Eigenmode analysis of electromagnetic fields in binary EUV masks

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Outline

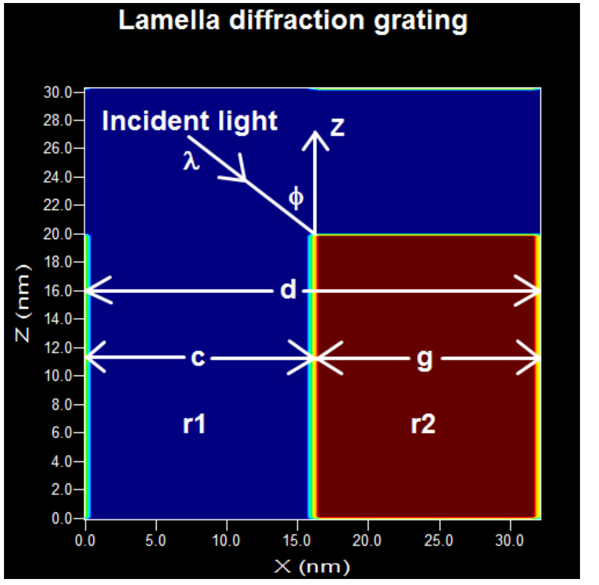
- Exact electromagnetic eigenmodes
- Rigorous solution using exact eigenmodes
- Dependence of aerial-image contrast on absorber thickness
- Attenuating PSM effect in complex 2D layout

Exact electromagnetic eigenmodes

- Exact electrimagnetic eigenmodes are given by Botten et. al. for L/S structures:
  - “The finitely conducting lamella diffraction grating”, Optica Acta, 28, 1087 (1981)

- These results are valid only for in-plane incidence, i.e. CRAO = 0
  - The results for non-zero CRAO are very similar.

An eigenmode is a product of a function of x and a function of z:



$$E(x,z) = u(x)e^{\pm j\mu z}$$

$$u(x) = \theta(x) + \omega\psi(x)$$

$$\theta(x) = \begin{cases} \cos(\beta x) \ , & 0 \le x \le c \\ \cos(\beta c)\cos[\gamma(x-c)] - \frac{\beta}{\gamma}\sin(\beta c)\sin[\gamma(x-c)] \ , & c \le x \le d \end{cases}$$

$$\psi(x) = \begin{cases} \frac{1}{\beta}\sin(\beta x) \ , & 0 \le x \le c \\ \frac{1}{\beta}\sin(\beta c)\cos[\gamma(x-c)] + \frac{1}{\gamma}\cos(\beta c)\sin[\gamma(x-c)] \ , & c \le x \le d \end{cases}$$

$$\beta^2 = k_1^2 - \mu^2 \qquad \omega = \frac{\tau - \theta(d)}{\psi(d)}$$

$$\gamma^2 = k_2^2 - \mu^2$$

$$k_1 = k_0 r_1 \qquad \tau = e^{j\alpha_0 d}$$

$$k_2 = k_0 r_2 \qquad \alpha_0 = k_0 \sin\phi$$

Eigenvalue μ

- μ is found by solving an eigenvalue equation:

$$\cos(\beta c)\cos[\gamma(d-c)] - \frac{1}{2}\left(\frac{\beta}{\gamma} + \frac{\gamma}{\beta}\right)\sin(\beta c)\sin[\gamma(d-c)] \quad = \quad \cos(\alpha_0 d)$$

- μ determines the wavelength and decay length of the eigenmode in the Z direction:

$$\lambda_n \quad = \quad 2\pi \,/\, \mathrm{Re}(\mu_n)$$
$$L_{\mathrm{deacay,n}} \quad = \quad 1 \,/\, \mathrm{Im}(\mu_n)$$

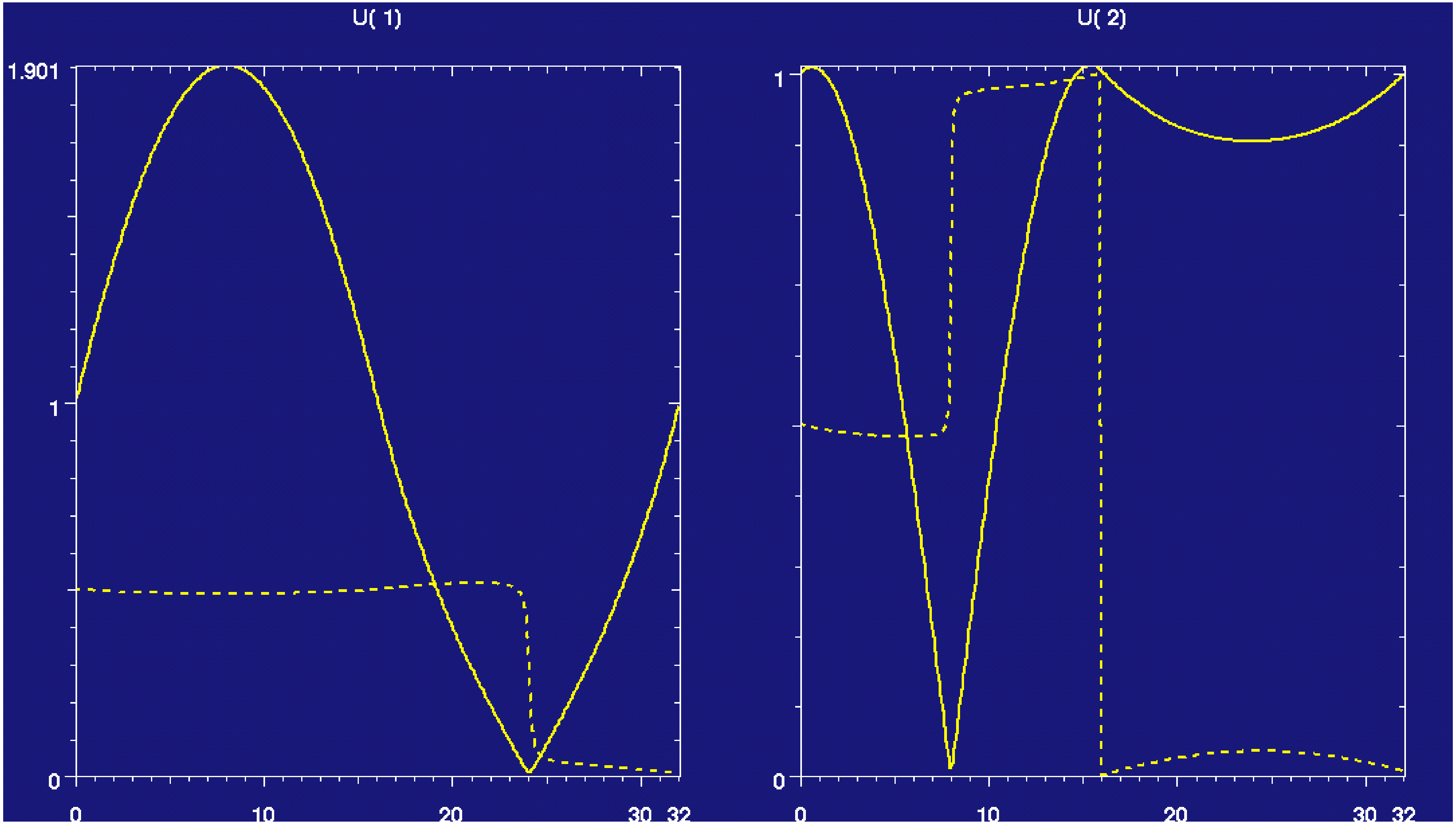
Eigenvalues for 4-nm equal L/S, 4X mask

c = 16 nm, d = 32 nm, λ = 13.5 nm, $\phi = 12^o.3422$

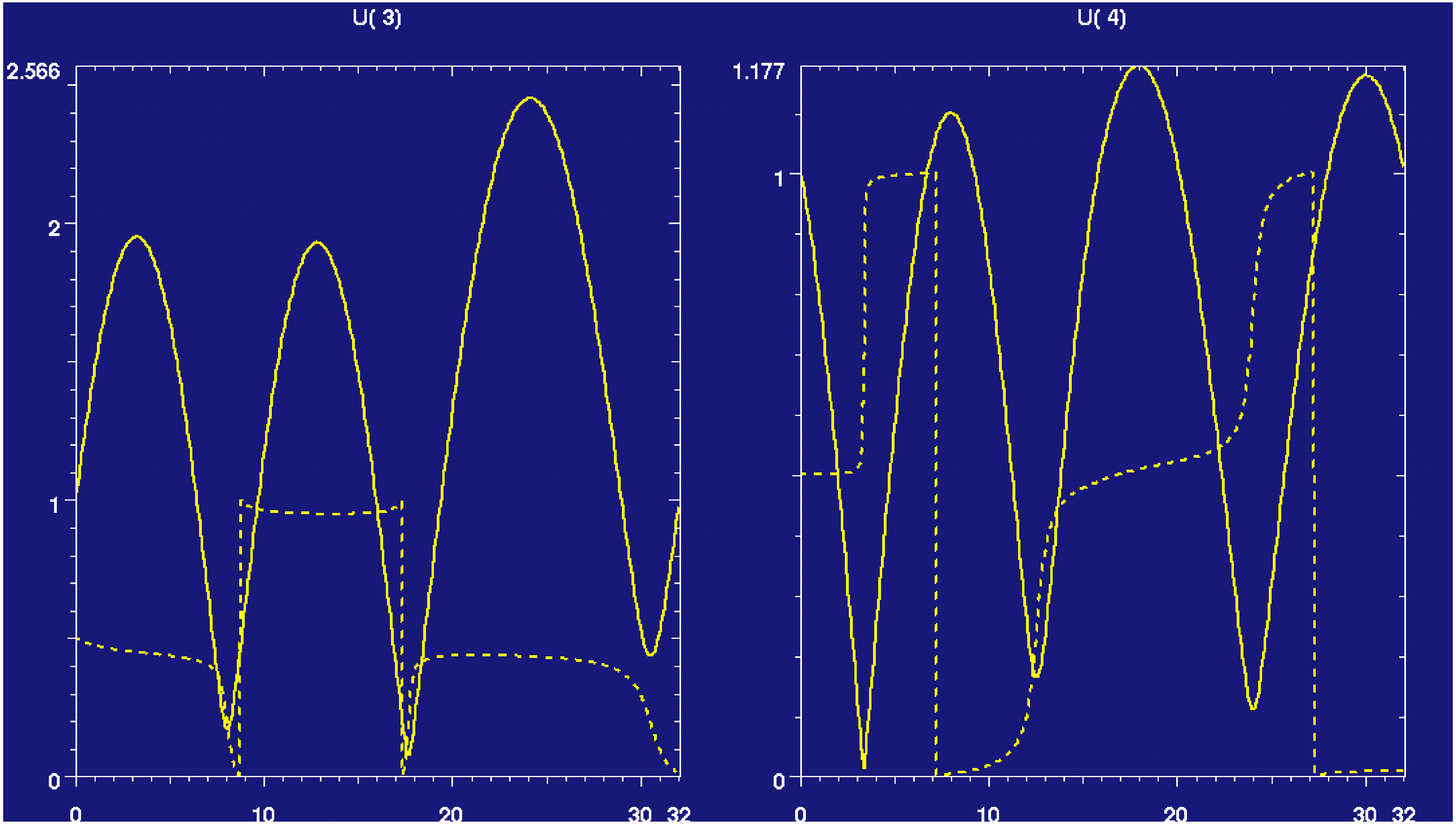
$r_1 = 1.0$, $r_2 = 0.883315 + 0.044277j$

