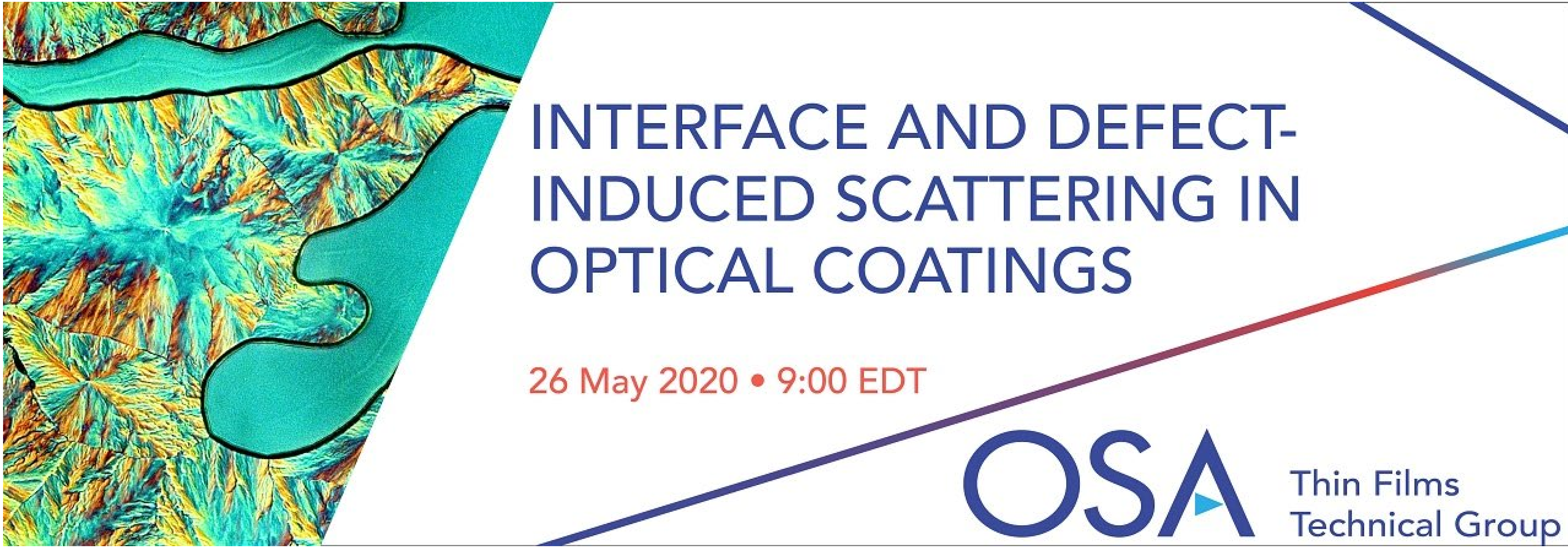
WE ARE ON

OSA Thin Films Technical Group

Interface and Defect-induced Scattering in Optical Coatings

Jinlong Zhang, Tongji University

The OSA Thin Films Technical Group Welcomes You!



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Our Technical Group at a Glance

Our Focus

- Optical thin films and interference coatings from fundamentals to applications
- Serving a global community with thousand members like YOU

Our Mission

- To connect people from academia, institutions and industries in the field
- To bridge the fundamentals, the know-hows and the new development
- To promote networking and career development through continuous learning

Where To Find Us

- Technical Group Website: www.osa.org/ThinFilmsTG
- LinkedIn: www.linkedin.com/groups/4783616
- Please let us know if you are interested in sharing your work or have ideas for our group activities

Today's Webinar

Interface and defect-induced scattering in optical coatings

Dr. Jinlong Zhang

Institute of Precision Optical Engineering, Tongji University
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Speaker's Short Bio:

Holds PhD in Optical Engineering from Zhejiang University
10+ years in design, simulation and deposition for high quality optical coatings
Extensive experience with developing nanostructure thin films

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Interface and defect-induced scattering in optical coatings

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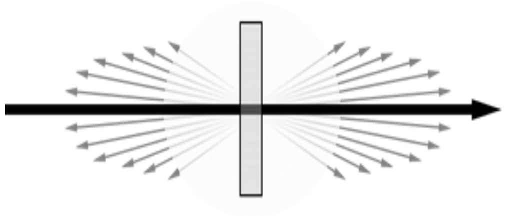
Institute of Precision Optical Engineering

Key Laboratory of Advanced Micro-Structured Materials MOE

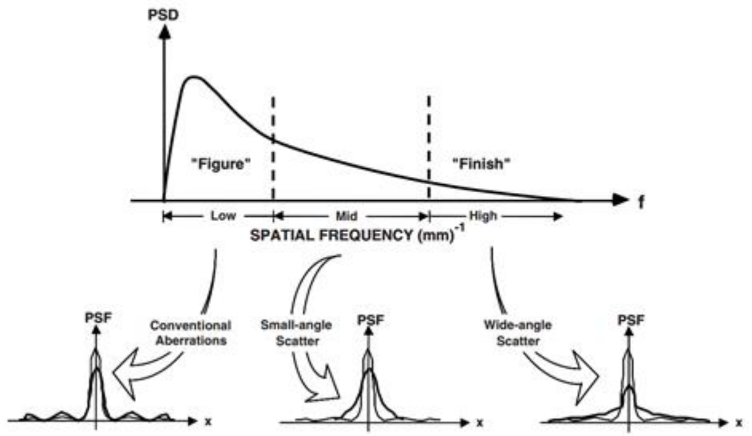
2020-05-26

Light scattering

Scattering light: Stray light that deviates from the mirror image due to structural defects in the film



- Reducing the optical throughput
- Decreasing the image resolution by the narrow-angle scattering
- Decreasing the image contrast or signal-to-noise ratio by the wide-angle scattering
- Formation of ghost images, …



$$PSF(\boldsymbol{r}) = PSF_{geom}(\boldsymbol{r}) * PSF_{scat}(\boldsymbol{r})$$

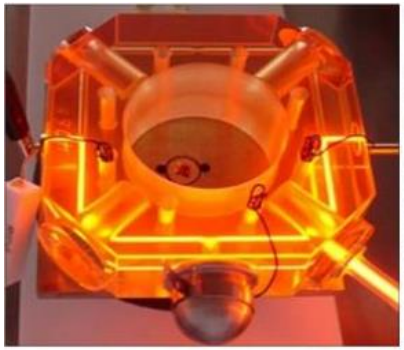
$$\sim ARS(a_j r)$$

Degradation the performance of optics

Background

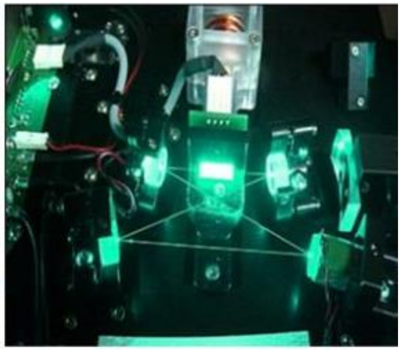
Light scattering

Particularly critical for optics at short wavelengths, high resolution imaging, ultra-low loss laser optics, etc.



laser gyroscope

gravitational wave detection



cavity ring-down spectroscopy

EUV mirror

- **Ultra-low loss laser coatings in the laser cavity mirrors need to control the scattering to ppm level**
- **Light scattering significantly enhanced due to the short wavelength**
- **The lock-in threshold of Laser Gyros is limited by scattering in the counterpropagating direction**

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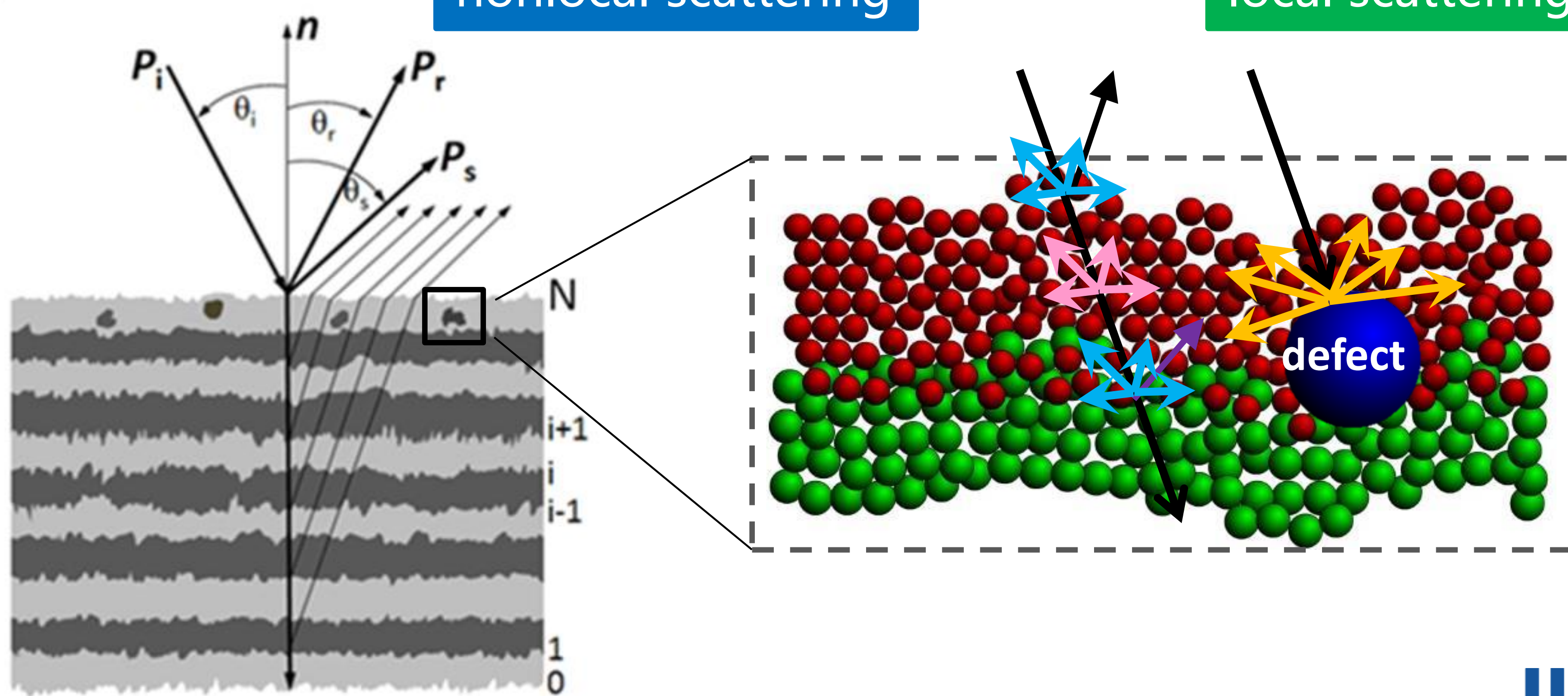
Sources of light scattering

Scattering loss

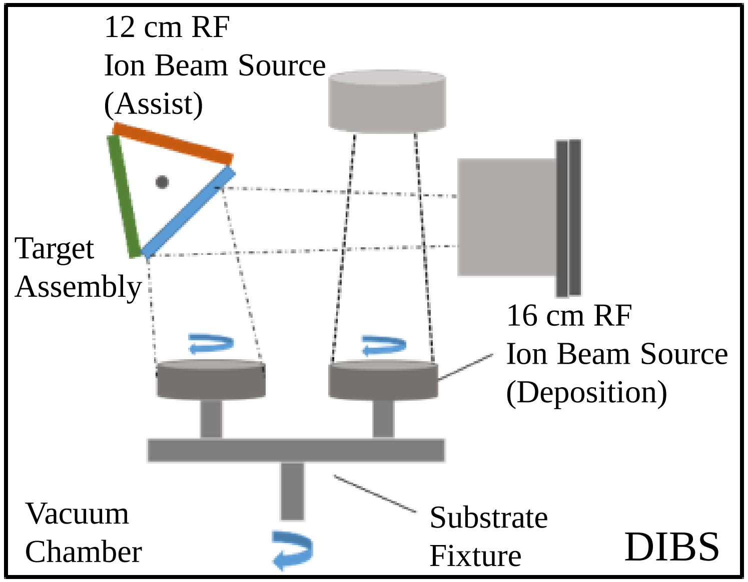
surface/interface roughness | bulk inhomogeneity | local defects

nonlocal scattering (surface/interface roughness, bulk inhomogeneity)

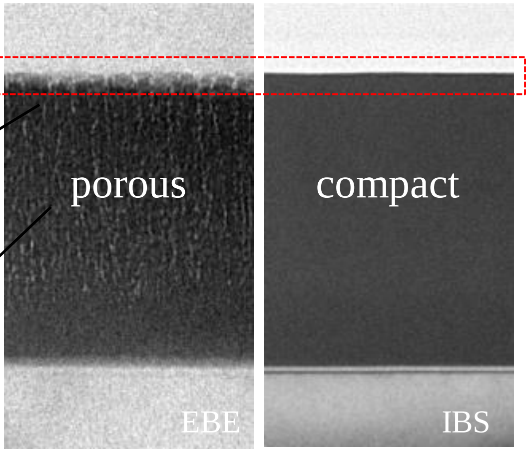
local scattering (local defects)



