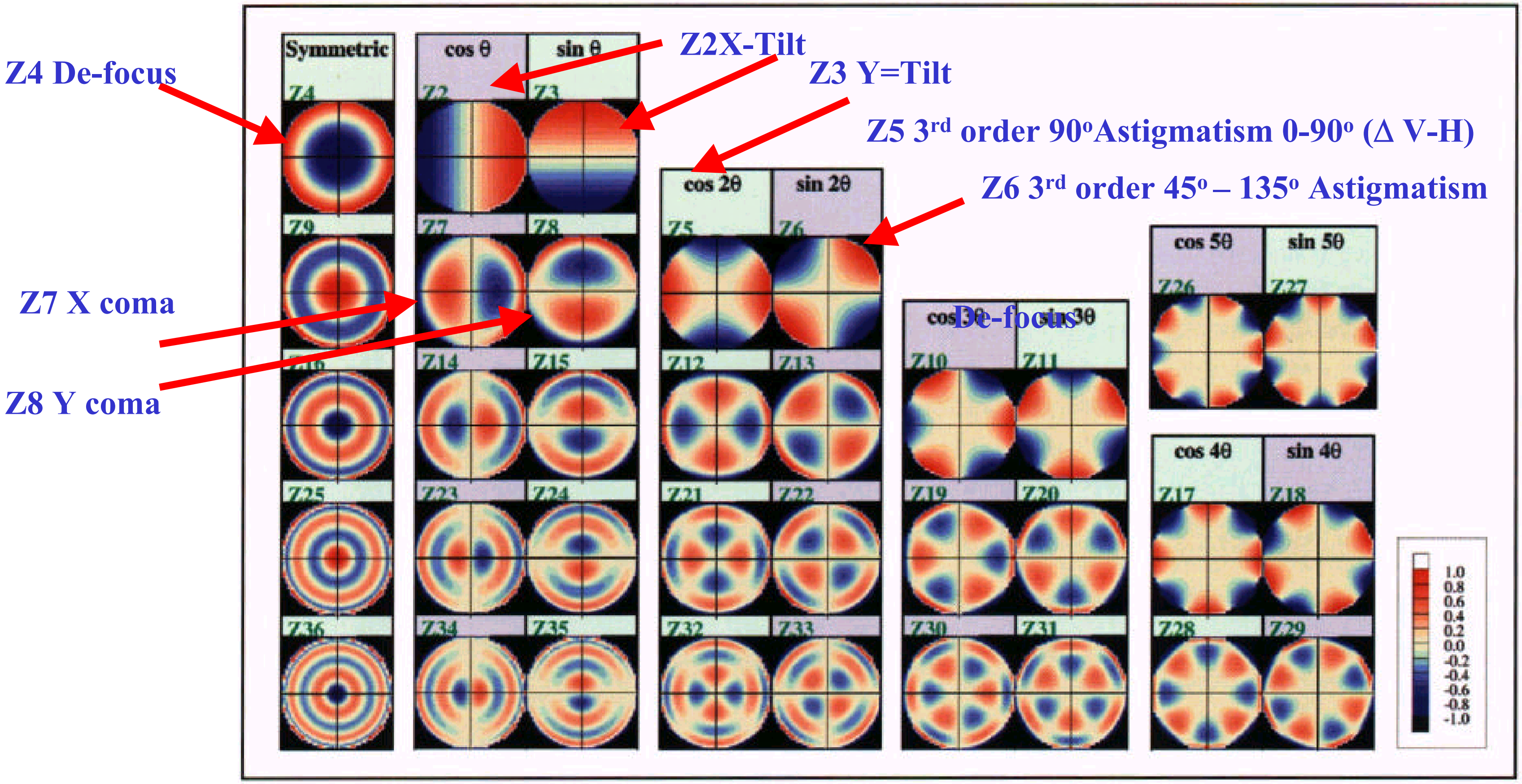
Zernike Polynomials:Another ordering method you might see:

