
Increasing the Reflectivity of Extreme Ultraviolet Multilayered Mirrors

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Introduction

- Computational study of reflectivity response of near-normal incidence multilayer mirrors in the 11-14 nm EUV spectral region
- Enhancement of R by
 1. Numerical optimization of the stack
 2. Incorporation of additional materials
 3. Optimal protective capping layer selection
- 30-100% optical throughput enhancement in a 9-mirror system

Numerical Methods - 1

- Characteristic matrix (TFCalc, Software Spectra Inc.)

M. Born and E. Wolf, *Principles of Optics*,
6th Ed. (Pergamon, Oxford, 1980), pp. 55-70

$$M = \prod_j \begin{pmatrix} \cos \delta_j & i\eta_j \sin \delta_j \\ i \sin \delta_j / \eta_j & \cos \delta_j \end{pmatrix}$$

$$\delta = 2\pi N_j d_j \cos \theta_j / \lambda \quad (\text{phase thickness})$$

$$\eta_j \quad (\text{admittance})$$

Numerical Methods - 2

- 4×4-matrix formulation (LPro, 4D Technology Ltd.)
D.W. Berreman, J. Opt. Soc. Am. **62**, 502-510 (1972)
- Recursive Fresnel formulae (CXRO Web site)
V.G. Kohn, Phys. Stat. Sol. (B) **187**, 61 (1995); http://www-cxro.lbl.gov/optical_constants/multi2.html
- Optical constants ($N=n-ik$):
B.L. Henke, E.M. Gullikson, and J.C. Davis, At. Data Nucl. Data Tables **54**, 181-342 (1993); http://www-cxro.lbl.gov/optical_constants

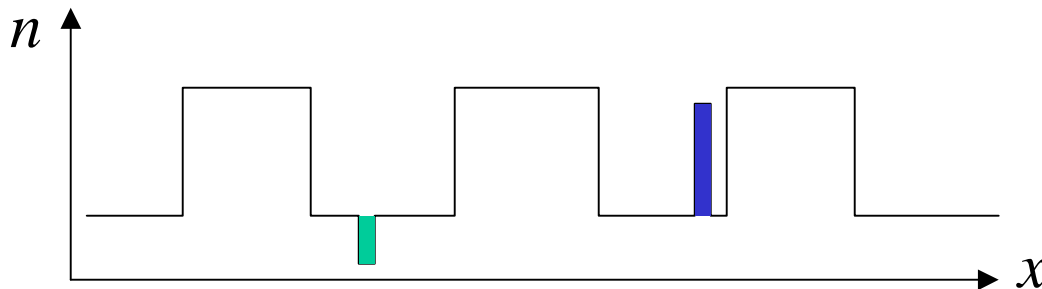
Optimization

- Based on principles of optimal control theory
- Merit (objective) function minimization in a multi-dimensional parameter space

- Targets: $R(\lambda_1 \dots \lambda_n)$;
constraints: $n(\lambda), k(\lambda)$

$$F = \left[\frac{1}{m} \sum_{j=1}^m \left(\frac{R(\lambda_j) - \tilde{R}_j}{\delta R_j} \right)^2 \right]^{1/2}$$

- Further minimization of F requires additional design variables - add layers: *Needle* optimization