1、J. C. Stover, Optical Scattering: Measurement and Analysis, 2nd ed., (SPIE, Bellingham, Wash., 1995)



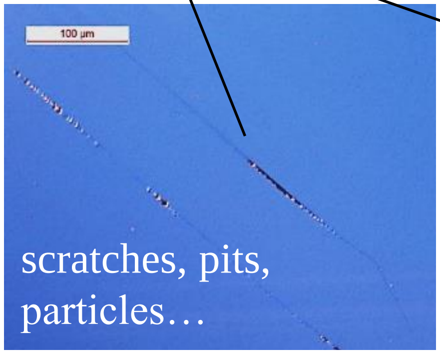
- smooth surface
- compact structure
- few defects from sputtering source

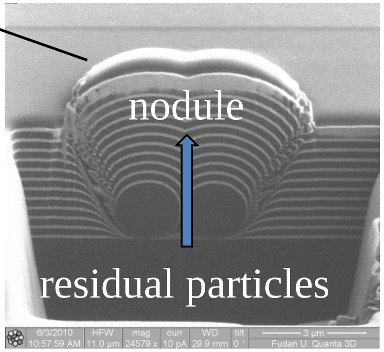


roughness-induced

bulk inhomogeneity-induced

defect-induced scattering





advanced substrate processing/cleaning technology

The best technical route: SiO_2/Ta_2O_5 by IBS

scratches, pits can be well controlled by super polishing

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Background

Interface scattering

Year	Research Unit	λ/nm	σ/nm	TIS_{exp}/ppm
1999	RUS, POLYUS	632.8	0.35	50
2001	UK, BAE	632.8	0.1	6
2004	USA, REO	632.8	0.053	0.8
2004	USA, LIGO	1064	< 0.05	>> 0.5
2012	USA, IDEX	633	< 0.05	>> 0.5

$$TIS = 1 - \exp\left[-\left(4\pi\sigma\cos\theta_i / \lambda\right)^2\right] \approx \left(4\pi\sigma\cos\theta_i / \lambda\right)^2$$

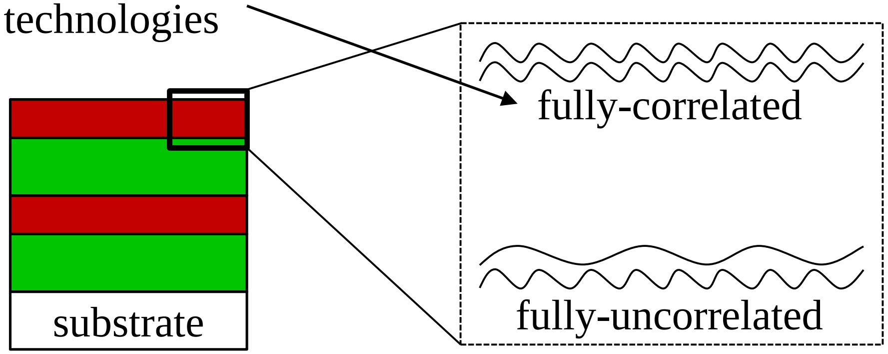
$$\sigma = \sqrt{2\pi \int_{\sin 2^\circ/\lambda}^{\sin 85^\circ/\lambda} PSD(\theta_s)\, \mathrm{d}\theta_s}$$ ~ISO: 13696

TIS_{exp} >> TIS_{theo}, interface scattering can not be neglected

$$ARS(\theta_s) \propto \sum_{i=0}^{N} \sum_{j=0}^{N} F_i F_j^* PSD_{ij}(f)$$

- reducing roughness
- reducing optical factor

state-of-the art deposition technologies



$$ARS(\theta_s) \propto \left|\sum_{j=0}^{N} F_j\right|^2 PSD(f)$$

$$F_j = \left(\varepsilon_j - \varepsilon_{j-1}\right) E\left(z_j, \theta_0\right) E\left(z_j, \theta_S\right)$$

- creating destructive interferences

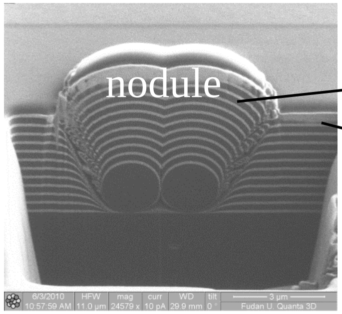
International round-robin experiment to test the International Organization for Standardization total-scattering draft standard

Lab	Sphere Type	Sphere Diameter (mm)	Range of Acceptance Angles (deg)	Angle of Incidence (deg)	Beam Diameter (mm)	Background Signal (ppm)	Relative Error (%)	Number of Points	Point Geometry
DMS	Coblentz	254	2.50–70.0	<2.0	2.5	5.0	2–3	3	Random
IOF	Coblentz	350	2.00–85.0	<1.0	0.3	<0.1	<10	201, 501, 1000	Line
JOP	Ulbricht	220	2.00–85.0	~0.2	1.0	1.4–4.0	<10	201	Line
LMTB	Ulbricht	150	2.90–70.0	<1.5	1.5	<5.0		202	Line
LZH	Ulbricht	250	2.00–88.0	<3.0	0.4	<0.5	<10	300, 380, 1000	Line
NAWC	Coblentz	220	2.85–80.0	~0.5	1.0	20.0	~3	19	Circle
LINOS	Ulbricht	150	2.00–82.0	<1.5	1.5	<5.0	<10	50	Line
TOL	Ulbricht	250		~5.0	1.0	9.0		129	Line
TUD	Ulbricht	152	1.90–82.0	~2.0	1.0	2.0	<10	51	Line

significantly different results

characterization and control of the local scattering is the key issue

problem: measurement uncertainty



local scattering
- key issue

nonlocal scattering
- fundamental issue

residual defects are unavoidable

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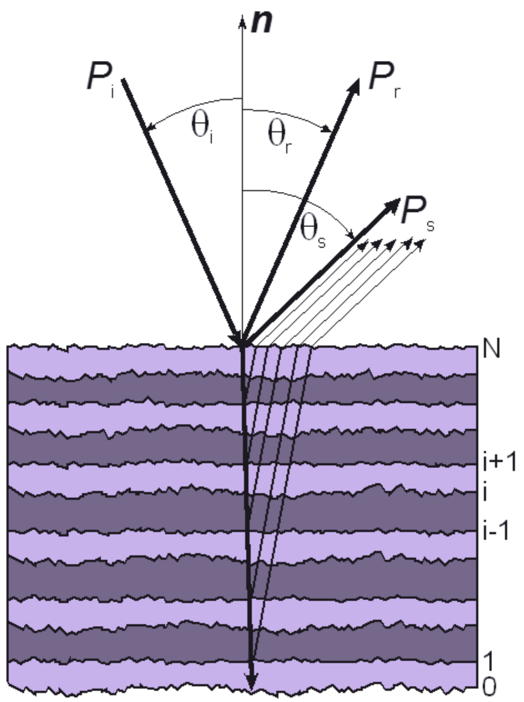


Vector perturbation theory (σ << λ)

$$ARS\left(\theta_s\right) \propto \frac{1}{\lambda^4}\sum_{i=0}^{N}\sum_{j=0}^{N} F_i F_j^* PSD_{ij}\left(f\right)$$

Optical factors

- Multilayer design
- Optical constants
- Polarization

Roughness factors

- PSDs of individual surfaces (*i* = *j*)
- Cross-correlation properties (*i* ≠ *j*)

$$F_j = \left(\varepsilon_j - \varepsilon_{j-1}\right) E\left(z_j, \theta_0\right) E\left(z_j, \theta_s\right)$$

Coating design, Correlation of PSD

Two approaches to control the interface scattering

1、J. M. Elson et al., *Appl. Opt.* 19, 669-679 (1980)
2、P. Bousquet et al., *J. Opt. Soc. Am.* 71, 1115-1123 (1981)

Relevant statistical surface characteristics:

- Surface height distribution function
- Surface autocovariance function

Surface Power Spectral Density function

$$PSD(f_x, f_y) = \lim_{L\to\infty} \frac{1}{L^2} |FT\{h(x,y)\}|^2$$

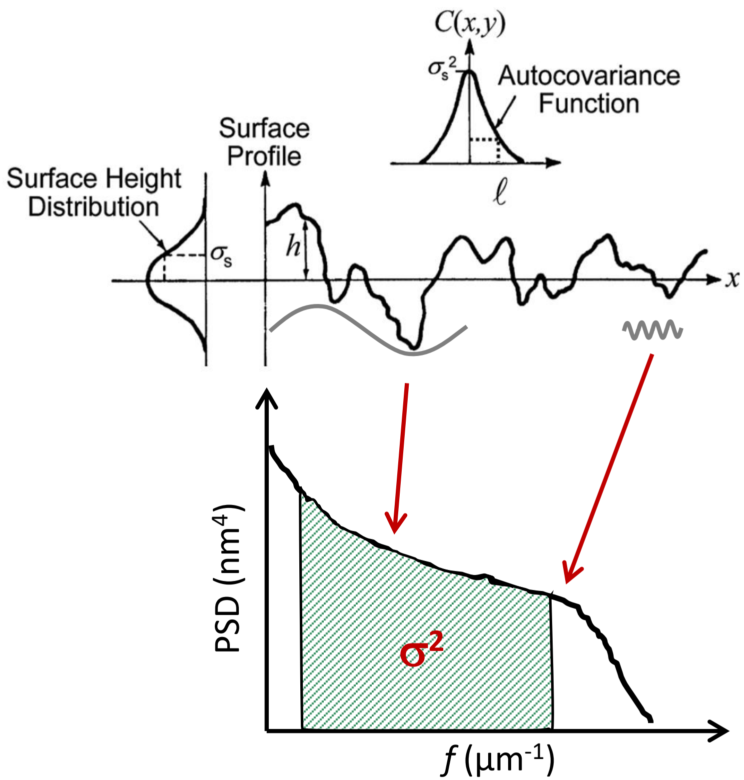
surface spatial frequencies — surface topography

- Power of different roughness components
- Fourier Transform of Autocovariance Function
- Isotropic roughness: PSD(f_x,f_y) → PSD(f)

Rms roughness

$$\sigma = \sqrt{2\pi \int_{f\min}^{f\max} PSD(f) f\, df}$$

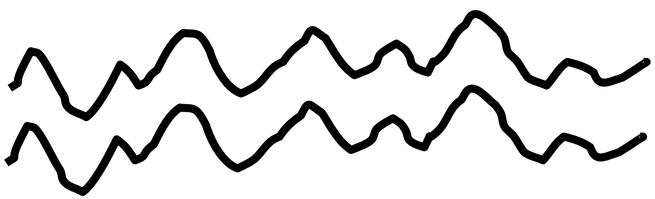
- Standard deviation of surface topography
- Band-limited / relevant roughness



1、 J E. Harvey, S. Schröder, N. Choi, *Opt. Eng.* 51(1) (2012) 2、 A. Duparré, J. M. Bennett et al., *Appl. Opt.* 41 (2002)
3、 J. M. Bennett, L. Mattsson, Introduction to Surface Roughness and Scattering, (OSA, Wash. D.C., 1999)

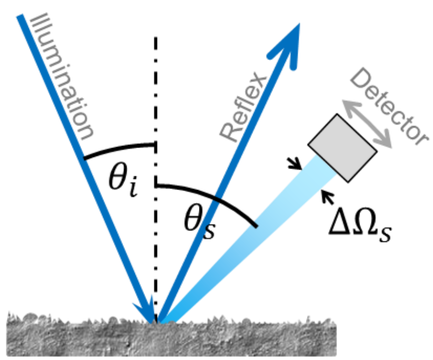
Correlation of interface roughness

Completely correlated interfaces model

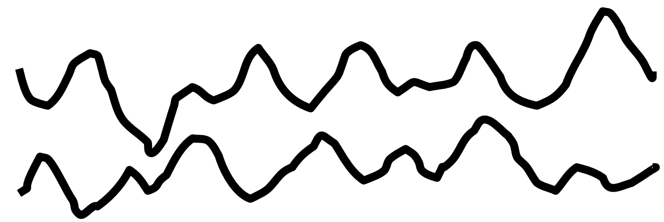


$PSD_F = PSD_S = PSD_{SF}$

$$ARS \propto \frac{1}{\lambda^4}\left|\sum_{j=0}^{N} F_j\right|^2 PSD(f)$$



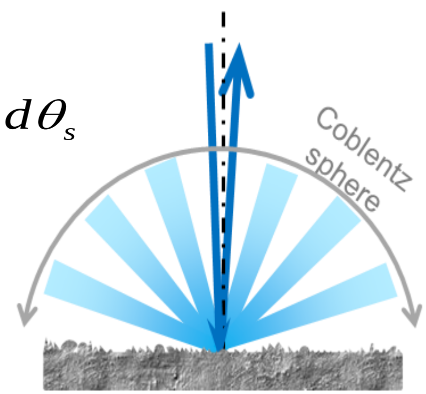
Completely non-correlated interfaces model