n	m	No.	Polynomial
4	4	16	$\rho^4 \cos 4\theta'$
		17	$\rho^4 \sin 4\theta'$
	3	18	$(5\rho^2 - 4)\rho^3 \cos 3\theta'$
		19	$(5\rho^2 - 4)\rho^3 \sin 3\theta'$
	2	20	$(15\rho^4 - 20\rho^2 + 6)\rho^2 \cos 2\theta'$
		21	$(15\rho^4 - 20\rho^2 + 6)\rho^2 \sin 2\theta'$
	1	22	$(35\rho^6 - 60\rho^4 + 30\rho^2 - 4)\rho \cos \theta'$
		23	$(35\rho^6 - 60\rho^4 + 30\rho^2 - 4)\rho \sin \theta'$
	0	24	$70\rho^8 - 140\rho^6 + 90\rho^4 - 20\rho^2 + 1$
5	5	25	$\rho^5 \cos 5\theta'$
		26	$\rho^5 \sin 5\theta'$
	4	27	$(6\rho^2 - 5)\rho^4 \cos 4\theta'$
		28	$(6\rho^2 - 5)\rho^4 \sin 4\theta'$
	3	29	$(21\rho^4 - 30\rho^2 + 10)\rho^3 \cos 3\theta'$
		30	$(21\rho^4 - 30\rho^2 + 10)\rho^3 \sin 3\theta'$
	2	31	$(56\rho^6 - 105\rho^4 + 60\rho^2 - 10)\rho^2 \cos 2\theta'$
		32	$(56\rho^6 - 105\rho^4 + 60\rho^2 - 10)\rho^2 \sin 2\theta'$
	1	33	$(126\rho^8 - 280\rho^6 + 210\rho^4 - 60\rho^2 + 5)\rho \cos \theta'$
		34	$(126\rho^8 - 280\rho^6 + 210\rho^4 - 60\rho^2 + 5)\rho \sin \theta'$
	0	35	$252\rho^{10} - 630\rho^8 + 560\rho^6 - 210\rho^4 + 30\rho^2 - 1$
6	0	36	$924\rho^{12} - 2772\rho^{10} + 3150\rho^8 - 1680\rho^6 + 420\rho^4 - 42\rho^2 + 1$

Basic Optics : Microlithography

10. Imaging Aberrations Fringe Zernike Polynomials:

Simulations from Canon (Phil Ware)

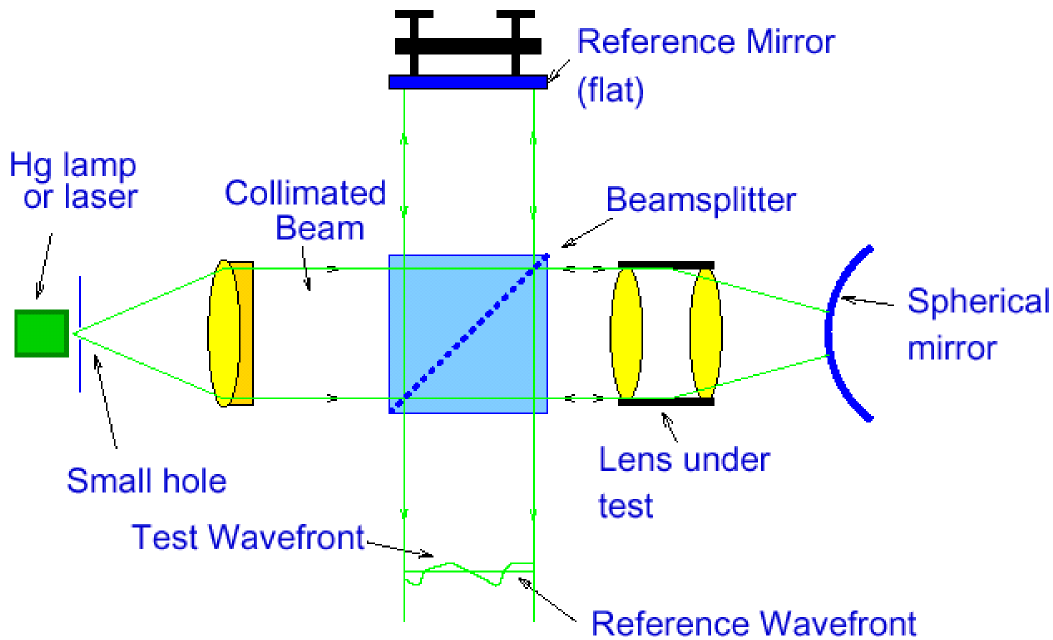


0-theta: spherical aberration (smaller CD for iso than dense patterns, best focus deviation for different sizes AAPSM)
1-theta: coma aberration (CD difference between both end of 5 bar patterns)
2-theta: astigmatism (CD difference between two different orientations 0-90, 45-135)
3-theta: three-leaf clover (CD difference between 0-60-120, 30-90-150)
4-theta, 5 theta: higher order aberrations.

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- Testing lens for Wavefront errors: interferometer (Twyman Green) : Siedel and Zernike mathematically describe these wavefront shapes = Quantified Aberration values!



Note the Double Pass through the lens under test.

