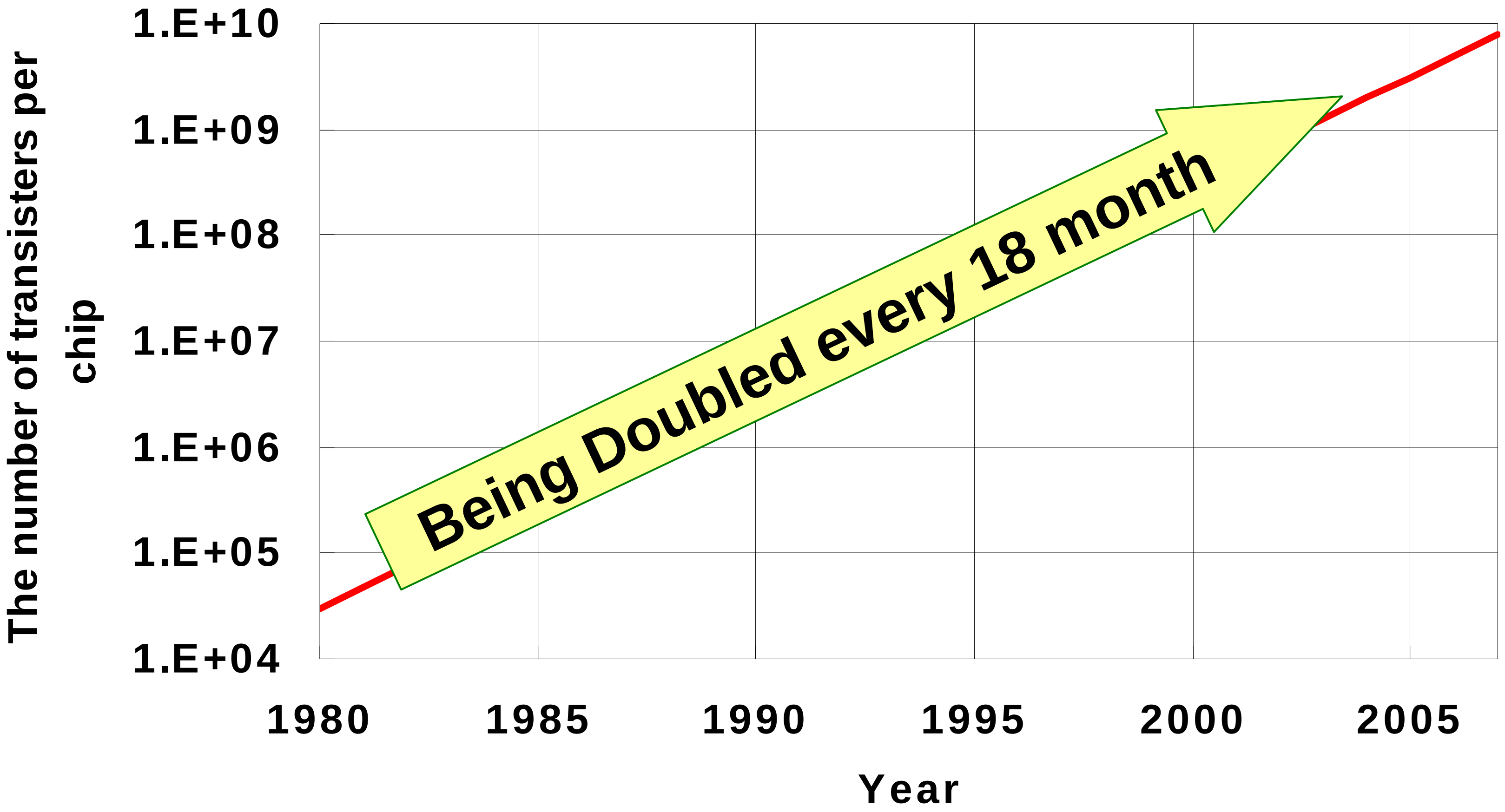
Lithographic Lenses

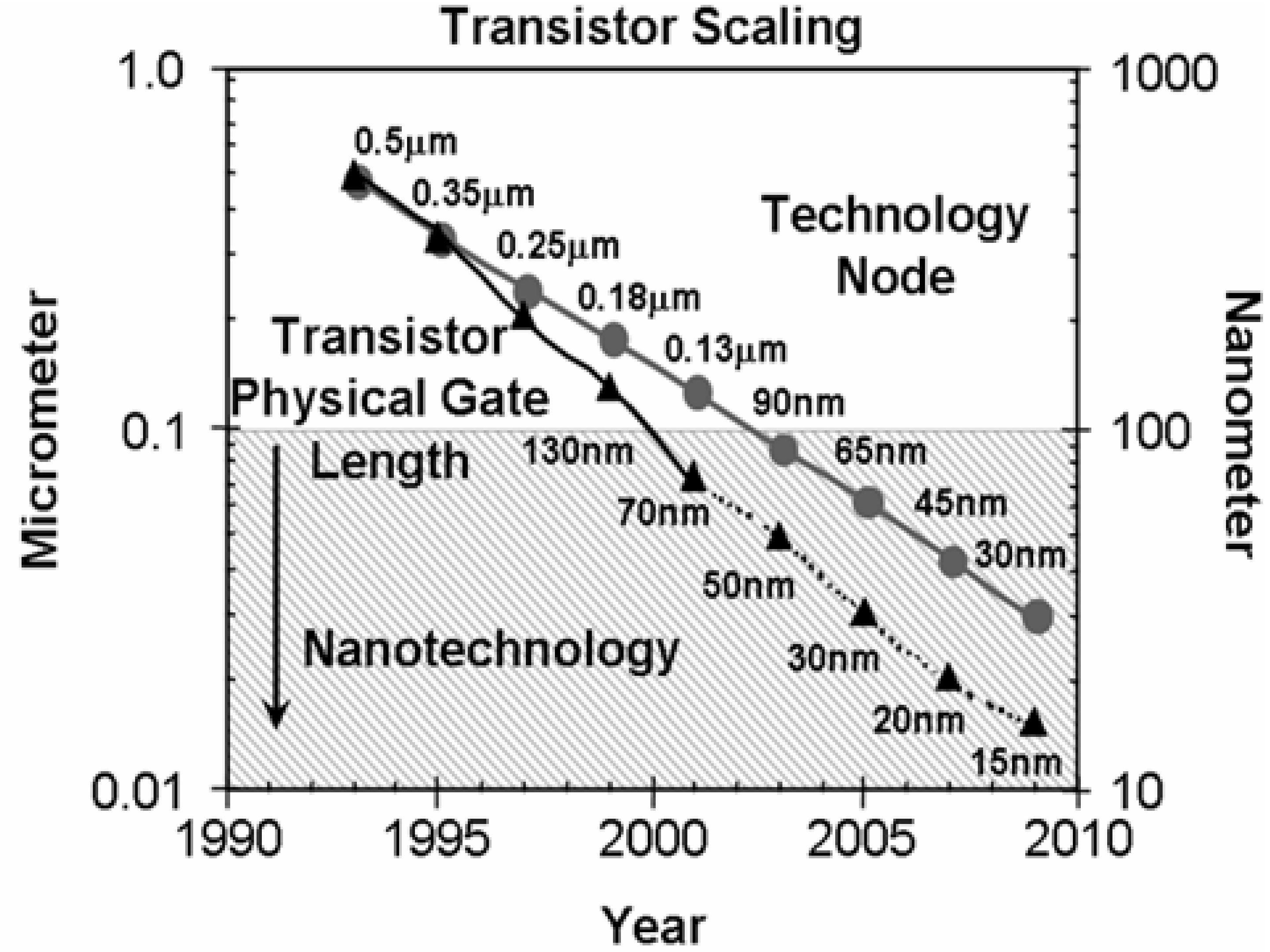
David M. Williamson

Moore’s Law – an enabler and example of exponential expansion – number of transistors per chip



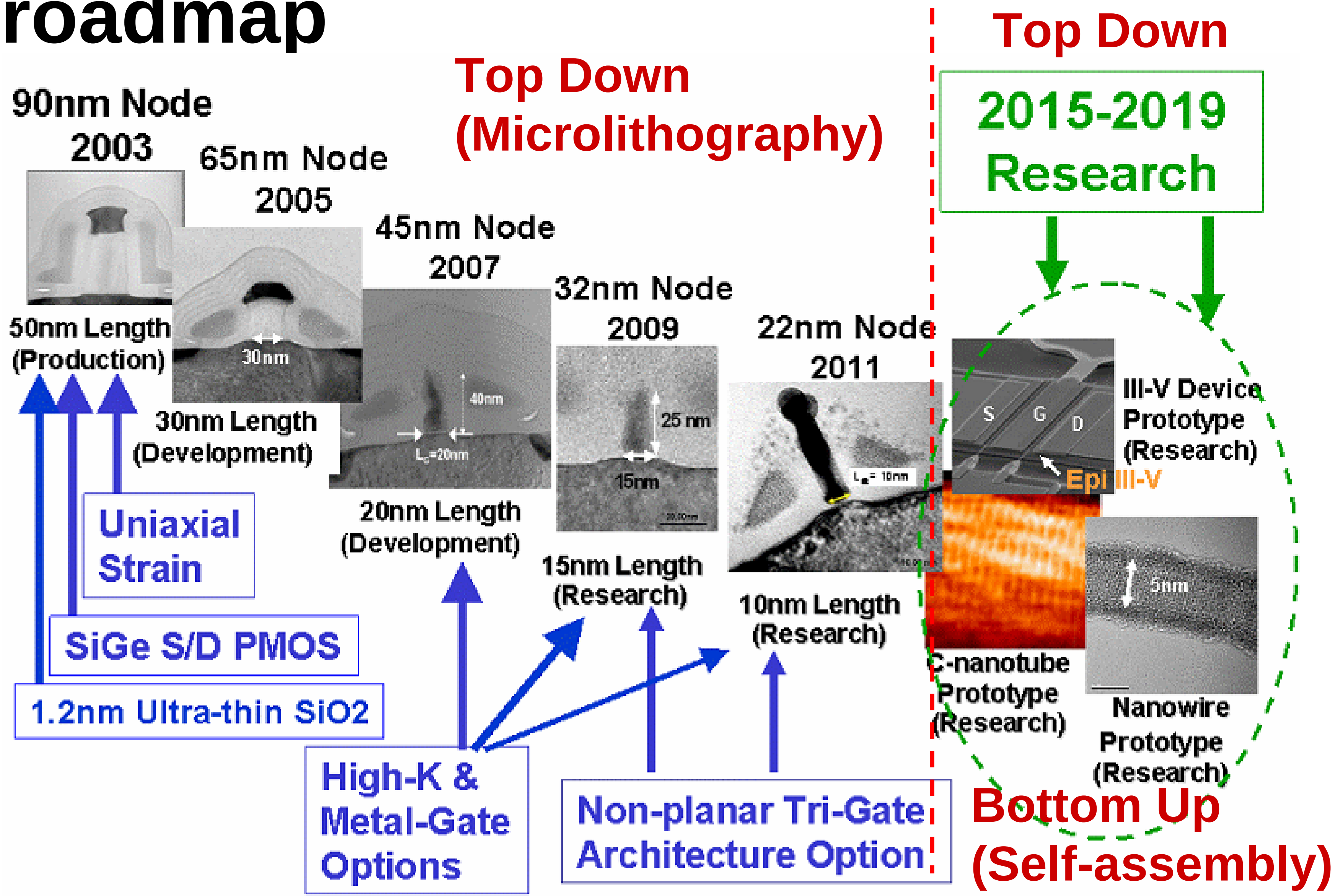
Mainframe Mini PC Workstation Laptop

Microlithography - Nanolithography



Ref: I. Adesida – Semiconductors in the Nanotechnology era

Transistor scaling and research roadmap



Top Down (Microlithography)