Mode number	TE eigenvalue, 4-nm L/S, 4X mask		
n	$\mu_n(\mathrm{nm}^{-1})$	$\lambda_n(\mathrm{nm})$	$L_{\mathrm{deacay,n}}(\mathrm{nm})$
1	$0.44772+0.00173j$	14.0	578.0
2	$0.41332+0.01254j$	15.2	79.7
3	$0.32972+0.01369j$	19.1	73.0
4	$0.31601+0.01626j$	19.9	61.5
5	$0.01881+0.21553j$	334.0	4.64
6	$0.02093+0.23007j$	300.2	4.35

Eigenmodes for 4-nm equal L/S, 4X mask

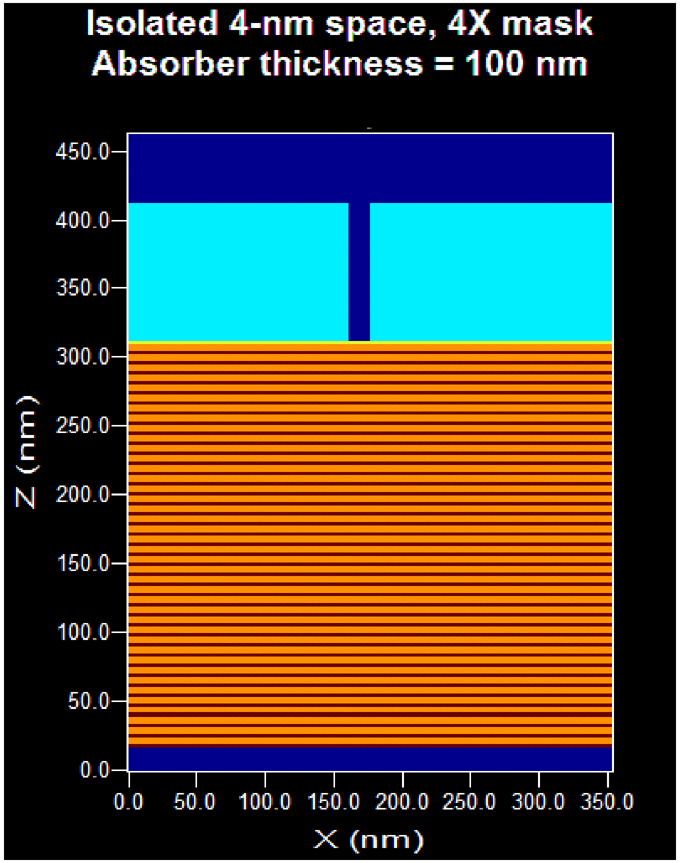


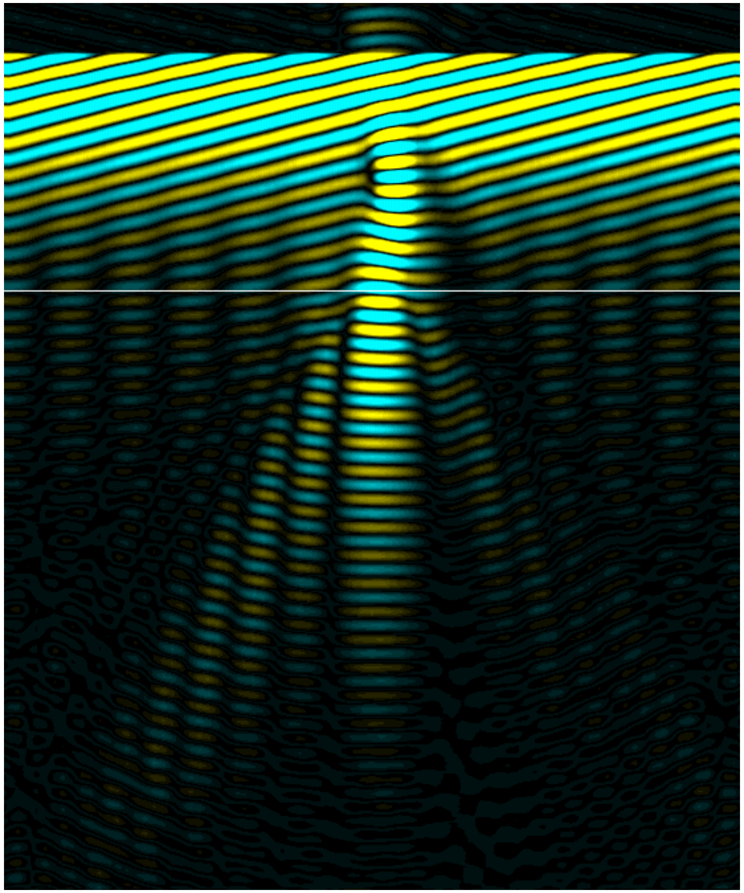
Eigenmodes for 4-nm equal L/S, 4X mask



Vertical propagation of lowest eigenmodes in an isolated 4-nm space, 4X mask

- Vertical propagation of the lowest eigenmodes reduces shadowing and mask-side non-telecentricity effects, as the following simulation shows:



