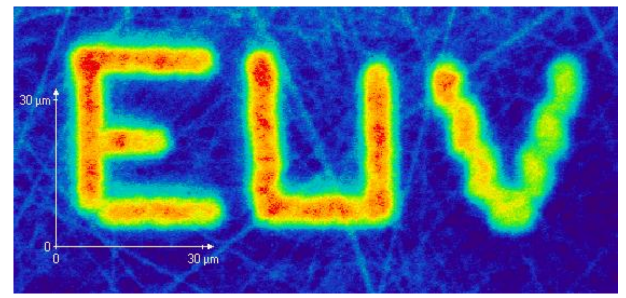

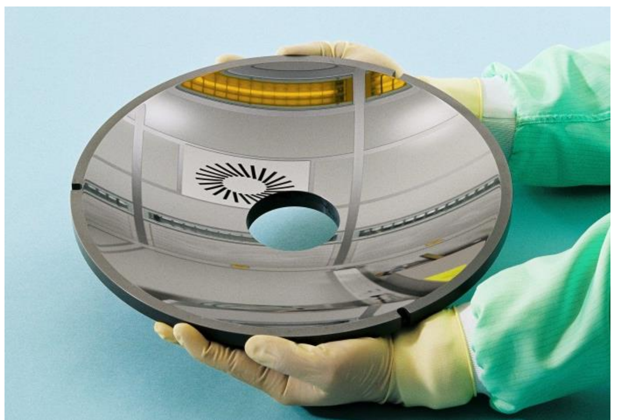

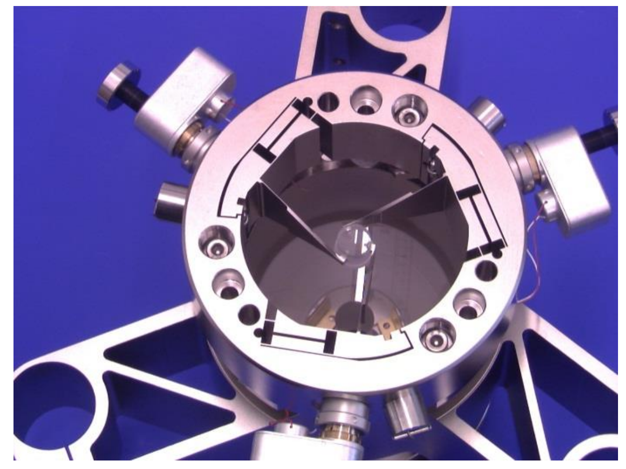

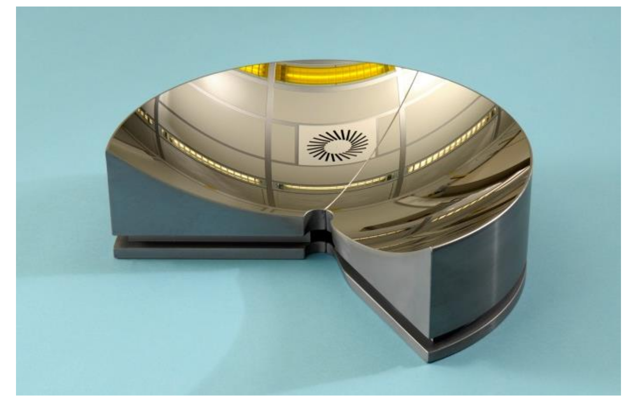

Multilayer EUV optics with integrated IR suppression gratings

Torsten Feigl, Marco Perske, Hagen Pauer, Tobias Fiedler
optiX fab GmbH

Uwe Zeitner, Robert Leitel, Hans-Christoph Eckstein, Philipp Schleicher, Sven Schröder, Marcus Trost, Stefan Risse, Ralf Steinkopf
Fraunhofer IOF

Christian Laubis, Frank Scholze
PTB Berlin

Berkeley, June 15, 2016

Outline

- Introduction
- EUV multilayer optics activities
- How to integrate IR suppression gratings into EUV multilayers
- Summary

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History of optiX fab.

1997: Start of EUV multilayer development @ Fraunhofer IOF

2000: First paper at SPIE “Microlithography” on Mo/Si multilayer mirrors

2002: Start of cooperation with semiconductor industry:

ASML, Cymer, Intel, Jenoptik, Schott Lithotec, Zeiss, etc.

2009: Coating of first NXE:3100 collector mirror

2011: Development of collector refurbishment technologies

History of optiX fab.

1997:	Start of EUV multilayer development @ Fraunhofer IOF
2000:	First paper at SPIE “Microlithography” on Mo/Si multilayer mirrors
2002:	Start of cooperation with semiconductor industry:
	ASML, Cymer, Intel, Jenoptik, Schott Lithotec, Zeiss, etc.
2009:	Coating of first NXE:3100 collector mirror
2011:	Development of collector refurbishment technologies

2012:	Foundation of Fraunhofer IOF spin-off company **optiX fab.**
2013:	August 1st: Operations start @ **optiX fab.**
June 2016:	Delivery of **4191 EUV and X-ray mirrors** to customers

optiX fab. organization

- Mission: Fabrication of customized EUV optics and optical components for EUV lithography @ 13.5 nm, for EUV, soft and hard X-ray applications, synchrotron and FEL beamlines, metrology, R&D, HHG sources, etc.
- Address: optiX fab GmbH
  Hans-Knöll-Str. 6
  D - 07745 Jena
- URL: www.optixfab.com
- Team:

Torsten Feigl

Marco Perske

Hagen Pauer

Tobias Fiedler

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Multilayers for 13.5 nm

Reflectance

80%
70%
60%
50%
40%
30%
20%
10%
0%

12.8 12.9 13 13.1 13.2 13.3 13.4 13.5 13.6 13.7 13.8 13.9 14 14.1 14.2

Wavelength, nm

R = 70.12 %

λ = 13.48 nm

FWHM = 0.528 nm

AOI = 5 deg.

Measured @PTB Berlin

Broadband Multilayers for 12.5 … 16.0 nm

Reflectance, %

25
20
15
10
5
0

10 11 12 13 14 15 16 17 18

Wavelength, nm

R ~ 20 %

λ = 12.5 … 16.0 nm

FWHM = 3.86 nm

AOI = 30 deg.

Measured @PTB Berlin

Beamsplitters for 13.5 nm

Reflectance, Transmittance, %

40
30
20
10
0

11.5 12.5 13.5 14.5 15.5

Wavelength, nm

R
T

R = 29.0 %

T = 21.5 %

λ = 13.5 nm

AOI = 45 deg.

Measured @PTB Berlin

Multilayers for the water window

Reflectivity in water window region (s-pol @ **AOI = 1.5deg**)

Reflectivity

20.00%
18.00%
16.00%
14.00%
12.00%
10.00%
8.00%
6.00%
4.00%
2.00%
0.00%

2.40 2.41 2.42 2.43 2.44 2.45 2.46 2.47 2.48 2.49 2.50

Wavelength, nm

Measured
@PTB Berlin

Multilayers for 8 … 12 nm

Reflectance, %

50
40
30
20
10
0

7.5 8.0 8.5 9.0 9.5 10.0 10.5 11.0 11.5 12.0 12.5 13.0

Wavelength, nm

Wavelength	AOI	Reflectance	FWHM
8.0 nm	5 deg	32.2 %	0.08 nm
9.0 nm	5 deg	36.0 %	0.11 nm
10.0 nm	5 deg	39.9 %	0.15 nm
11.0 nm	5 deg	46.3 %	0.23 nm
12.0 nm	5 deg	49.1 %	0.33 nm