Top Down

2015-2019 Research

90nm Node 2003

50nm Length (Production)

65nm Node 2005

30nm Length (Development)

45nm Node 2007

20nm Length (Development)

32nm Node 2009

15nm Length (Research)

22nm Node 2011

10nm Length (Research)

III-V Device Prototype (Research)

C-nanotube Prototype (Research)

Nanowire Prototype (Research)

Uniaxial Strain

SiGe S/D PMOS

1.2nm Ultra-thin SiO2

High-K & Metal-Gate Options

Non-planar Tri-Gate Architecture Option

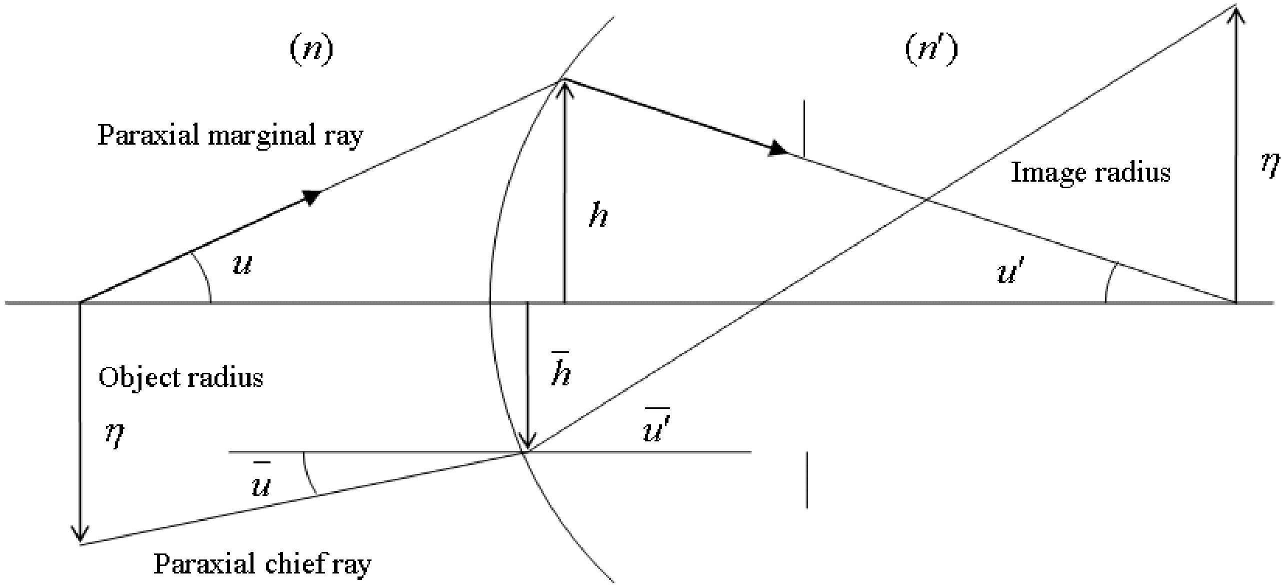
Bottom Up (Self-assembly)

Ref: I. Adesida – Semiconductors in the Nanotechnology era

Exponential Expansion in Microlithography – The Lagrange Invariant

$$H = n(u\bar{h} - \bar{u}h) = n'(u'\bar{h} - \bar{u}'h)$$

$$= n'u'\eta'$$

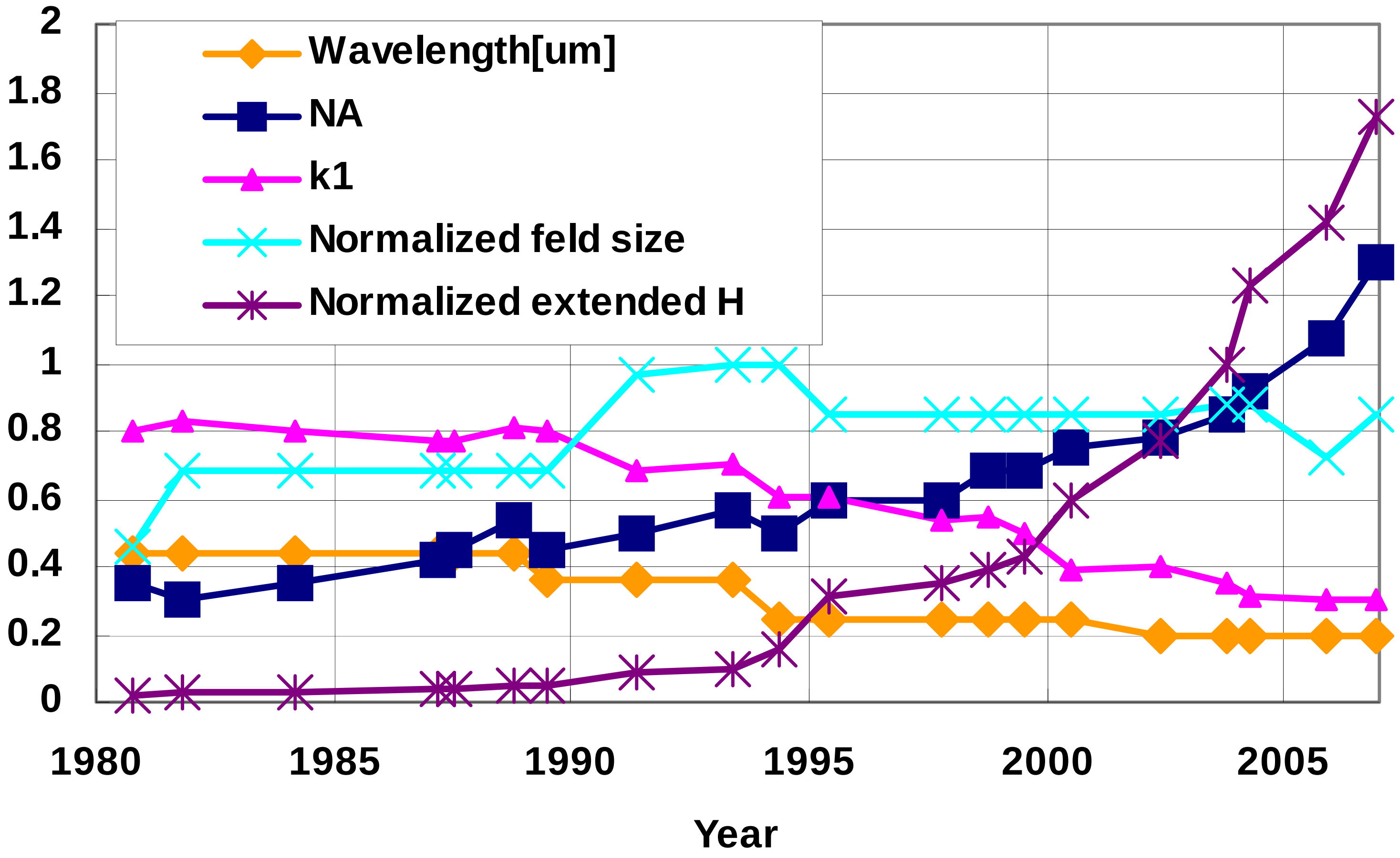


Ref: M.J. Kidger, Fundamental Optical Design

Rayleigh Resolution and DOF

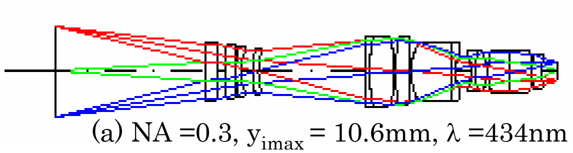
- Applied to Microlithography:
- Resolution = $k_1 \dfrac{\lambda}{NA}$
- Paraxial Depth of Focus = $k_2 \dfrac{n\lambda}{NA^2}$
- k_1 and k_2 are functions of the lithographic process (reticle, photoresist, illumination) and the level of residual aberrations in the projection optics

Extended Lagrange Invariant



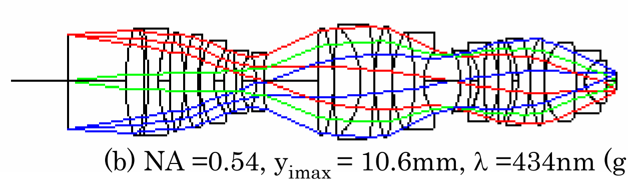
Extended H:

$$\frac{NA \cdot y_{i\max}}{\lambda \cdot k_1}$$



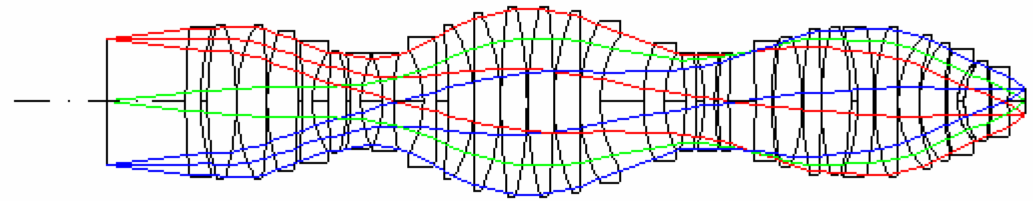
(a) NA =0.3, y_{imax} = 10.6mm, λ =434nm (g-line)

Extended *H* = *8840*



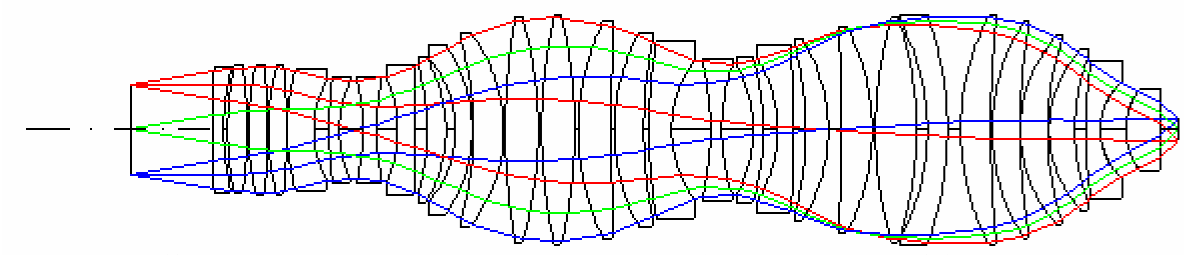
(b) NA =0.54, y_{imax} = 10.6mm, λ =434nm (g-line)