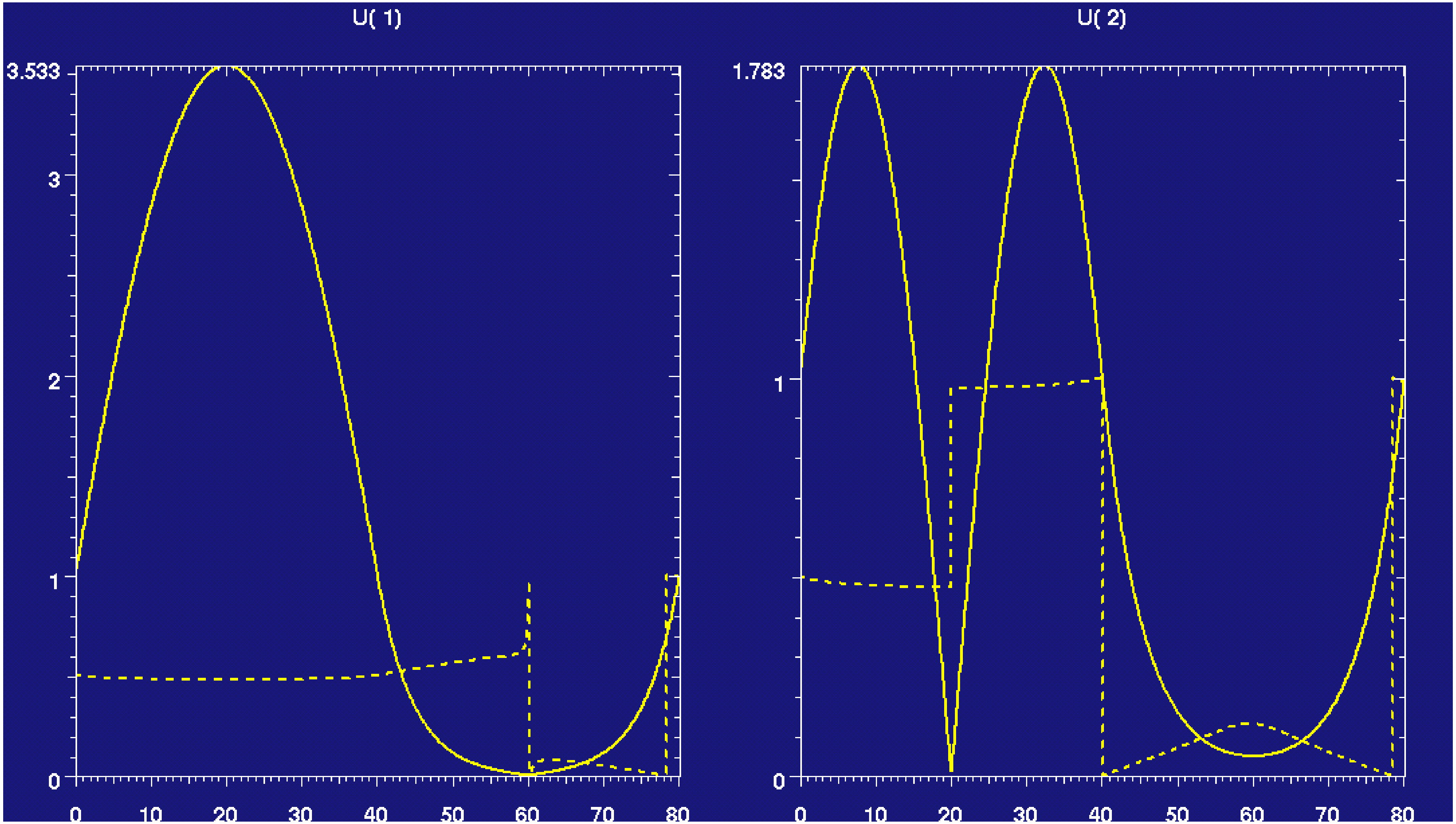


Eigenvalues for 10-nm equal L/S, 4X mask

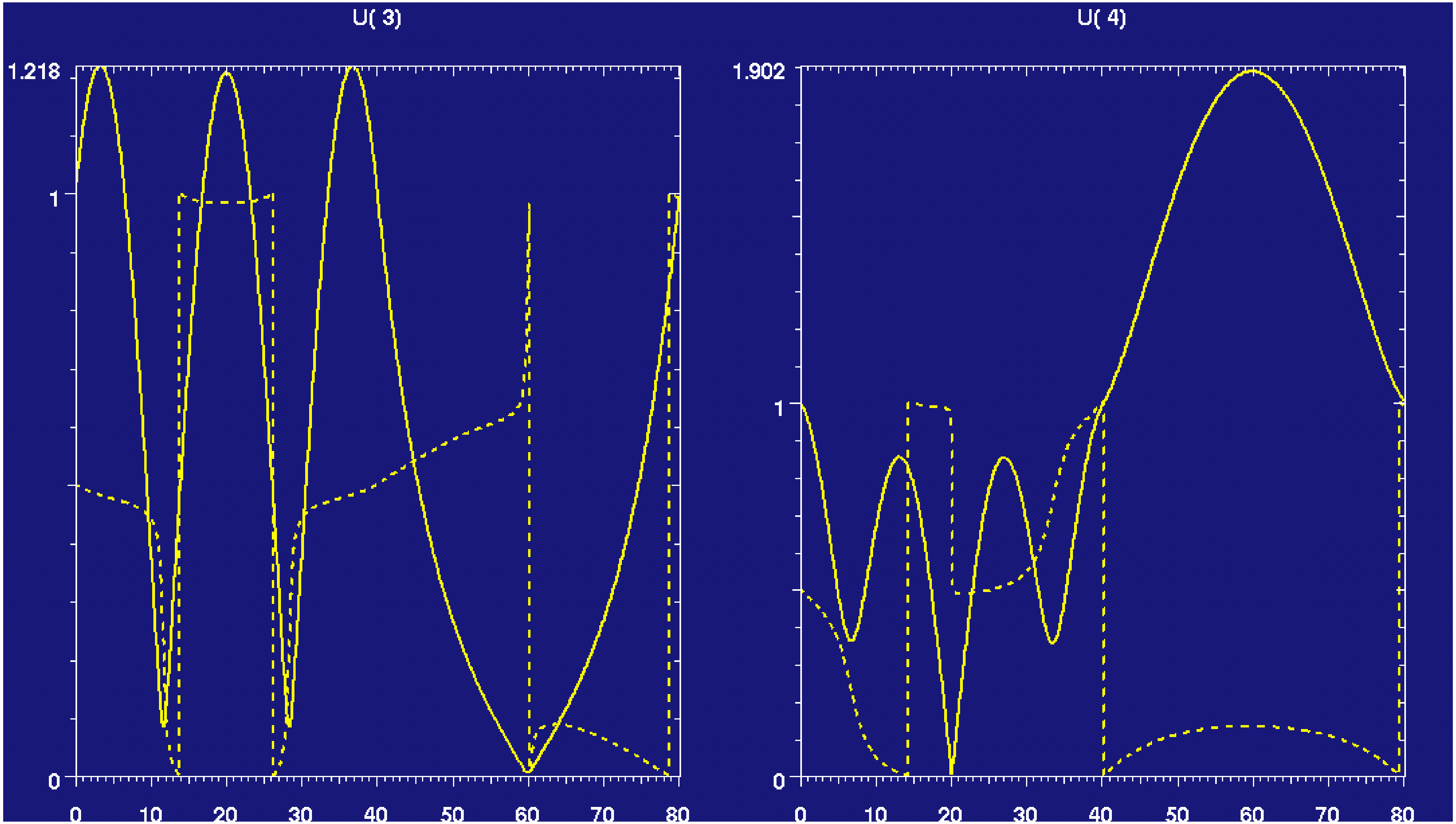
c = 40 nm, d = 80 nm, λ = 13.5 nm, ϕ = 4^{o}.7323

Mode number n	TE eigenvalue, 10-nm L/S, 4X mask $\mu_n (\mathrm{nm}^{-1})$	$\lambda_n (\mathrm{nm})$	$L_{\mathrm{deacay,n}} (\mathrm{nm})$
1	$0.46096+0.00028j$	13.6	3603.6
2	$0.44759+0.00127j$	14.0	786.8
3	$0.42575+0.00368j$	14.8	271.7
4	$0.40567+0.01764j$	15.5	56.7
5	$0.39152+0.00969j$	16.0	103.3
6	$0.38487+0.01729j$	16.3	57.8
7	$0.33920+0.01219j$	18.5	82.0
8	$0.33917+0.01661j$	18.5	60.2
9	$0.25953+0.01902j$	24.2	52.6
10	$0.25634+0.01695j$	24.5	59.0
11	$0.09213+0.05008j$	68.2	20.0
12	$0.08172+0.05377j$	76.9	18.6
13	$0.01707+0.26078j$	368.1	3.83

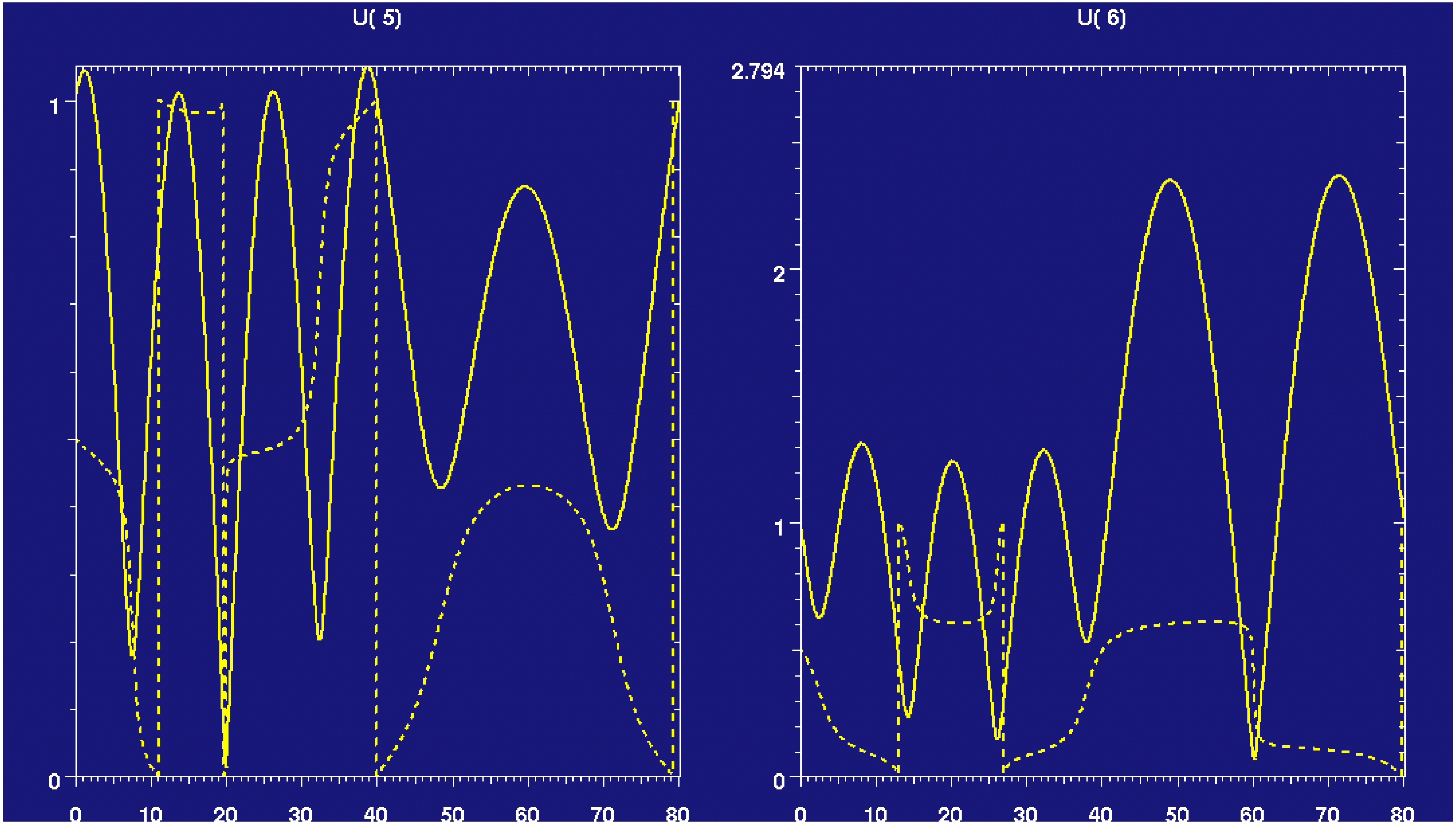
Eigenmodes for 10-nm equal L/S, 4X mask



Eigenmodes for 10-nm equal L/S, 4X mask



Eigenmodes for 10-nm equal L/S, 4X mask



Rigorous solution using exact eigenmodes

Rigorous solution using exact eigenmodes

- Top surface of grating at Z = 0. Bottom surface at Z = -h
- Electric field in the three regions are expanded in eigenmodes of the corresponding regions:

$$E(x,z) = \begin{cases} \left(e^{-j\chi_0 z} + \sum_p R_p e^{j\chi_p z}\right) e^{j\alpha_p x}, & z \geq 0 \\ \sum_m \left(a_m e^{-j\mu_m z} + b_m e^{j\mu_m z}\right) u_m(x), & -h \leq z \leq 0 \\ \sum_p T_p \left[e^{-j\eta_p (z+h)} + M_p e^{j\eta_p (z+h)}\right] e^{j\alpha_p x}, & z \leq -h \end{cases}$$

$$\chi_p = \sqrt{k_0^2 - \alpha_p^2}$$

$$\eta_p = \sqrt{k_3^2 - \alpha_p^2}$$

$$\alpha_p = \alpha_0 + \frac{2\pi p}{d}$$

- M_p is the multilayer reflectivity for diffraction order p
- Four sets of unknowns: R_p, a_m, b_m and T_p