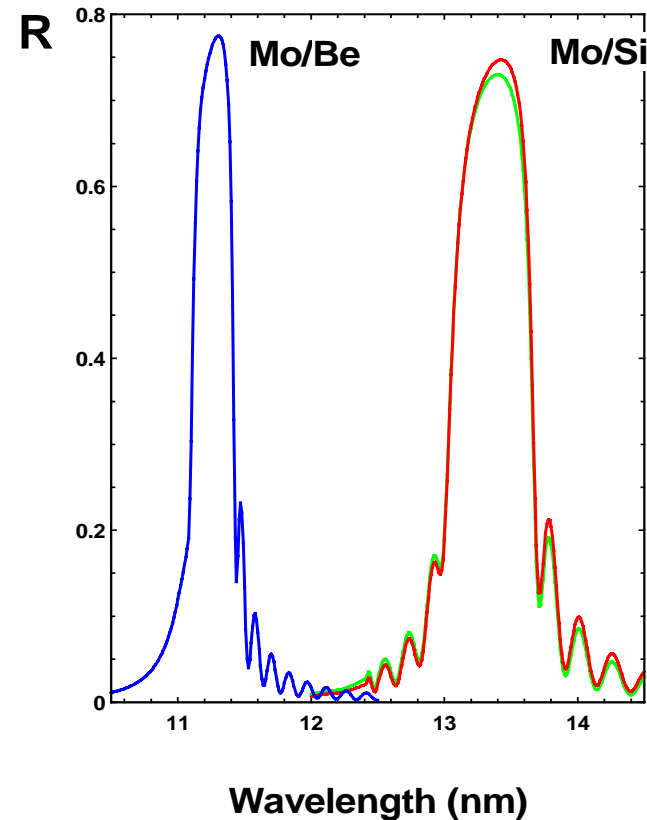


High R normal incidence EUV Mirrors

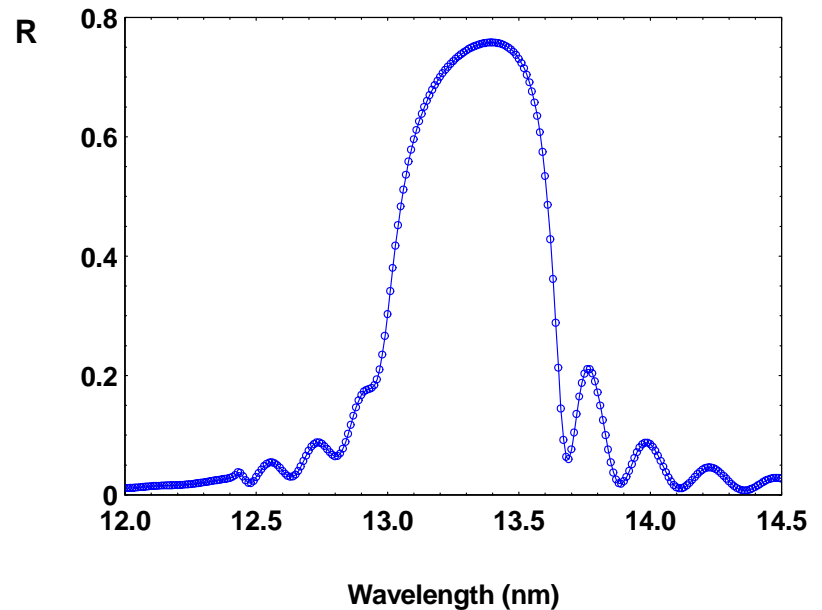
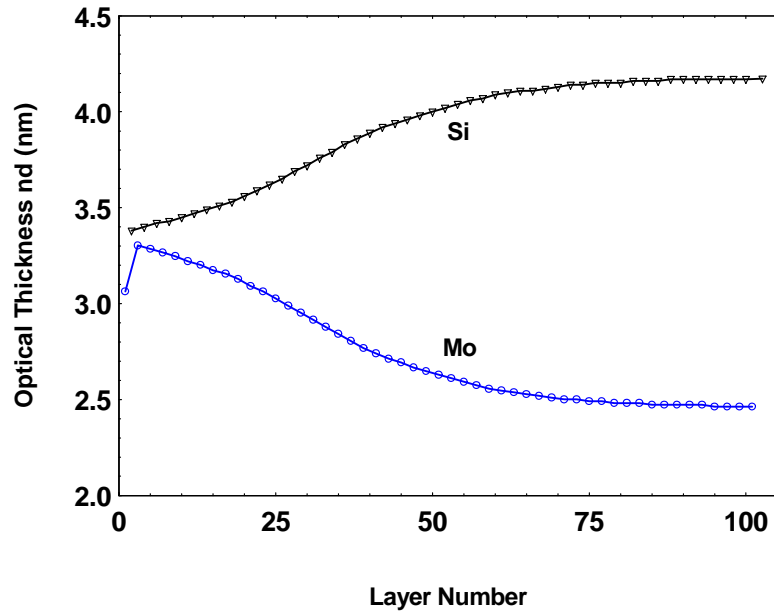
- Mo/Be 80 periods (11.3 nm)
- Mo/Si 50 periods (13.4 nm)
- Constant partition ratio Γ :

$$\Gamma = \frac{d_{Mo}}{d_{Mo} + d_{Si/Be}} = 0.4$$

- $R(\text{peak}) = 0.775$ - Mo/Be
- $R(\text{peak}) = 0.747$ - Mo/Si
- $R(\text{peak}) = 0.730$ - Mo/Si
(2nm SiO₂ cap)