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- Testing lens for Wavefront errors: interferometer (Twyman Green) : Interferograms:

Interference between reference (flat) wavefront and double pass through test lens.

$$\text{Bright Fringe} \rightarrow \text{OPD} = \pm n\lambda$$

$$\text{Dark Fringe} \rightarrow \text{OPD} = \pm(n + 1/2)\lambda$$

We get Contour Map of OPD. So Contour Map of

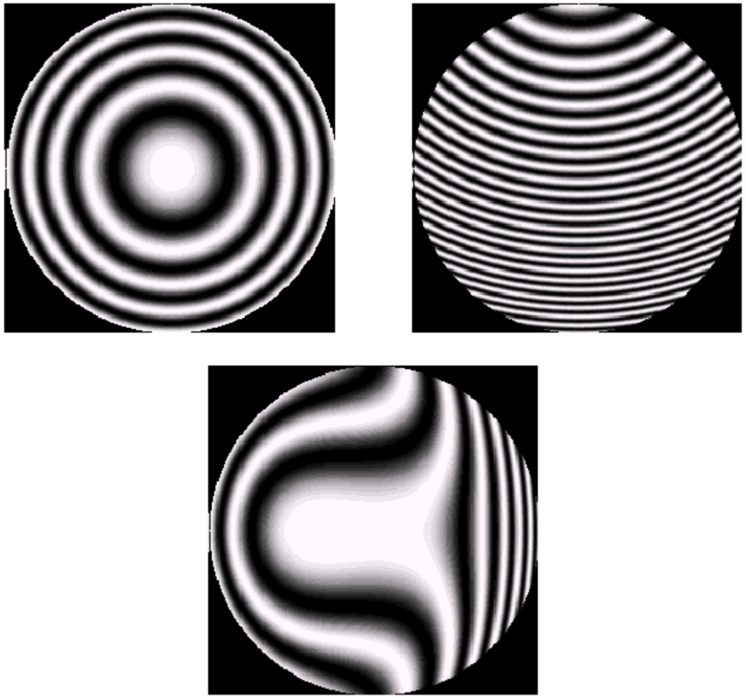
$$2W(u,v)$$

the wavefront aberration function.

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

- Testing lens for Wavefront errors: interferometer (Twyman Green) : Interferograms:



Wavefronts with, 2λ of defocus, 2λ of defocus plus 3λ of tilt, and mixed aberrations.

Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

http://wyant.optics.arizona.edu/seidelWavefrontMaps/seidel.htm

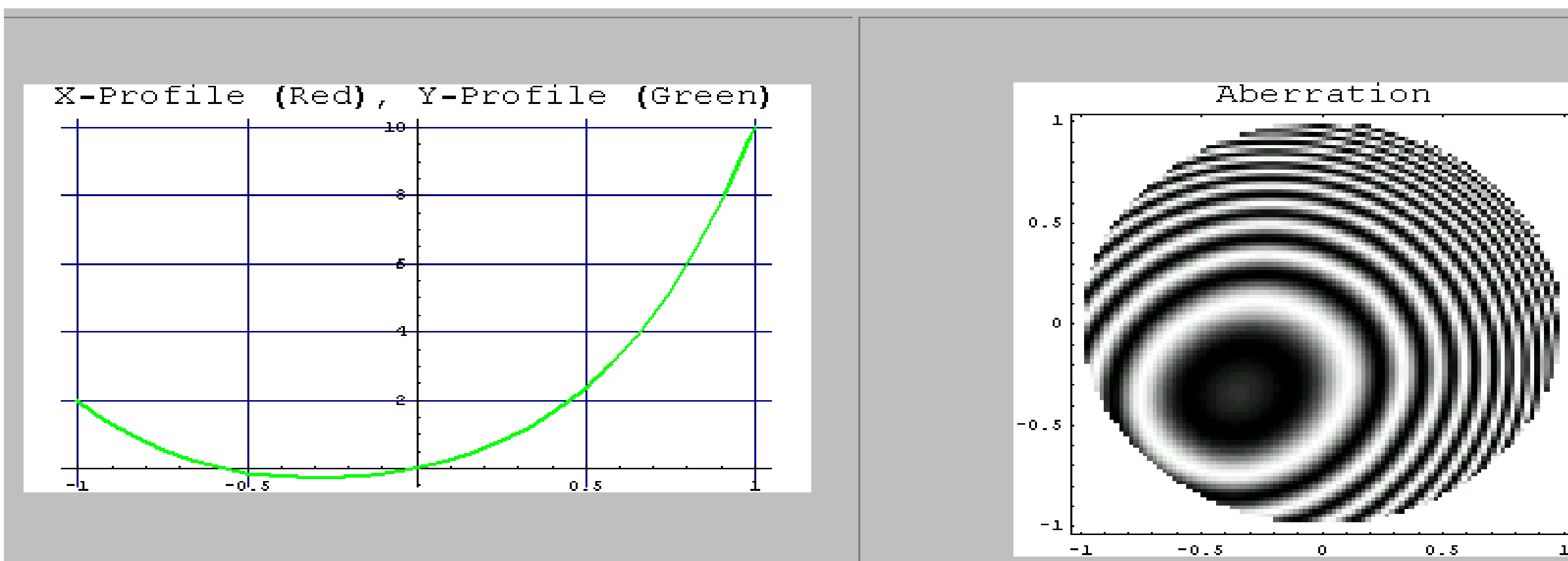
Wavefront Maps and Profiles for Seidel Aberrations