$PSD_{SF} = 0$

$$ARS \propto \frac{1}{\lambda^4}\sum_{j=0}^{N}\left|F_j\right|^2 PSD(f)$$

$$TS_b = 2\pi\int_{2^\circ}^{85^\circ} ARS(\theta_s)\sin\theta_s d\theta_s$$



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Coating design to control Interface scattering

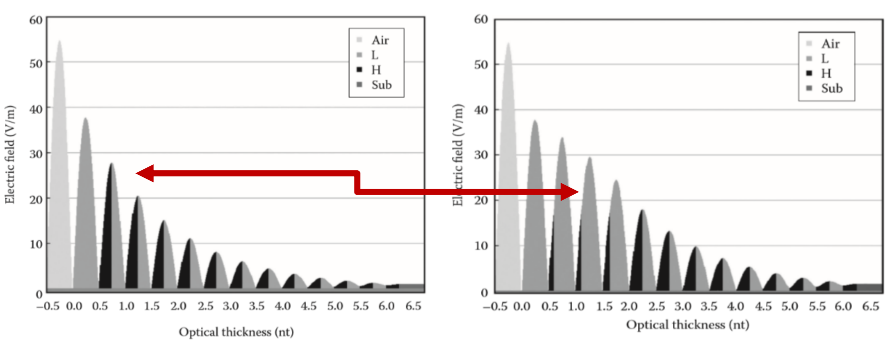
$$ARS(\theta_s) \propto \frac{1}{\lambda^4}\sum_{i=0}^{N}\sum_{j=0}^{N} F_i F_j^* PSD_{ij}(f)$$

Previous methods to adjust optical factors

Completely non-correlated interfaces model

↓

To change the interface electric field



Completely correlated interfaces model

↓

Eliminate F_i for a single layer with a particular thickness

air – n_0
material - n
substrate - n_S

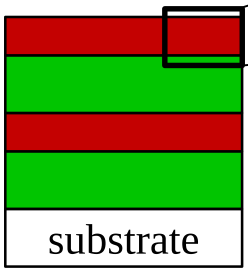
interface 0 – σ_0
interface 1 – σ_1

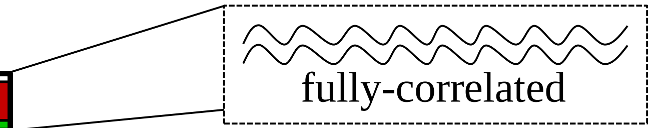
optical thickness: $ne = p\lambda$

complete cancellation of backscattering

1. Apfel J H. Optical coating design with reduced electric field intensity[J]. Applied optics, 1977, 16(7): 1880-1885.
2. C. Amra, G. Albrand, P. Roche, Theory and application of antiscattering single layers: antiscattering antireflection coatings, Appl. Opt. 25(16), 2695-2702 (1986).

state-of-the art deposition technologies for low-loss coatings

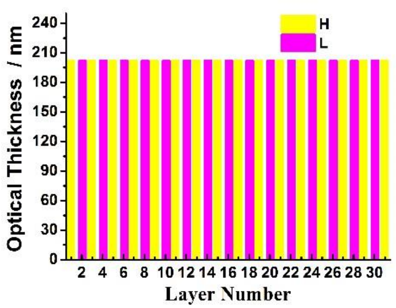




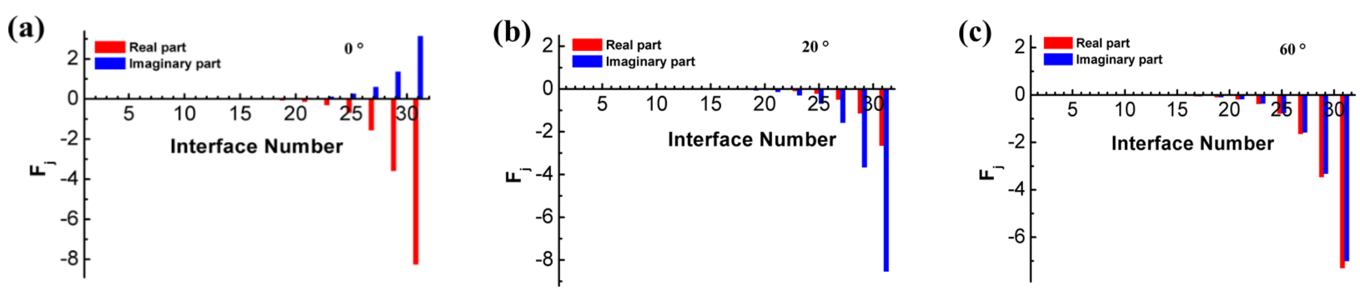
$$ARS \propto \frac{1}{\lambda^4}\left|\sum_{j=0}^{N} F_j\right|^2 PSD(f)$$

$$F_j = \left(\varepsilon_j - \varepsilon_{j-1}\right) E\left(z_j, \theta_0\right) E\left(z_j, \theta_s\right)$$

Optical factors are located at the H on the L interfaces (odd numbers), they are complex and in the same phase



QWHR, s- incident, 800nm

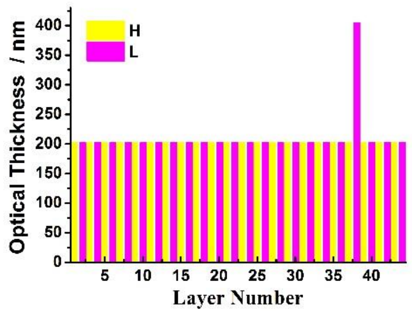


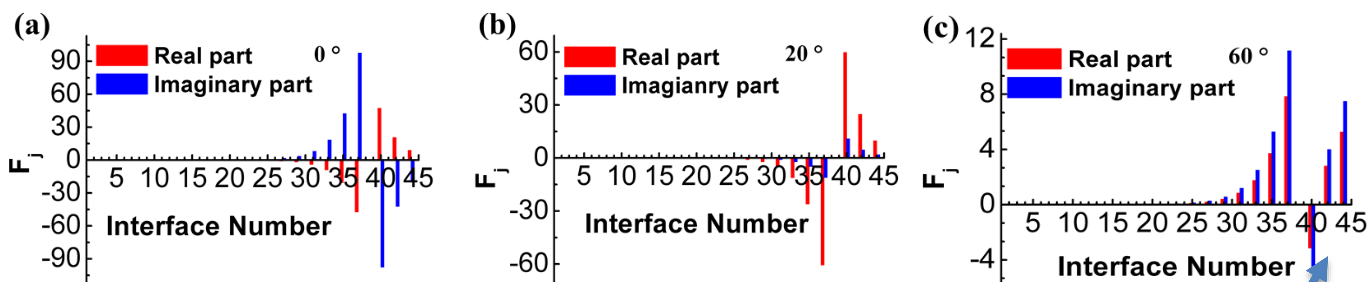
Light scattered from various interfaces are constructive interference

There is no solution of HR coating design to obtain destructive interferences of the scattering

Interface scattering

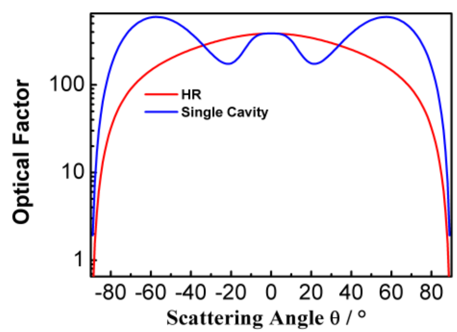
Add FP structure in HR coating, not modify reflection $F_j = \left(\varepsilon_j - \varepsilon_{j-1}\right) E\left(z_j, \theta_0\right) E\left(z_j, \theta_s\right)$





ε_j-ε_{j-1} exhibits opposite sign on both sides of the cavity, optical factors at the interfaces are in opposite phase

$$ARS \propto \frac{1}{\lambda^4}\left|\sum_{j=0}^{N} F_j\right|^2 PSD_{ij}(f)$$



F_j at top interfaces are in phase with that at inner interfaces due to the accumulation of the phase difference in large scattering angle

Reduce scattering in the near specular range from 10 to 35 degree, an increased value of the optical factors in large scattering angles

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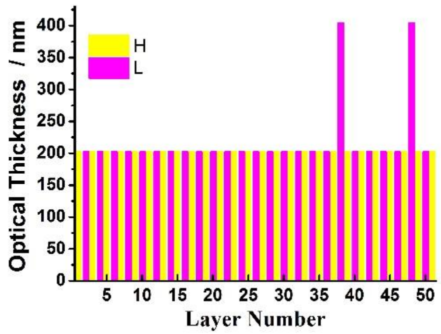
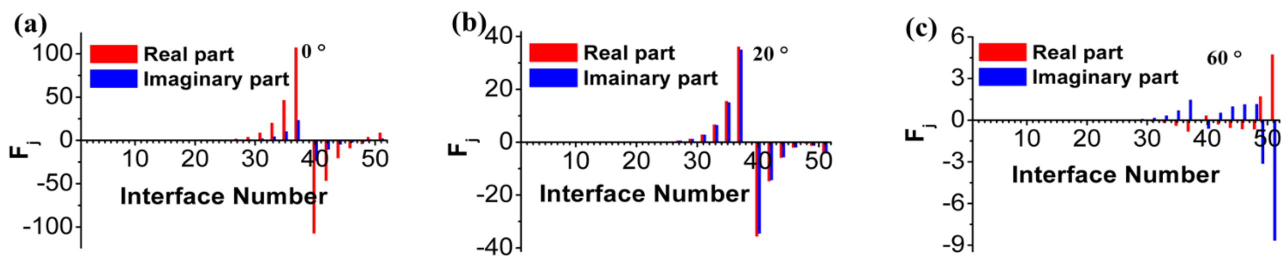
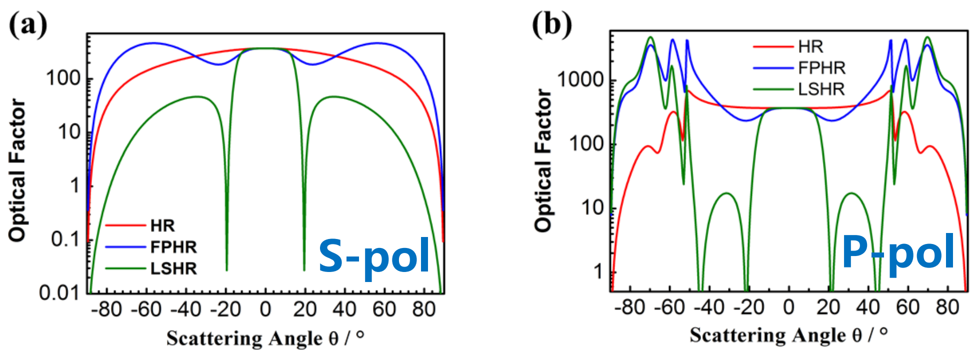
A proper HR coating structure with two FP cavities





optical factors at interfaces have opposite phase

optical factors at the top two interfaces have opposite phase

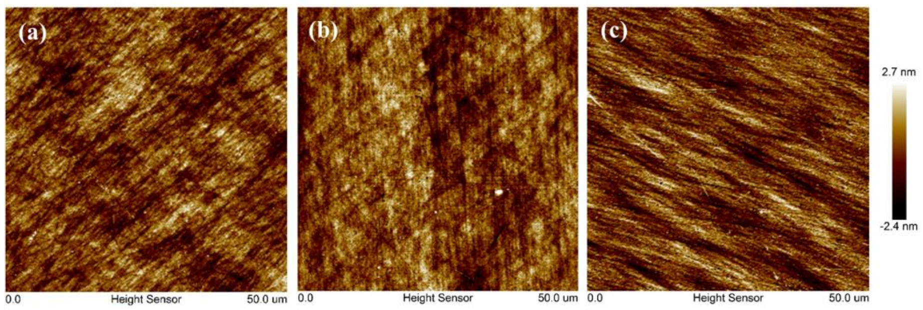


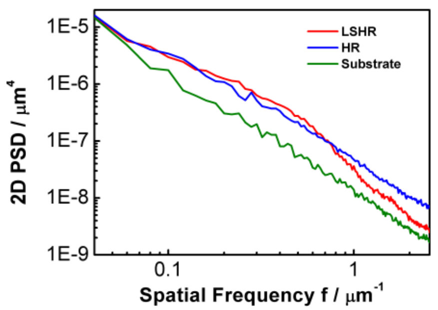
It is still possible to reduce the total scattering in the entire reflection hemisphere

The destructive interference occurs in all directions for s-pol.
The destructive interference does not occur in large scattering angles for p-pol.