Extended *H* = *16320*



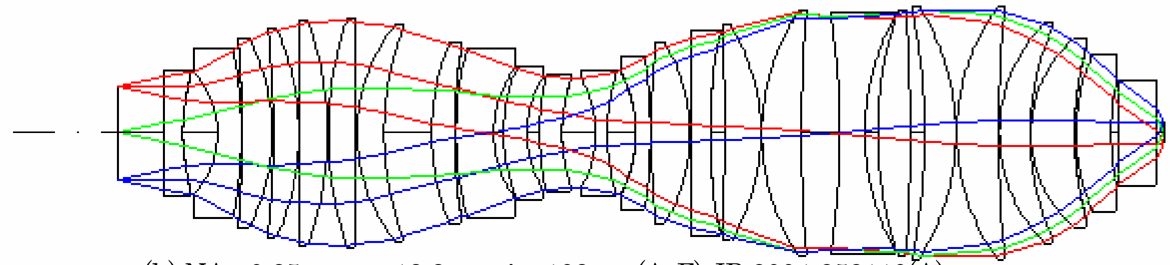
(d) NA =0.57, y_{imax} = 15.6mm, λ =365nm (i-line) JP-H8-190047(A)

Extended *H* = *34600*



(f) NA =0.68 y_{imax} = 13.2mm, λ =248nm (KrF) JP-2000-121933(A)

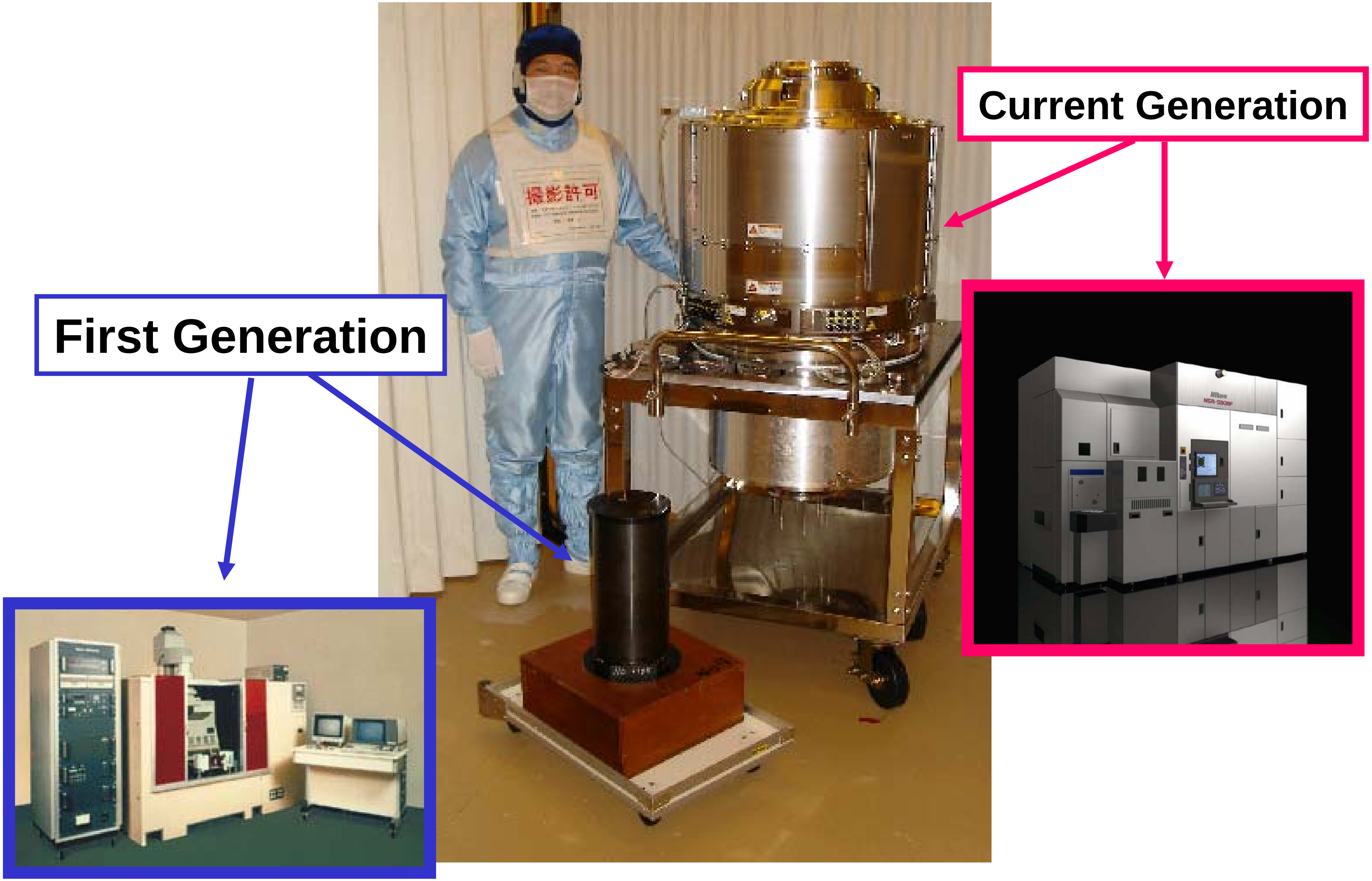
Extended *H* = *66000*



(h) NA =0.85 y_{imax} = 13.8mm, λ =193nm (ArF) JP-2004-252119(A)

Extended *H* = *170000*

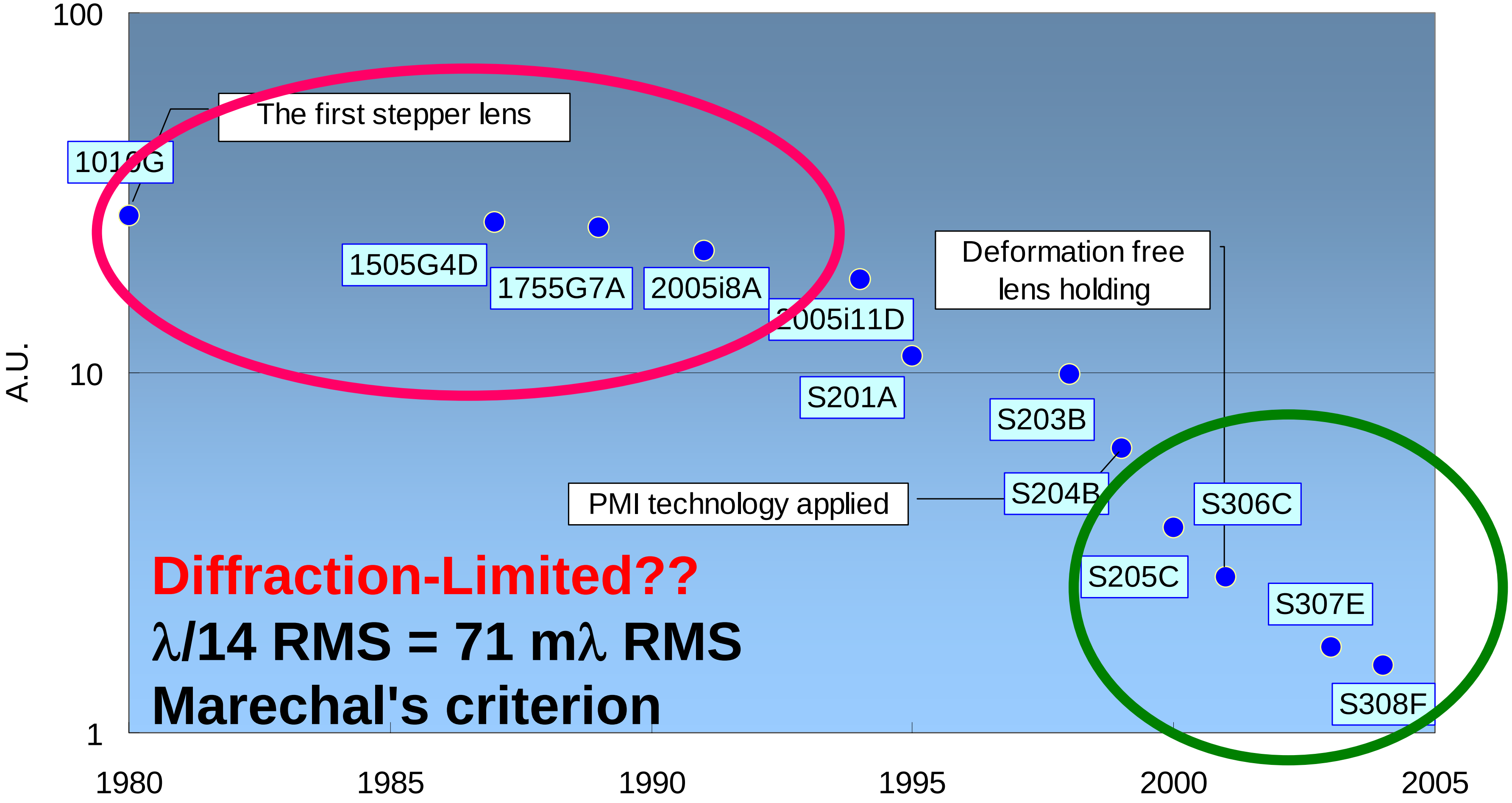
Increased ~ 20x



Current Generation

First Generation

History of Nikon’s as-manufactured lens aberration levels



Diffraction-Limited??