x-Tilt [2] x, **y-Tilt** [2] y, **Focus** [2] (x^2+y^2), **x-Coma** [2] $x(x^2+y^2)$, **y-Coma** [2] $y(x^2+y^2)$,

x-Astigmatism [2] x^2, **y-Astigmatism** [2] y^2, **Spherical** [2] $(x^2+y^2)^2$

Little of each

$$\text{Aberration} = 2x + 2x^2 + 2y + 2y^2 + 2(x^2+y^2) + 2x(x^2+y^2) + 2y(x^2+y^2) + 2(x^2+y^2)^2$$



10. Imaging Aberrations, Defocus, and Zernike Polynomials

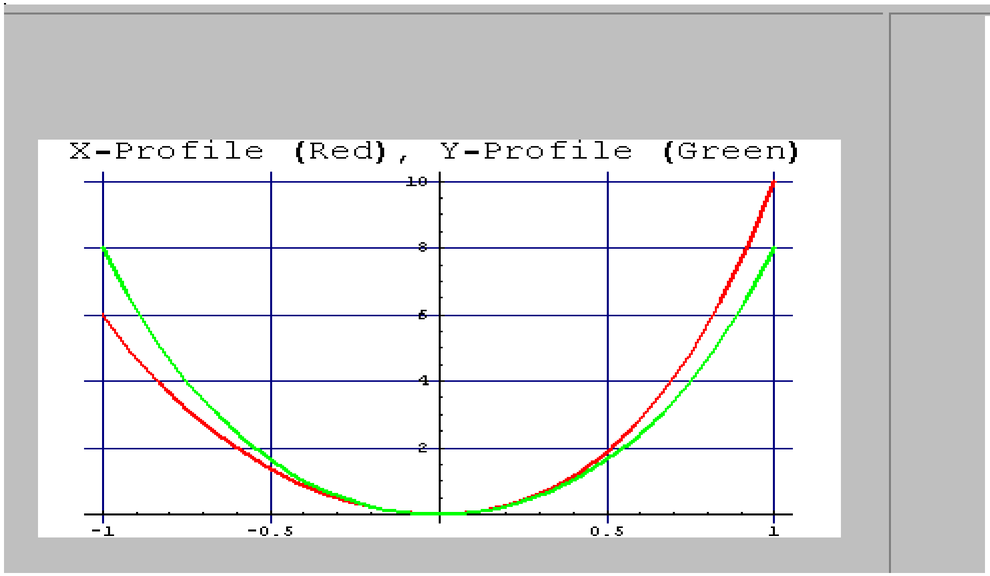
http://wyant.optics.arizona.edu/seidelWavefrontMaps/seidel.htm

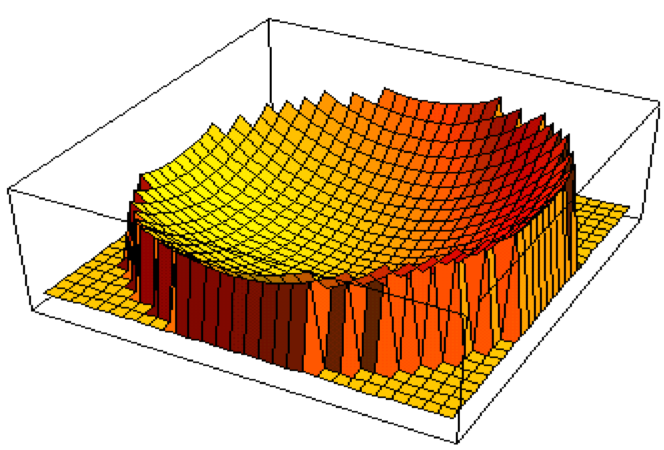
Wavefront Maps and Profiles for Seidel Aberrations

x-Tilt 0 x, **y-Tilt** 0 y, **Focus** 4 (x^2+y^2), **x-Coma** 2 $x(x^2+y^2)$, **y-Coma** 0 $y(x^2+y^2)$,