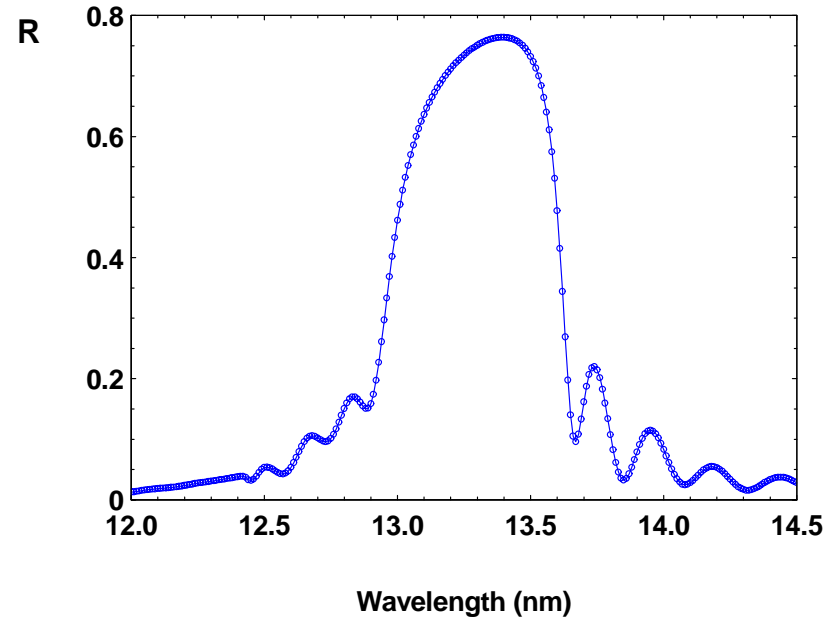
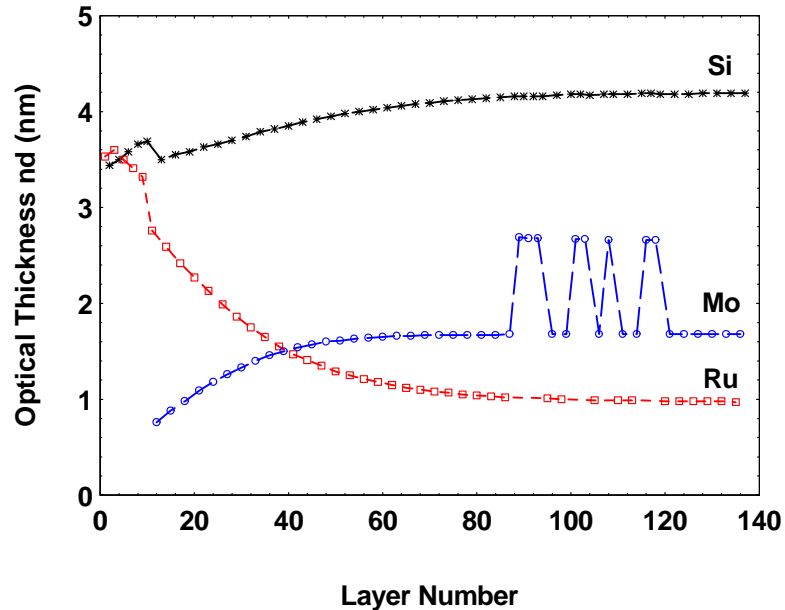


Mo/Si - optimized



- Peak $R = 0.758$; FWHM = 0.61 nm
- 1.7 nm Ru capping layer (B, Rh, ...)

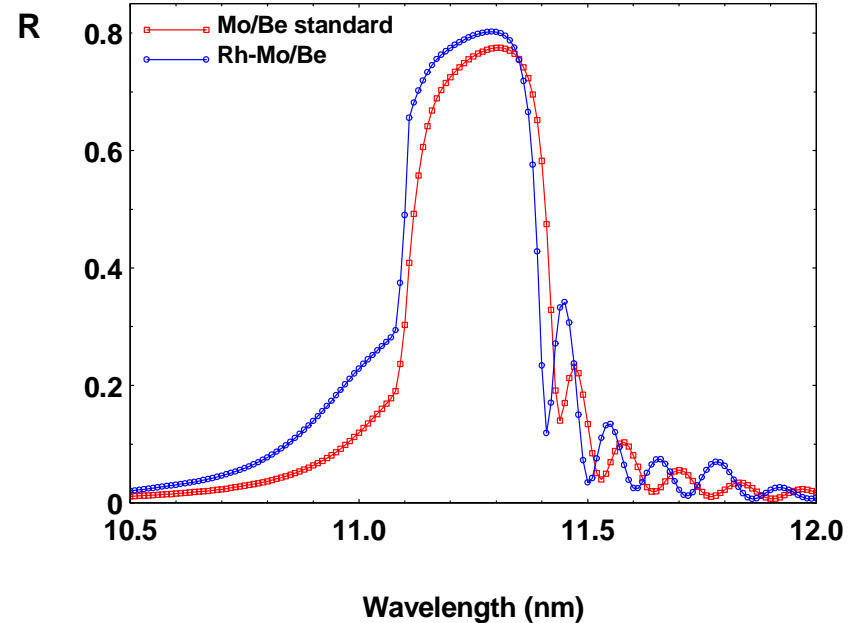
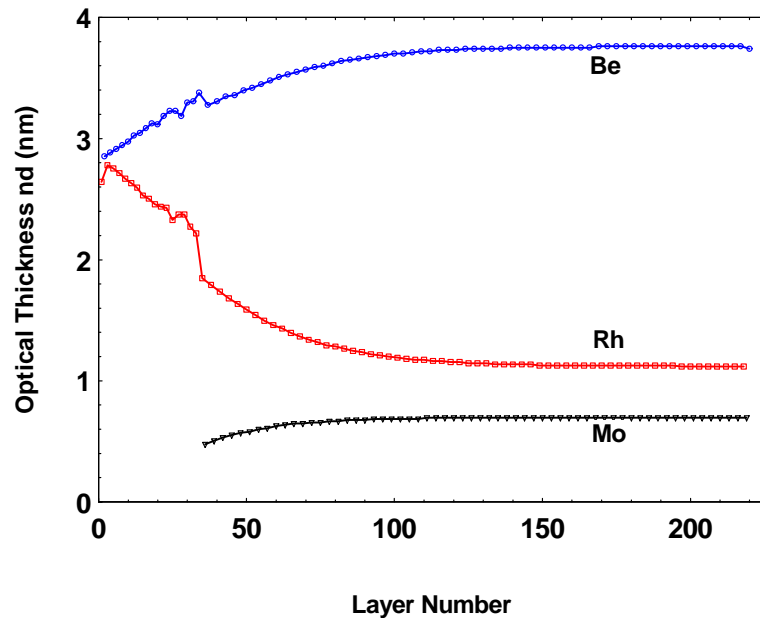
Ru-Mo/Si