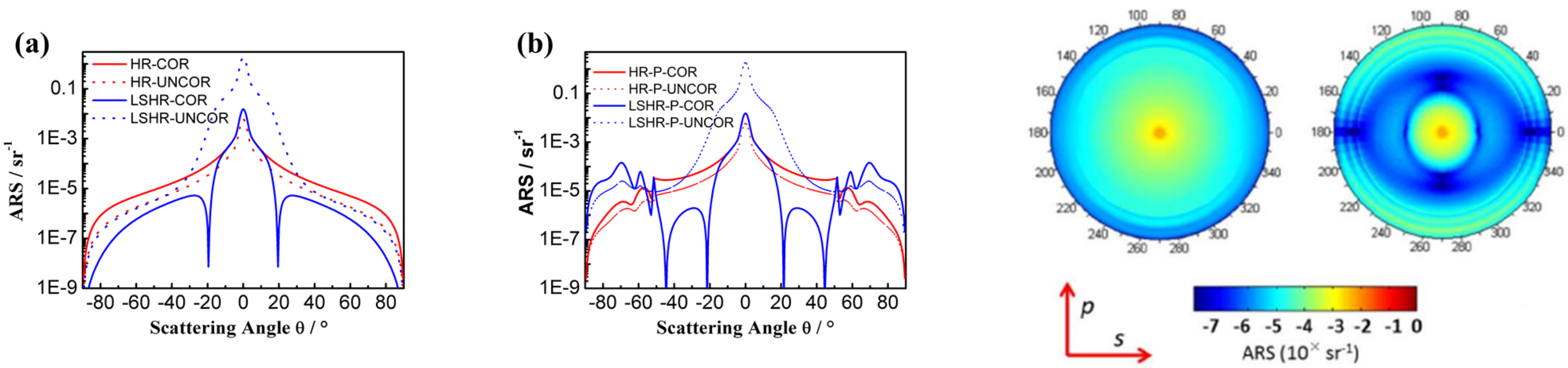
Interface scattering

The QWHR and LSHR coatings were deposited by ion-assisted deposition





The PSD functions fitted with ABC model, The PSDs of both coatings are quite similar



The destructive superposition of the optical factors results in the omnidirectional suppression of ARS for s-polarization

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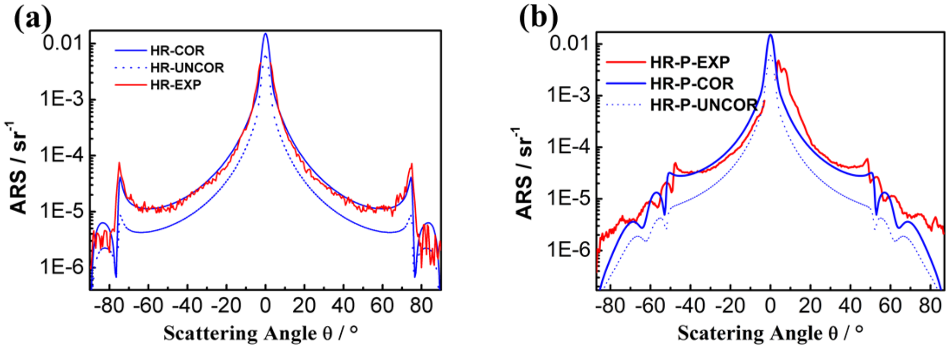
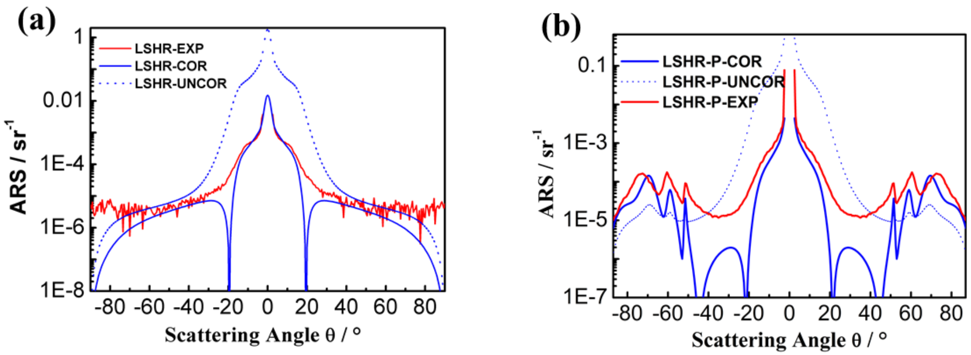
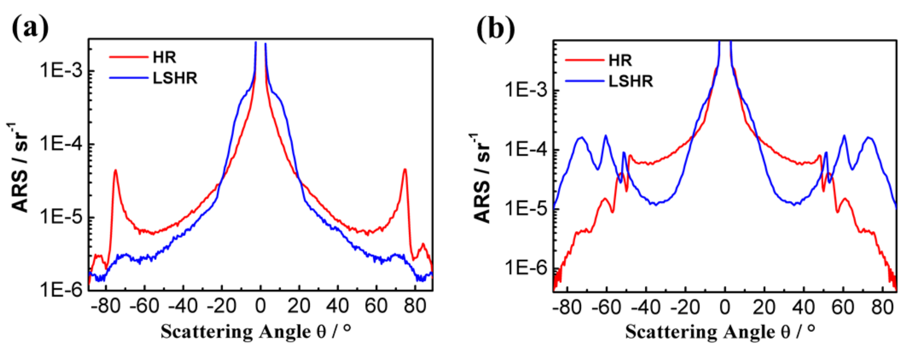
Interface scattering



The experimental results show good correspondence to the theoretical, indicate high correlation of interface



An obvious deviation in the scattering angle between 10 and 30 degrees



The TS for LSHR/QWHR is 1.93E-4, and 2.46E-4 respectively

Further control interface correlation

J. Zhang, et al., Reducing light scattering in high-reflection coatings through destructive interference at fully correlated interfaces, Opt. Lett. 42(23), 5046-5049 2017.

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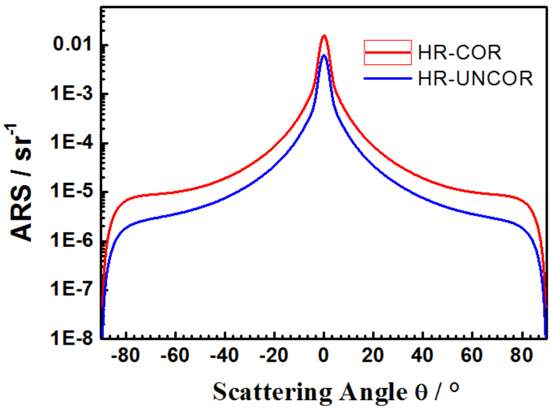
Modify the correlation of PSD

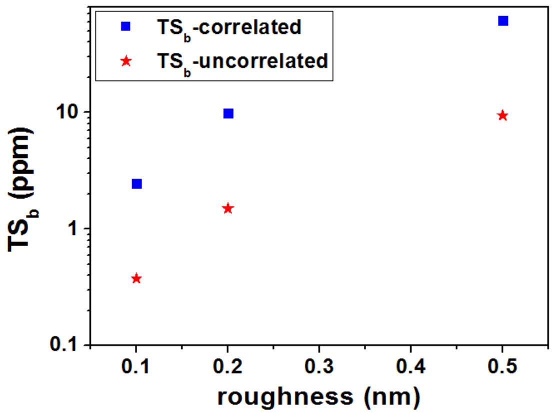
Interface scattering

$$ARS(\theta_s) \propto \frac{1}{\lambda^4} \sum_{i=0}^{N} \sum_{j=0}^{N} F_i F_j^* PSD_{ij}(f)$$

Traditional means of optimizing PSD

- Reducing substrate roughness and Reducing surface roughness





Scattering of QWHR is lower in the case of fully uncorrelated interfaces

The approach to optimize the correlation of interface roughness $PSD_{ij}(f)$ to reduce interface scattering

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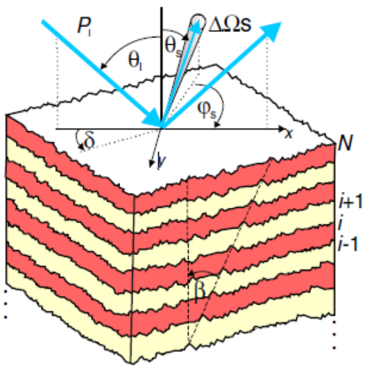
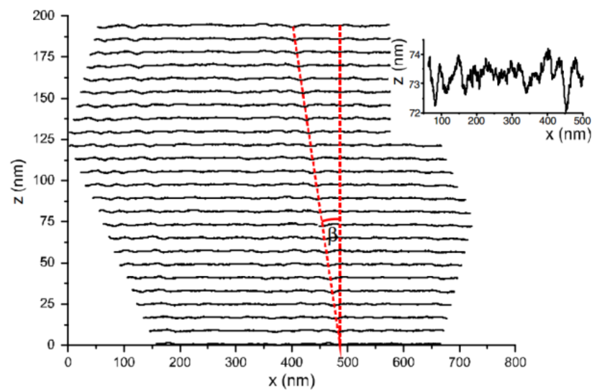
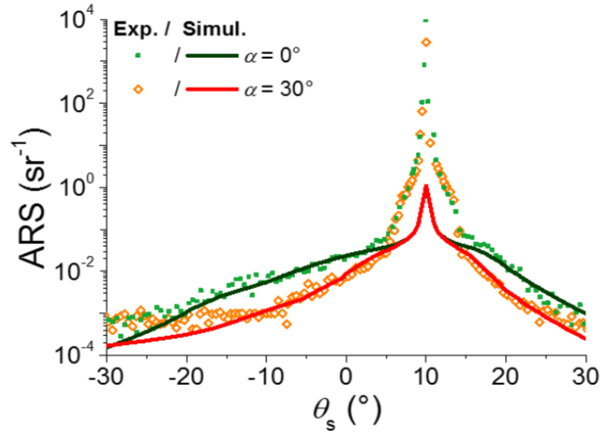
Modulating $PSD_{ij}(f)$ by oblique multilayer deposition

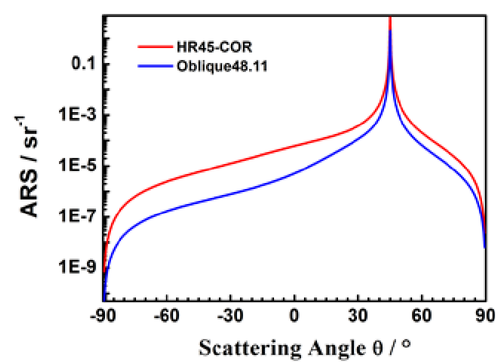
$$\mathrm{PSD}_{ij,\mathrm{oblique}}(f) = \mathrm{PSD}_{ij,\mathrm{normal}}(f)e^{-2\pi i\times f(z_i-z_j)\tan\beta\cos(\varphi_s+\delta)}$$







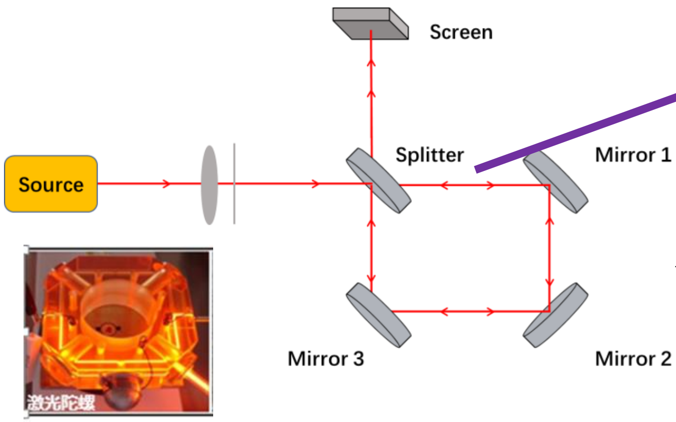
The total scattering loss is reduced by 28% with deposition angle of 30° in Mo/Si (HL)^25, λ=13.5nm



QWHR coating at 800nm

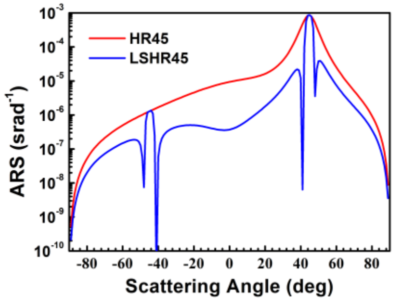
1、M. Trost, T. Herffurth, et al., *Appl. Opt*. 53(4), A197-A204 (2014)

Scattering study for Laser gyro



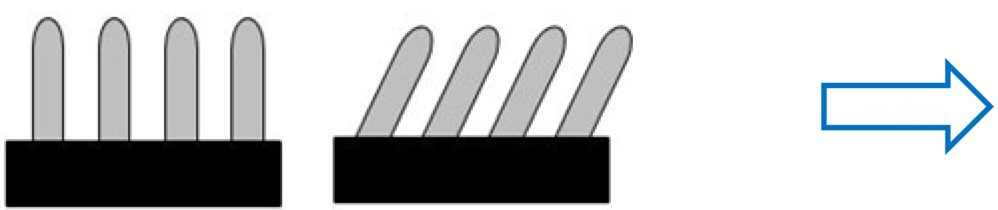
The lock-in threshold of Laser Gyros is limited by scattering in the counterpropagating direction

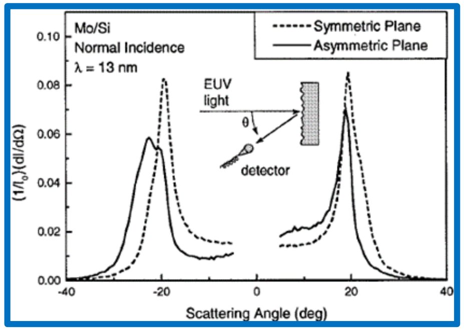
$$ARS(\theta_i,\pi,\theta_i)=\frac{k^4}{\pi^2}\cos^3\theta_i\cdot|r(\theta_i)|^2\cdot\mathrm{PSD}\left(2k\sin\theta_i\right)$$



In the case of fully correlated roughness, the backscattering intensity could be only reduced through a decrease in the reflectivity

Oblique deposition make the scattering pattern asymmetric





Suppressed backscattering in towards the incident beam by oblique deposition

1. Gullikson E M, Stearns D G. Asymmetric extreme ultraviolet scattering from sputter-deposited multilayers[J]. Physical Review B, 1999, 59(20): 13273.