x-Astigmatism 2 x^2, **y-Astigmatism** 2 y^2, **Spherical** 2 $(x^2+y^2)^2$

Aberration = $2x^2+2y^2+4(x^2+y^2)+2x(x^2+y^2)+2(x^2+y^2)^2$





Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

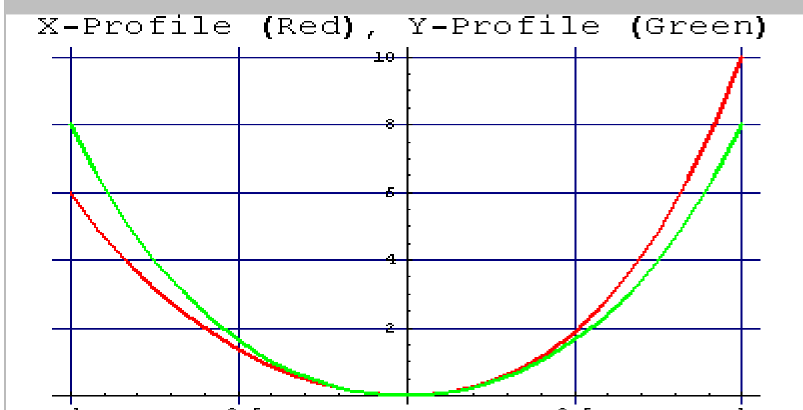
http://wyant.optics.arizona.edu/seidelWavefrontMaps/seidel.htm

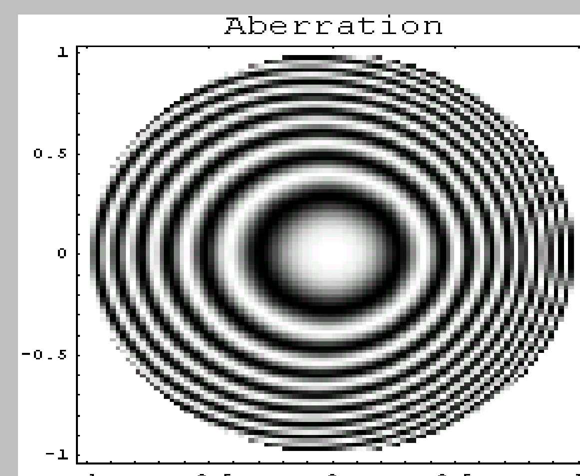
Wavefront Maps and Profiles for Seidel Aberrations

x-Tilt 0 x, **y-Tilt** 0 y, **Focus** 4 (x^2+y^2), **x-Coma** 2 $x(x^2+y^2)$, **y-Coma** 0 $y(x^2+y^2)$,

x-Astigmatism 2 x^2, **y-Astigmatism** 2 y^2, **Spherical** 2 $(x^2+y^2)^2$

$$\text{Aberration} = 2x^2 + 2y^2 + 4(x^2+y^2) + 2x(x^2+y^2) + 2(x^2+y^2)^2$$





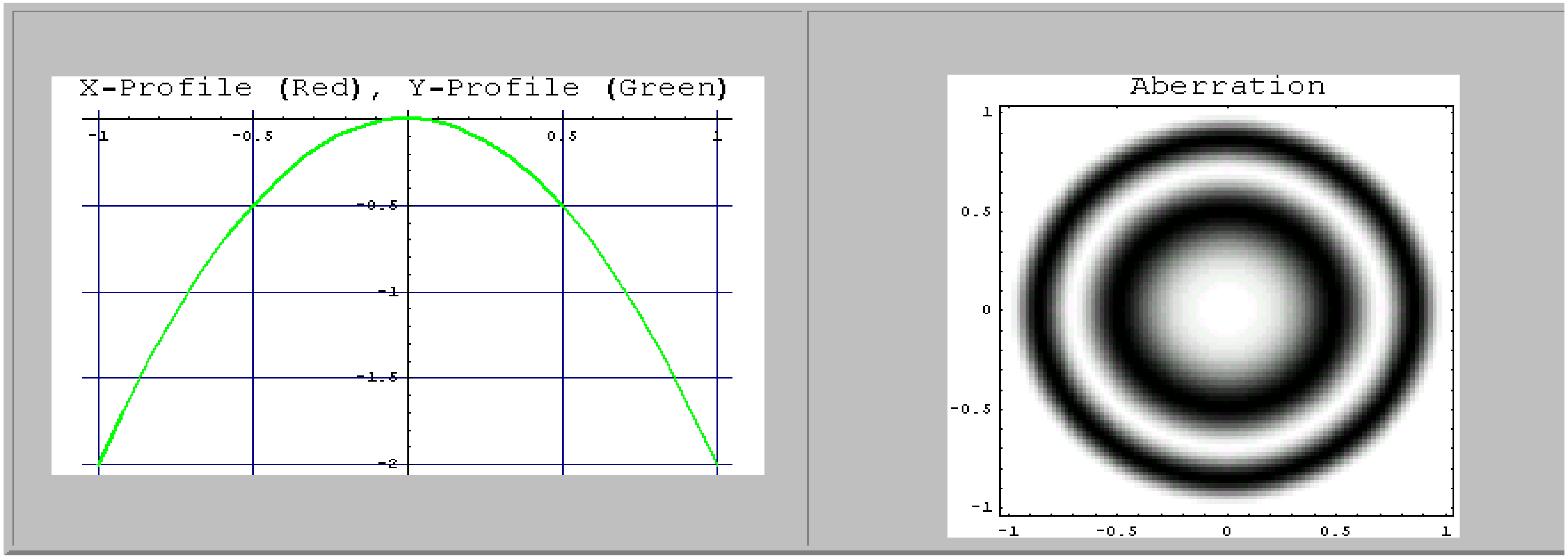
Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