Four boundary conditions

- Continuity of electric field at Z = 0:

$$\sum_p (\delta_{p0} + R_p) e^{j\alpha_p x} = \sum_m (a_m + b_m) u_m(x)$$

- Continuity of magnetic field at Z = 0:

$$\sum_p \chi_p (\delta_{p0} - R_p) e^{j\alpha_p x} = \sum_m \mu_m (a_m - b_m) u_m(x)$$

- Continuity of electric field at Z = -h:

$$\sum_m \left(a_m e^{j\mu_m h} + b_m e^{-j\mu_m h} \right) u_m(x) = \sum_p T_p (1 + M_p) e^{j\alpha_p x}$$

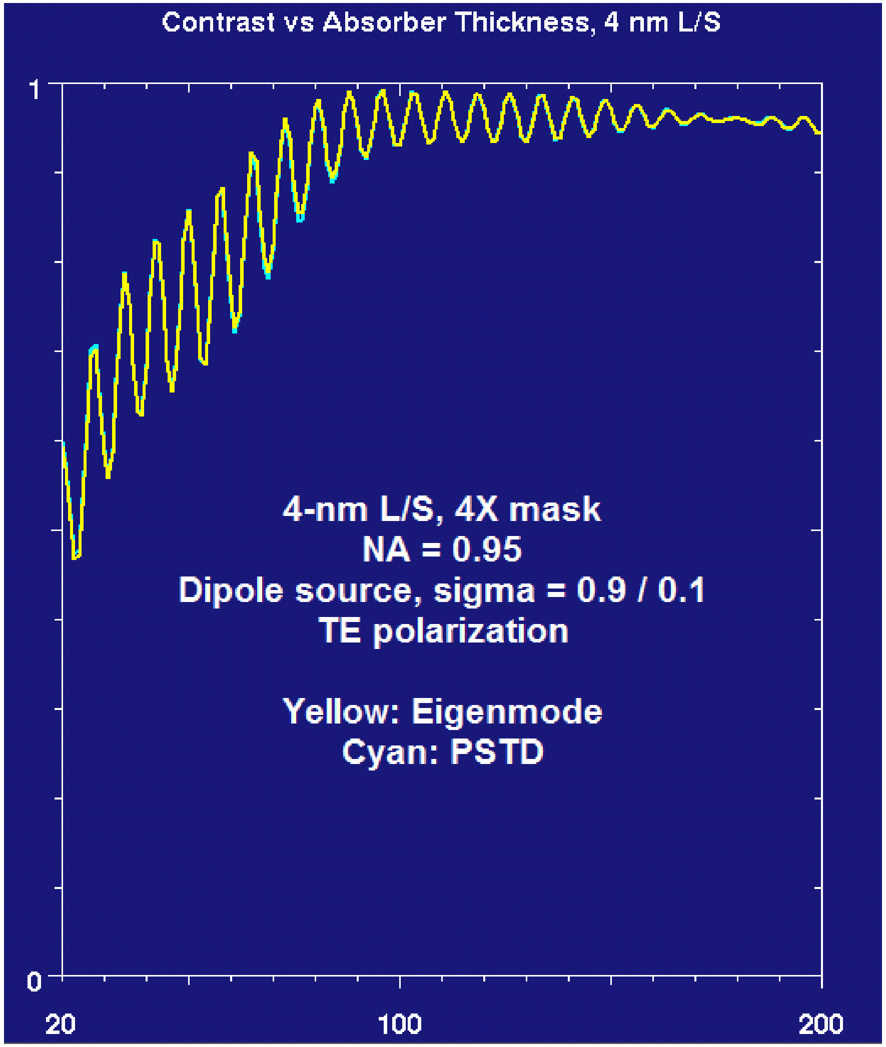
- Continuity of magnetic field at Z = -h:

$$\sum_m \mu_m \left(a_m e^{j\mu_m h} - b_m e^{-j\mu_m h} \right) u_m(x) = \sum_p \eta_p T_p (1 - M_p) e^{j\alpha_p x}$$

- Thus we can solve for the four sets of unknowns R_p, a_m, b_m and T_p

Dependence of aerial-image contrast on absorber thickness: 4-nm L/S, 4X mask, NA = 0.95

Dependence of contrast on absorber thickness: 4-nm L/S



Excellent agreement between PSTD and eigenmode results

Top-surface fields (Z = 0)

- Just above the grating surface:

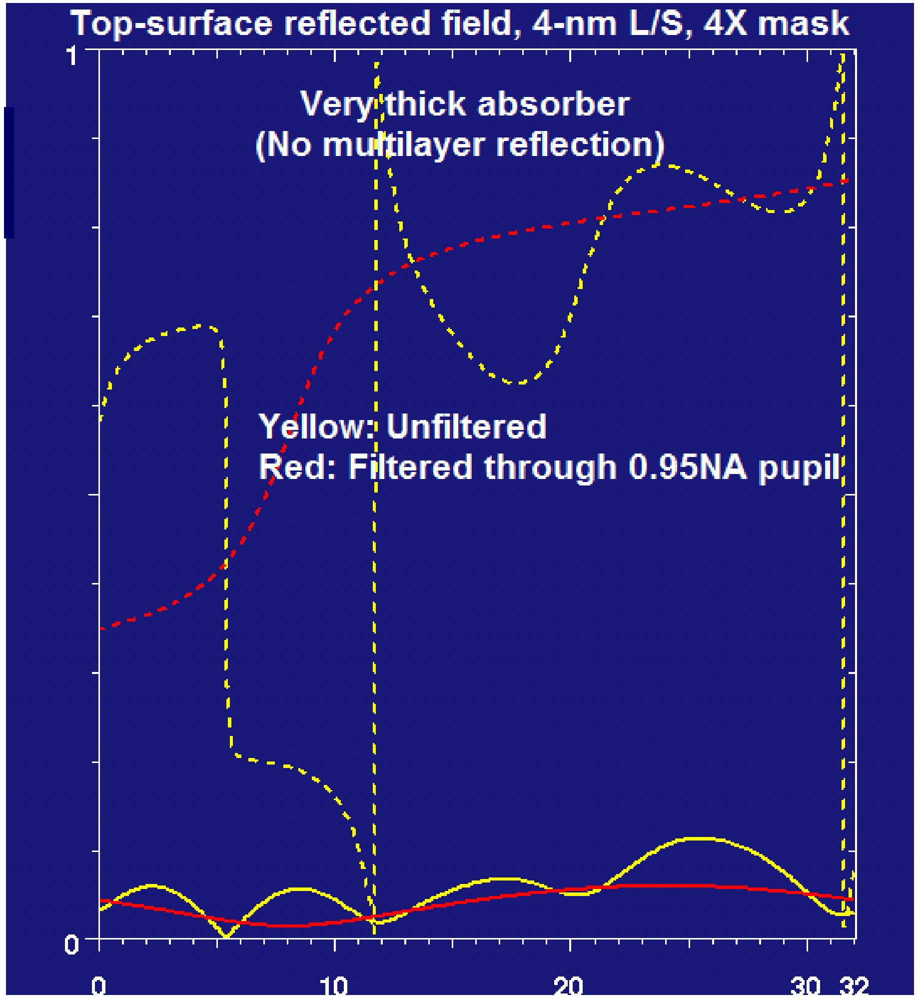
$$E(x,z) \quad = \quad \left(e^{-j\chi_0 z} + \underbrace{\sum_p R_p e^{j\chi_p z}\right) e^{j\alpha_p x}}_{\text{Total up-going field}}$$

- Just below the grating surface:

$$E(x,z) \quad = \quad \sum_m \left(a_m e^{-j\mu_m z} + \underbrace{b_m e^{j\mu_m z}\right) u_m(x)}_{\text{Individual up-going eigenmodes}}$$

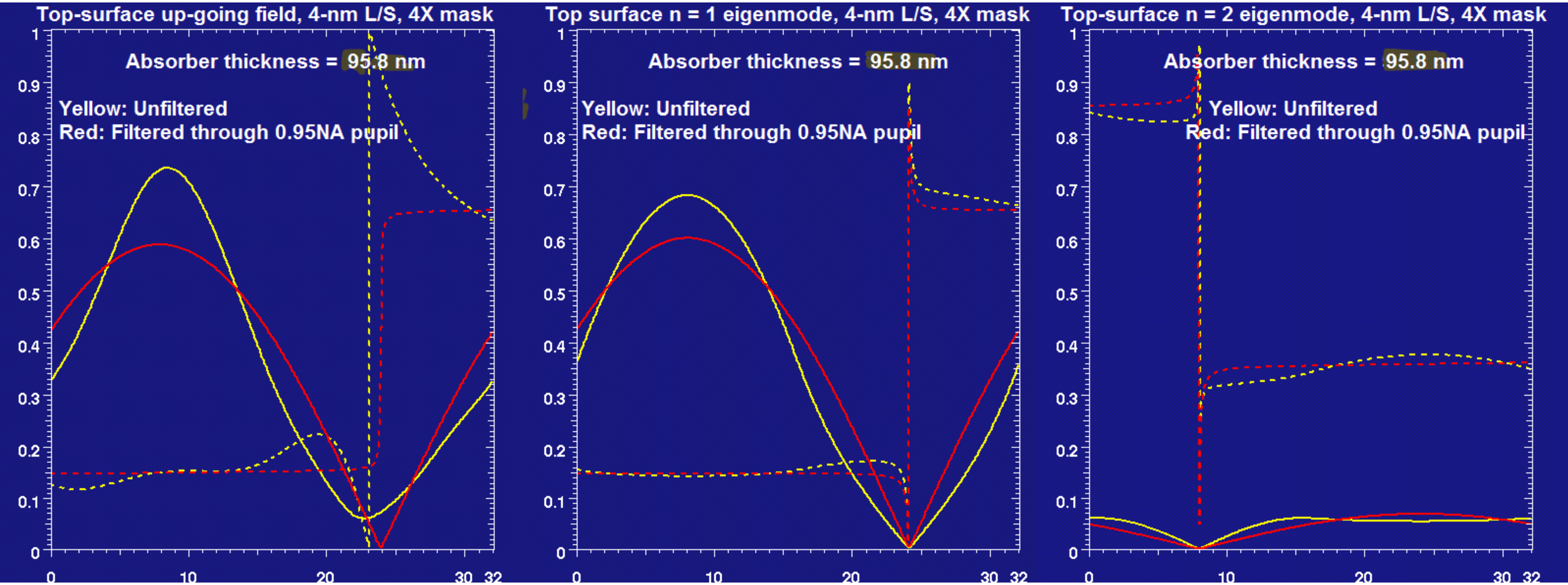
- The total up-going field at Z = 0 consists of:
  - Top-surface reflected field in absence of multilayer reflection
  - Up-going eigenmodes due to multilayer reflection