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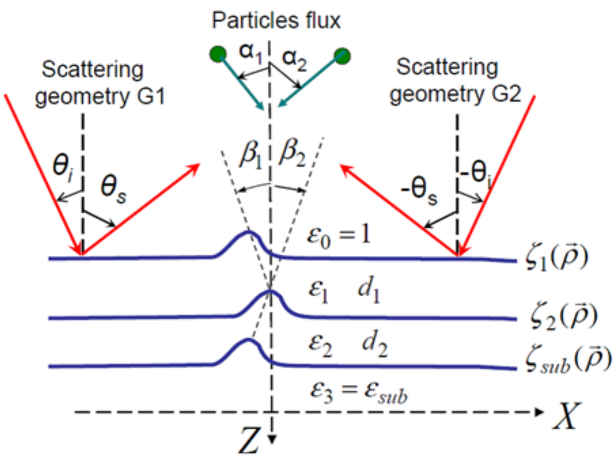
A simplified model of a bi-layer by oblique deposition on a substrate



$$Z_2(\vec{\rho}) = Z_{sub}(\vec{\rho} + \vec{n}_x d_2 \tan\beta_2),$$
$$Z_1(\vec{\rho}) = Z_{sub}(\vec{\rho} + n_x d_2 \tan\beta_2 + n_x d_1 \tan\beta_1)$$

FT

$$Z_2^F(\vec{\nu}) = Z_{sub}^F(\vec{\nu})\, e^{i\eta_2}, \quad Z_1^F(\vec{\nu}) = Z_{sub}^F(\vec{\nu})\, e^{i(\eta_1+\eta_2)},$$
$$\eta_j \equiv -2\pi\nu_x d_j \tan\beta_j$$

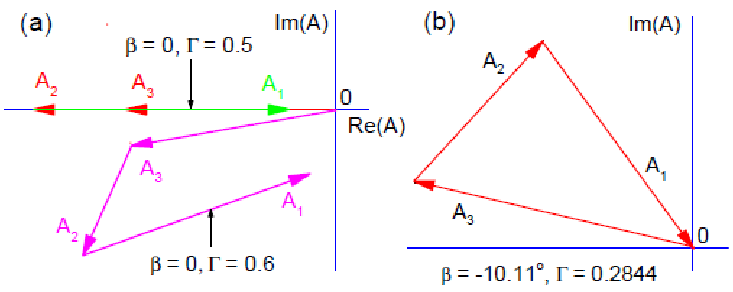
$$ARS(\theta_s,\theta_i) \sim 1 + \underbrace{\frac{\varepsilon_2-\varepsilon_1}{\varepsilon_3-\varepsilon_2}\cdot\frac{E_0(z_2,\theta_i)E_0(z_2,\theta_s)}{E_0(z_3,\theta_i)E_0(z_3,\theta_s)}}_{C\cdot\exp(i\gamma_2)}\cdot e^{i\eta_2} + \underbrace{\frac{\varepsilon_1-\varepsilon_0}{\varepsilon_3-\varepsilon_2}\cdot\frac{E_0(z_1,\theta_i)E_0(z_1,\theta_s)}{E_0(z_3,\theta_i)E_0(z_3,\theta_s)}}_{B\cdot\exp(i\gamma_{12})}\cdot e^{i(\eta_1+\eta_2)}$$

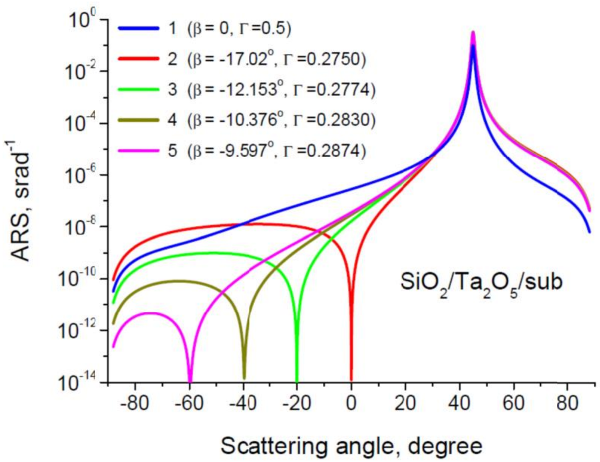
The condition of total scattering suppression

$$ARS = 1 + C e^{ic} + B e^{ib} = 0$$

J. Zhang, et al,. Opt. Express, 27(11), 15262-15282 2019.

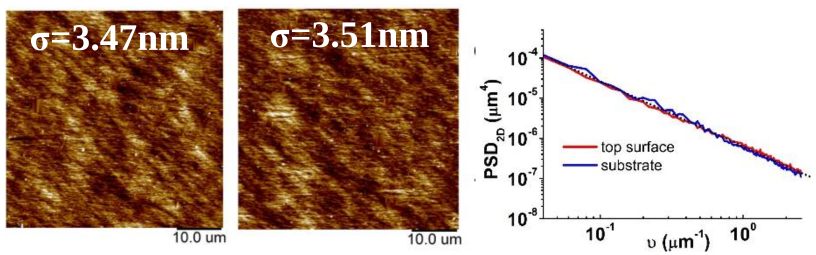
$$ARS = 1 + C e^{ic} + B e^{ib} = 0$$



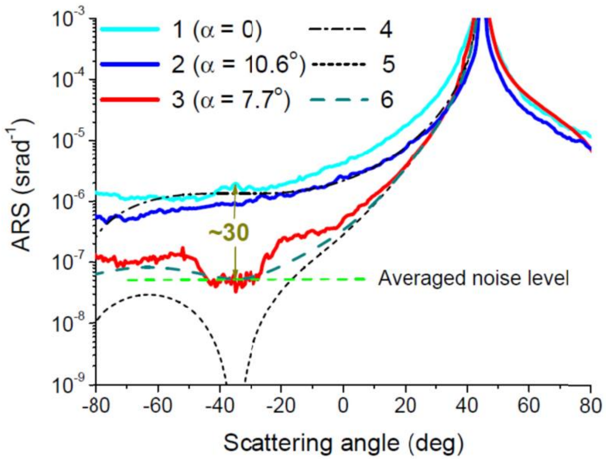


Design bi-layers providing total scattering suppression at any desired scattering angle

IBS to deposit the bi-layer

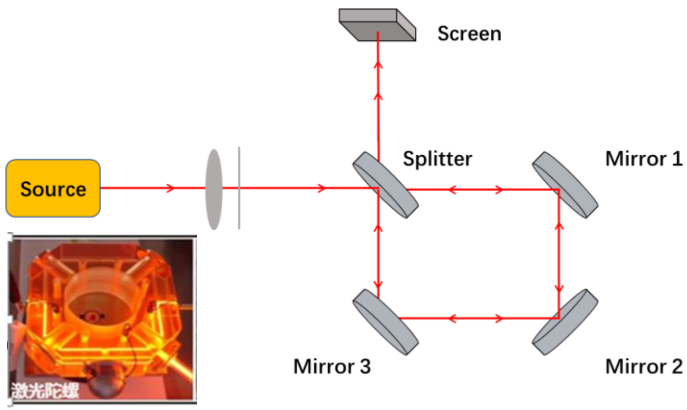


The growth angle is difficult to determine

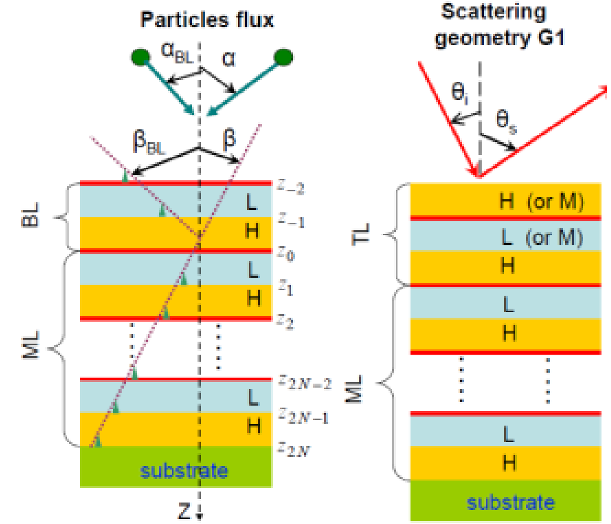


The suppression of backscattering in the desired direction due to interference was experimentally observed

Suppresses scattering of HR coatings for both counter-propagating waves at once



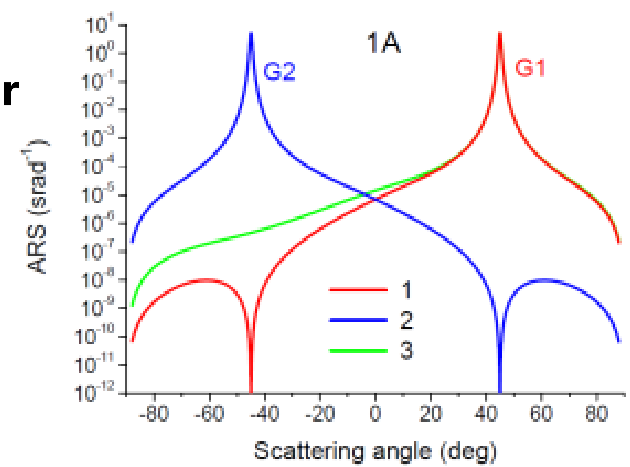
Quarter wave layers



The condition of the scattering suppression for bi-layer

$$A(\theta_i=-\theta_s=45^\circ)=\frac{k^2}{4\pi}(1-\varepsilon_L)\cdot E_0^2(\theta_i)\cdot\frac{\kappa_H^2}{\kappa_L^2}\cdot\frac{e^{2i\eta_{BL}}}{1-e^{-i\eta}\,\kappa_L^2/\kappa_H^2}\cdot\zeta_{ML}^F(\vec{v})$$

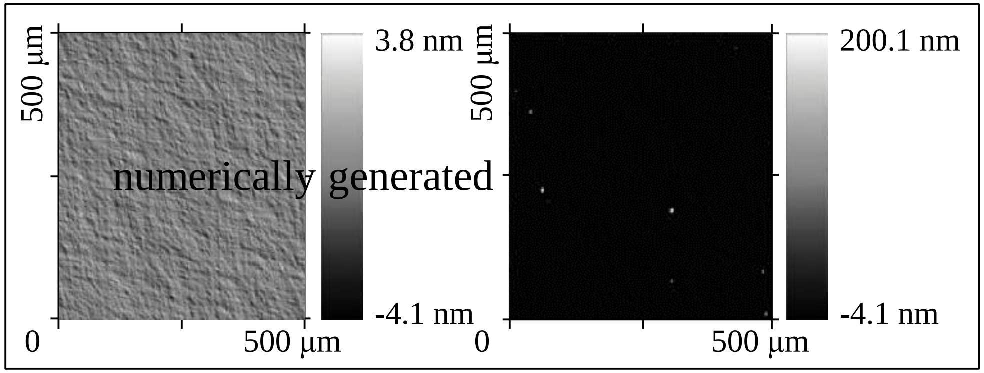
$$\times\underbrace{\left[1-\frac{\varepsilon_L-\sin^2\theta_i}{\varepsilon_H-\sin^2\theta_i}\left(\frac{\varepsilon_H-\varepsilon_L}{\varepsilon_L-1}e^{-i\eta_{BL}}+e^{-i\eta}\right)\right]}_{F}=0;\quad \kappa_{H,L}=\frac{2\pi}{\lambda}\sqrt{\varepsilon_{H,L}-\sin^2\theta_i}$$

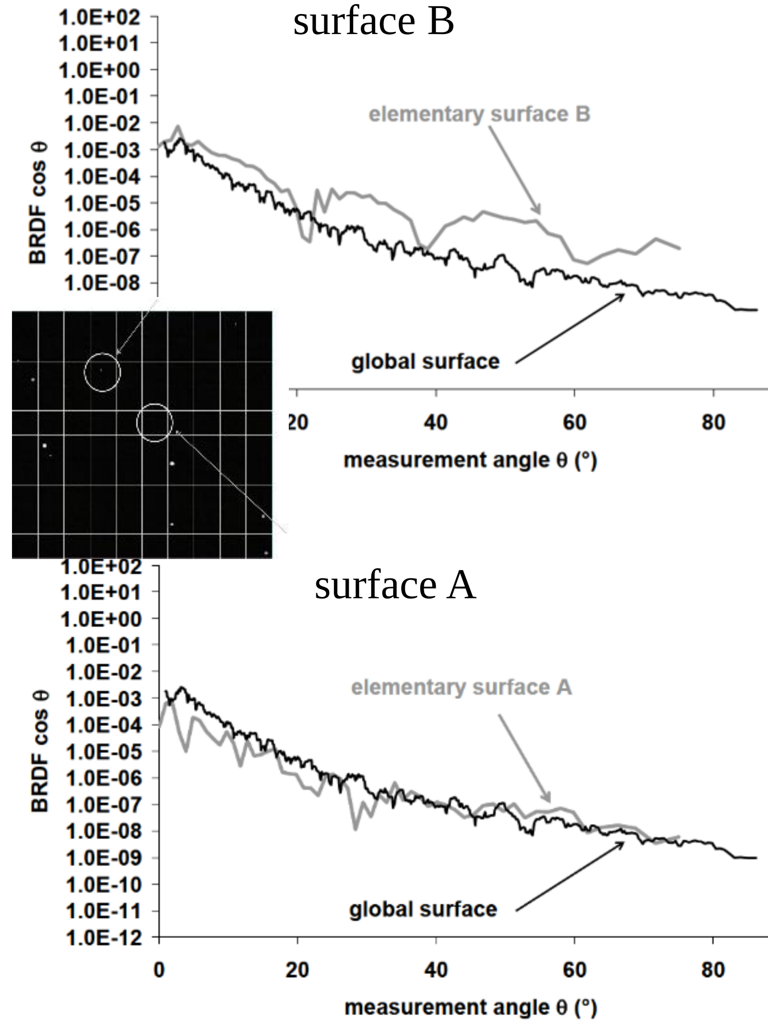


The maximal field intensity is achieved on the mirror top resulting in increasing absorption and parasitic scattering from the contamination

simple shaped defect

e.g., dome shaped defect on sub.