http://wyant.optics.arizona.edu/seidelWavefrontMaps/seidel.htm

- **Defocus: Z4**

$$\text{Aberration} = -2\,(x^2 + y^2)$$



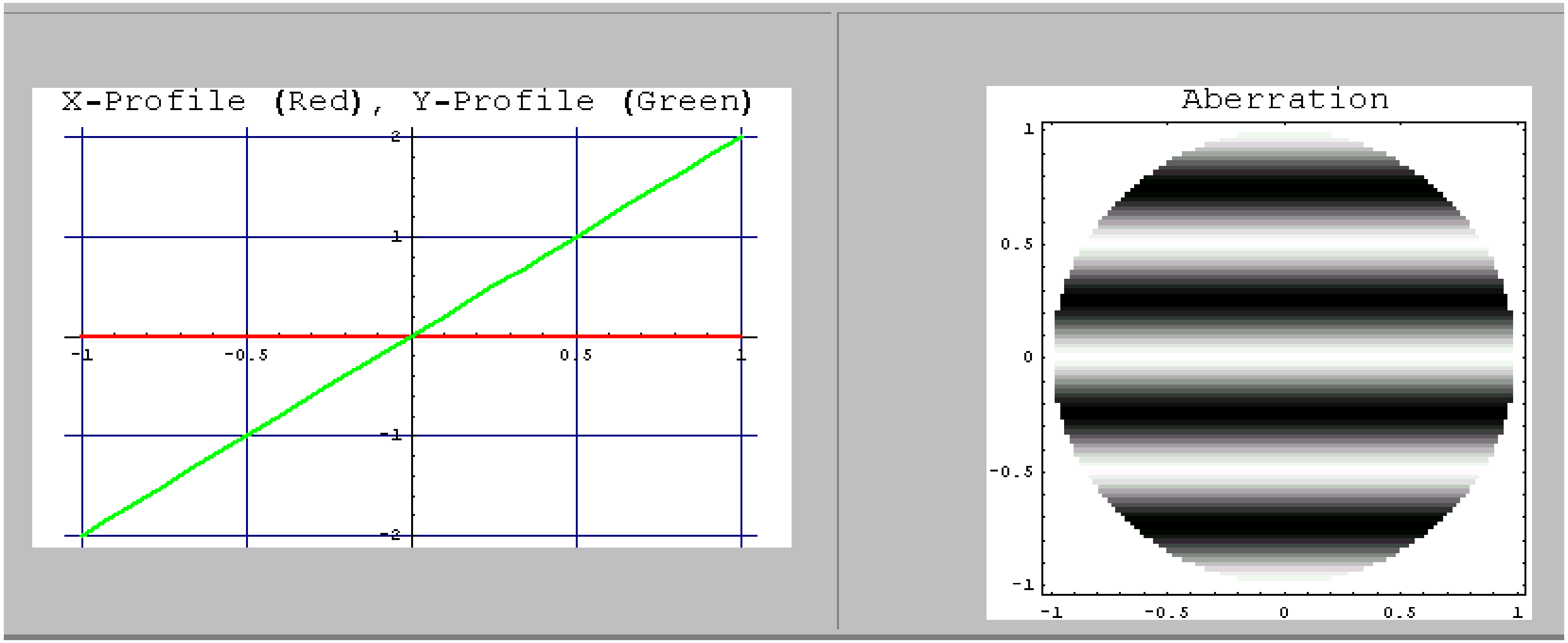
Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