Top-surface reflected field, 4-nm L/S (in absence of multilayer reflection)



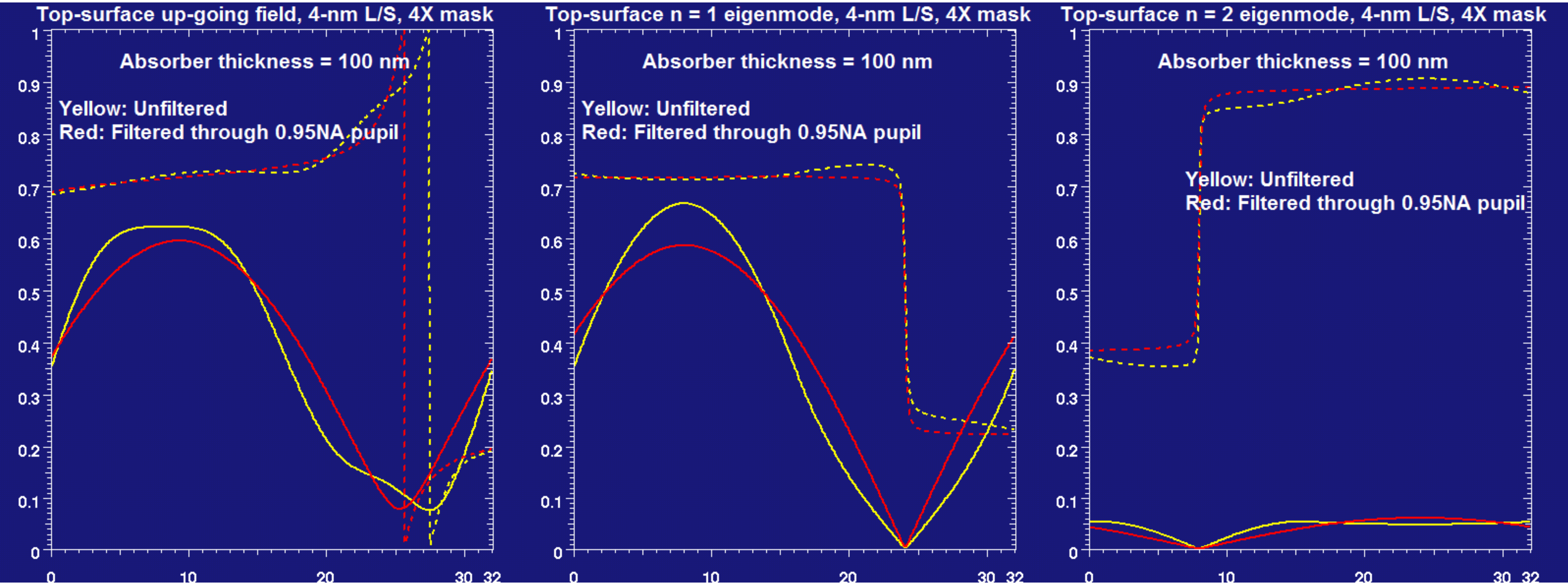
- Only the filtered field (red) goes through the 0.95NA pupil

Top-surface fields, 4-nm L/S
Absorber thickness = 95.8 nm



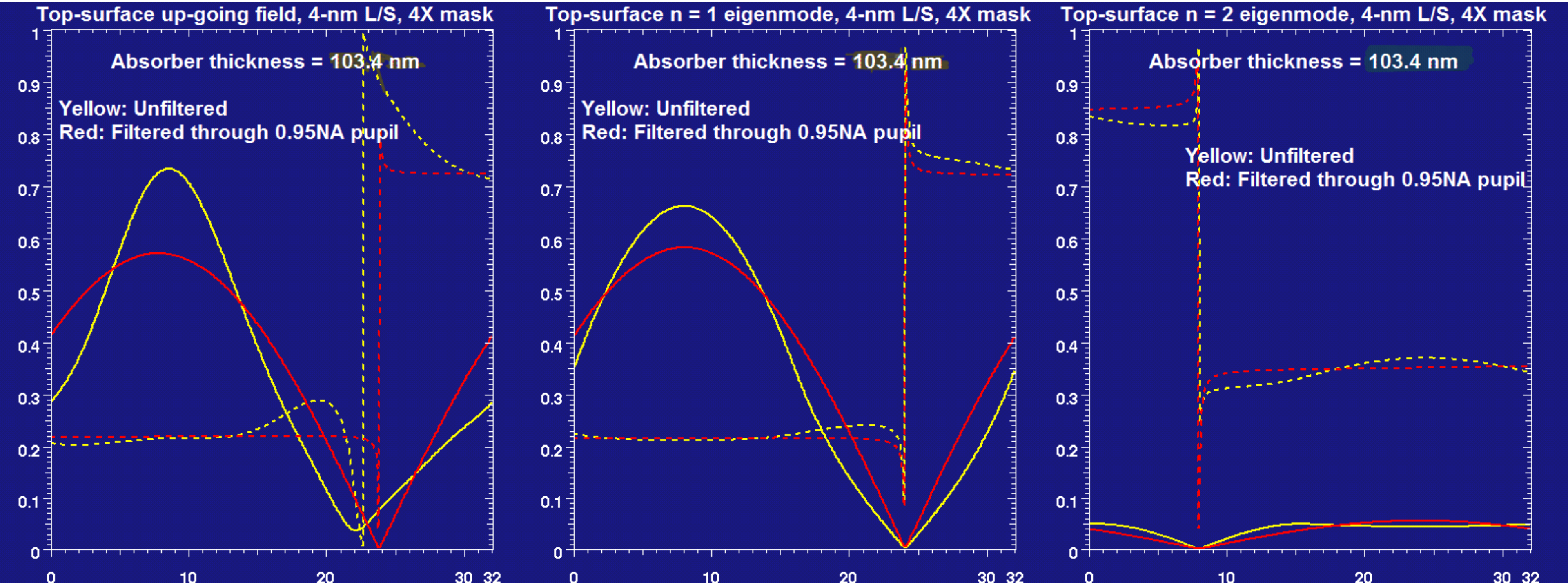
- At X = 24 nm, the n = 2 eigenmode field is approximately equal to but 180^o out of phase with the top-surface reflected field, leading to almost zero at the position of aerial-image minimum.

Top-surface fields , 4-nm L/S
Absorber thickness = 100 nm



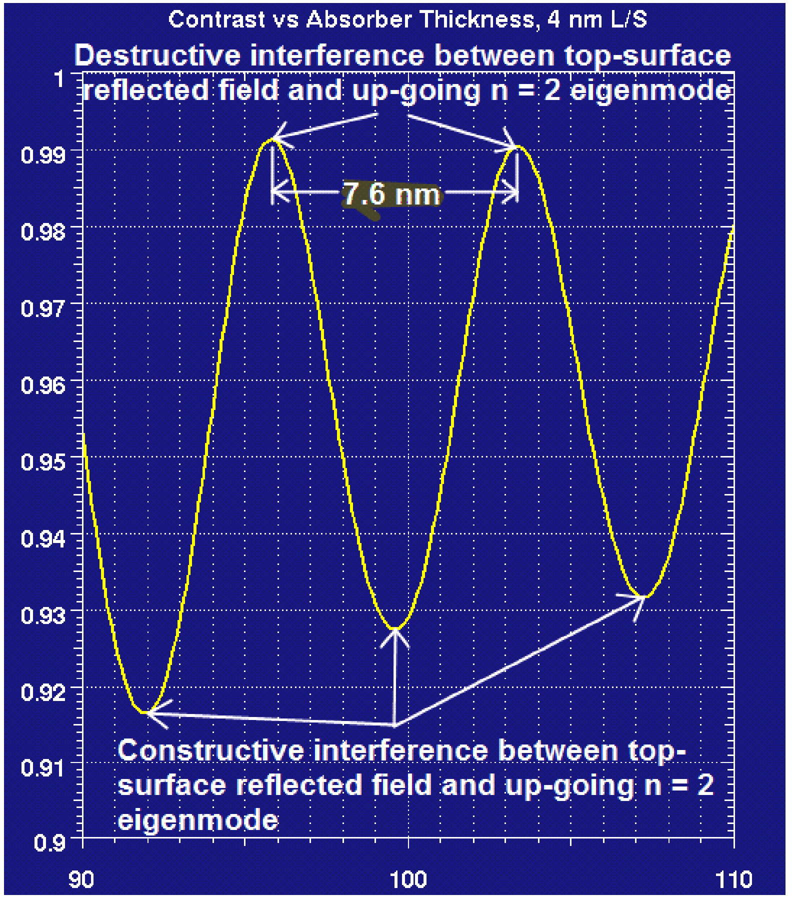
- At X = 24 nm, the n = 2 eigenmode field is approximately equal to and in phase with the top-surface reflected field, leading to a large value at the position of aerial-image minimum.

Top-surface fields , 4-nm L/S
Absorber thickness = 103.4 nm



- At X = 24 nm, the n = 2 eigenmode field is again approximately equal to but 180° out of phase with the top-surface reflected field, leading to almost zero at the position of aerial-image minimum.