λ/14 RMS = 71 mλ RMS

Marechal's criterion

Small aberrations!! ☺

5-15 mλ RMS

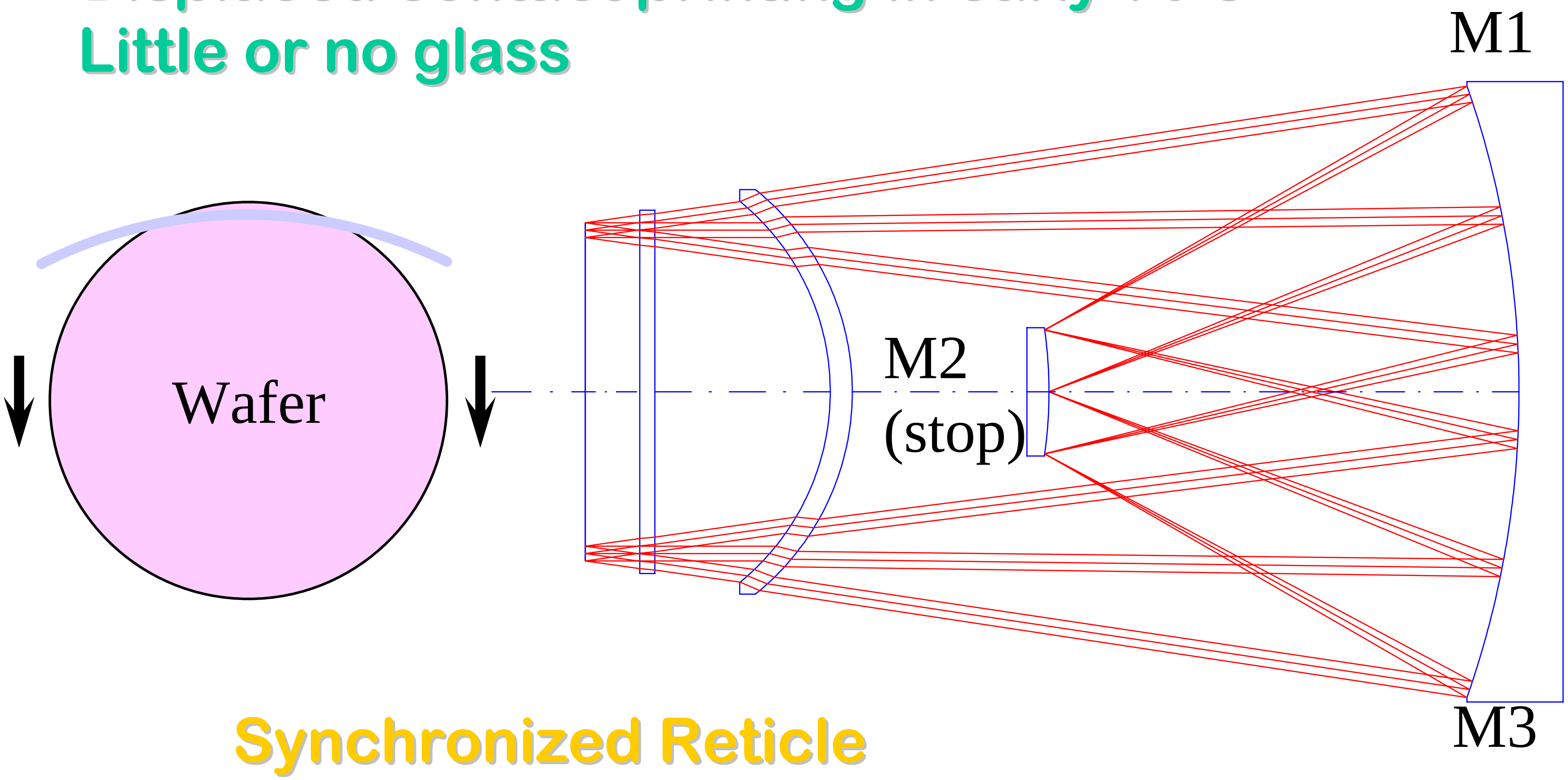
Limits to expansion?

- Theoretical
  - Zero aberrations
  - NA =1 (in air)
  - K1 = 0.25 (0 and 1st diffracted orders)
- Practical
  - Glass (Fused Silica) blank diameter and optical quality - homogeneity, birefringence
  - □ λ= 193nm (157nm) – glass transmission
- Some limits are moveable, with innovation

3-mirror Offner 1x NA 0.14

3000-1500 nm node

Displaced contact printing in early 70's
Little or no glass



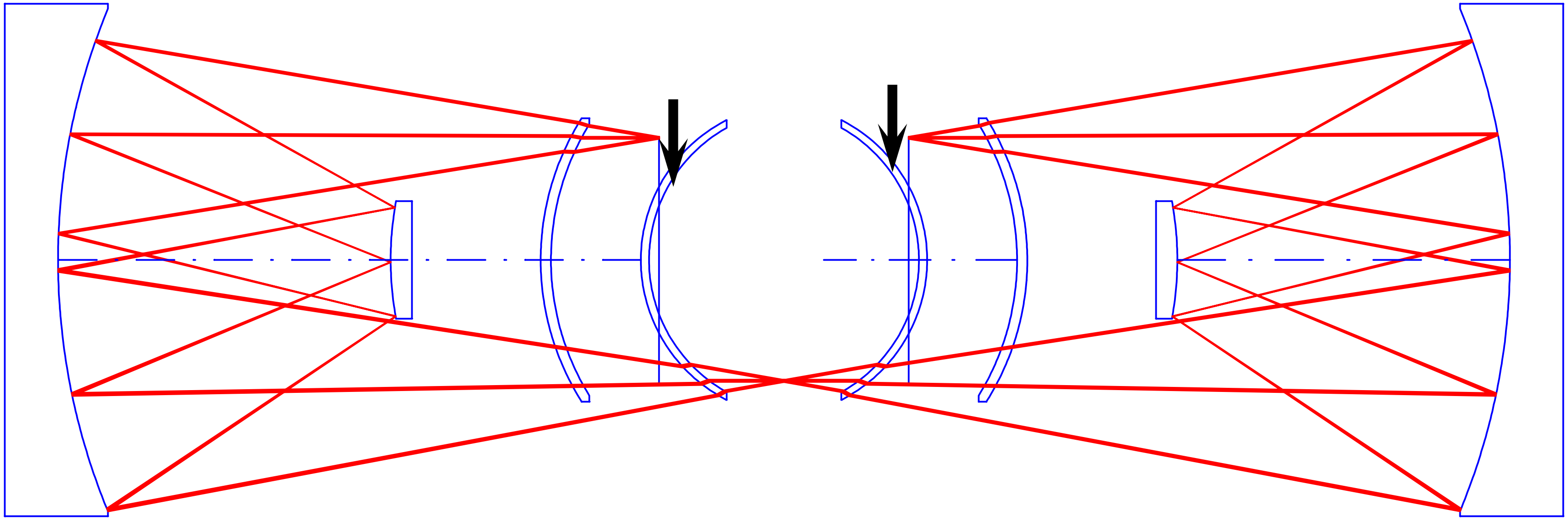
Synchronized Reticle
and wafer scanning

Micralign M500 - 1x NA 0.166

1200-800 nm node

DUV, 248nm, broadband (Hg lamp)