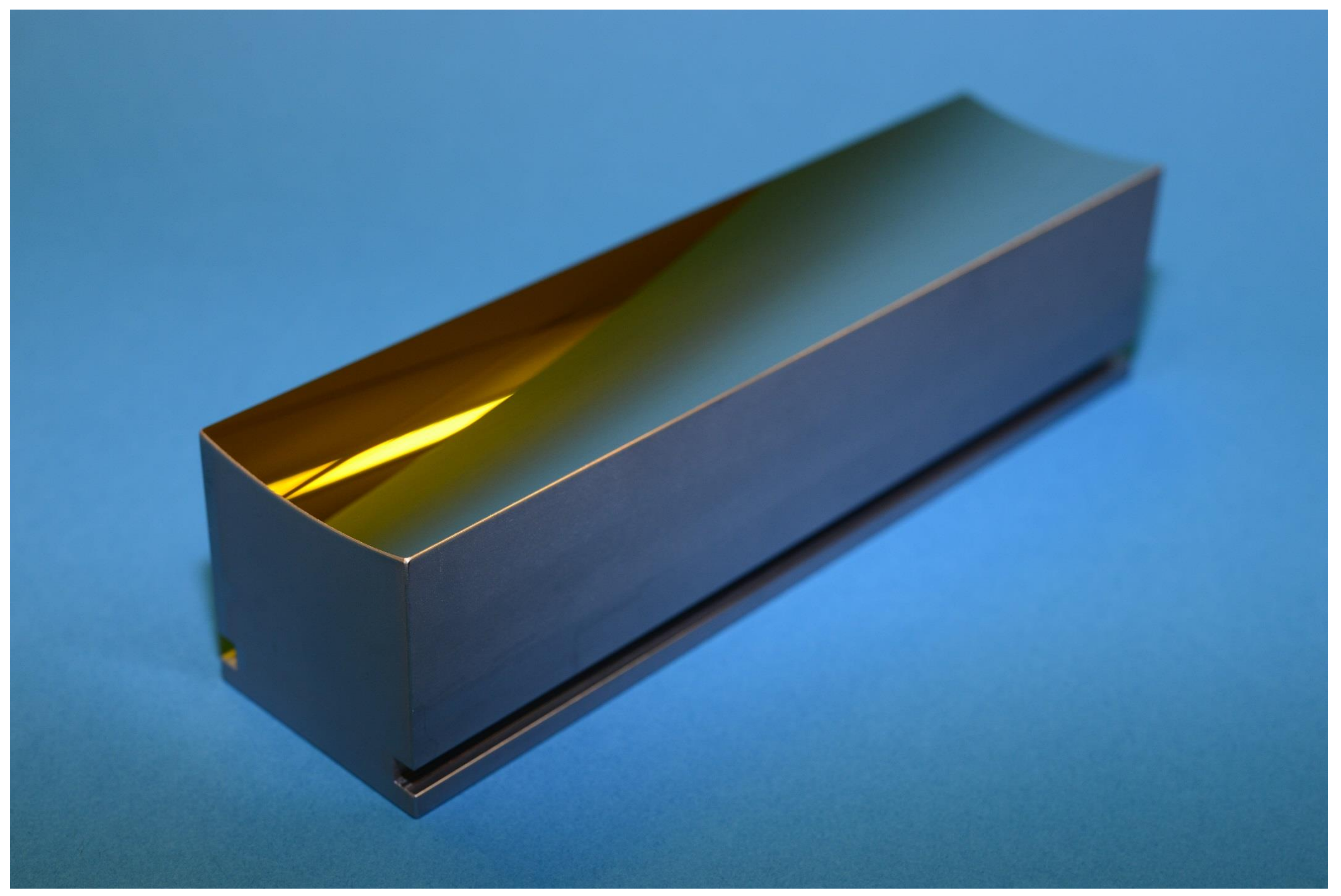
Measured
@PTB Berlin

Narrowband Multilayers for 30 … 38 nm

Wavelength	AOI	Reflectance	FWHM	ML Design
30.0 nm	5 deg	36.1 %	2.17 nm	
30.0 nm	15 deg	11.5 %	0.60 nm	narrow band
37.9 nm	15 deg	36.7 %	3.28 nm	
38.0 nm	15 deg	7.4 %	0.86 nm	narrow band

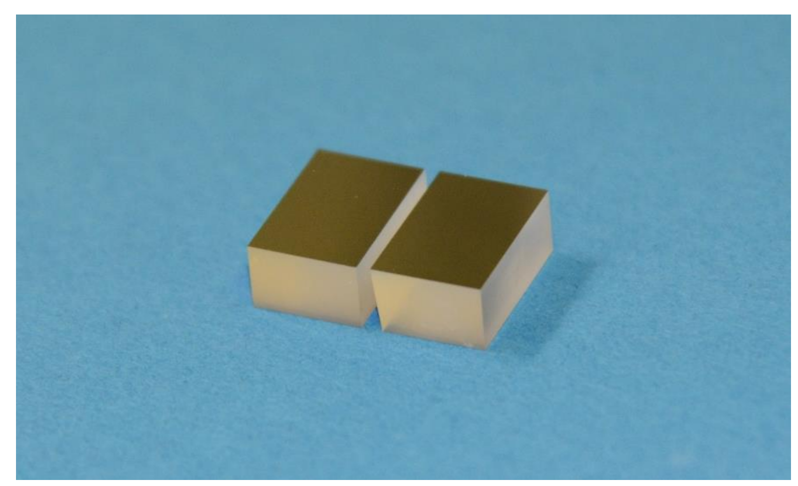
Measured
@PTB Berlin

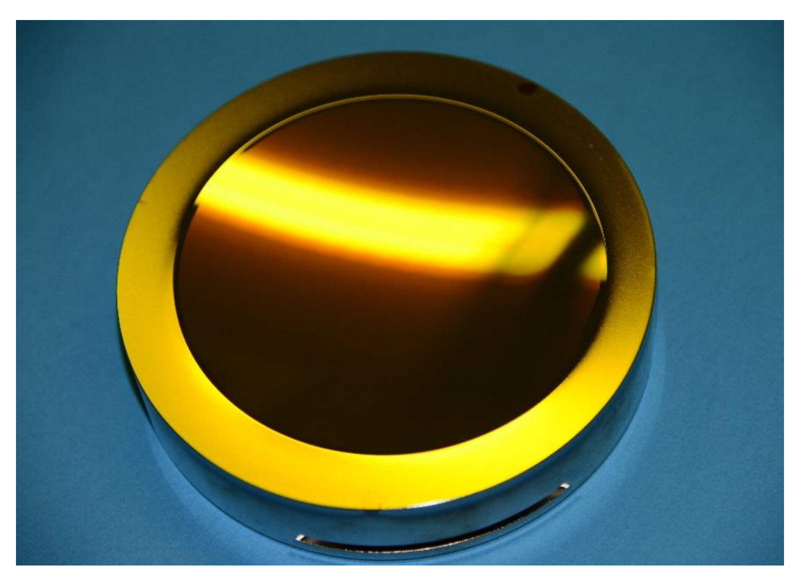
Gold coated synchrotron optics



optiX fab.

EUV optics – made by optiX fab





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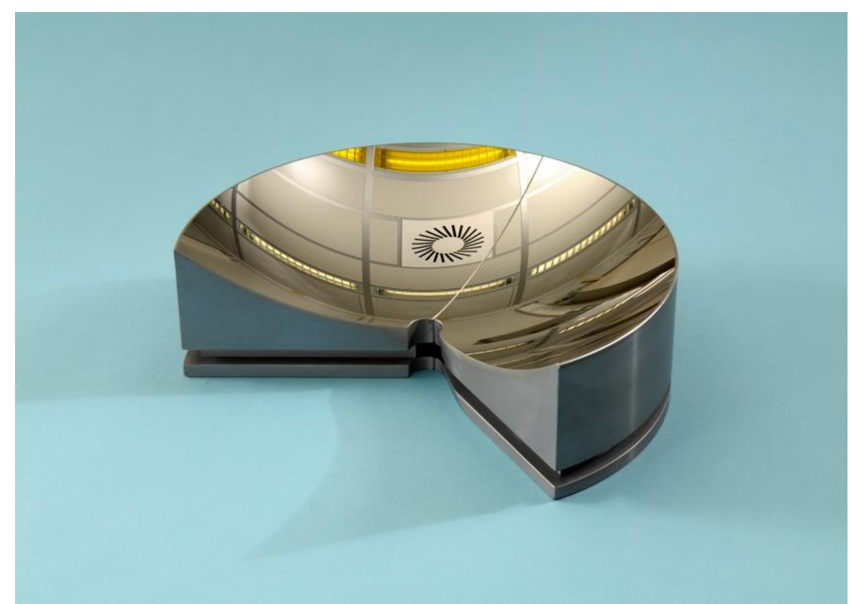
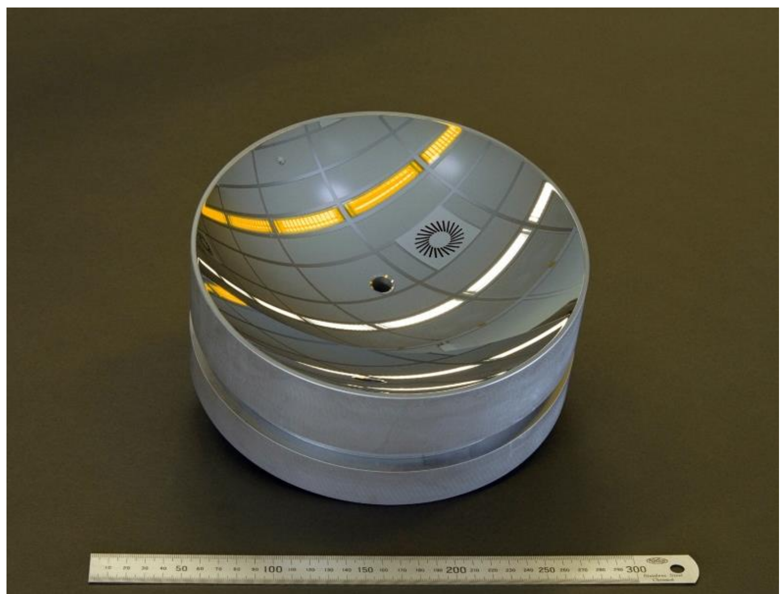
EUV lithography: Lithography gets extreme