- Peak $R = 0.764$; FWHM = 0.64 nm
- 1.7 nm Ru capping layer

	13.4 nm	
	n	k
Mo	0.9227	0.0062
Ru	0.8898	0.0165
Si	0.9999	0.0018

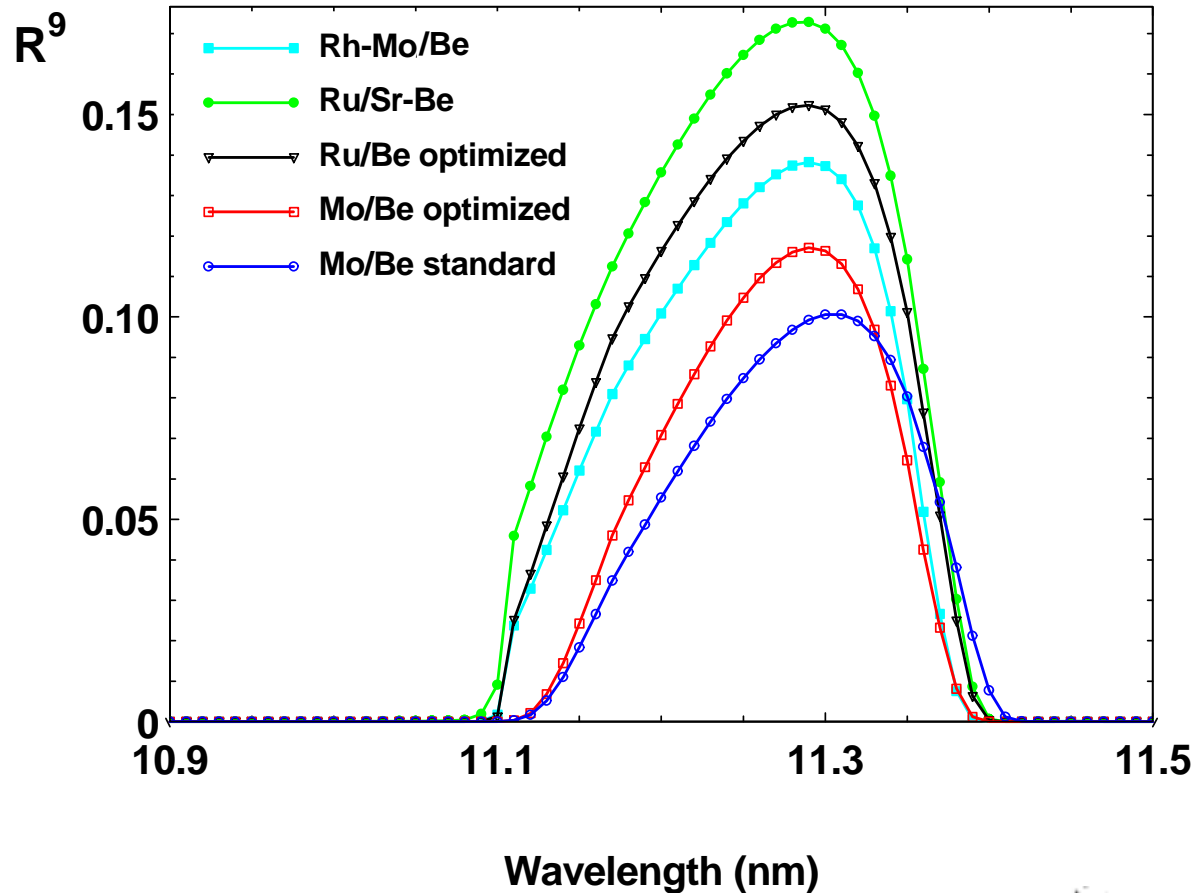
Rh-Mo/Be



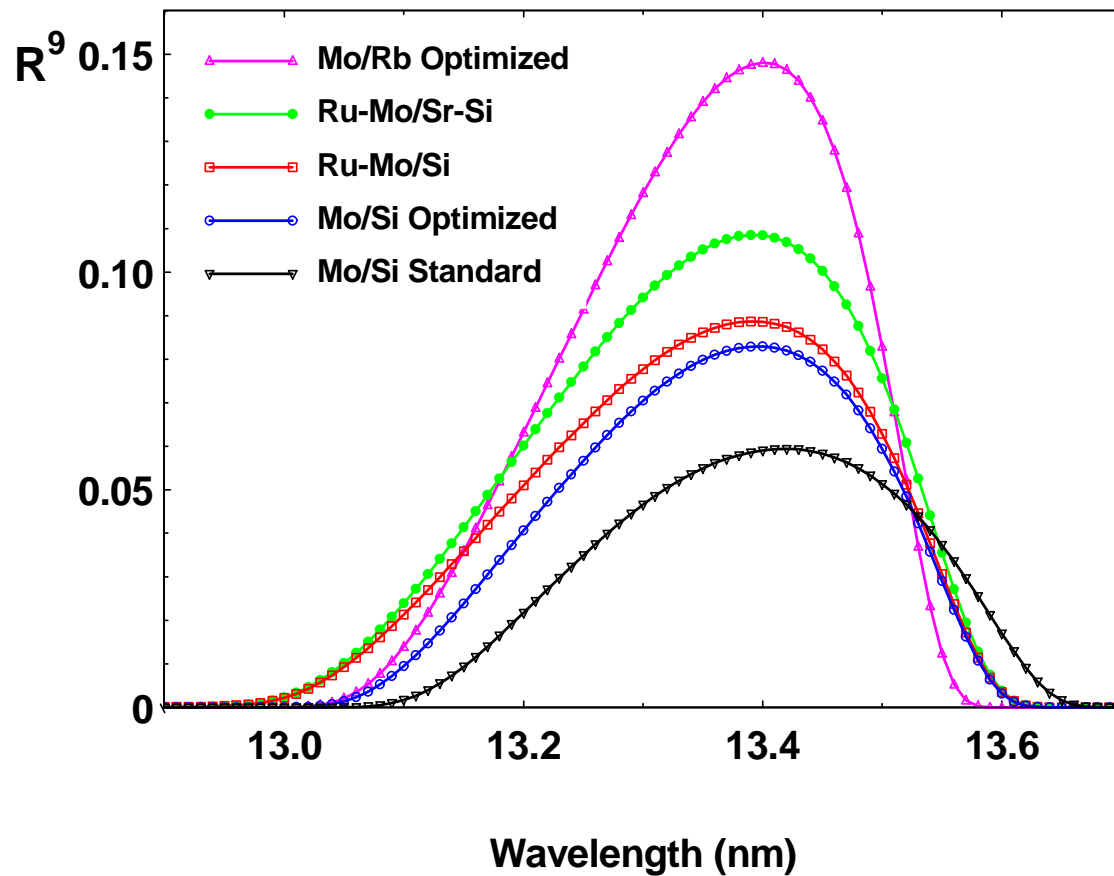