Ref: U.S.Patent 4,293,186 Offner



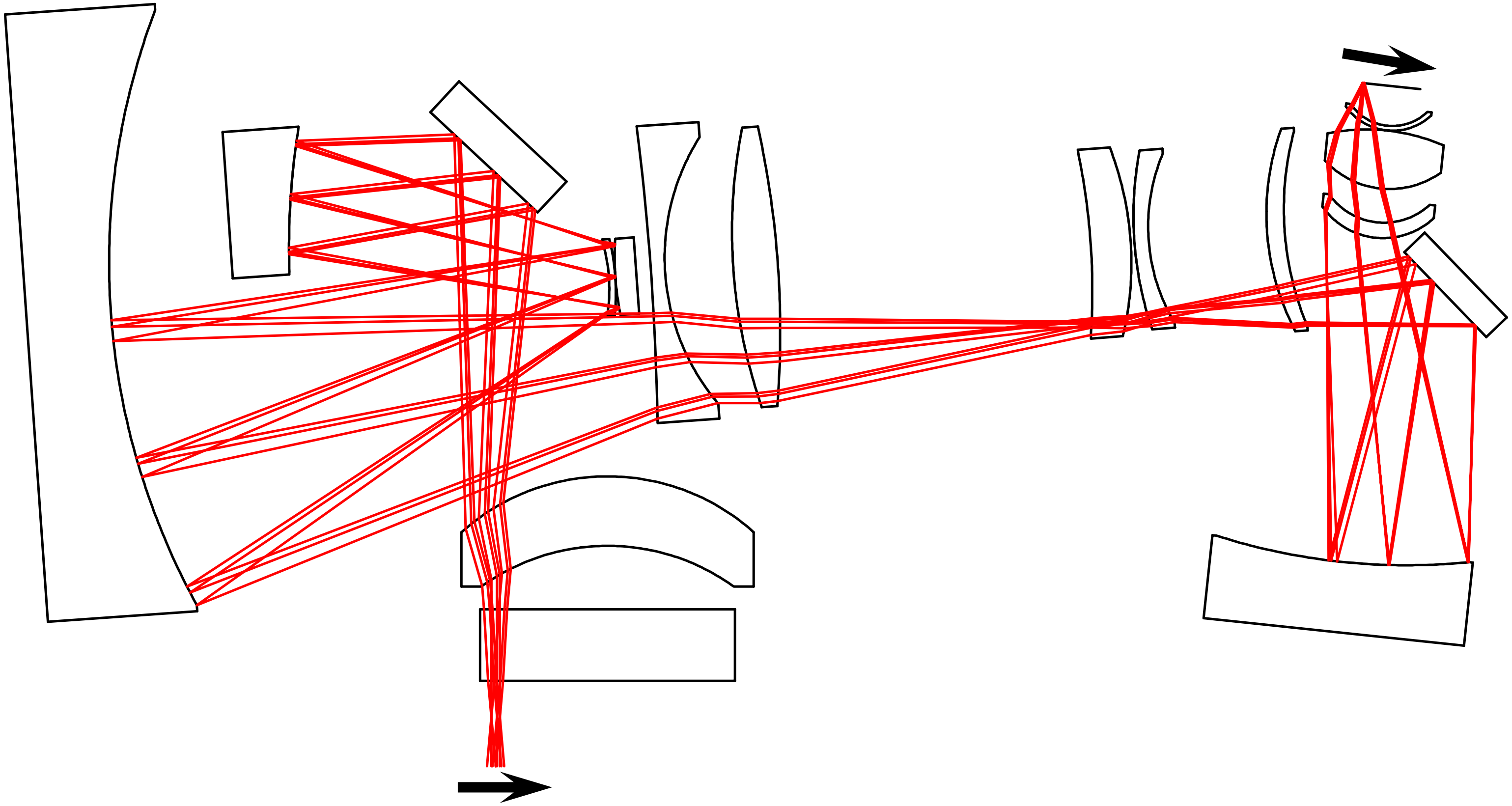
Micrascan I – 4x NA 0.35

700-500 nm node

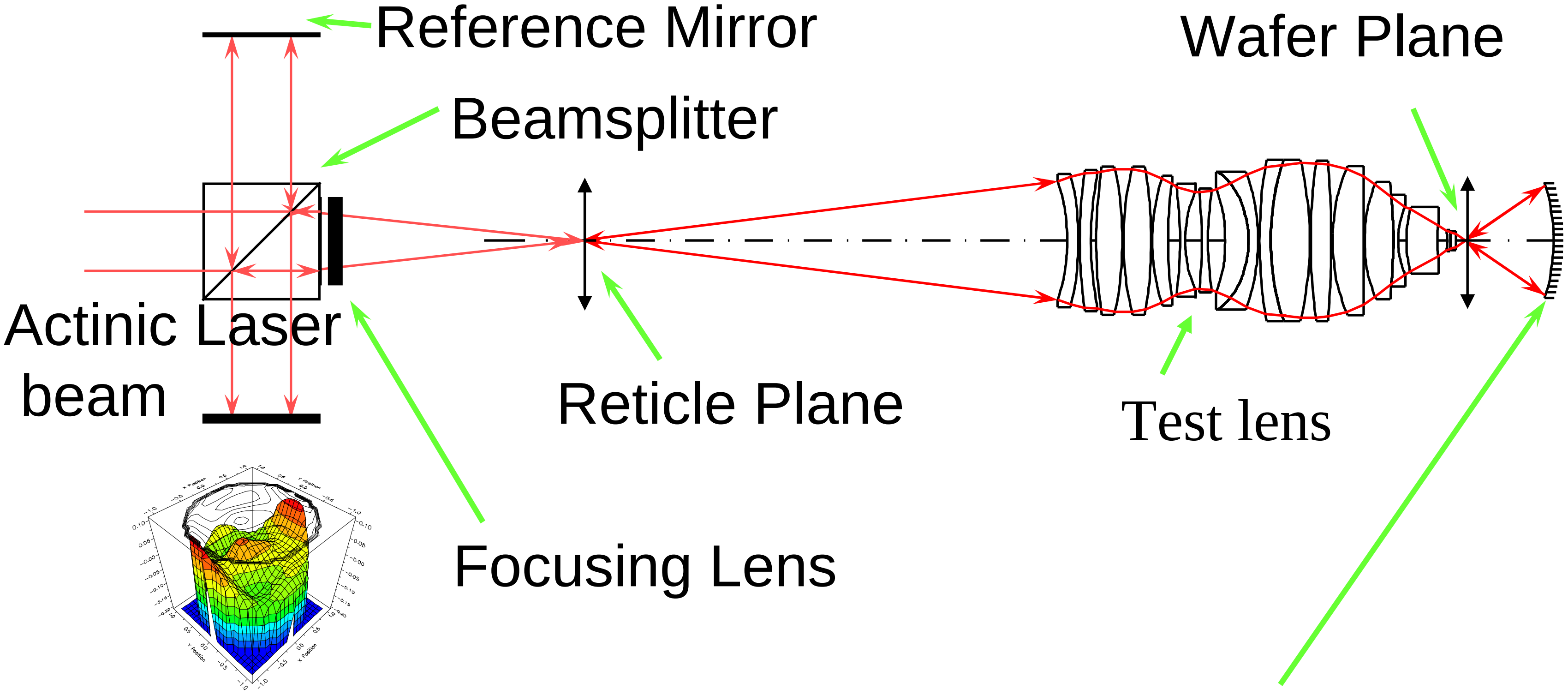
Reduction step-and-scan

Continued use of broadband DUV

Ref: U.S.Patent 4,747,678 Shafer et al.



Phase-Measuring Interferometry – wavefront and distortion vs. field position



Reference Mirror

Wafer Plane

Beamsplitter

Actinic Laser beam

Reticle Plane

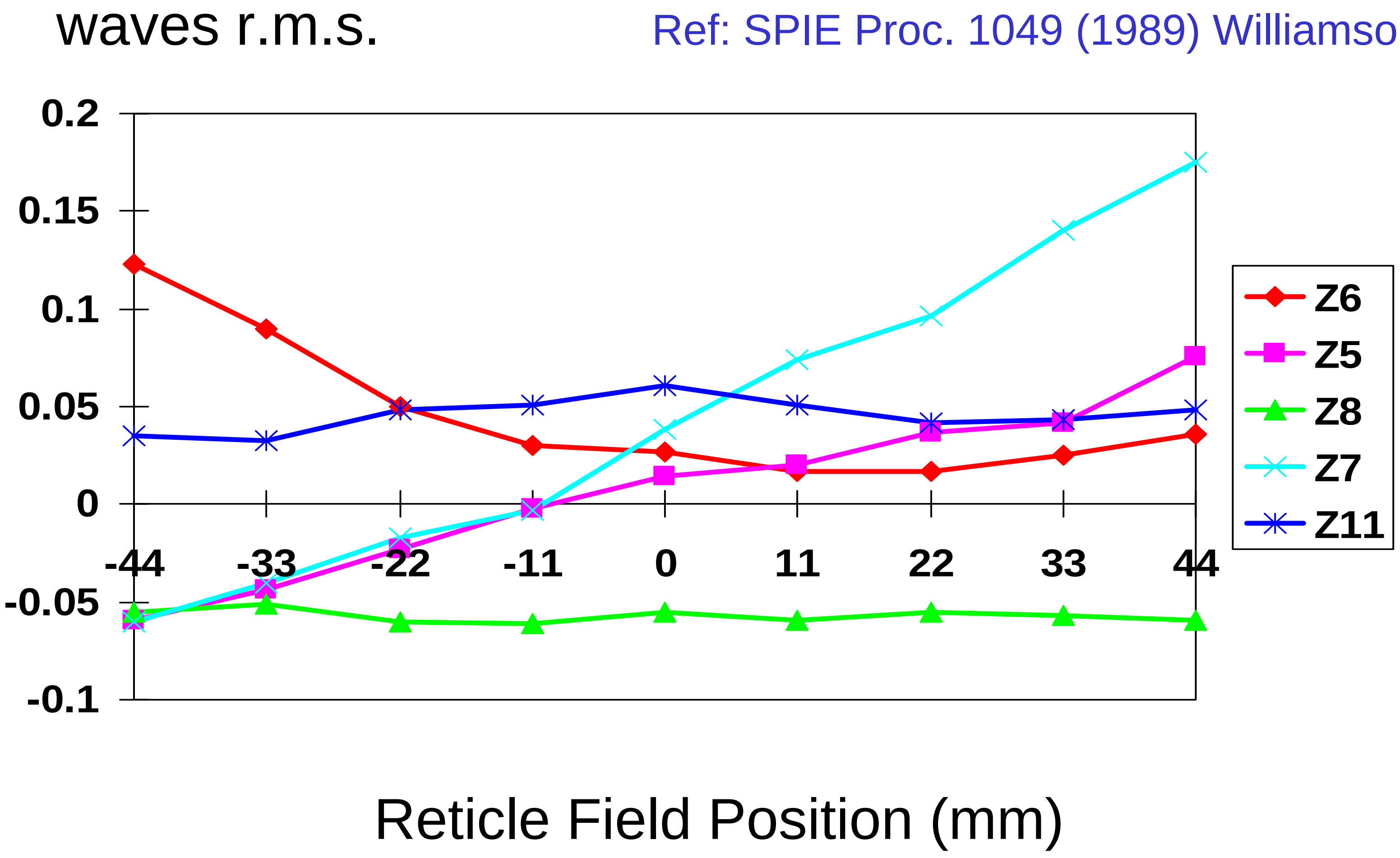
Test lens

Focusing Lens

Retro-Mirror

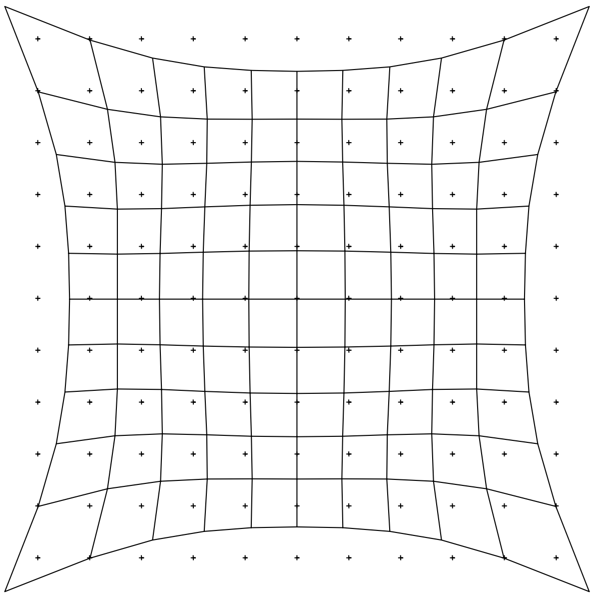
PMI-measured Zernike aberrations across field

Ref: SPIE Proc. 1049 (1989) Williamson



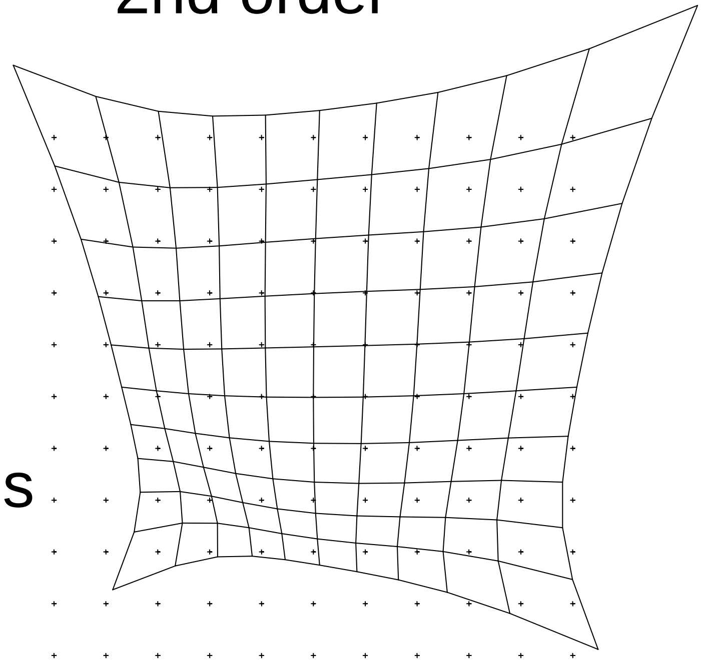
Sym. and asym. Distortion – measured by Zernike wavefront tilt - Z2, 3 terms

Barrel/Pincushion
3rd and 5th order



0.02
microns

Keystone and bow
2nd order



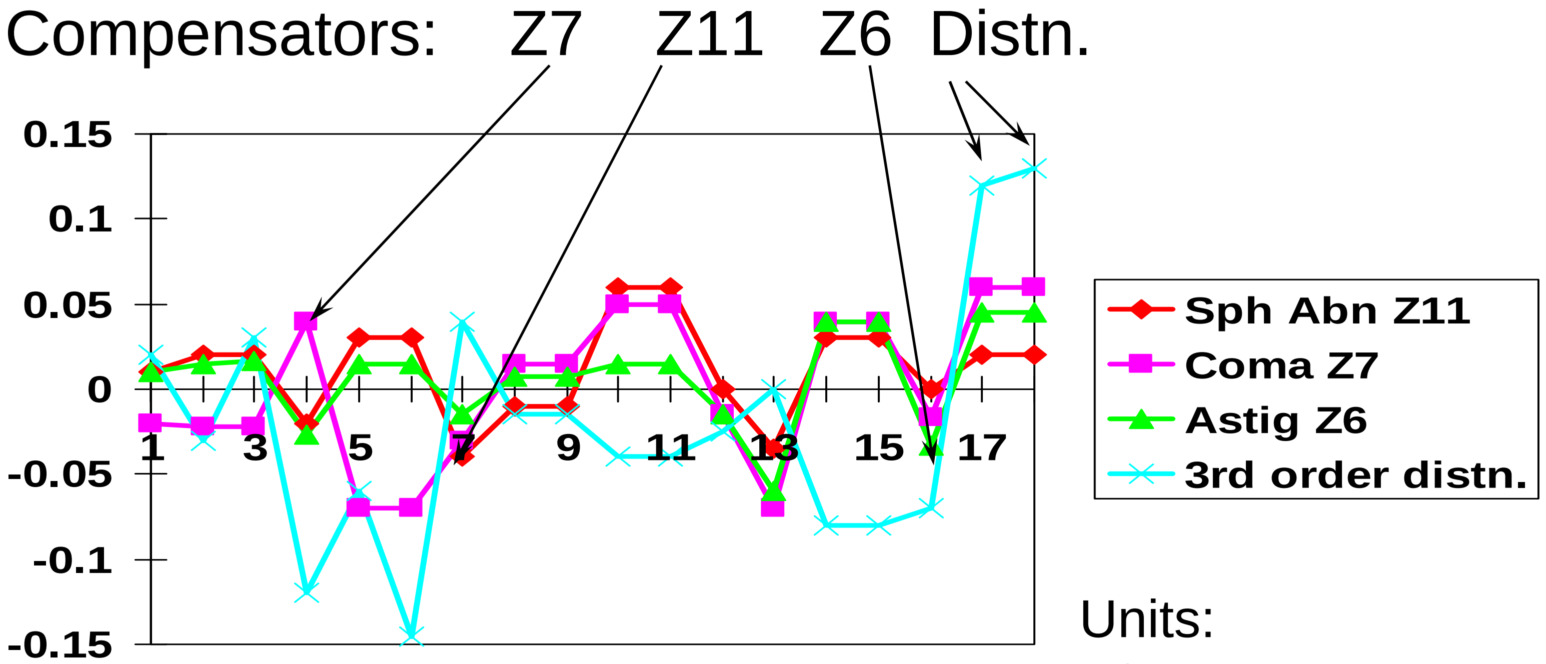
Aberrations compensateable by element shifts