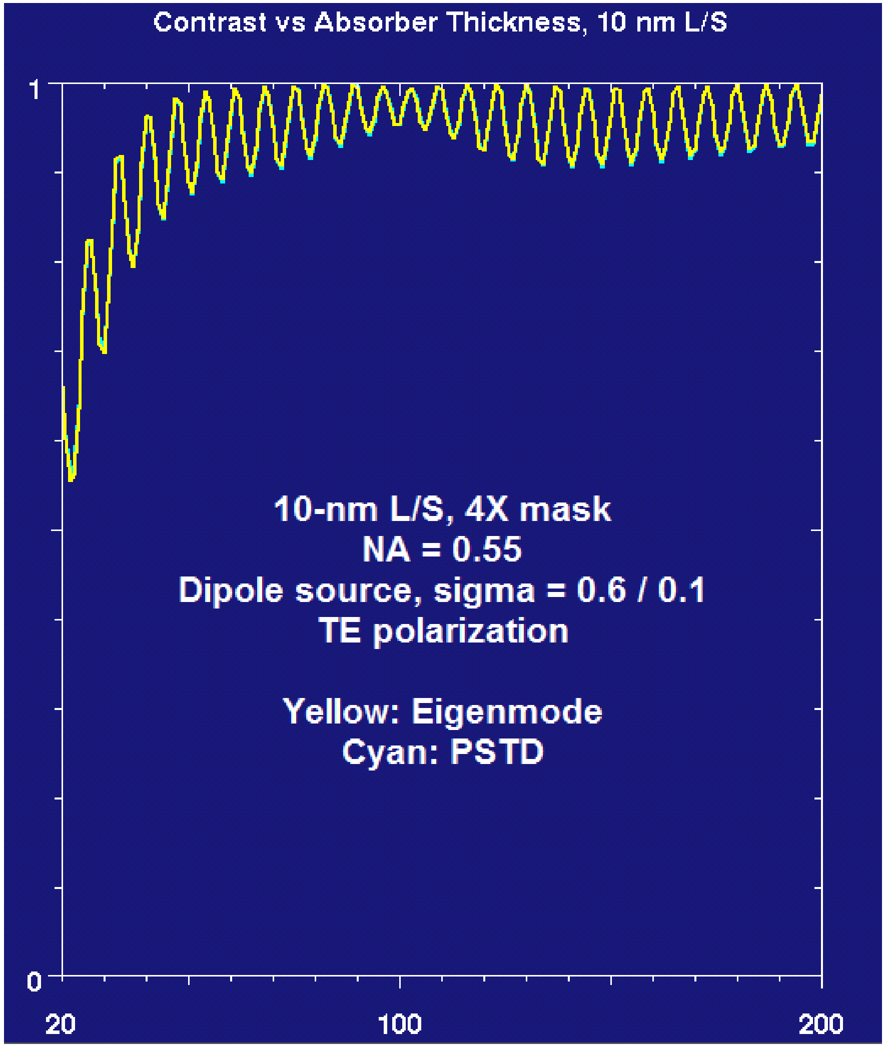
Dependence of contrast on absorber thickness , 4-nm L/S



- Standing-wave period in contrast curve is 7.6 nm
- This is equal to one-half of the wavelength of the n = 2 eigenmode (λ_2 = 15.2 nm)
- This is similar to a built-in attenuating PSM effect

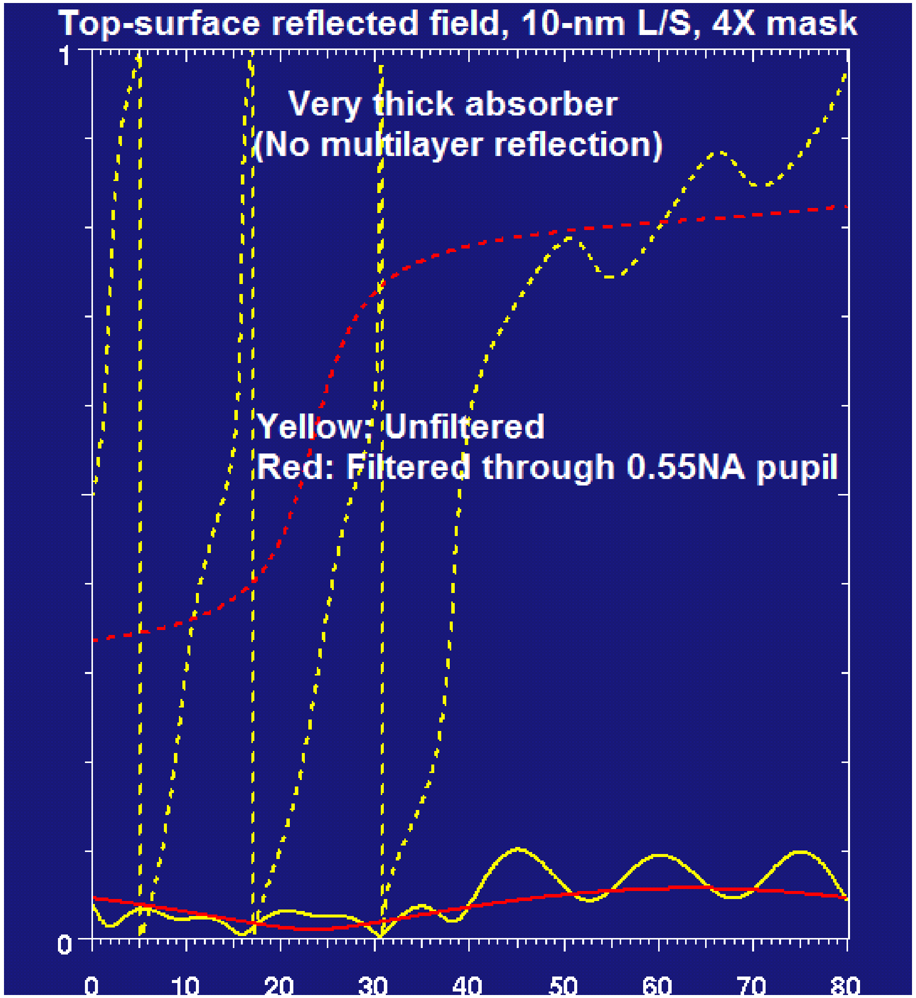
Dependence of aerial-image contrast on absorber thickness: 10-nm L/S, 4X mask, NA = 0.55

Dependence of contrast on absorber thickness: 10-nm L/S



Excellent agreement between PSTD and eigenmode results

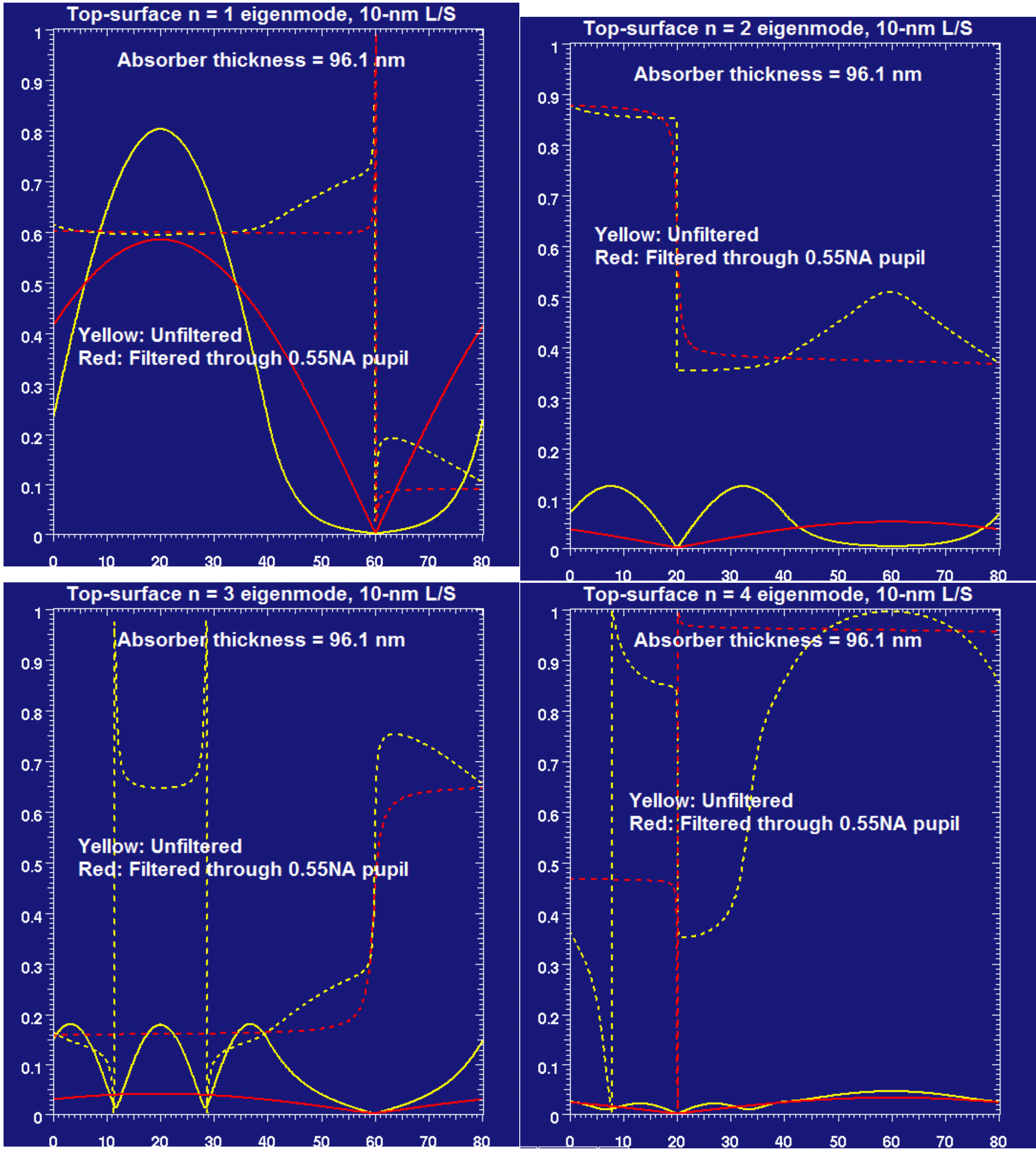
Top-surface reflected field, 10-nm L/S (in absence of multilayer reflection)