Reticle stage
Intermediate focus
Illuminator
Collector
CO_2 laser
Projection optics
Wafer stage
Source

[*Nature Photonics* **4**, 24-26 (2010)]

Multilayer coated collector optics for LPP sources





EUV LPP collector with dual-wavelength spectral purity filter

IR wavelength

beam stop

EUV

IR wavelength

EUV LPP collector with integrated spectral purity filter

IR wavelength

beam stop

EUV

IR wavelength

EUV collector
with integrated
binary phase grating

Principle of EUV multilayer with integrated phase grating

EUV-
output

Aperture stop

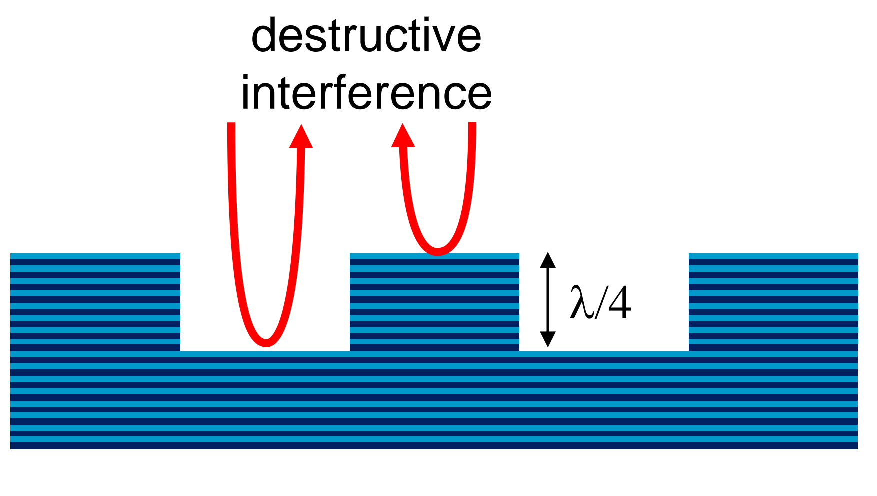
$n = 1$

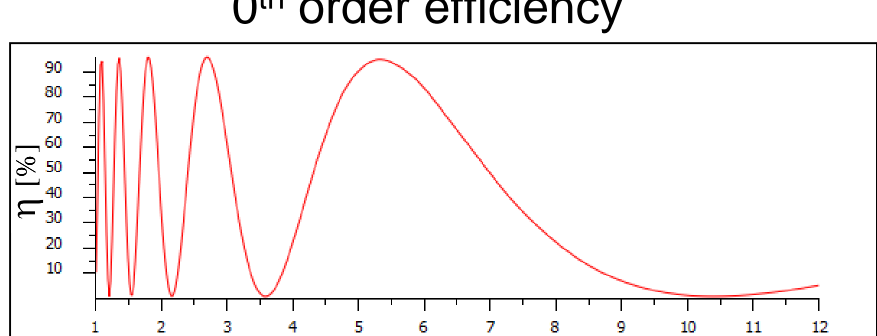
EUV- + IR-
radiation

Diffracted IR

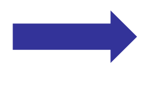
binary Mo/Si
multilayer grating

Grating integration by multilayer structuring





λ = 10.6 µm → h = 2.65 µm



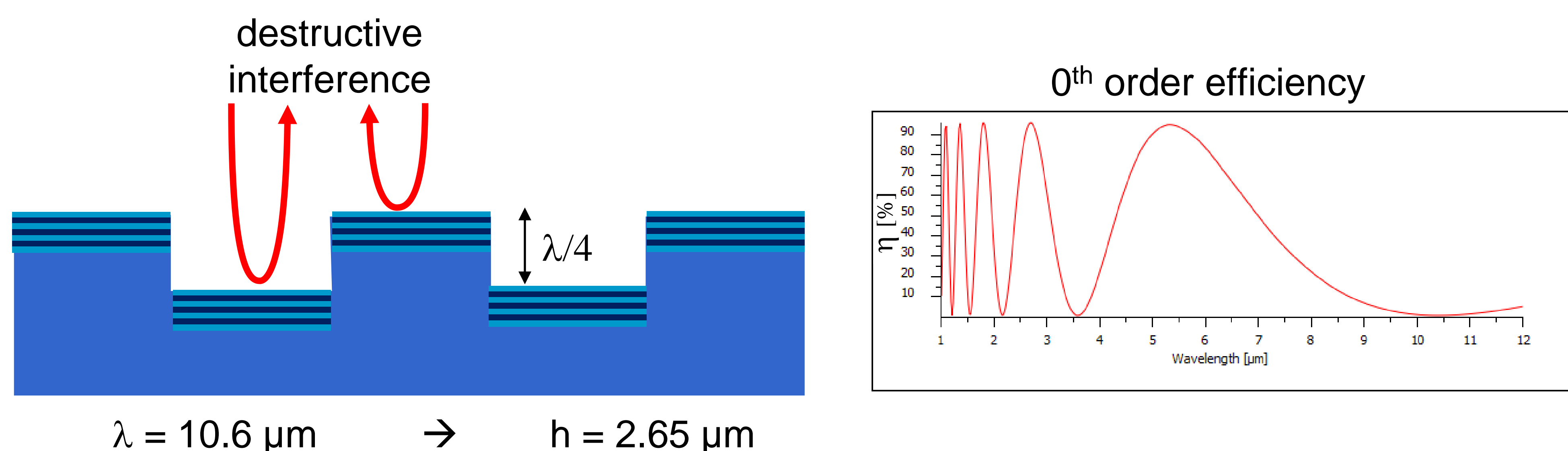
Requires a suitable process for the structuring of the multilayer stack without degrading the EUV-reflectivity

PROs and CONs of multilayer structuring

PROs	CONs
■ Established process for small-size and flat substrates	■ Scaling of technology to collector dimensions requires specialized etching vacuum system ■ Technology requires N = 500 Mo/Si pairs (10 times more compared to normal collector coating) ■ open multilayer structure

optiX fab.