- Peak $R = 0.802$; FWHM = 0.30 nm
- 1.5 nm Rh capping layer

	11.3 nm	
	n	k
Be	1.0081	0.0010
Mo	0.9514	0.0046
Rh	0.9236	0.0089

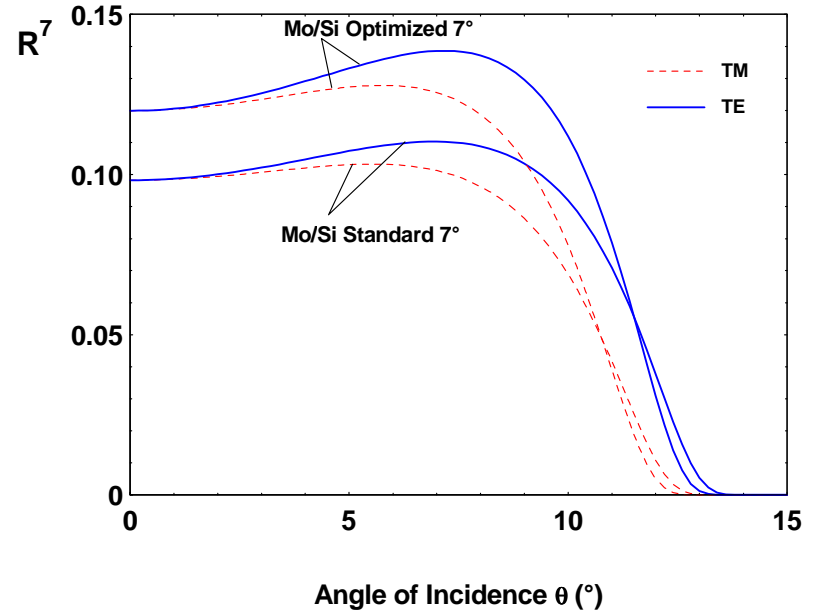
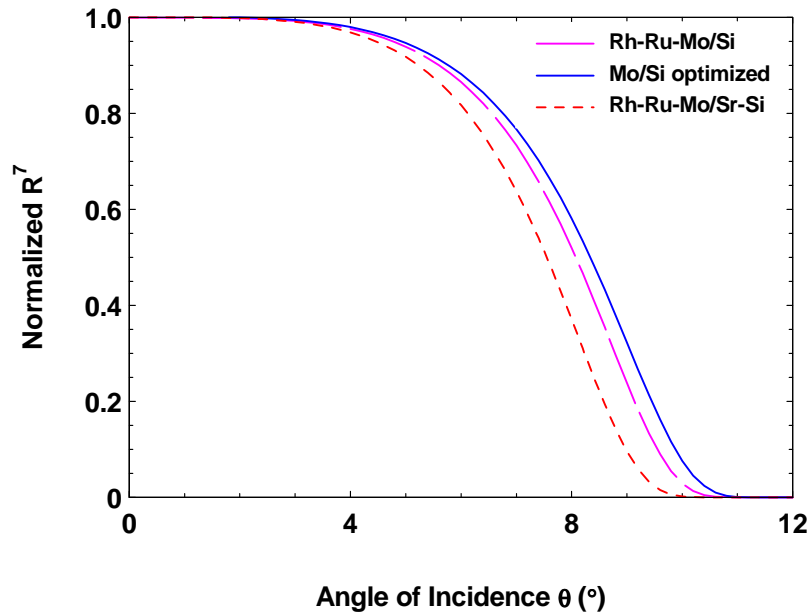
9-mirror spectral response (11.3 nm)