Symmetrical 3rd order	Zernike #
Using OSA ordering (e.g. Zemax)	
Spherical aberration	Z11 mean
Coma	Z7 tilt
Astigmatism	Z6 bow
Distortion (Barrel-Pincushion)	Z2, Z3 cubic
Asymmetric 2nd order	
On-axis coma	Z7, Z8 mean
On-axis astig.	Z5, Z6 mean
Astigmatic field tilt	Z5, Z6 tilt
Tangential, Sagittal distortion	Z2, Z3 bow

Compensators

- To have independent control of all the second and third-order aberrations effected by element movements requires:
    - 4 independent axial adjustments
    - 4 independent decentration adjustments
    - clocking, or change of astigmatic elements
- In addition to first-order image parameters:
    - symmetrical - linear magnification and focus
    - asymmetric - image tilt and decentration

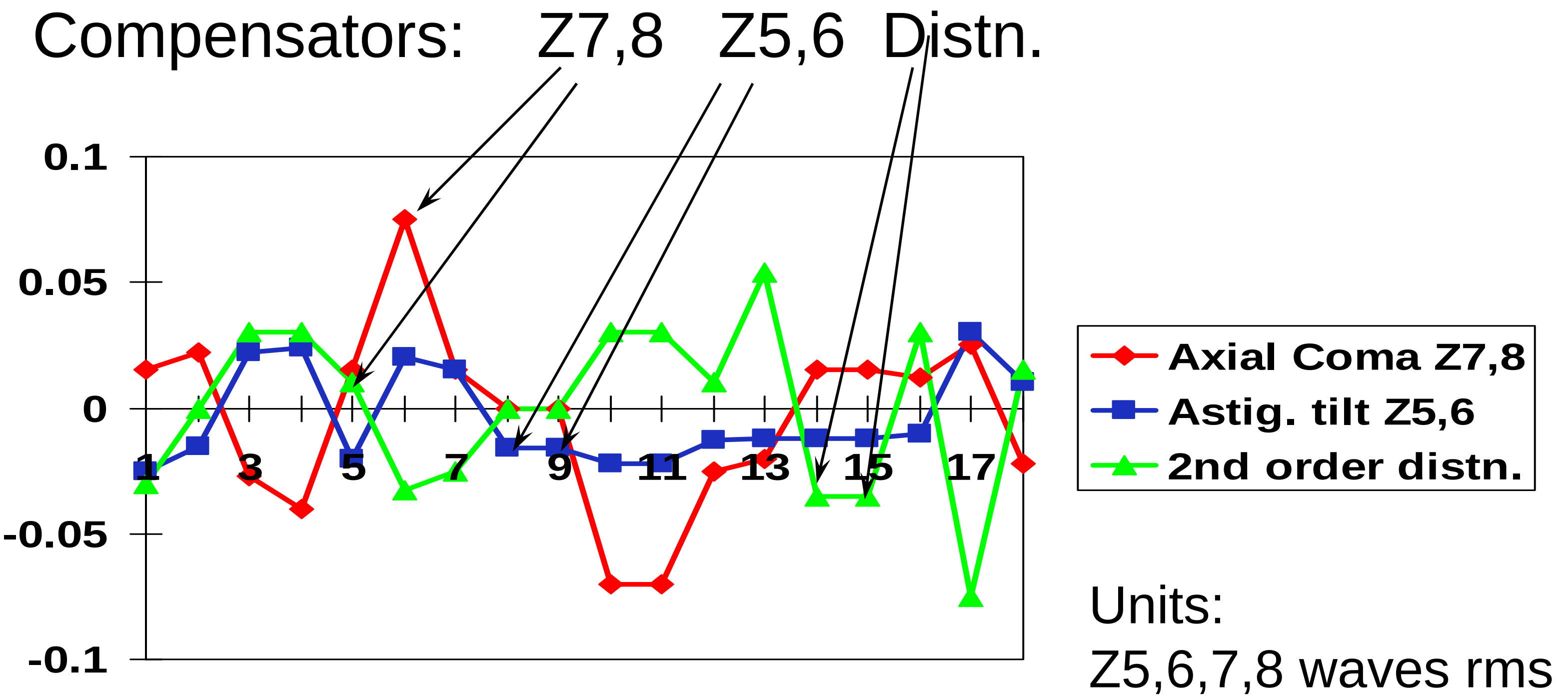
Sensitivity to element axial shift



Units:
Z6,7,11 waves r.m.s
Distn. microns

Element # moved axially by 25 microns

Sensitivity to element decentration



Compensators: Z7,8 Z5,6 Distn.

Units:
Z5,6,7,8 waves rms
Distn. microns

Element # decentered by 5 microns

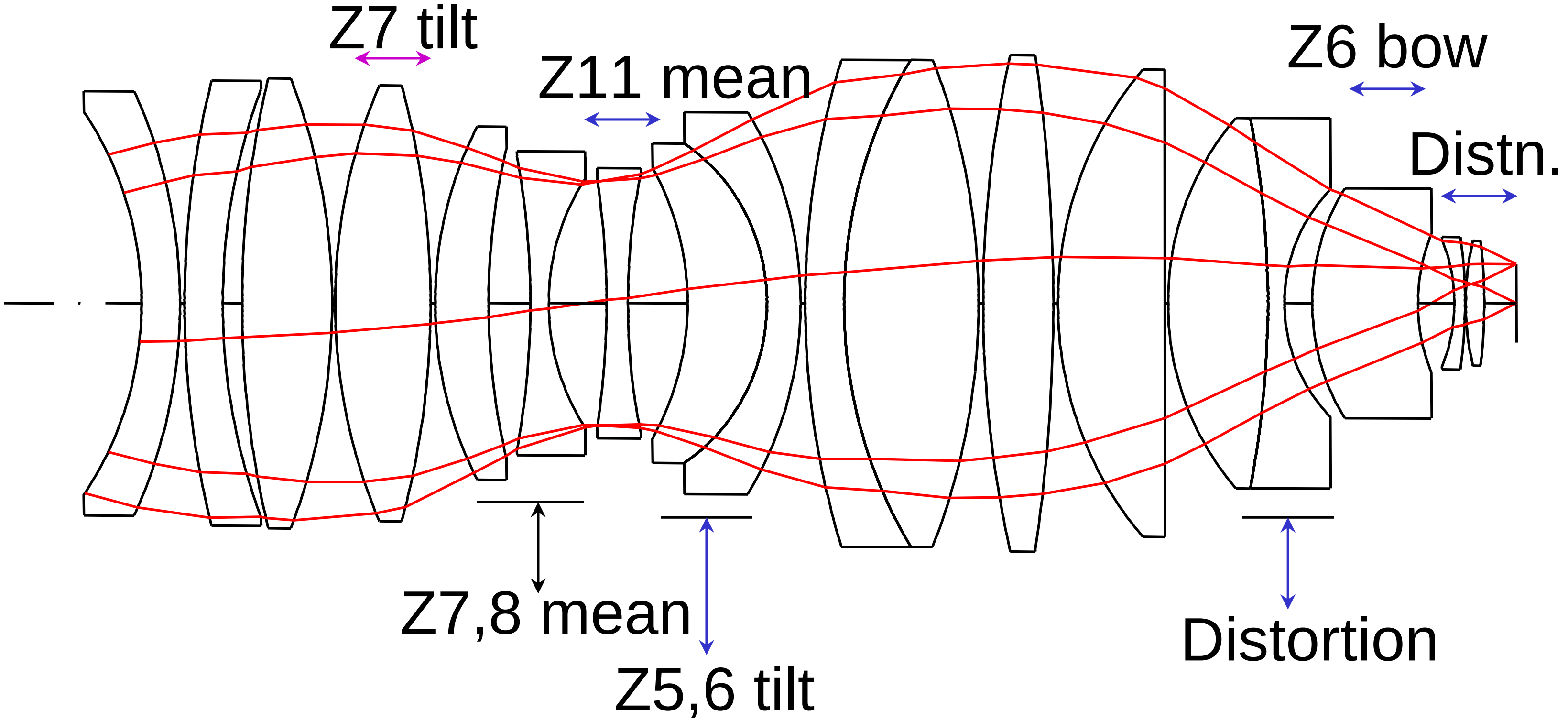
Compensator selection

- Historically, this has been done by the optical designer, looking at an aberration sensitivity matrix, working within practical constraints:
  - Which elements are most easily moved?
  - Which elements are too sensitive?
  - Which elements have the most independent effects on different aberrations? – orthogonality
- More recently, selection is assisted by Singular Value Decomposition (SVD) of the sensitivity matrix, which gives the most orthogonal set of compensators