Grating integration by substrate structuring

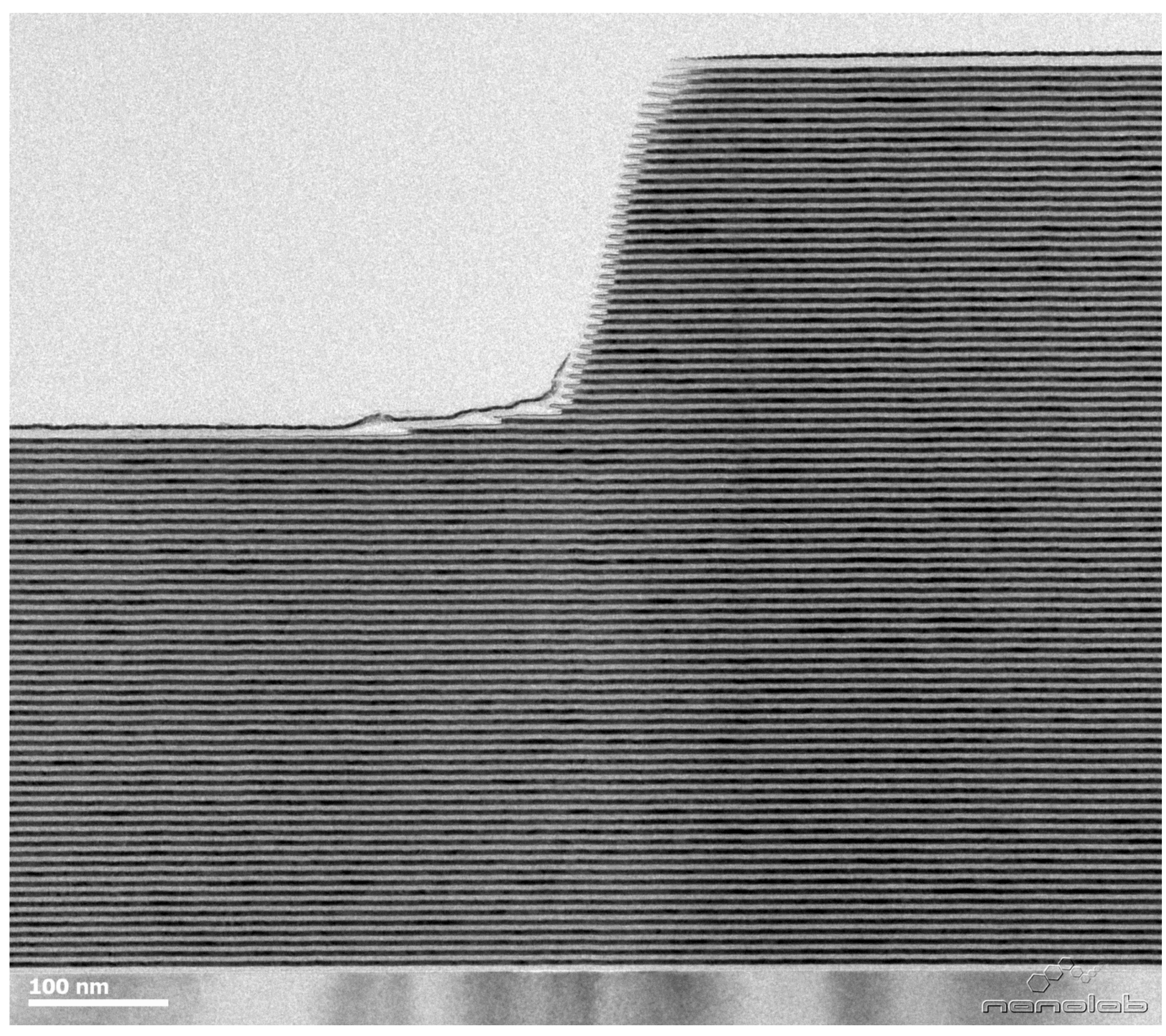


Requires a suitable process for the structuring of the substrate without increasing HSFR roughness

PROs and CONs of substrate structuring

PROs	CONs
■ Number of Mo/Si pairs: N = 50 ■ No open multilayer structure	■ HSFR of grating bottom and top of s < 0.3 nm rms (main challenge) ■ Scaling of technology to collector dimensions requires specialized etching vacuum system

Grating integration by multilayer structuring

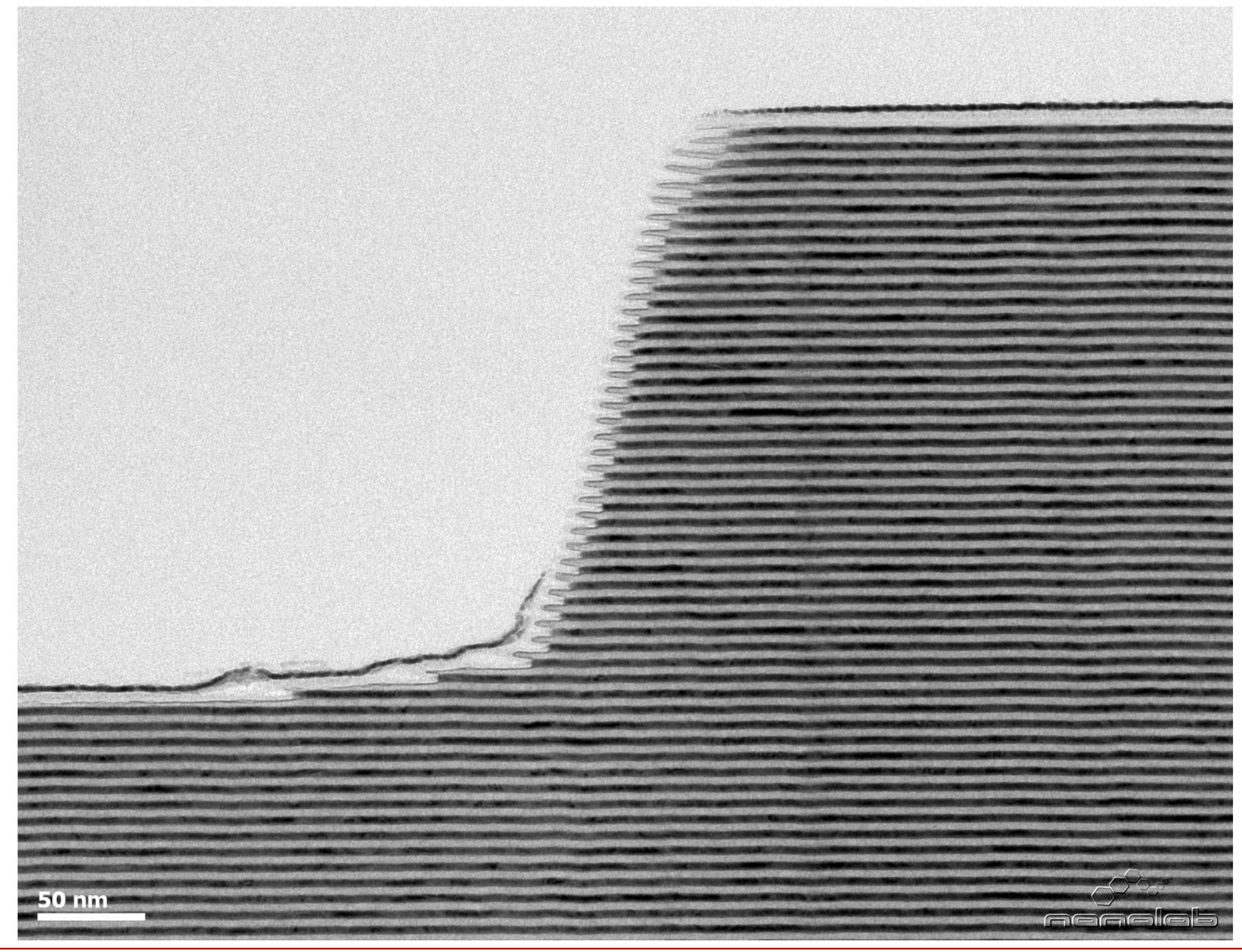


YAG laser grating:

Wavelength:	1064 nm
Grating period:	100 µm
Grating height:	275 nm

optiX fab.

Grating integration by multilayer structuring



optiX fab.

Grating integration by multilayer structuring

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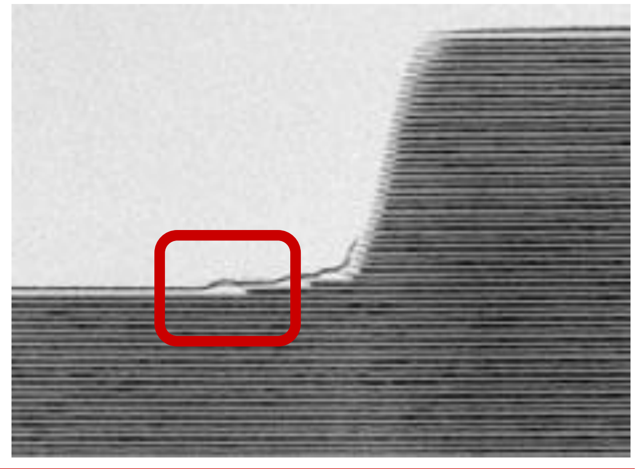
Wavelength:	1064 nm
Grating period:	100 µm
Grating height:	275 nm



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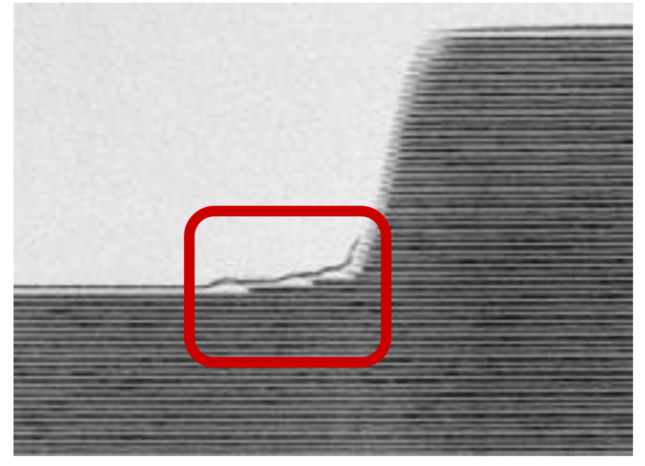