9-mirror spectral response (13.4 nm)

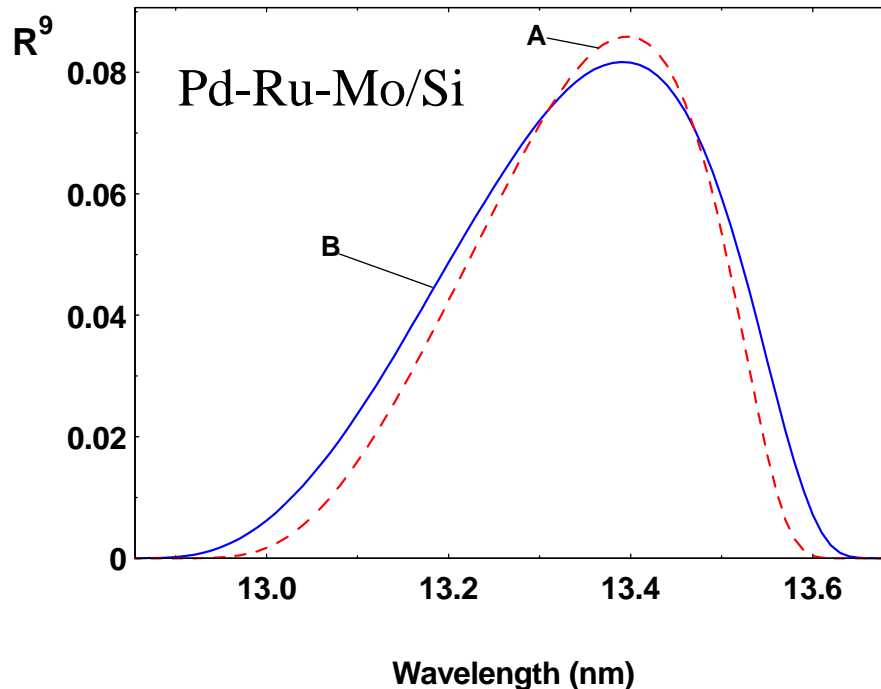


Angular response



- Angular bandwidth (2θ) is 0.4 - 1.3° lower for multi-component stacks but effective throughput is higher due to increased R

Spectral broadening



11% increase in integrated R^9

- (A) Single reflectivity target: 13.4 nm - FWHM = 0.31 nm
- (B) Reflectivity targets: 13.1, 13.25, 13.4, 13.5, 13.57 nm
FWHM = 0.37 nm