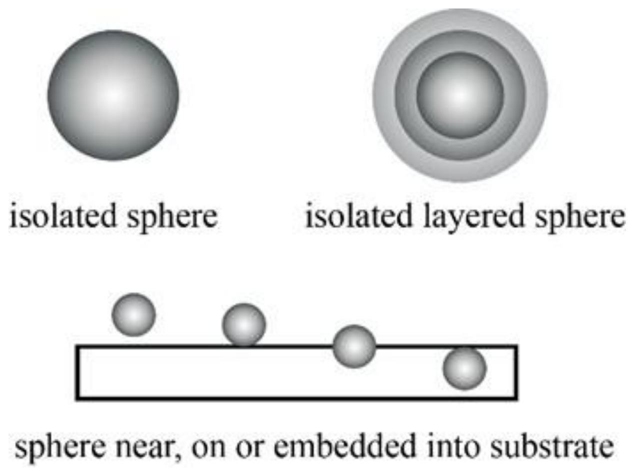
based on first-order perturbation

$$BRDF\cos\theta \propto \left[\frac{J_1\left(\frac{2\pi a}{\lambda}\sin\theta\right)}{\frac{2\pi a}{\lambda}\sin\theta}\right]^2$$

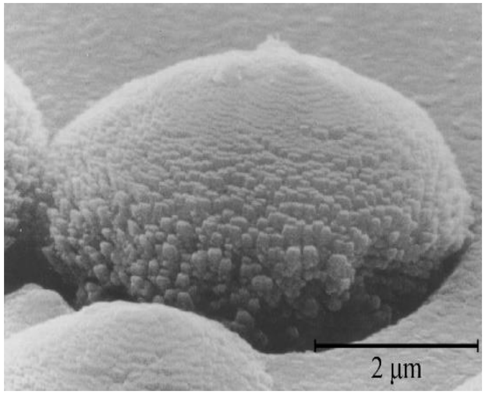
$$\sin\theta_m \approx \frac{Z_m}{\pi}\frac{\lambda}{2a}$$

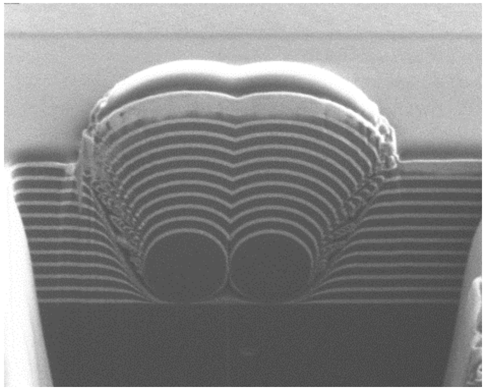
M. Zerrad, M. Lequime, C. Deumié, C. Amra, "Development of a goniometric light scatter instrument with sample imaging ability," Proc. of SPIE 7102, 7102071-71020715 (2008).

Simplified models in traditional analytical methods



The actually complex-shaped nodular defects

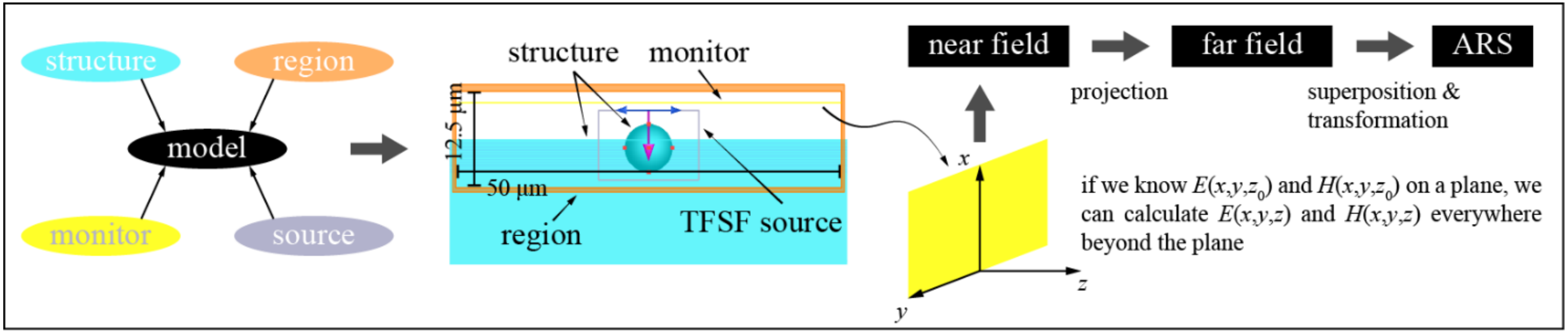




FDTD method is widely used in solving the scattering problem of the structure on the order of illumination wavelength

1、A. Doicu, Y. Eremin, et al., *Opt. Com.* 159(4), 266-277 (1999)
2、M J. Brett, R N. Tait, et al., *J. Mat. Sci.* 3(1), 64-70 (1992)

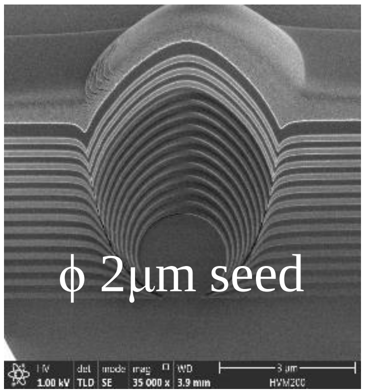
FDTD simulation process

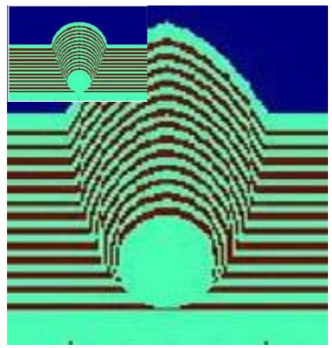


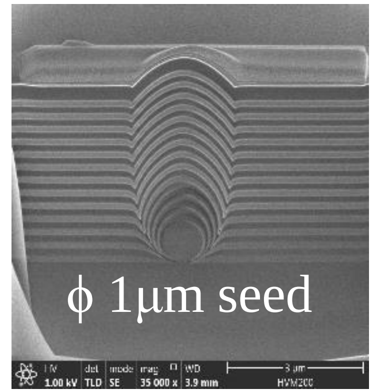
- region: PML boundary condition
- TFSF source: E=1 V·m^{-1}, λ=1064 nm, linear polarization, normal incidence

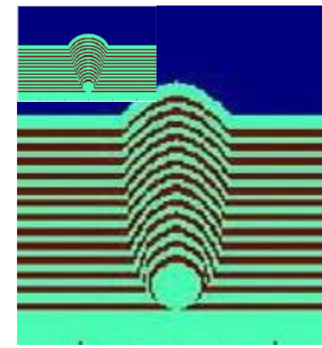
TFSF (total field scattered field) source separates the simulation region into two regions, the region inside TFSF box contains total field, the region outside contains only scattered field

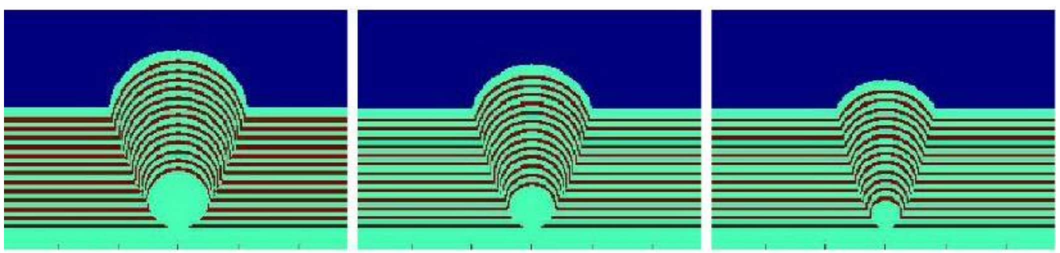
SEM cross-sectional micrographs











(d) 2.5*dt* - 2 μm (e) 2.5*dt* - 1.5 μm (f) 2.5*dt* - 1 μm

FS-fused silica substrate, H-Ta_2O_5, L-SiO_2, FS|$(HL)^{13}$L|Air @1064nm

the real shapes are exactly different from the 2.5dt models

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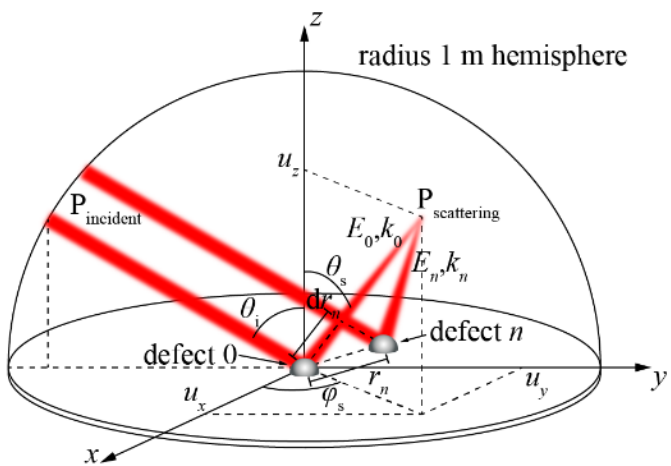
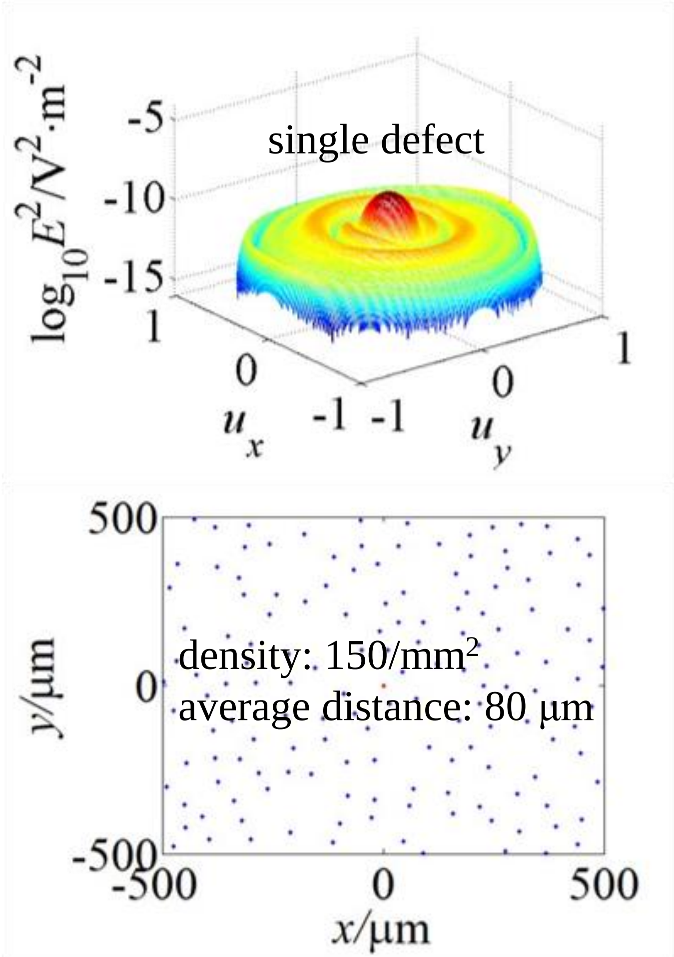
Far field superposition