http://wyant.optics.arizona.edu/seidelWavefrontMaps/seidel.htm

- **Y Tilt : Z3**

Aberration = $2y$



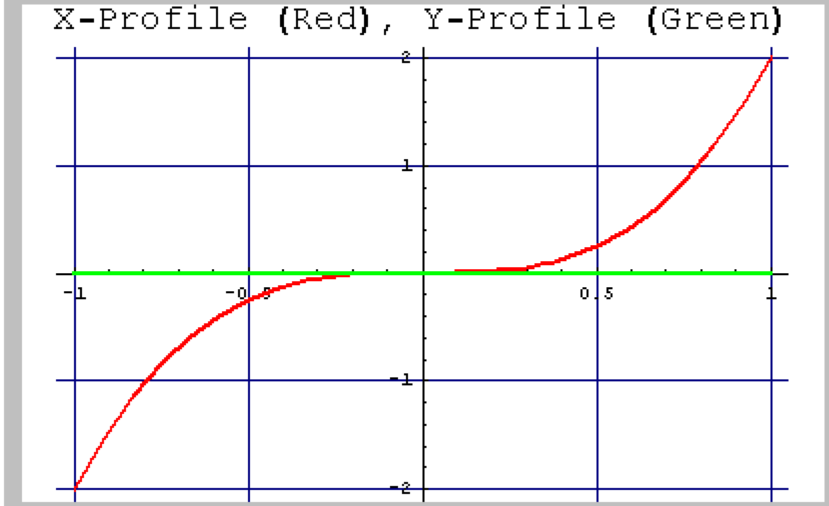
Basic Optics : Microlithography

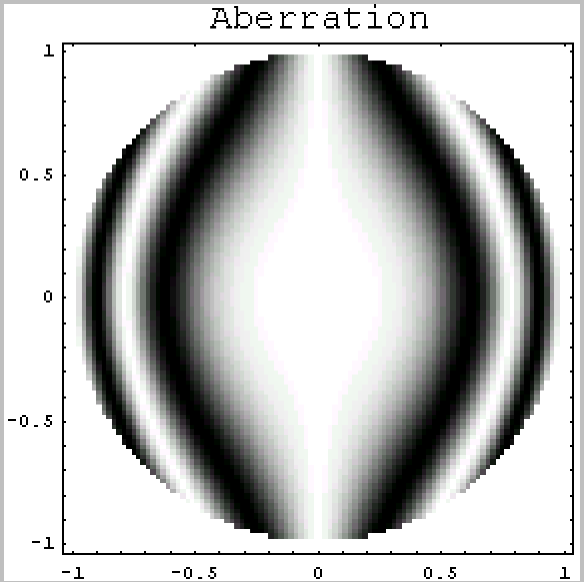
10. Imaging Aberrations, Defocus, and Zernike Polynomials