Si and Rb-based 50-period stacks

$\lambda = 13.4 \text{ nm}$

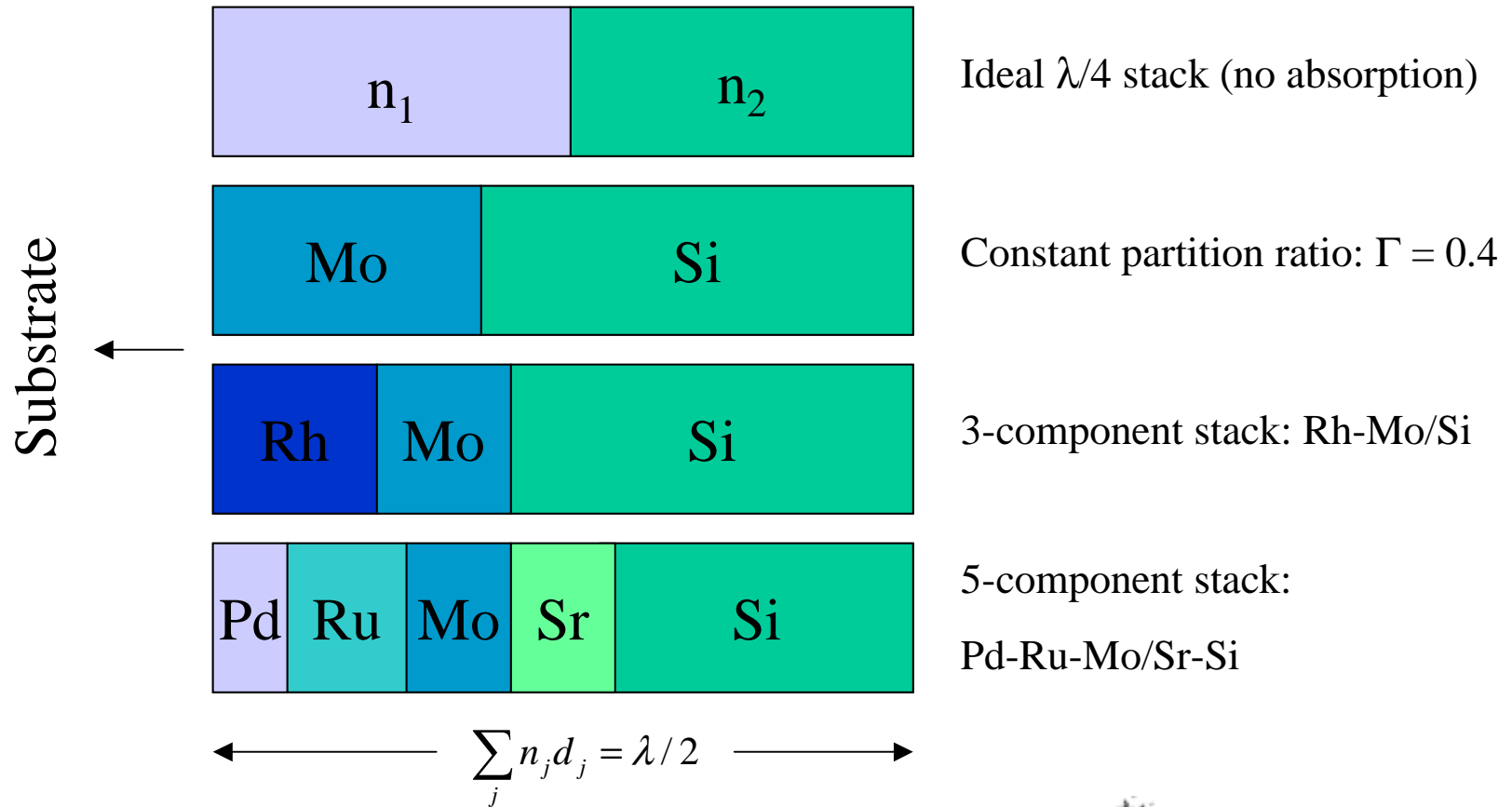
	Optimized	Capping Layer	Peak Reflectivity (R)	R ^o (Peak) Rel. Units	R ^o (Integ.) Rel. Units
Mo/Si	No	2nm Si + 2nm SiO ₂	0.731	1.00	1.00
Mo/Si	No	2nm SiO ₂	0.741	1.13	1.07
Mo/Si	No	2nm B	0.751	1.27	1.25
Mo/Si	Yes	2nm B	0.752	1.29	1.26
Mo/Si	No	1.5nm Ru	0.757	1.37	1.35
Mo/Si	Yes	1.7nm Ru	0.758	1.39	1.36
Rh-Mo/Si	Yes	1.7nm Ru	0.762	1.45	1.38
Mo/RbCl-Si	Yes	1.5nm Ru	0.761	1.44	1.39
Ru-Mo/Si	Yes	1.5nm Rh	0.760	1.42	1.41
Ru-Mo/Si	Yes	1.7nm Ru	0.765	1.51	1.50
Ru-Mo/Si	Yes(Needle)	1.5nm Ru	0.764	1.48	1.59
Rh-Mo/RbCl-Si	Yes	1.7nm Ru	0.764	1.49	1.38
Pd-Ru-Mo/Si	Yes	1.5nm Rh	0.761	1.44	1.39
Ru-Mo/RbCl-Si	Yes	1.5nm Ru	0.767	1.54	1.56
Rh-Mo/Sr-Si	Yes	1.6nm Ru	0.779	1.77	1.56
Ru-Mo/Sr-Si	Yes	1.5nm Ru	0.781	1.81	1.68
Ru-Mo/Sr-Si	Yes(Needle)	1.5nm Ru	0.781	1.81	1.88
Ru/Rb	Yes	1.5nm Ru	0.779	1.77	1.41
Mo/Rb	Yes	1.5nm Ru	0.809	2.49	2.13
Ru-Mo/Sr-Rb	Yes	1.5nm Ru	0.814	2.63	2.20