Grating integration by multilayer structuring

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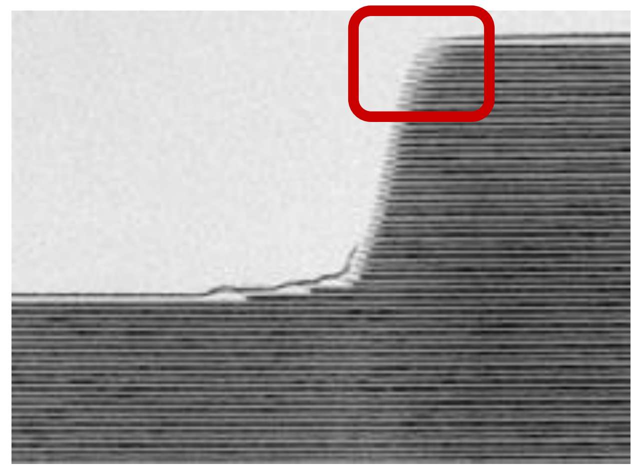

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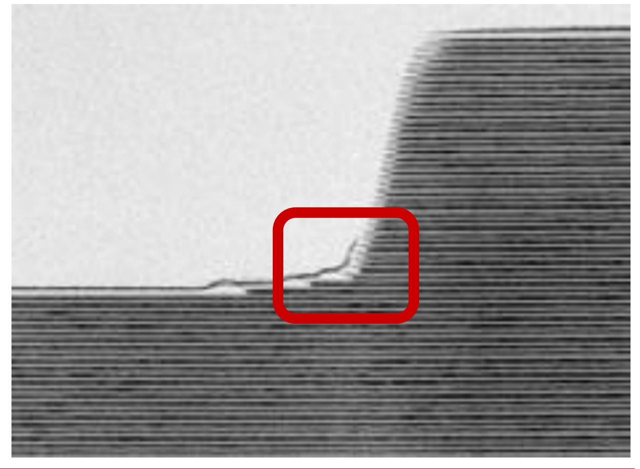

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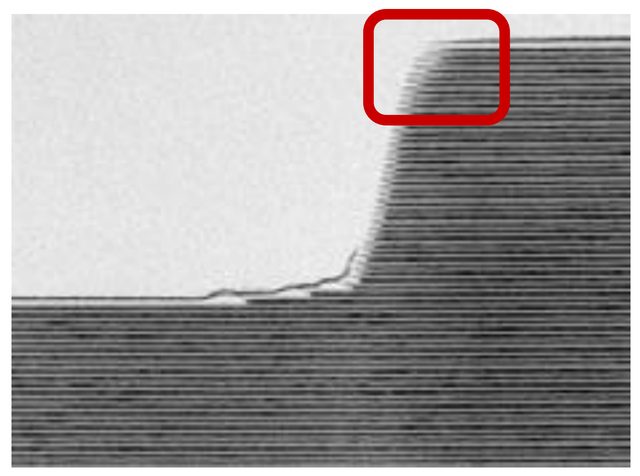
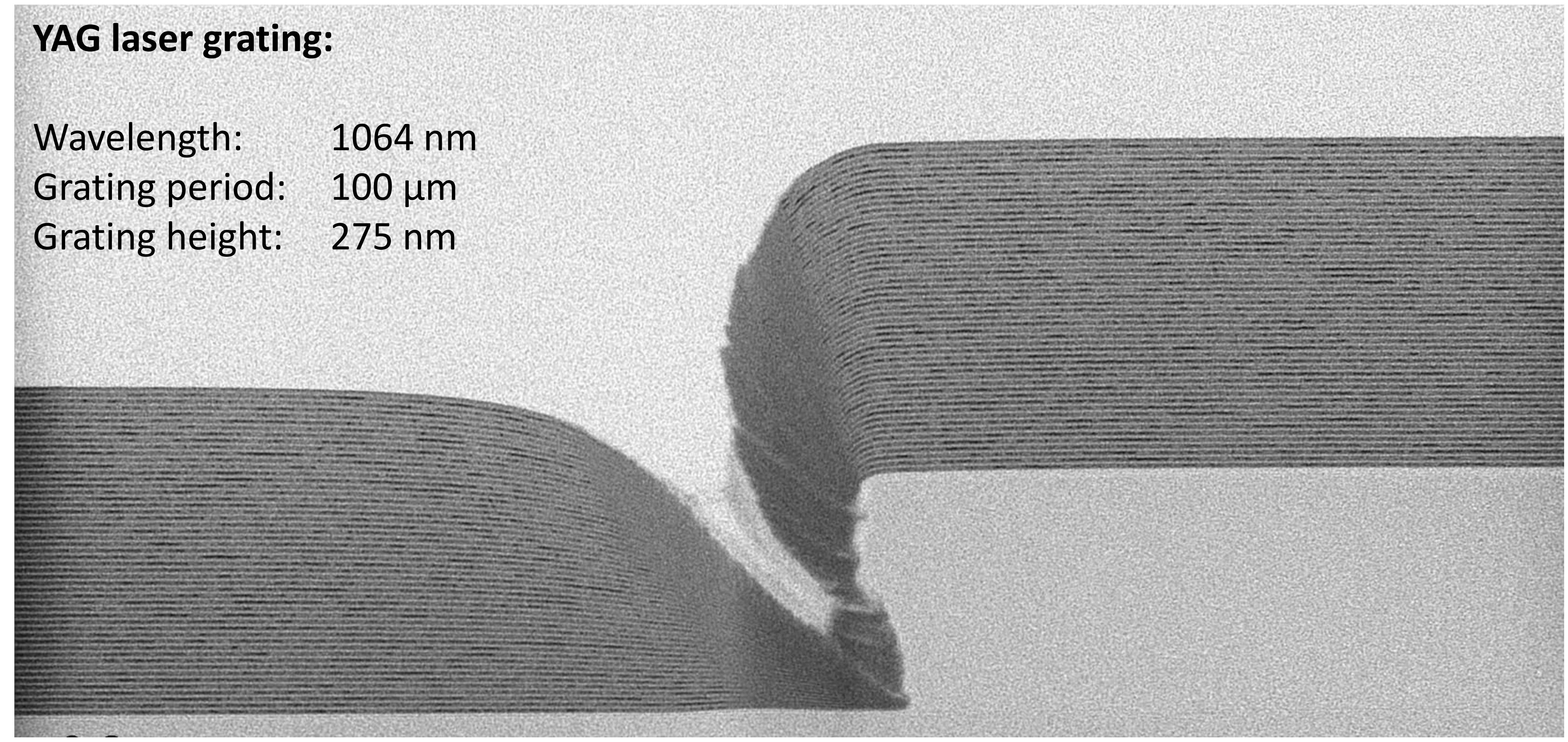


Grating integration by substrate structuring



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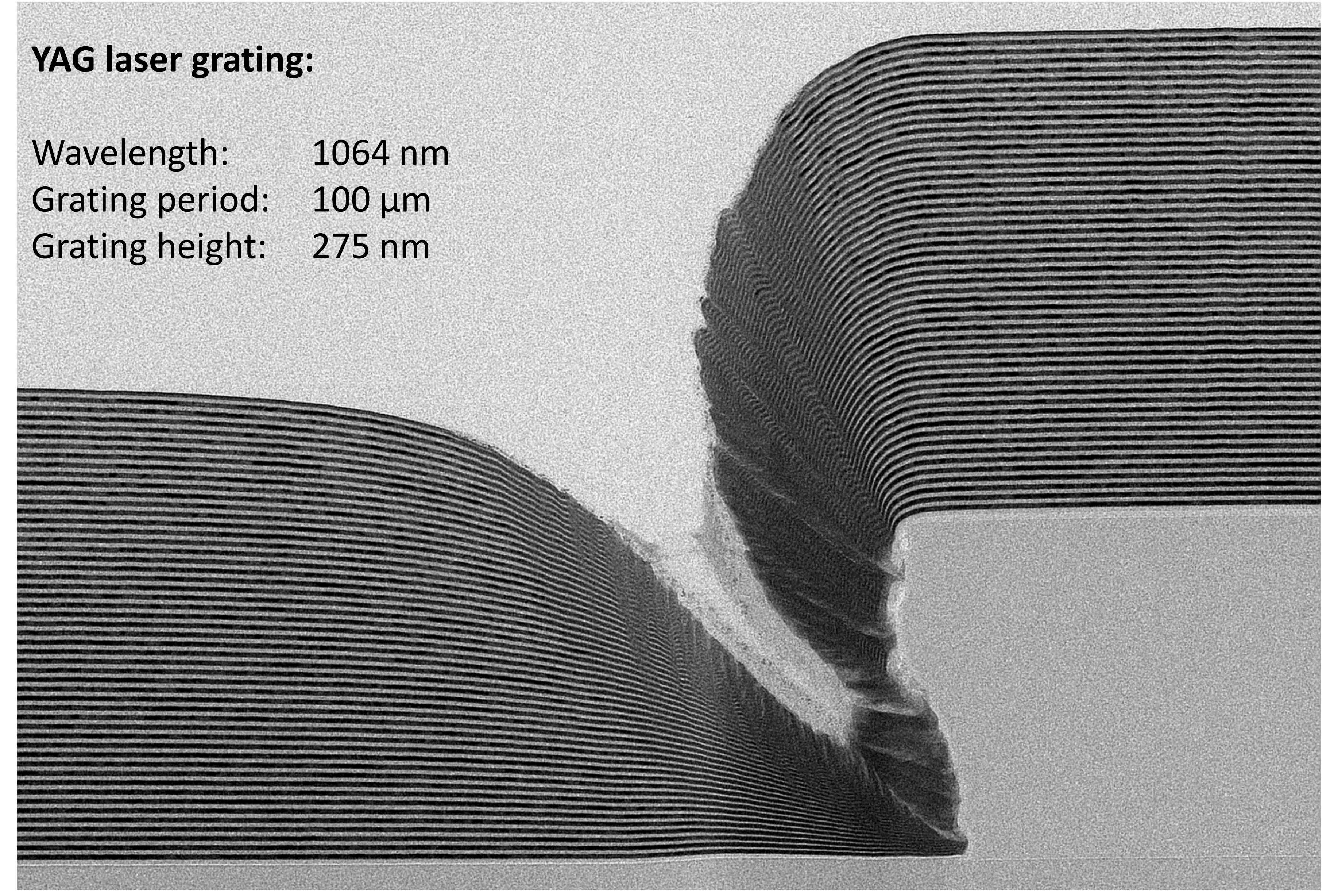
Grating integration by substrate structuring