- Only the filtered field (red) goes through the 0.55NA pupil

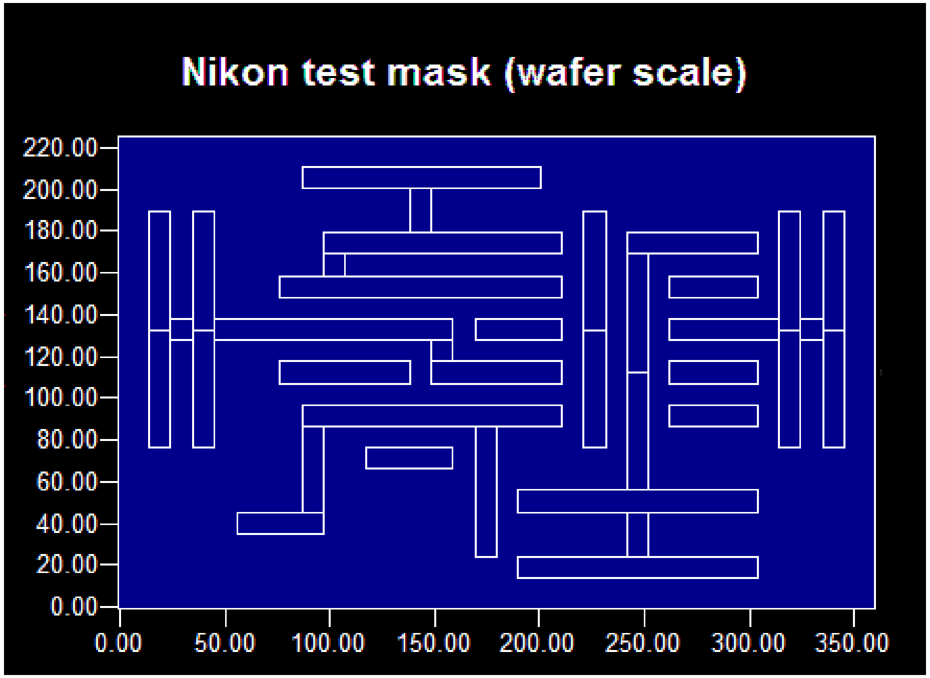
Top-surface eigenmodes 10-nm L/S Absorber thickness 96.1 nm

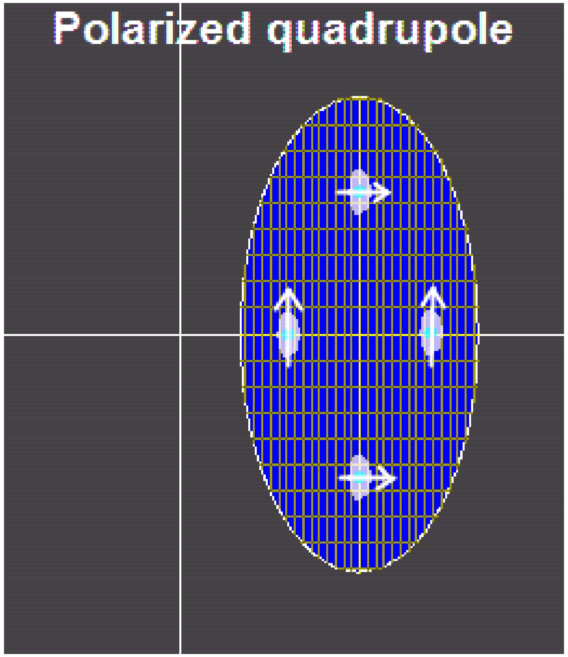
- Eigenmodes n = 1 and 3 contribute to the peak intensity
- Eigenmodes n = 2 and 4 contribute to the contrast
- As a result, standing-wave period in the contrast vs absorber-thickness curve is not simply related to the wavelength of any one eigenmode.



Attenuating PSM effect in complex 2D layout

Nikon test mask with 10-nm features

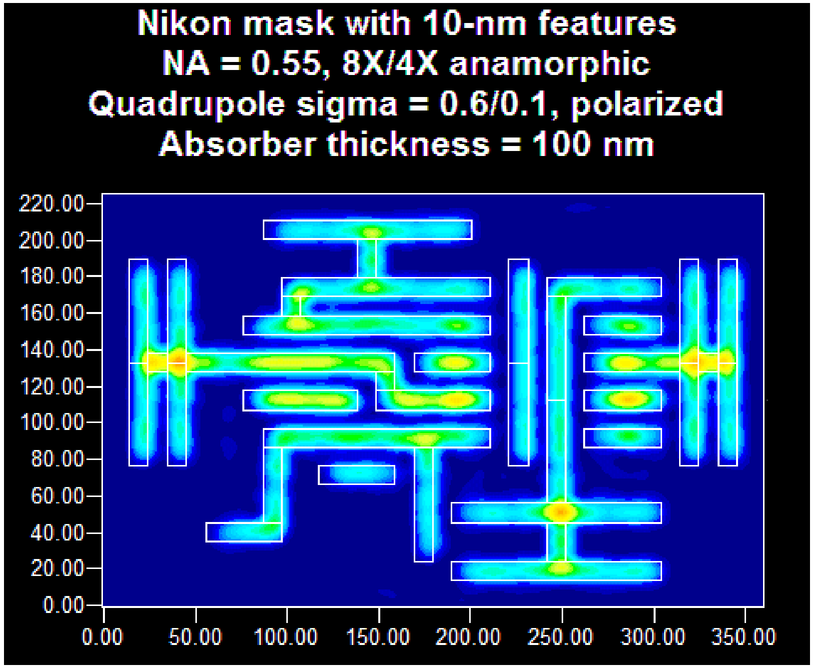


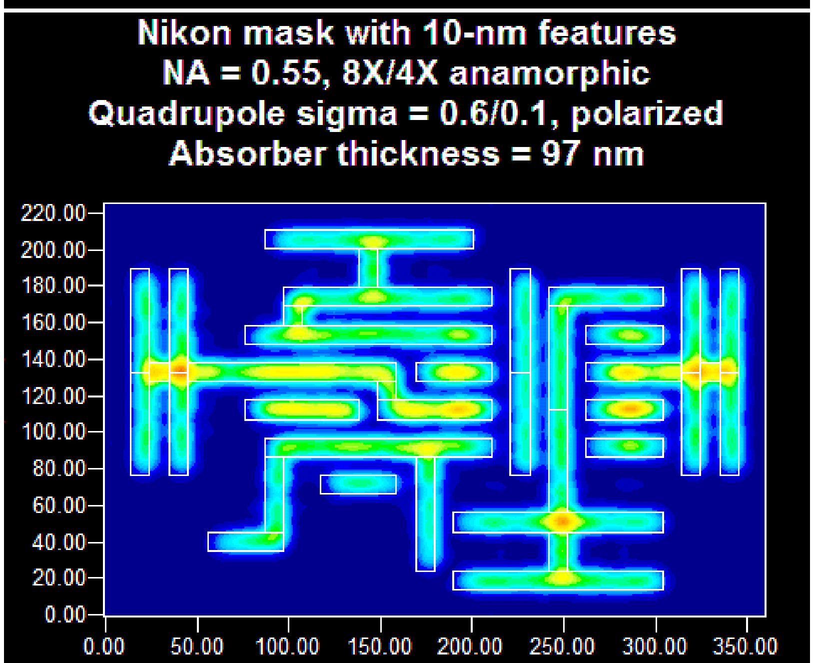


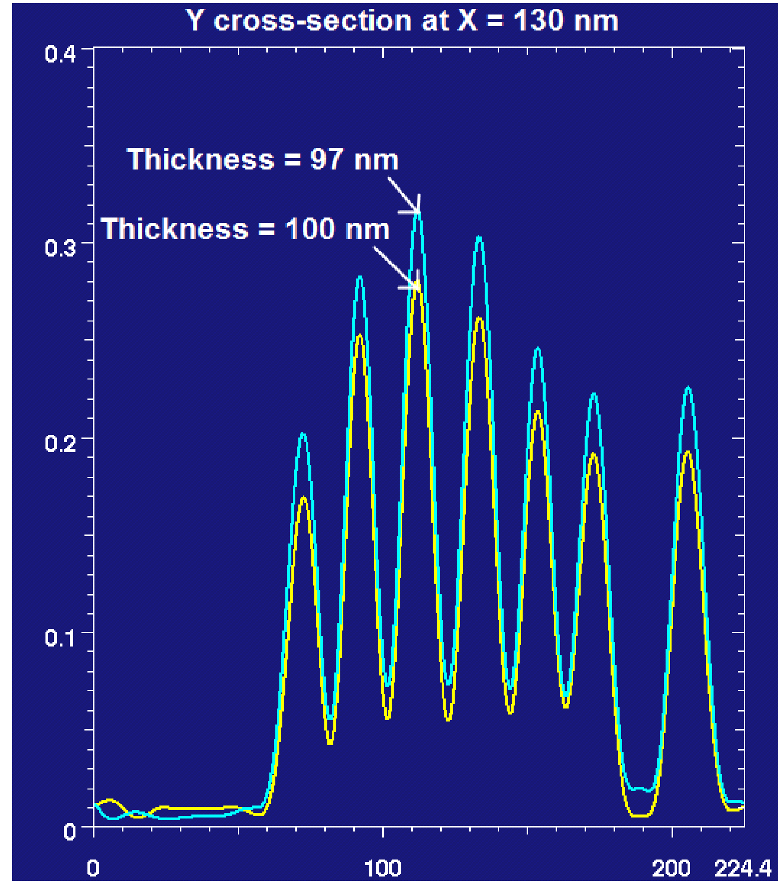
NA = 0.55, 8X/4X anamorphic optics, CRAO = 6°