Be-based 80-period stacks

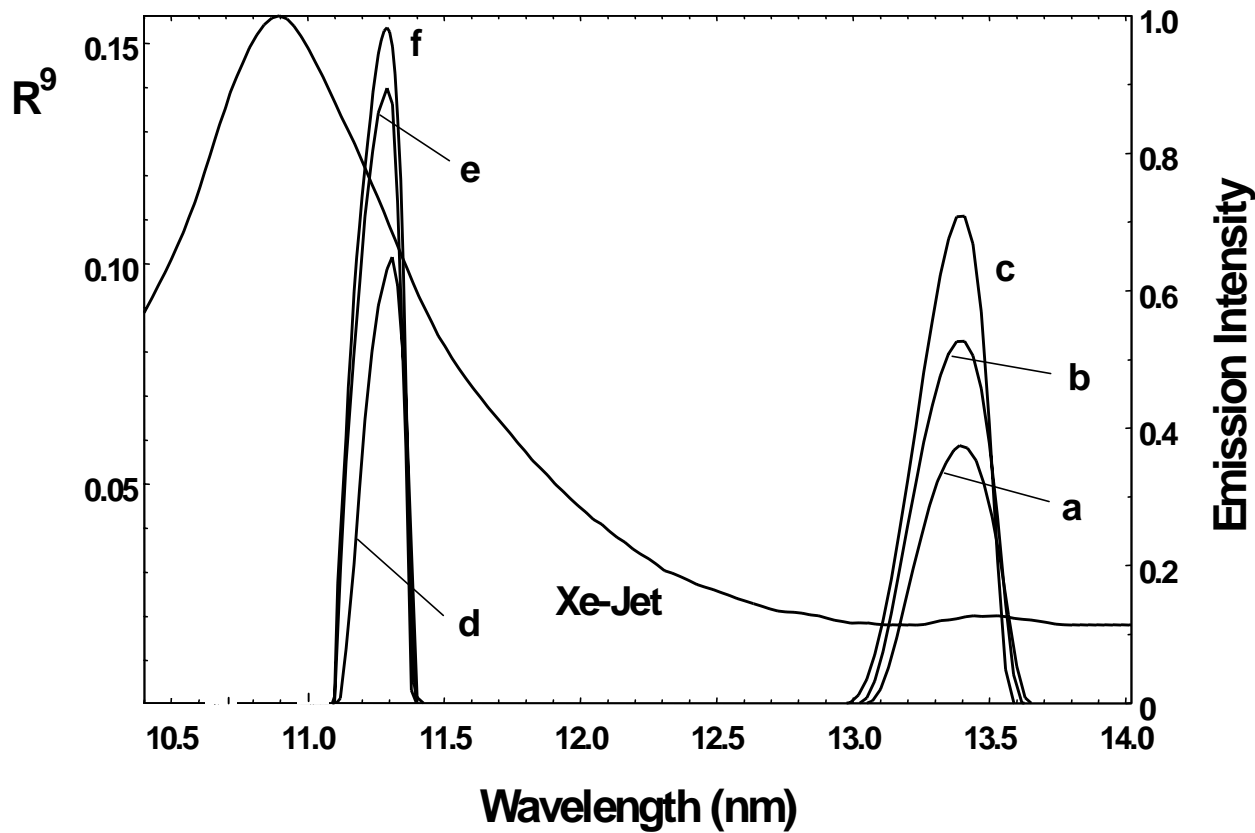
$\lambda = 11.3 \text{ nm}$

	Optimized	Capping Layer	Peak Reflectivity (R)	R ^o (Peak) Rel. Units	R ^o (Integrated) Rel. Units
Mo/Be	No	None	0.775	1.00	1.00
Mo/Be	No	1.5nm Rh	0.782	1.08	1.08
Mo/Be	Yes	None	0.780	1.06	1.00
Mo/Be	Yes	1.5nm Ru	0.788	1.16	1.08
Ru/Be	Yes	1.5nm Rh	0.810	1.49	1.68
Ru/Be	Yes	1.5nm Ru	0.811	1.50	1.70
Rh/Be	No	1.5nm Rh	0.783	1.10	1.33
Rh/Be	Yes	1.5nm Rh	0.793	1.23	1.29
Rh/Be	Yes (Needle)	1.5nm Rh	0.811	1.50	1.77
Mo/Sr-Be	Yes	1.5nm Rh	0.799	1.32	1.21
Ru/Sr-Be	Yes	1.5nm Ru	0.823	1.72	2.00
Rh/Sr-Be	Yes	1.5nm Rh	0.810	1.49	1.64
Rh/Sr-Be	Yes	1.5nm Ru	0.811	1.50	1.67
Rh-Mo/Be	Yes	1.5nm Rh	0.803	1.37	1.47
Ru-Mo/Be	Yes (Needle)	1.5nm Ru	0.812	1.52	1.72

Structure of multi-component Bragg reflectors



Xenon-jet laser-induced plasma source



	Stack	λ (nm)	Relative throughput
a	Mo/Si (Unopt.)	13.4	1.0
b	Mo/Si (Opt.)	13.4	1.4
c	Rh-Ru-Mo/Sr-Si	13.4	1.7
d	Mo/Be (Unopt.)	11.3	5.7
e	Rh-Mo/Be	11.3	8.5
f	Pd-Rh-Ru-Mo/Be	11.3	9.5

Conclusions

- Optimized, multi-component stacks will yield enhanced reflectivity
- Choice of capping layer important - surface oxides must be avoided
- 30-100% increase in throughput in a 9-mirror system
- Fabrication of optimized Mo/Si stack, and deposition of non-standard materials should be investigated