optiX fab.

Grating integration by substrate structuring

YAG laser grating:

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Grating period:	100 µm
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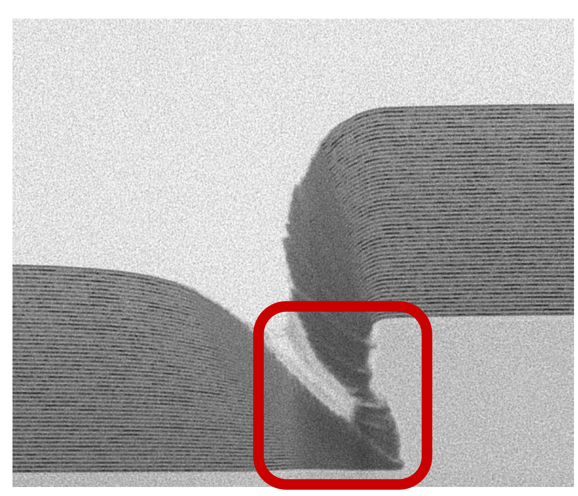

Grating integration by substrate structuring

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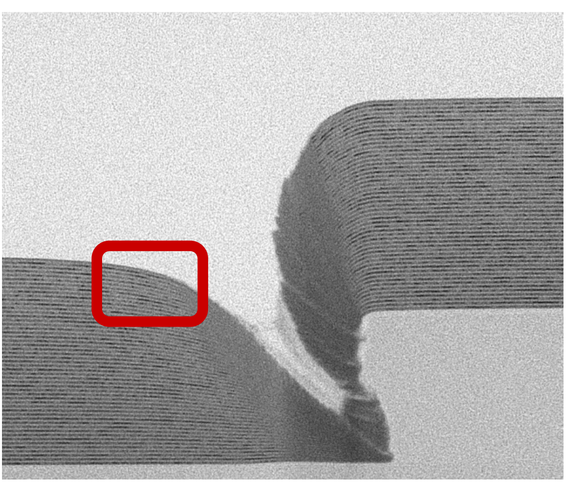

Grating integration by substrate structuring

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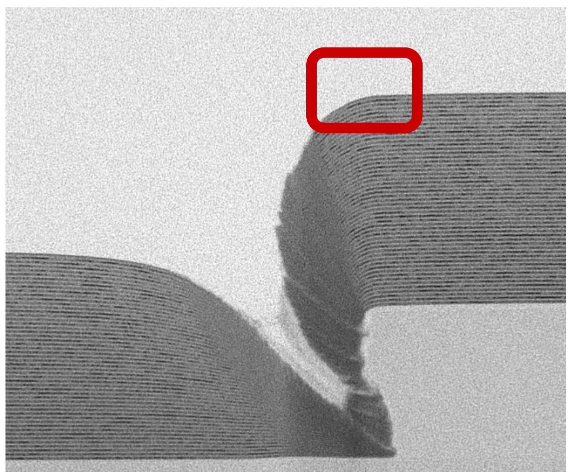
Grating height:	275 nm



Theoretical reflectance of Mo/Si multilayer for normal incidence

Reflectance (%)

100
80
60
40
20
0

Multilayer
resonance

Metallic
reflection

1
10
100
1000
10000

λ (nm)

R = 84.0 %

@ 10.6 µm

R = 49.2 %

@ 1064 nm

Measured reflectance!