Quadrupole source, sigma = 0.6/0.1, polarized or unpolarized

Effect of absorber thickness: 100 nm vs 97 nm

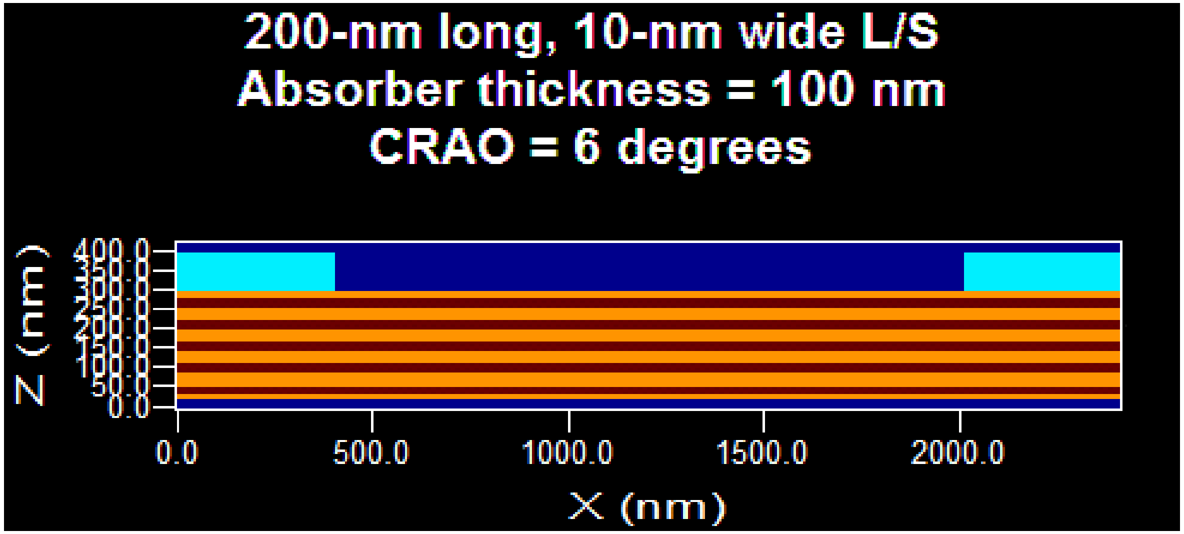


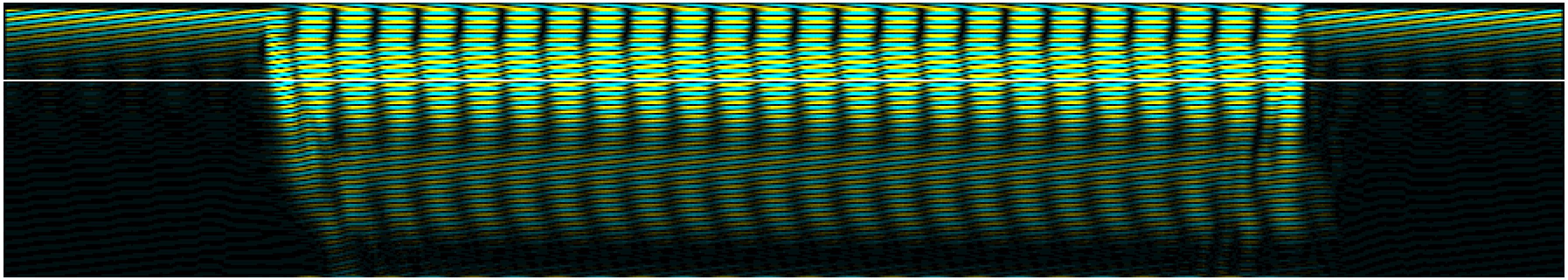




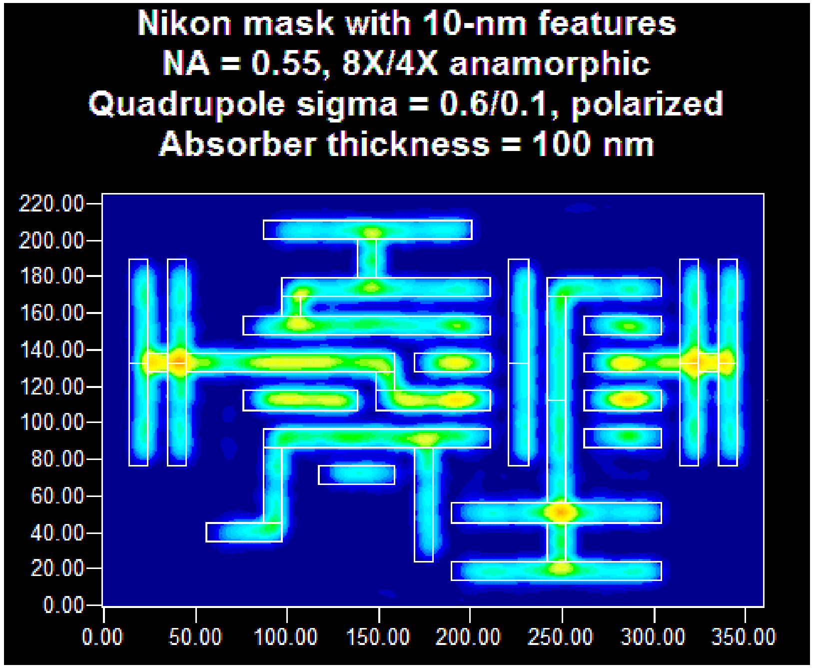
- The 97-nm result has more background flare than the 100-nm result.
- Shadowing and non-telecentricity are small in the transverse direction but large in the longitudinal direction.

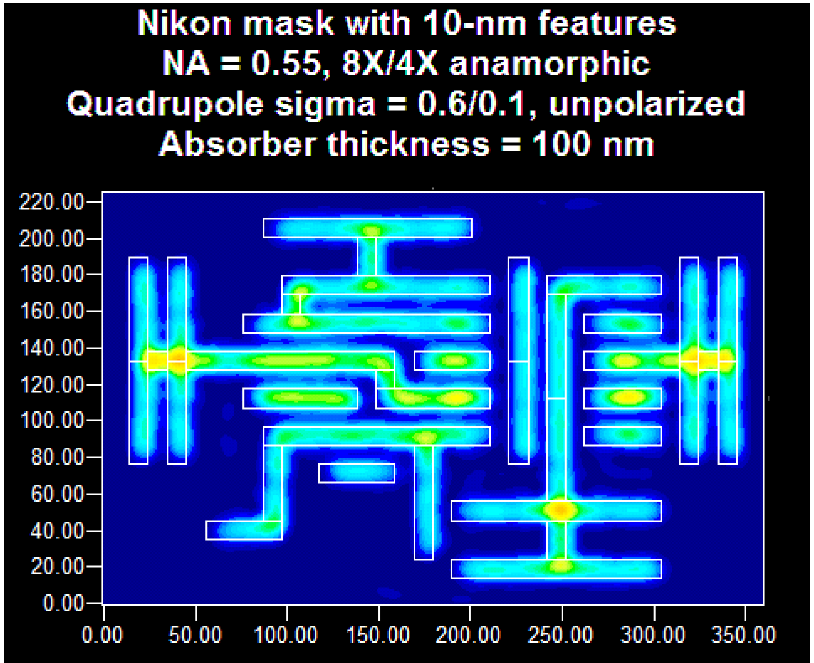
Shadowing and non-telecentricity effects in longitudinal direction, 10-nm L/S, CRAO = 6°

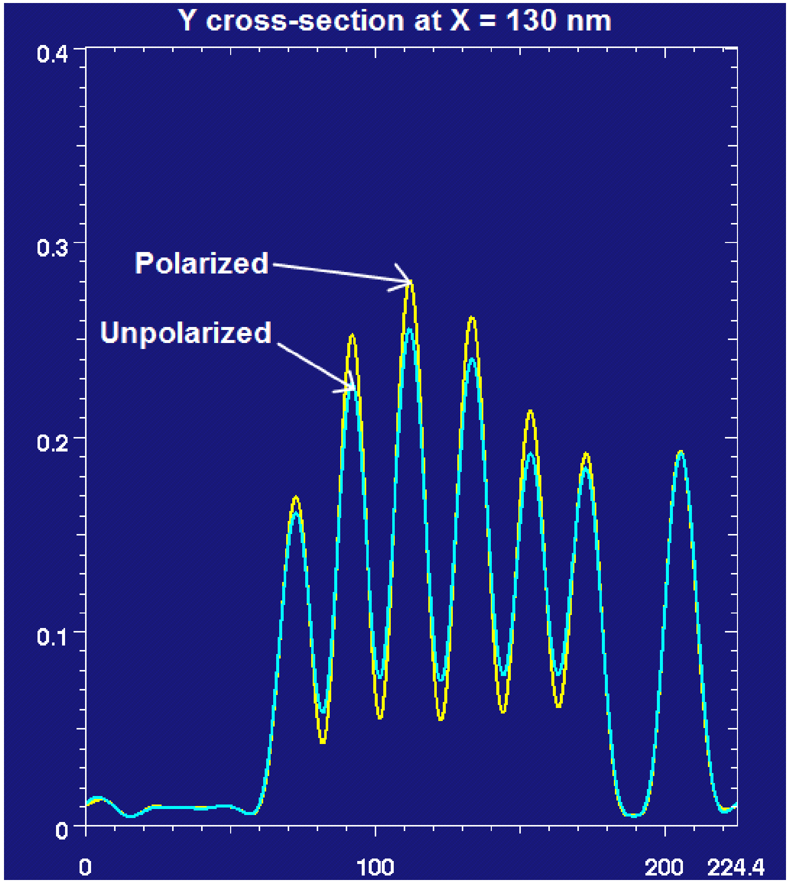




Effect of polarization: Polarized vs unpolarized







- The unpolarized result has less contrast than the polarized result.
- Again, shadowing and non-telecentricity are small in the transverse direction but large in the longitudinal direction.

Summary

- In 4X binary EUV mask for printing 4-nm and 10-nm L/S, there exist low-loss electromagnetic eigenmodes:
  – Vertical propagation in the mask structure greatly reduces shadowing and non-telecentricity effects, thus allowing the use of thick absorber layers.
- Standing-wave patterns in peak-intensity and contrast vs absorber-thickness curves are due to interference between various reflected eigenmodes with the top-surface reflected wave:
  – This is a built-in attenuating PSM effect in binary EUV masks.
  – Absorber thickness must be chosen carefully (e.g. by simulation) to obtain maximum aerial-image contrast.
- Moderately complicated 2D layouts with 10-nm features can be printed with EUV using NA = 0.55 and 8X/4X anamorphic optics:
  – Shadowing/non-telecentricy in the transverse direction are not an issue, but they are still an issue in the longitudinal direction.
  – Polarization may also be an issue for 10-nm features.