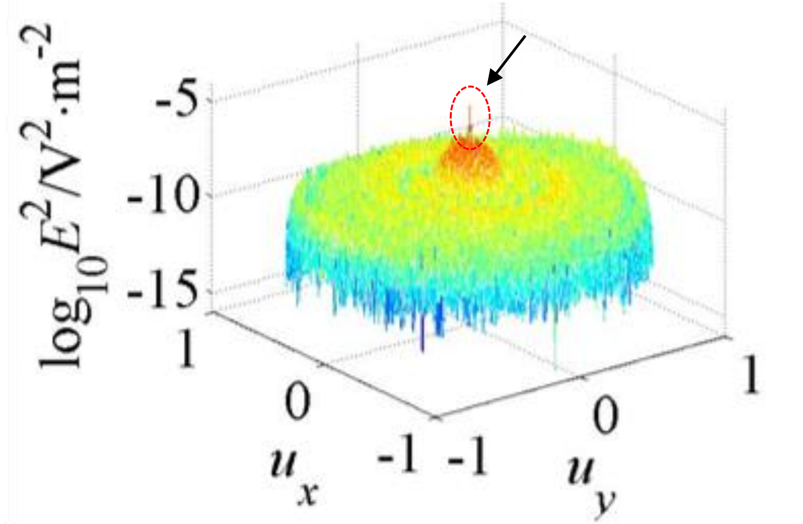


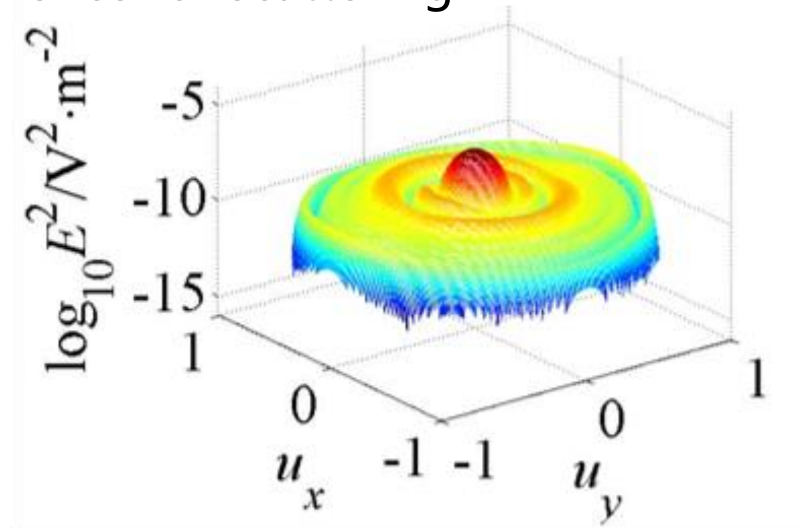
$$\begin{cases} E^2_{\text{amplitude}} = \left(\sum E_0 e^{ik_0 \cdot dr_n}\right) \cdot \left(\sum E_0 e^{ik_0 \cdot dr_n}\right)^* \\ E^2_{\text{intensity}} = nE_0^2 \end{cases}$$



amplitude superposition **intensity superposition**

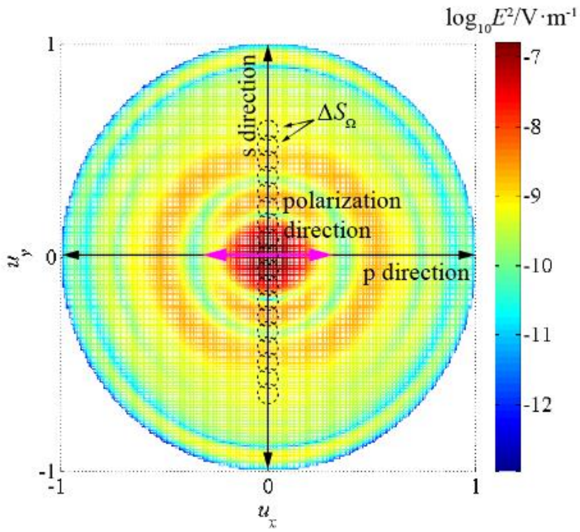
make no difference for scattering

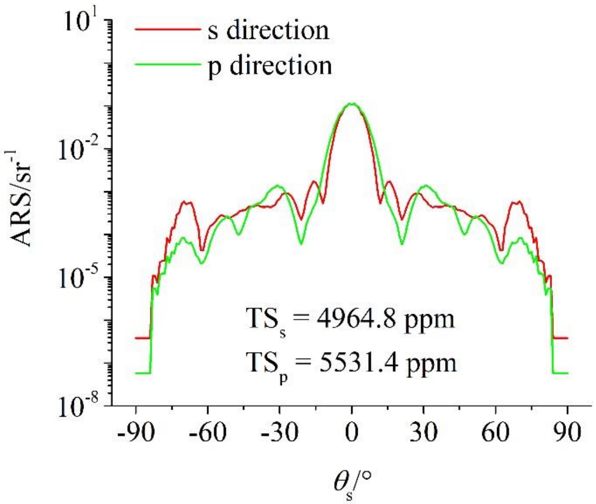




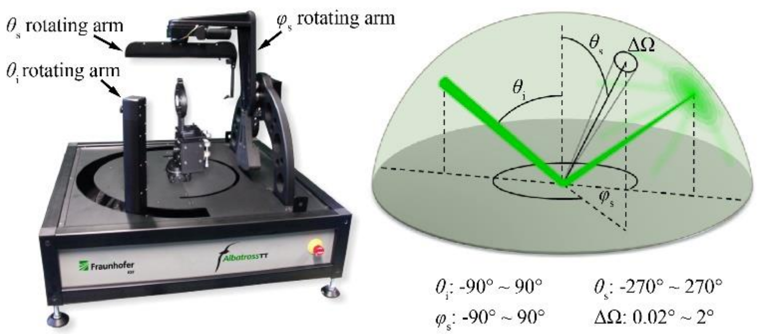
when the average distance >> defect size, except for the enormous burrs and a coherent enhancement at the center, the rough outlines of the amplitude and intensity superposition are same

Far field to ARS

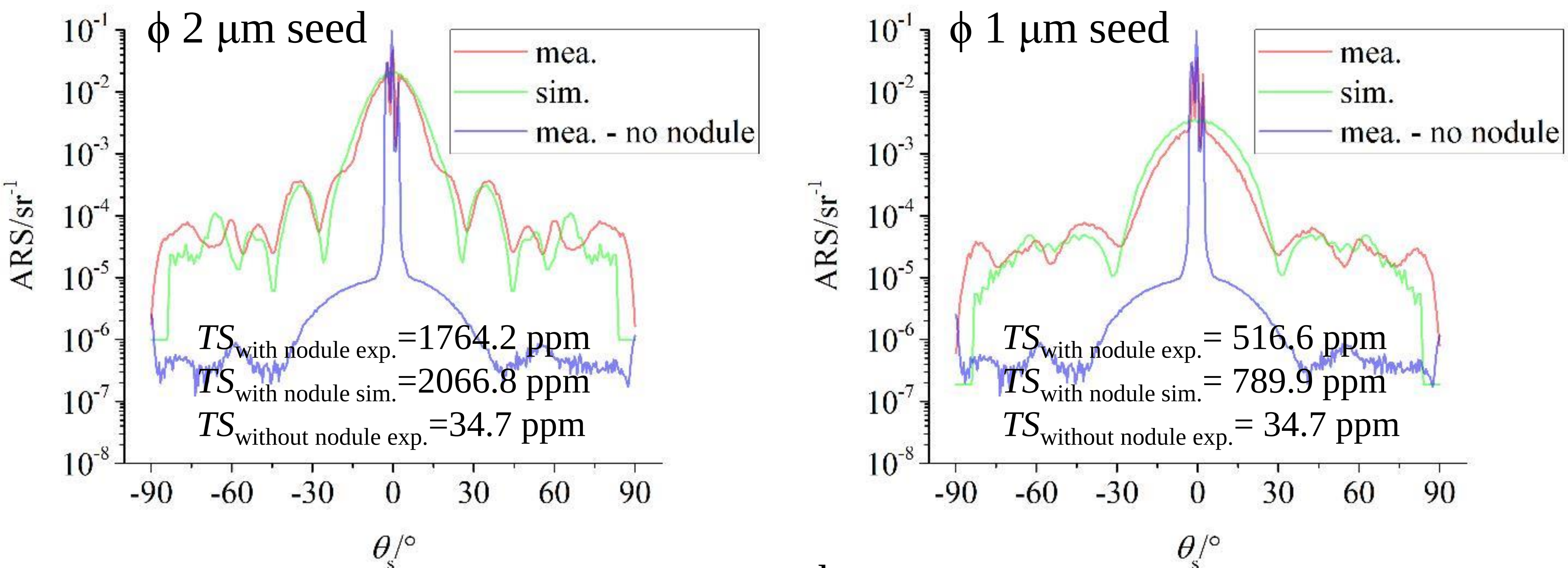




$$ARS = \frac{\mathrm{d}P_\mathrm{s}}{P_\mathrm{i}\mathrm{d}\Omega} = \frac{\frac{1}{2}\sqrt{\frac{\varepsilon_0}{\mu_0}}E^2 \cdot \mathrm{d}S_\Omega}{P_\mathrm{i}\frac{\mathrm{d}S_\Omega}{r^2}}$$



Scattering measurement results vs. simulation results – s direction



match

simulation ⟷ measurement

The characteristics of the defect-induced and roughness-induced scattering are significantly different.

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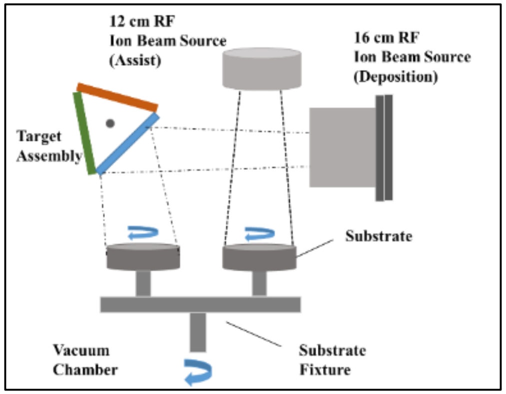
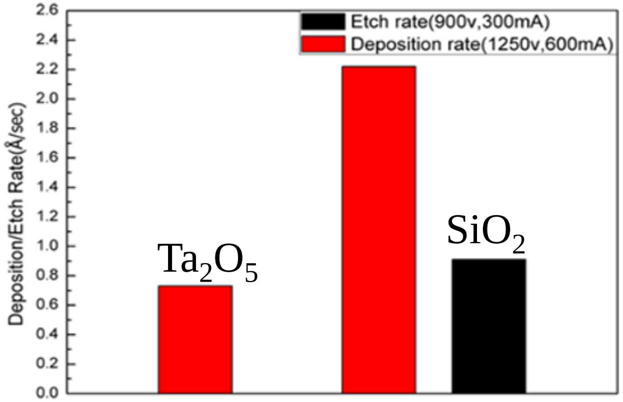
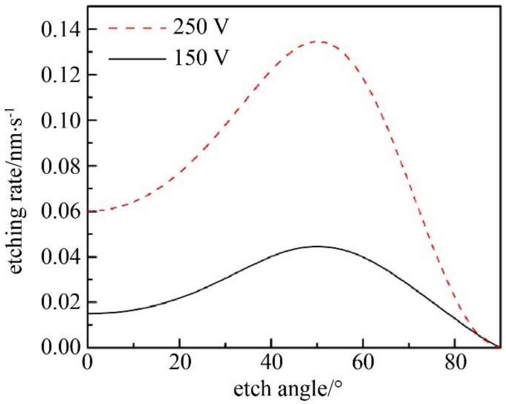
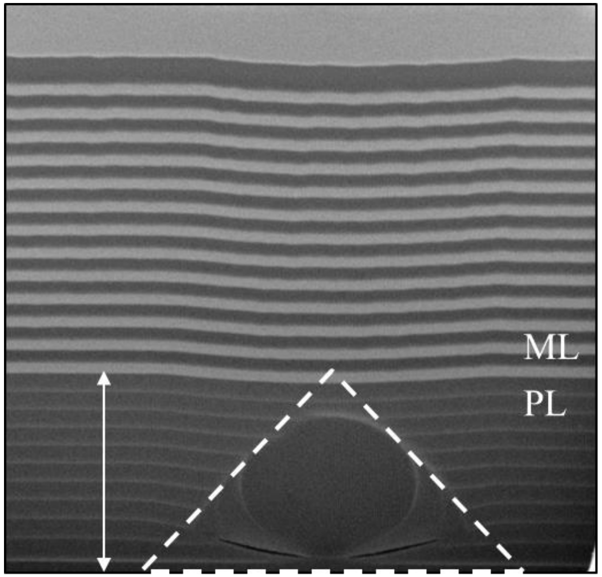
DIBS, 12 cm ion beam source for etching