EUV LPP collector with dual-wavelength spectral purity filter

10.6 µm and 1064 nm

+ 1st order

beam stop

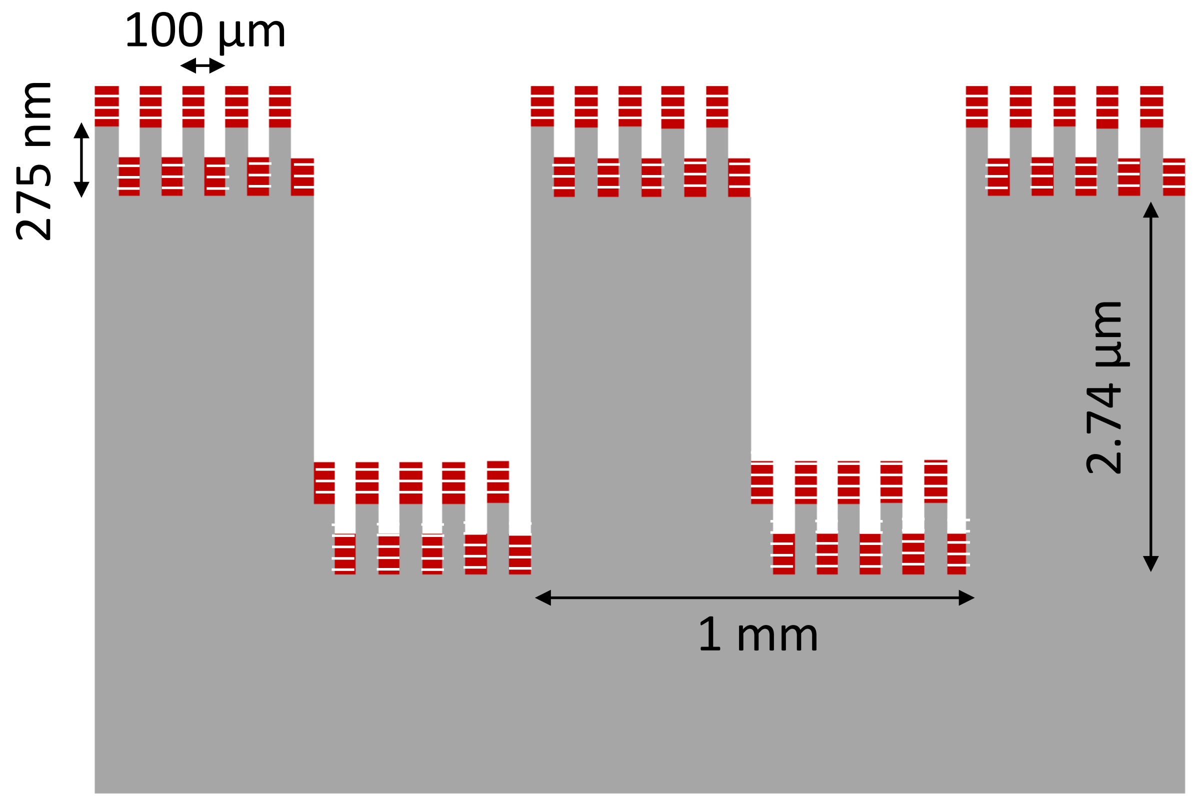
EUV

- 1st order

10.6 µm and 1064 nm

EUV collector with integrated binary phase grating

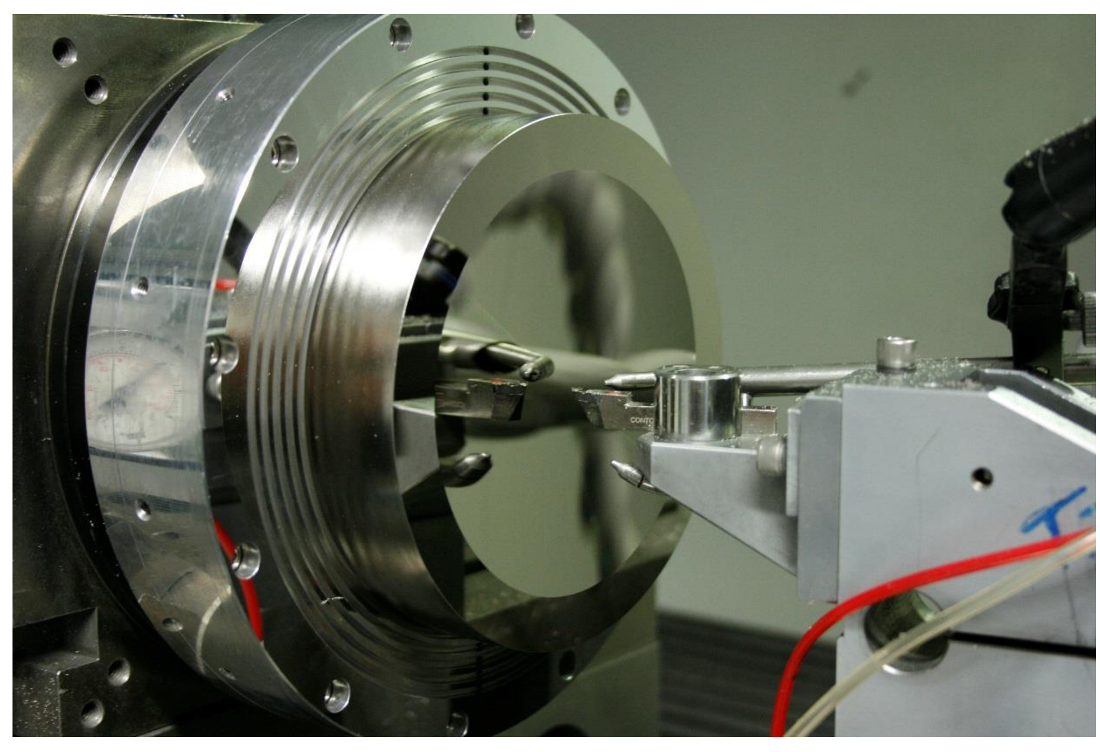
Dual-wavelength Spectral Purity Filter



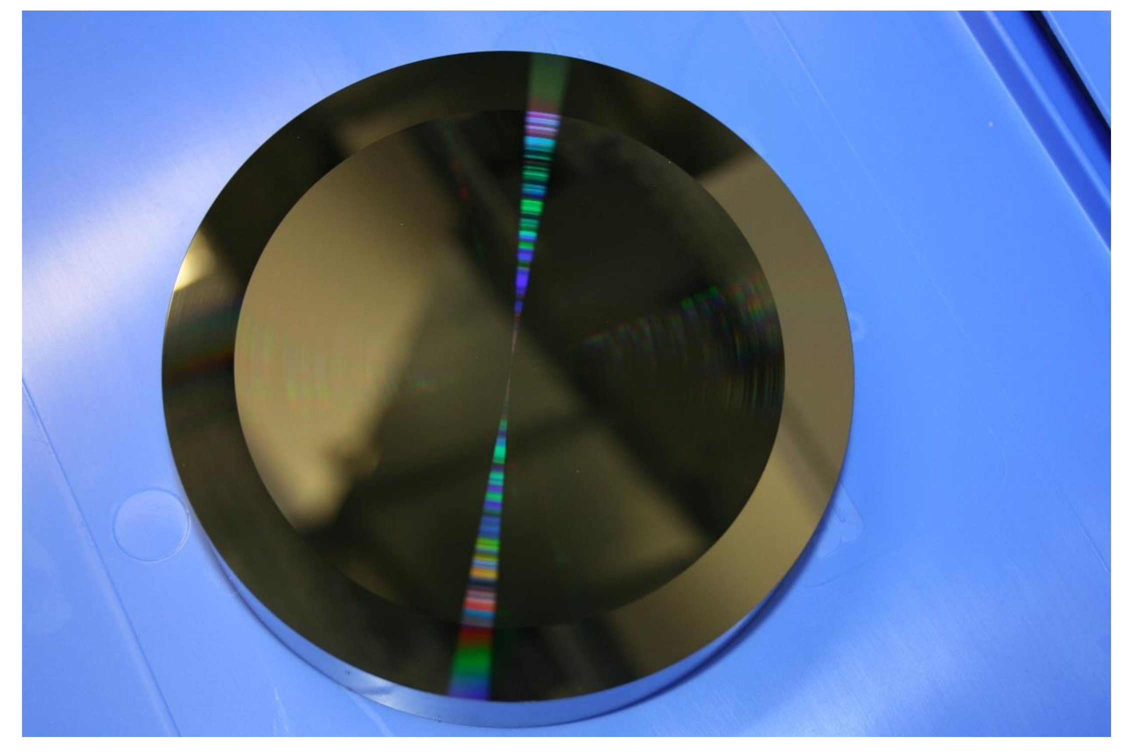
CO_2 laser grating:
Grating period: 1 mm
Grating height: 2.74 nm

YAG laser grating:
Grating period: 100 µm
Grating height: 275 nm

Sub-aperture EUV collector substrate fabrication



- Material: Aluminum-Silicon alloy, Ni plated
- Form: spherical, ROC = 300 mm, Ø 150 mm
- Technology: diamond turning + polishing



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White light interferometry of grating structure

zygo 3D Model

zygo 3D Model

zygo 3D Model

nm

+1195.27

-2731.63

zygo 3D Model

AFM surface roughness analysis of grating bar and groove

rms roughness on BAR-groove:
σ_{RMS} = 0.24 nm

rms roughness on GROOVE-groove:
σ_{RMS} = 0.22 nm

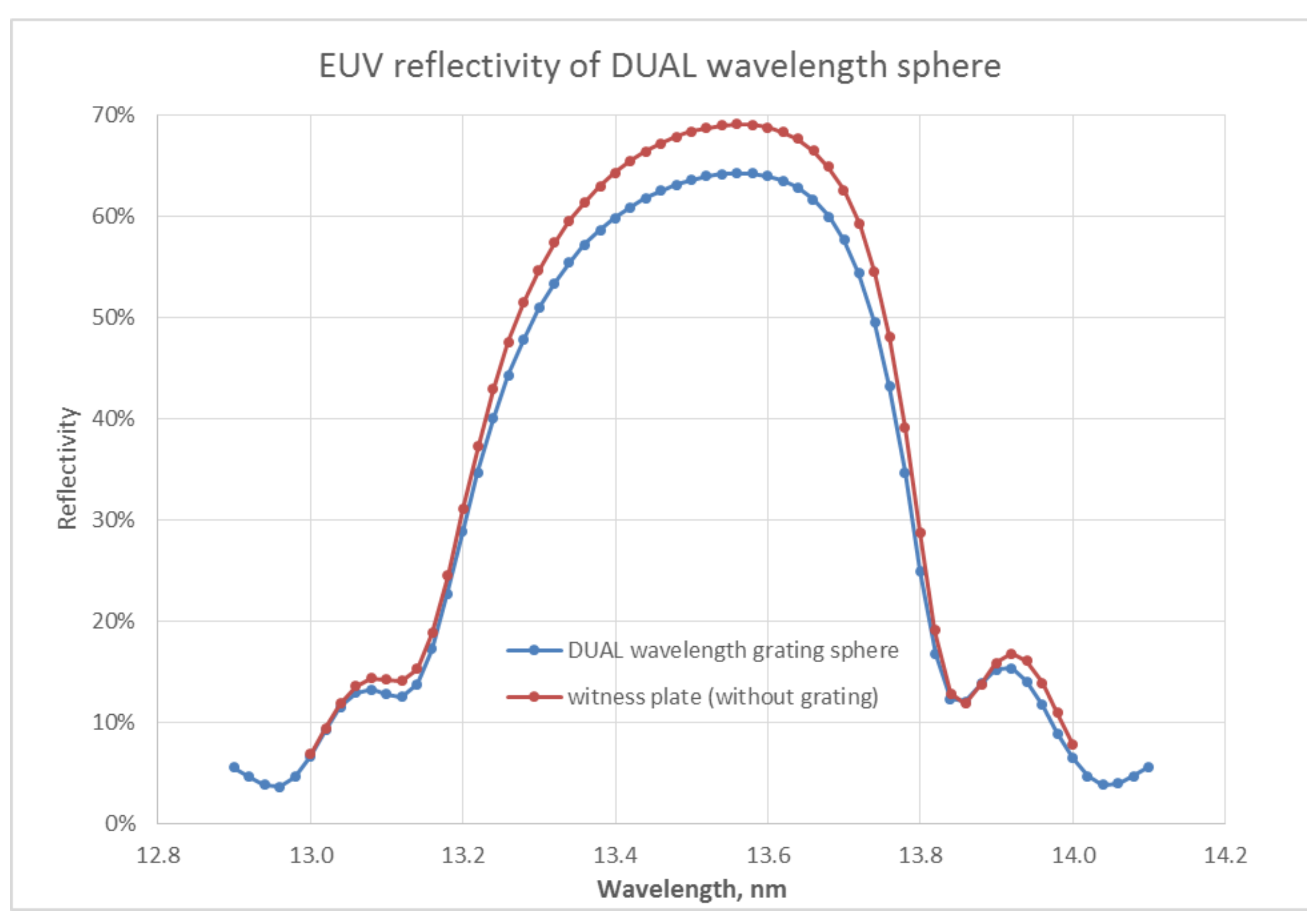
rms roughness on BAR-bar:
σ_{RMS} = 0.20 nm