Compensators for a NA 0.42 I-line lens

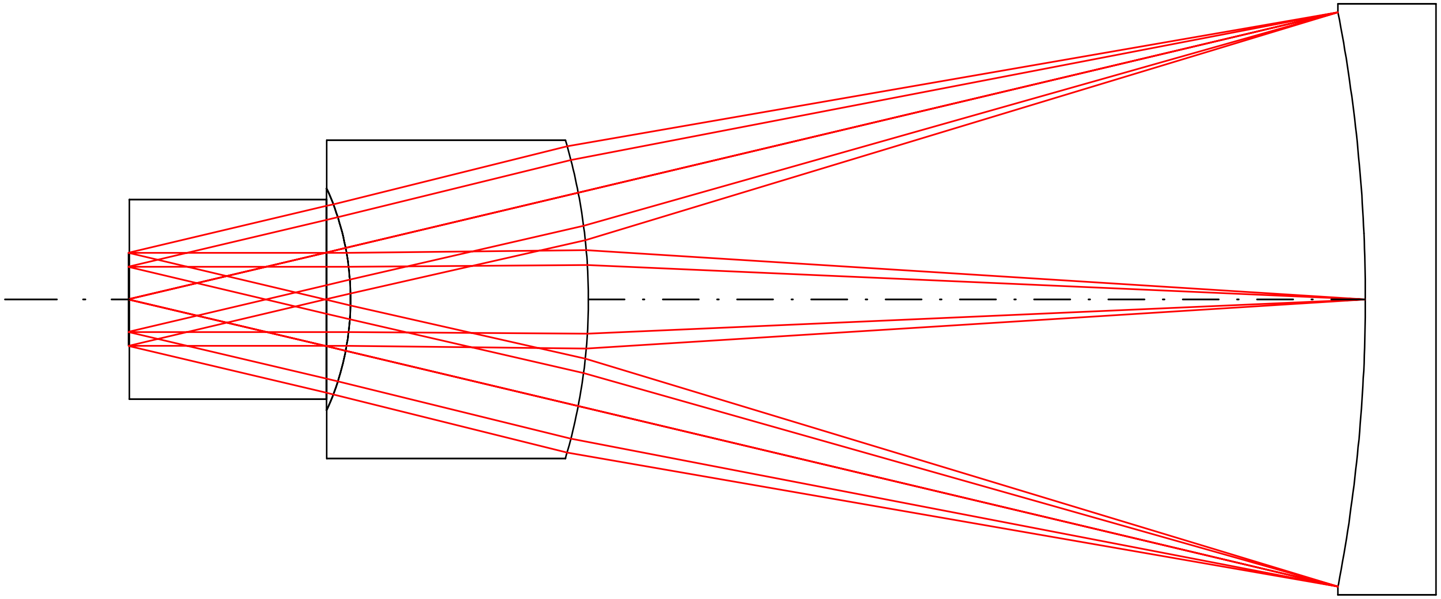
700-500 nm node

Ref: SPIE Proc. 1049 (1989) Williamson



Wynne-Dyson 1x NA 0.35

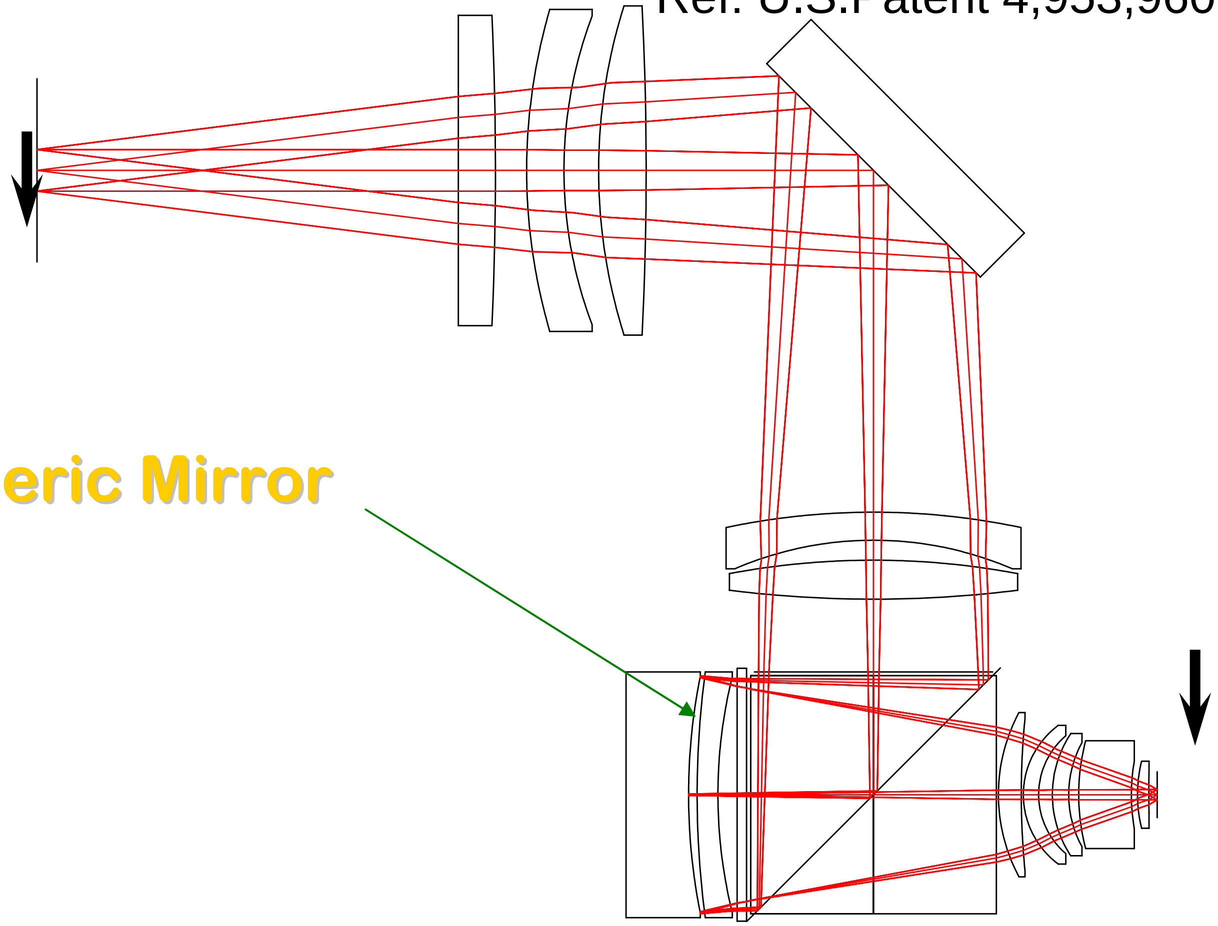
Ref: German Patent 1 957 628 Wynne



Micrascan II 4x NA 0.5

350-250 nm node

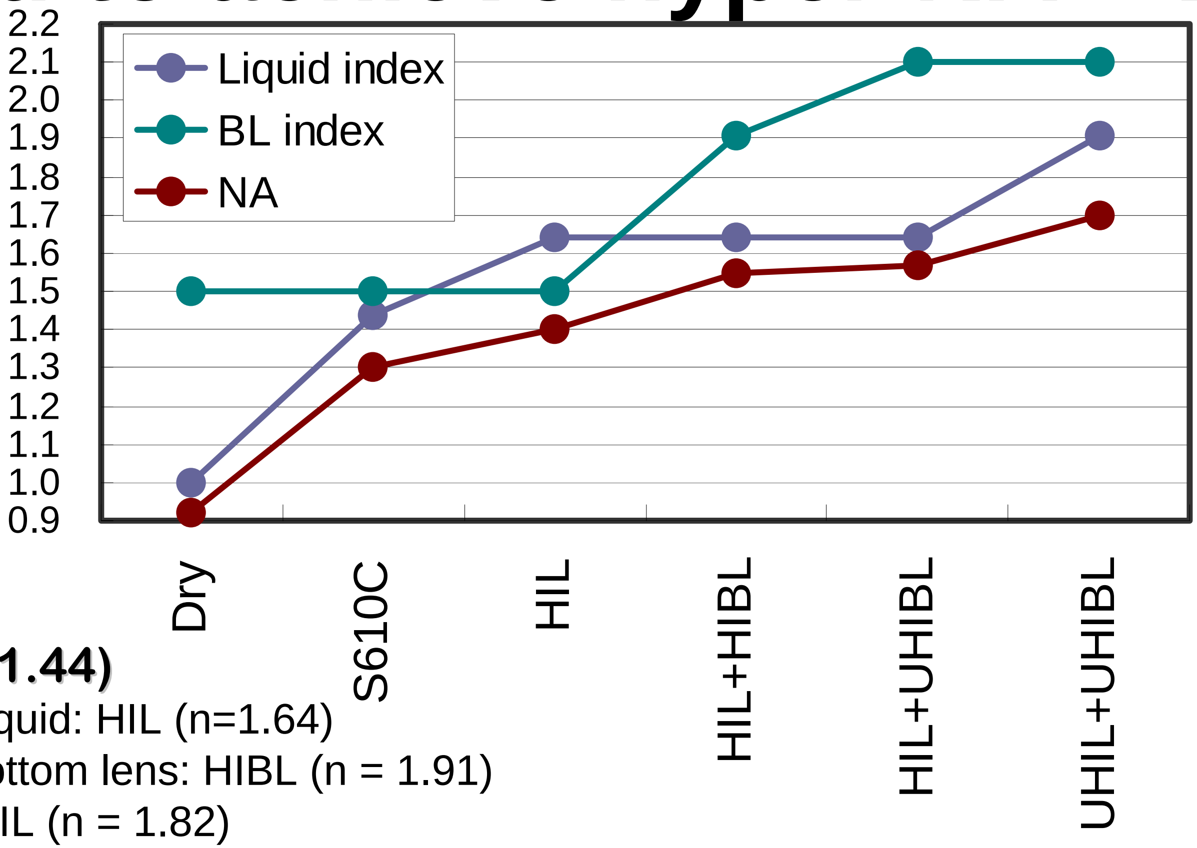
On-axis step-and-scan
Continued use of broadband DUV



Ref: U.S.Patent 4,953,960 Williamson

Aspheric Mirror

NA 1.0 limit in air – Immersion in liquid to achieve hyper-NA > 1.0



Water (n = 1.44)

High index Liquid: HIL (n=1.64)

High index bottom lens: HIBL (n = 1.91)

Ultra HIL: UHIL (n = 1.82)

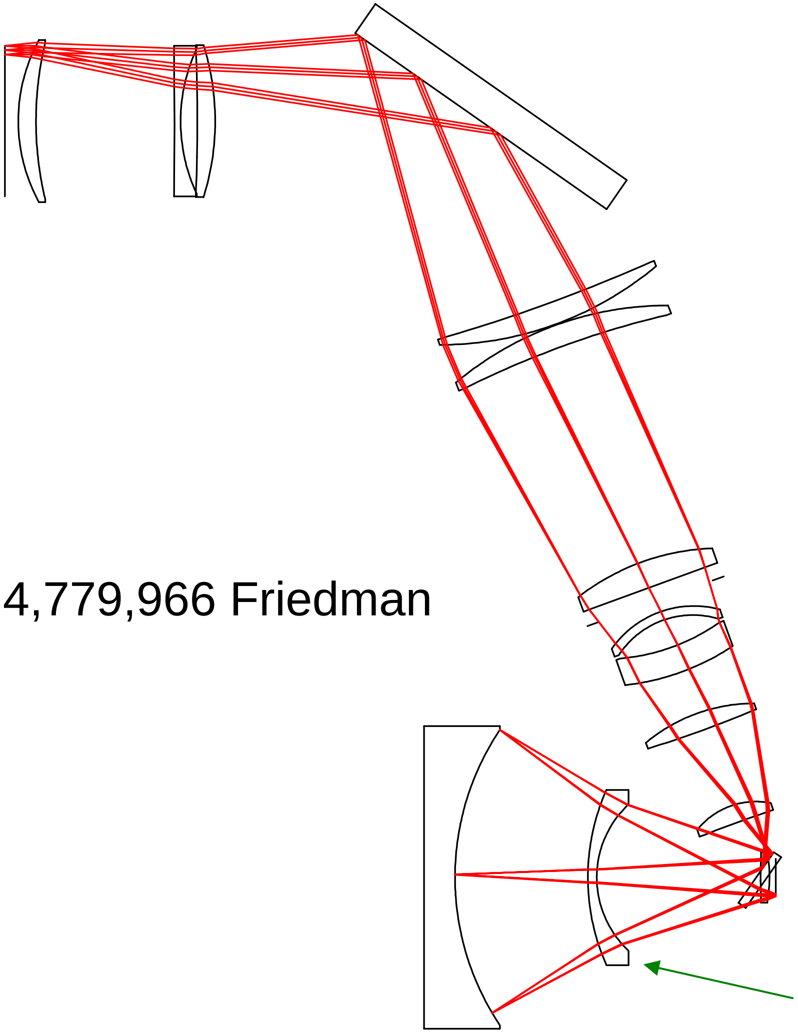
Ultra HIBL: UHIBL (n= 2.1)