http://wyant.optics.arizona.edu/seidelWavefrontMaps/seidel.htm

- **3rd order X Coma : Z7**

$$\text{Aberration} = 2x(x^2 + y^2)$$

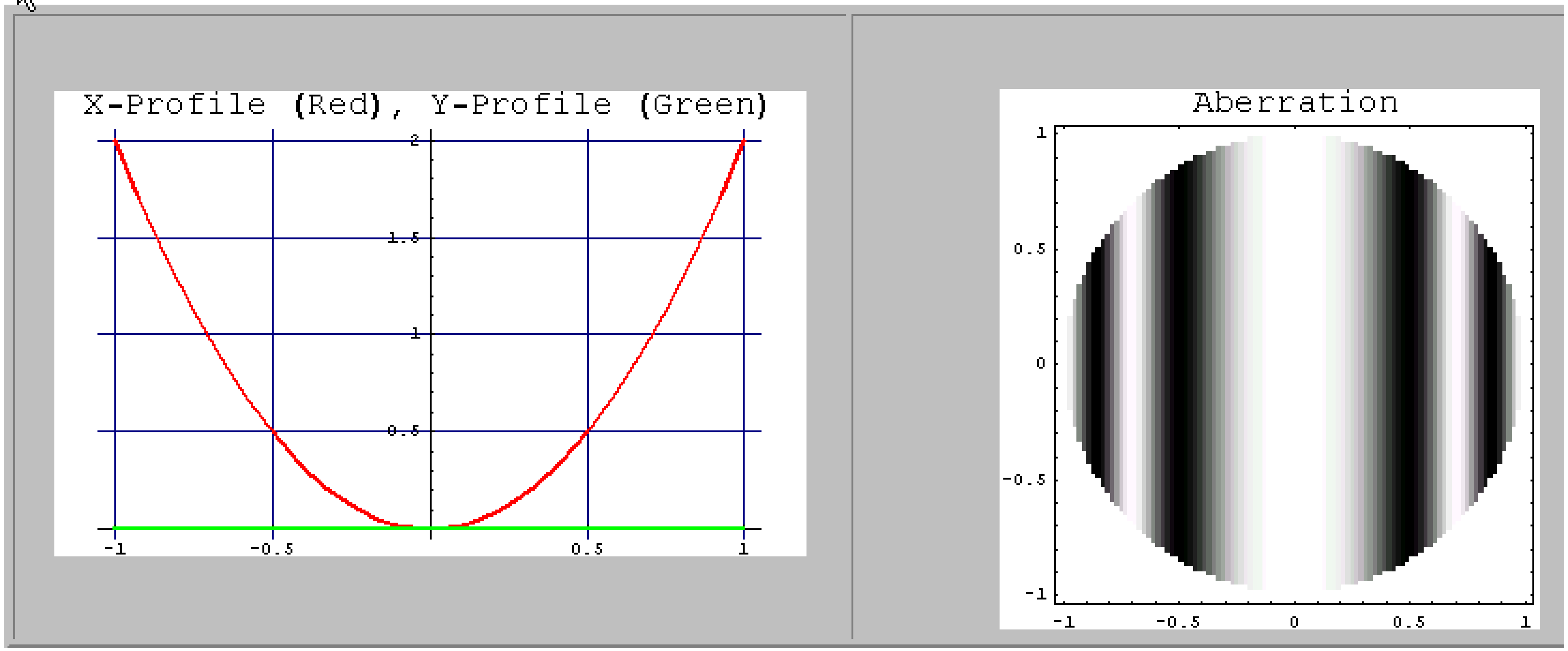




Basic Optics : Microlithography
10. Imaging Aberrations, Defocus, and Zernike Polynomials
http://wyant.optics.arizona.edu/seidelWavefrontMaps/seidel.htm

- **3rd order Astigmatism : Z5**

Aberration = $2x^2$



Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

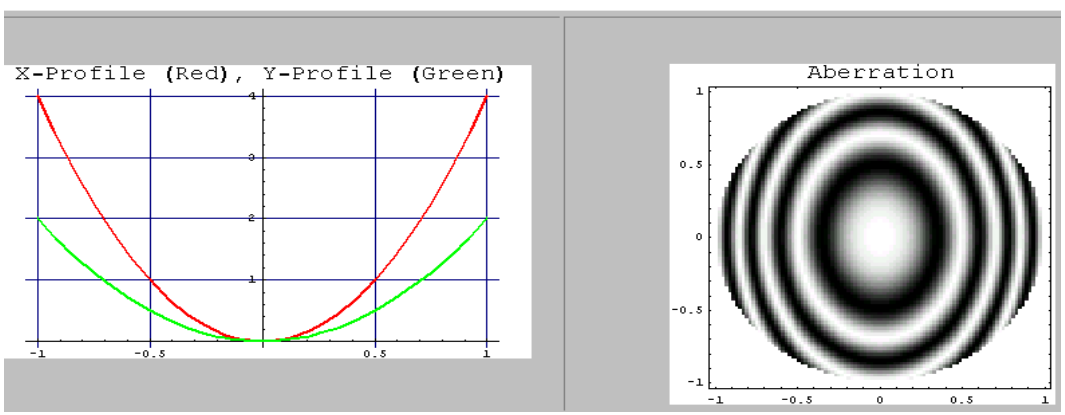
http://wyant.optics.arizona.edu/seidelWavefrontMaps/seidel.htm

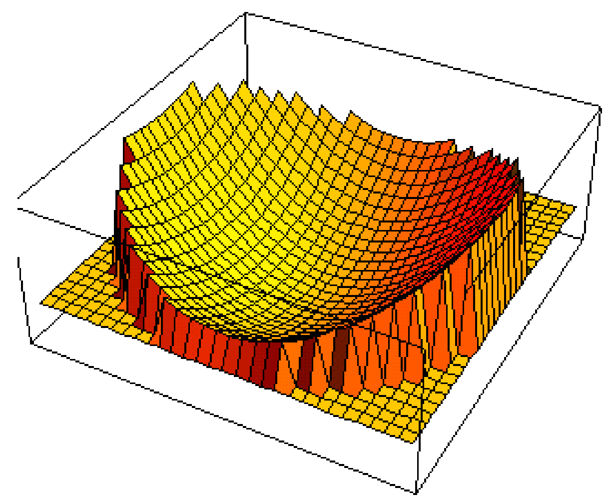
- **3rd order Astigmatism and 45 astigmatism : Z5 and Z6**

x-Tilt [0] x, **y-Tilt** [0] y, **Focus** [0] (x^2+y^2), **x-Coma** [0] $x(x^2+y^2)$, **y-Coma** [0] $y(x^2+y^2)$,

x-Astigmatism [4] x^2, **y-Astigmatism** [2] y^2, **Spherical** [0] $(x^2+y^2)^2$

Aberration = $4x^2 + 2y^2$





Basic Optics : Microlithography

10. Imaging Aberrations, Defocus, and Zernike Polynomials

http://wyant.optics.arizona.edu/seidelWavefrontMaps/seidel.htm

- **3rd order Spherical : Z9**

  Aberration = $2\,(x^2 + y^2)^2$