rms roughness on GROOVE-bar:
σ_{RMS} = 0.24 nm

Coating of Mo/Si multilayers

- Substrate size:
  up to Ø 700 mm
- six deposition targets
- deposition of graded multilayers on curved substrates
- Installation: 2009

EUV reflectance measurement @ PTB Berlin



EUVR on grating structure

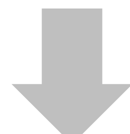
R = **64.24 %**

λ_{center} = 13.50 nm

EUVR on witness sample

R = **69.05 %**

λ_{center} = 13.50 nm



4.8 % (abs.) EUVR loss due to dual-wavelength grating structure

Measurement of IR grating efficiency @ 10.6 µm and 1064 nm

Beam conditioning system

150 mm sub-aperture EUV collector with integrated SPF, 3D-positioning-system

10.6 µm

1064 nm

IR lasers

ϑ_i

$\Delta\Omega_s$

φ_s

ϑ_s

IR detector (PMT, 3D positioning)

Dual grating efficiency @ 10.6 µm

10.6 µm

sphere with DUAL grating for 10.6 µm + 1,064 nm

IR grating effiency, %

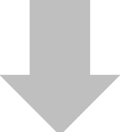
35
30
25
20
15
10
5
0

-20 -19 -18 -17 -16 -15 -14 -13 -12 -11 -10

AOI, degree

Grating efficiency @ 10.6 µm

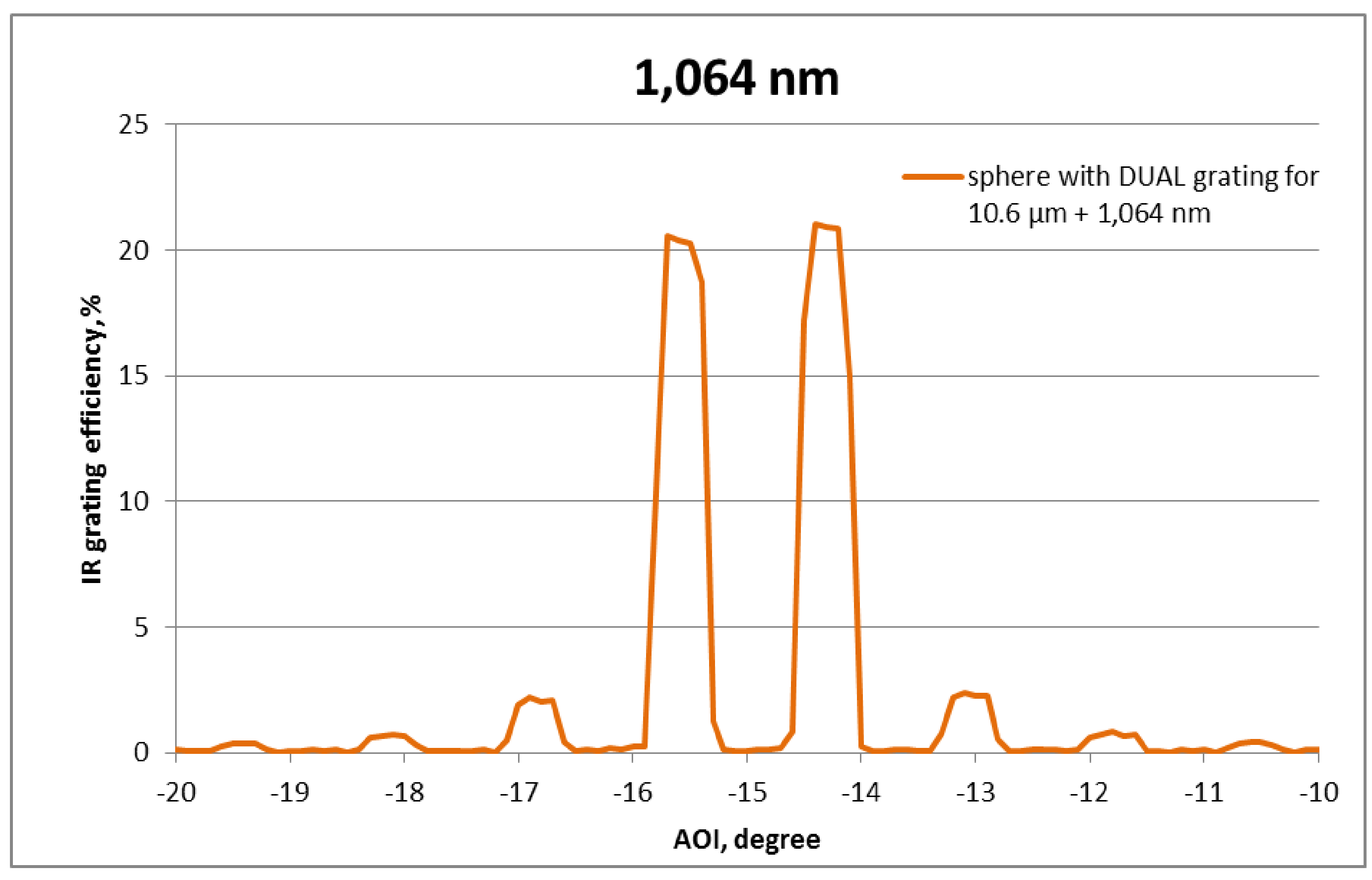
0th order:	**0.32 %**
- 1st order:	28.7 %
+ 1st order:	31.4 %



IR suppression factor:

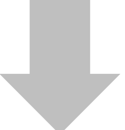
260

Dual grating efficiency @ 1064 nm



Grating efficiency @ 1064 nm

0th order:	**0.08 %**
- 1st order:	21.0 %
+ 1st order:	20.5 %



IR suppression factor:

620

Scanning Electron Microscopy of dual-wavelength SPF

BAR

GROOVE

100 µm | 100 X | SEM 3.00 kV | WD = 12.3 mm SE2 | 21 Oct 2014 | Fraunhofer IOF

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Summary

- Fabrication of customized EUV and VUV multilayer optics from 2 nm to 200 nm
- New reflectance level for EUV lithography optics: R = 70.12 % @ 13.50 nm
- Development of multilayer collector mirrors with integrated IR suppression
- Comparison of multilayer and substrate etching
- Strengths and weaknesses of both methods
- Greatest strength of substrate structuring: no open multilayer structure
- Outlook: Improving of substrate edge angle to optimize ML groth

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- **EUV team @ Fraunhofer IOF:**
  Christoph Damm, Wilko Fuhlrott, Matthias Hauptvogel, Tobias Herffurth, Nils Heidler, Robert Jende, Jan Kinast, Sylke Kleinle, Sandra Müller, Thomas Müller, Michael Scheler, Mathias Rohde, Steffen Schulze, Ronald Schmidt, Uta Schmidt, Mark Schürmann, Sergiy Yulin

- **EUV reflectivity measurement team @ PTB Berlin**
  Christian Buchholz, Annett Barboutis, Andreas Fischer, Florian Knorr, Heiko Mentzel, Jana Puls, Anja Schönstedt, Michael Sintschuk, Christian Stadelhoff

Special Thanks

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  Shaojie (Jeff) Wang, Charlene Sun, Peng Ziang, Xiuhong Han

Thank you.

optiX fab.

www.optixfab.com

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Reflectance (%)

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Multilayer resonance

Metallic reflection

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λ (nm)

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Measured reflectance!