Material development is key –
Transmission and Intrinsic Cubic Birefringence

Hyper-NA Catadioptric designs

- Reversal of classical Catadioptric design philosophy (low refracting power):
  - Less emphasis on chromatic correction, more emphasis on lens diameter reduction
  - Mirrors correct the monochromatic aberrations of the lenses, specifically Petzval sum
  - Monochromatic aberrations must be ~ zero
  - Pupil obscuration must be avoided
  - Higher Dioptric power, greater complexity
  - Non-polarizing

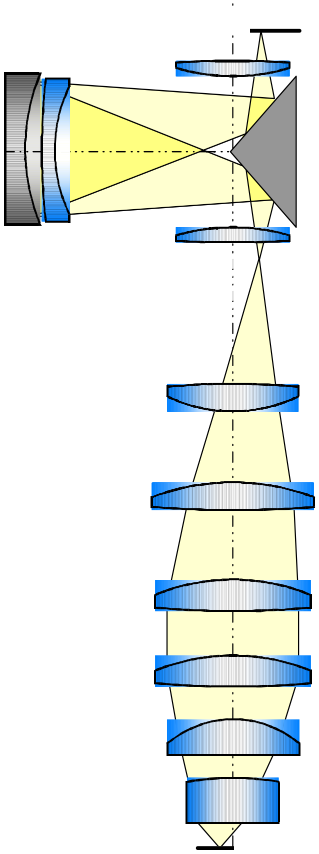
Schupmann principle – Off-axis dioptric 4x relay + 1x catadioptric relay NA 0.4

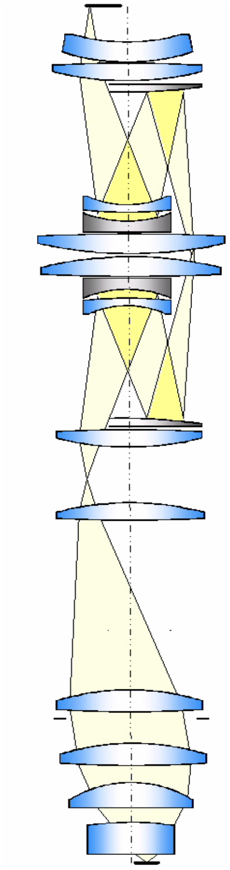


Ref: U.S.Patent 4,779,966 Friedman

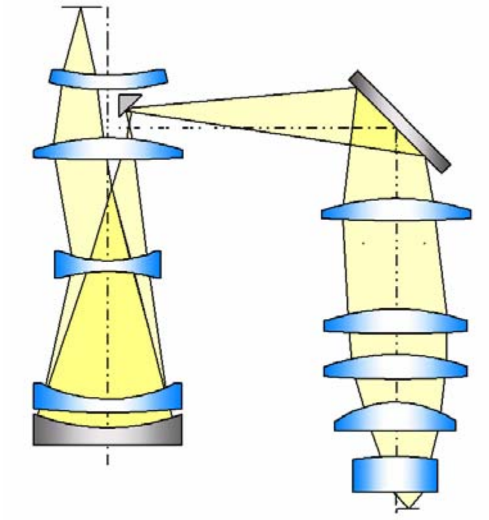
Schupmann Lens

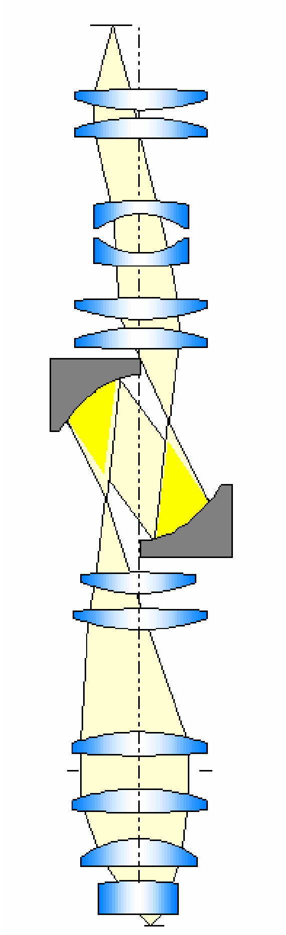
Hyper-NA Catadioptric folding arrangements





45-32 nm node





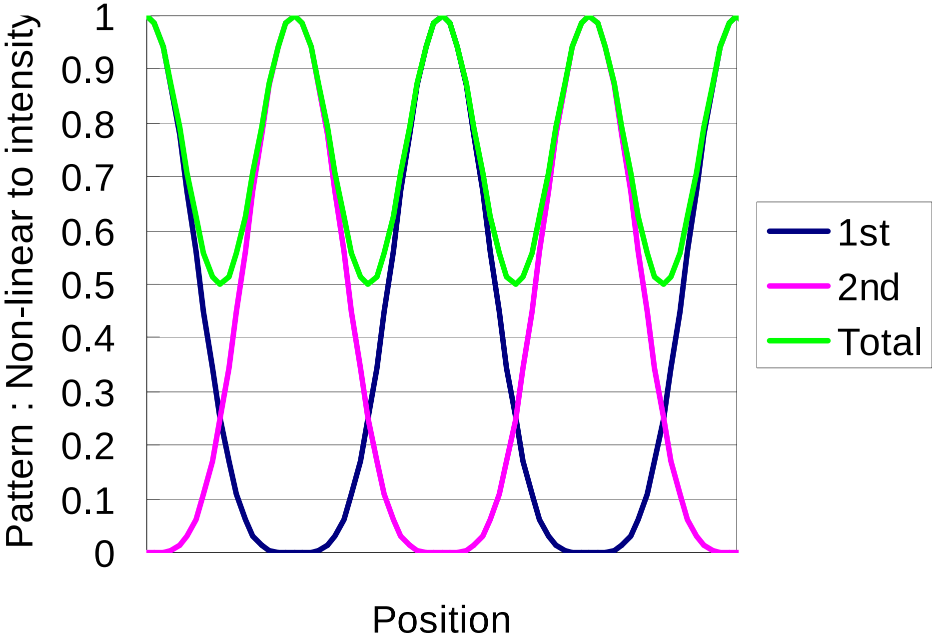
Which is the Global Optimum?

Limits of DUV vs. 1st Generation EUV Lithography

NA	**Half-pitch Resolution (nm)** **$0.3\ \lambda\ /NA$**	**Paraxial DOF (nm)** **$n.\ \lambda\ /NA^2$**
1.4	41 @ λ193nm	162
1.7	34 @ λ193nm	121
0.25	16 @ λ13 nm	214

Non-linear patterning

- Double patterning
  - Beyond optical limit
  - Non-linear resist
  - Double processing

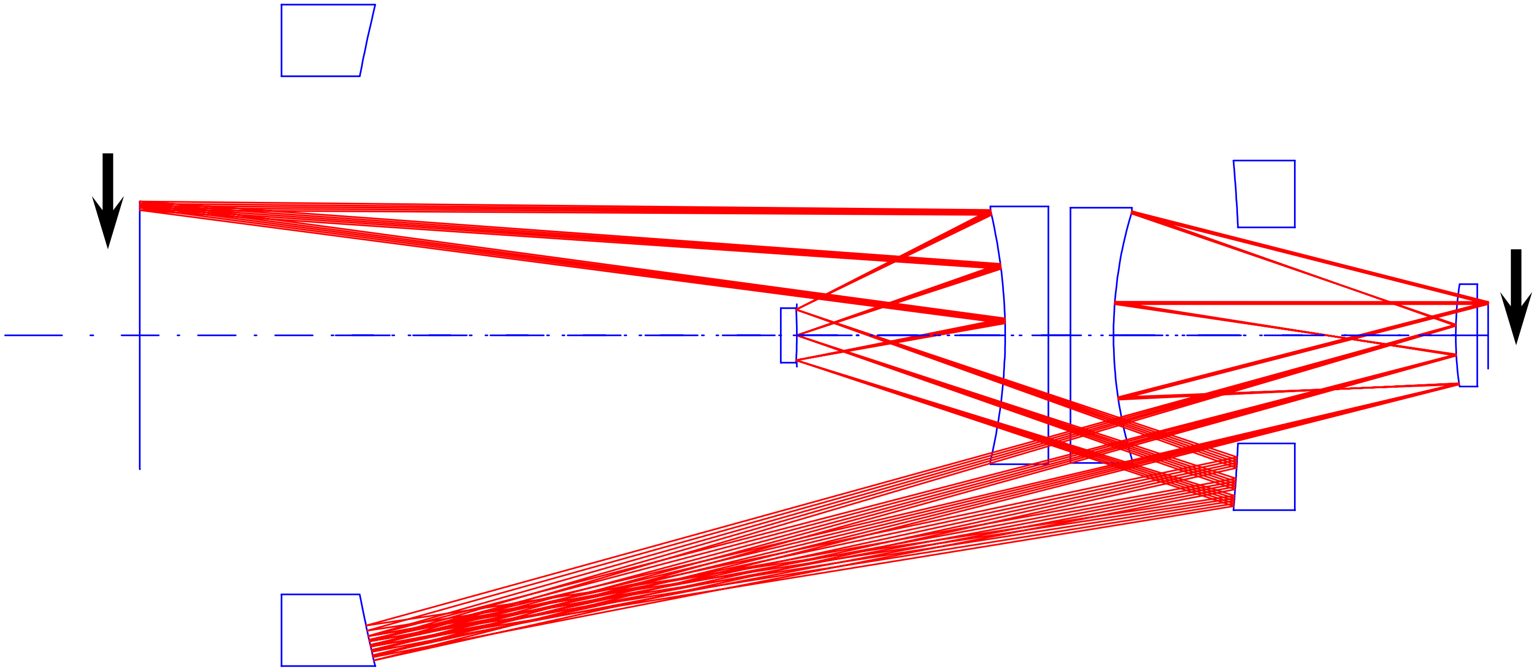


Non-linearity is necessary to go beyond optical resolution limit of $k_1 = 0.25$

EUV (λ13.4nm) 4x NA 0.25

90-16 nm node

Ref: U.S.Patent 5,815,310 Williamson



Extended H = 1,000,000 @ k1 = 0.25
~ 100x 1st Gen. lens

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