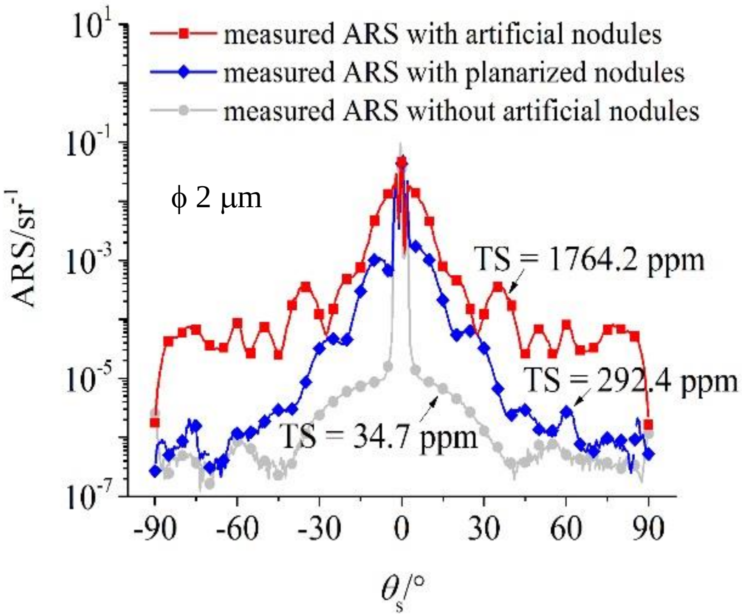


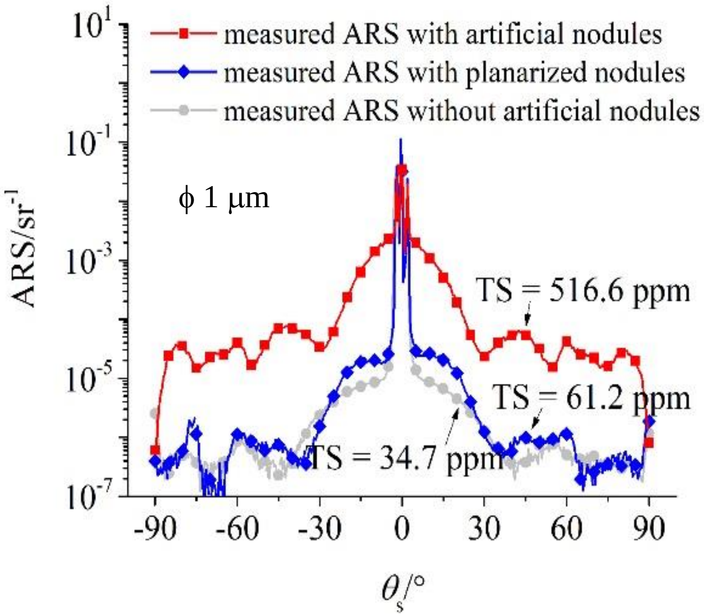




Seed is completely embedded in the planarization layer, nodule is eliminated effectively.

Scattering measurement results before and after planarization





TS is effectively decreased after plan, for ϕ1μm seed it almost reach to level of without nodule, but for ϕ2μm seed it still large.

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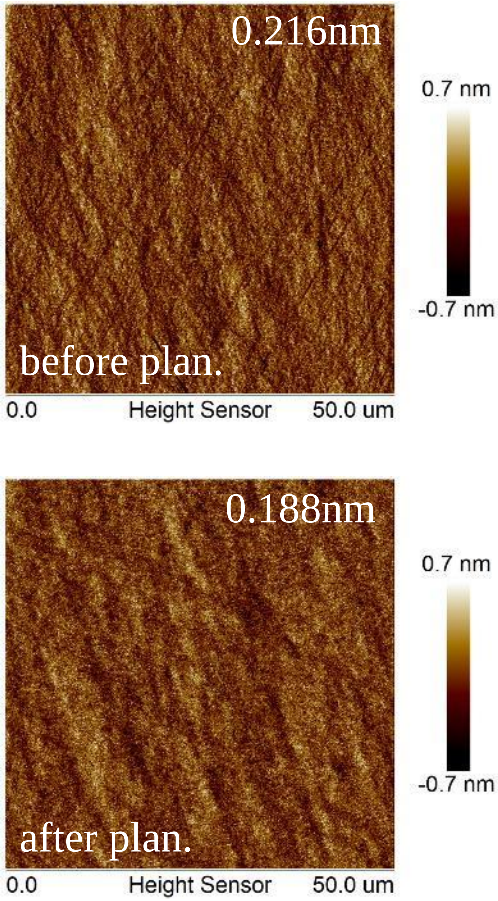
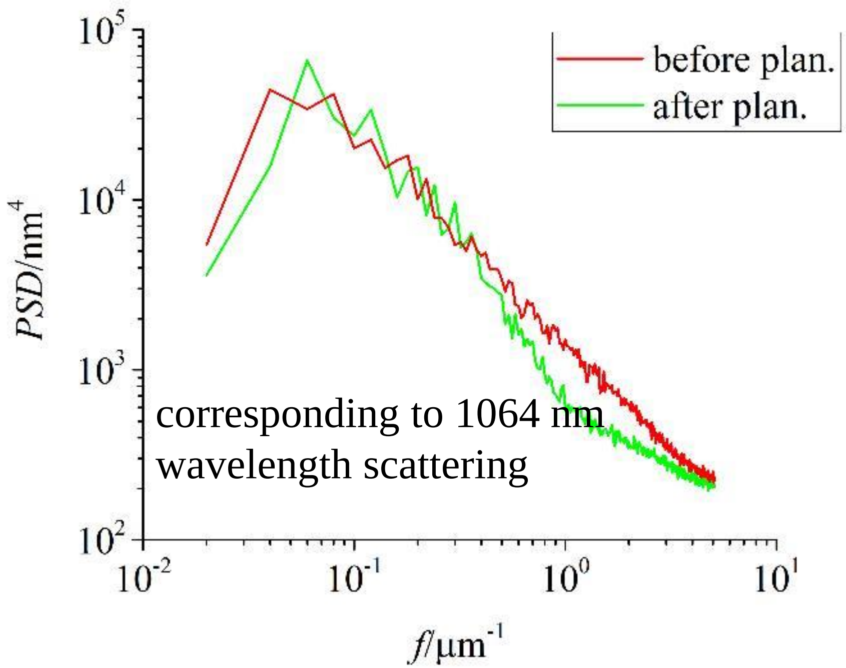
Roughness after planarization





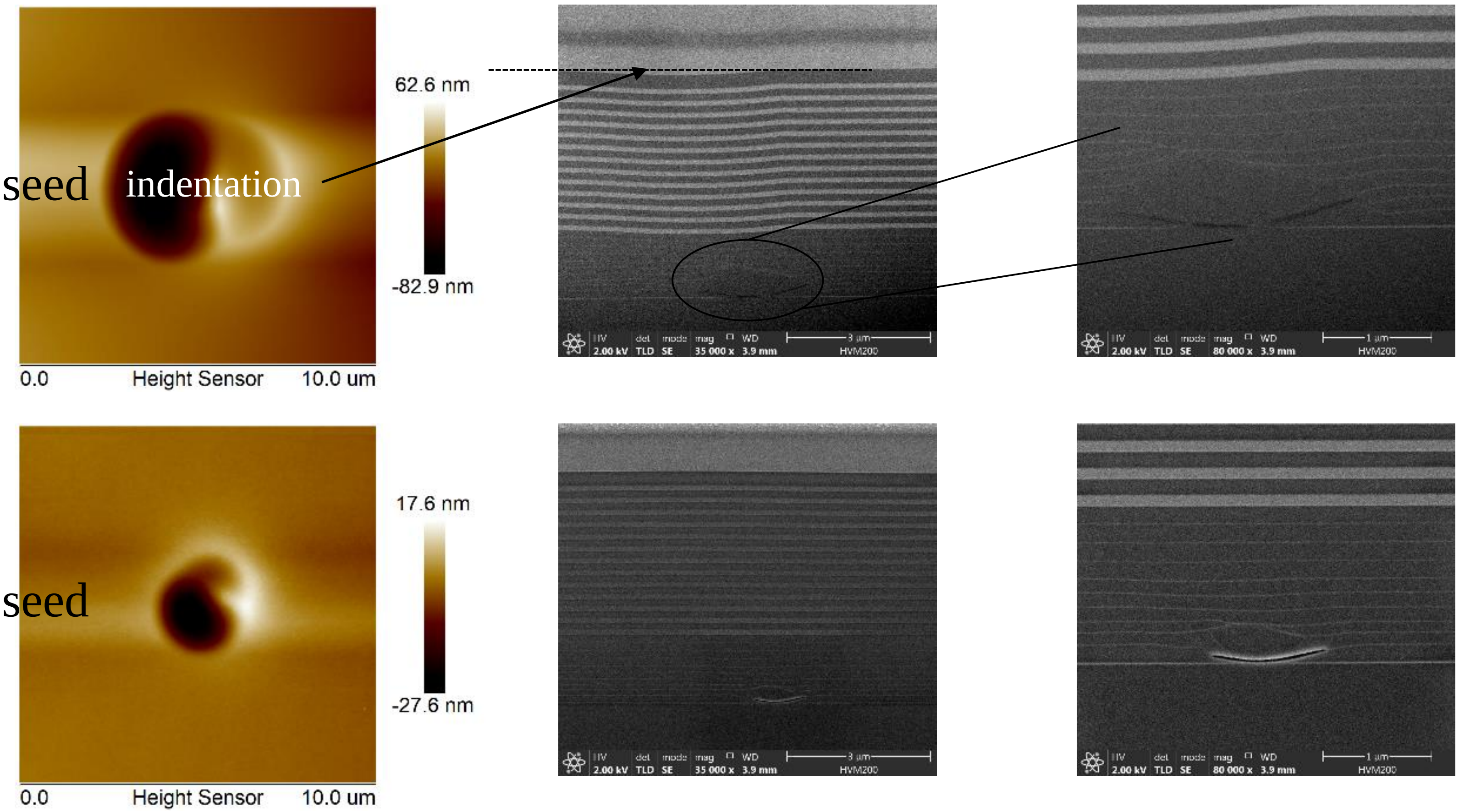
Planarization process decreases the roughness, so the roughness-induced scattering in theory

Micrograph of nodule after planarization

AFM micrograph | **SEM cross-section micrograph**

ϕ 2μm seed

ϕ 1μm seed



The nodule was completely eliminated, even there existed a indentation upon the seed and the seed was etched partly.

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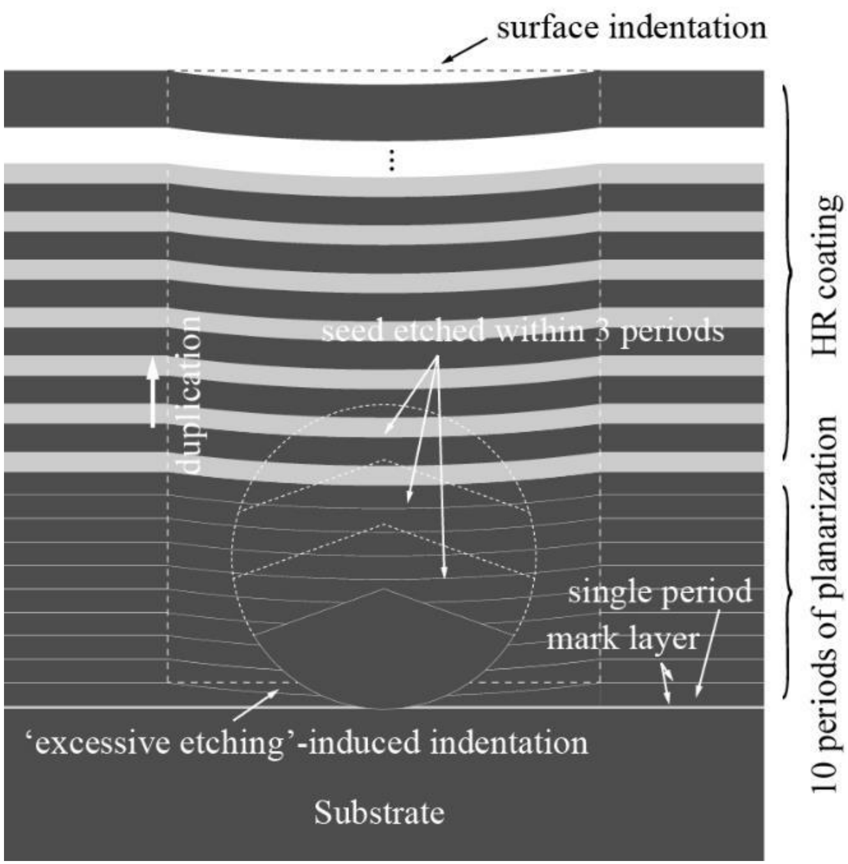
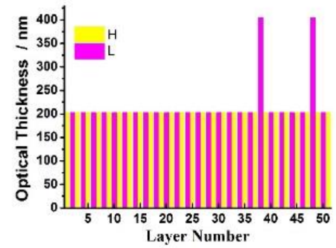
Schematic diagram of nodule after plan

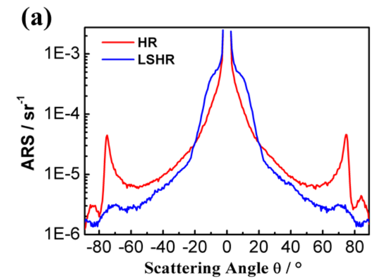


- **Surface indentation is the reason for not complete elimination of the nodular defect-induced scattering**
- **Surface indentation may be caused by excessive etching**

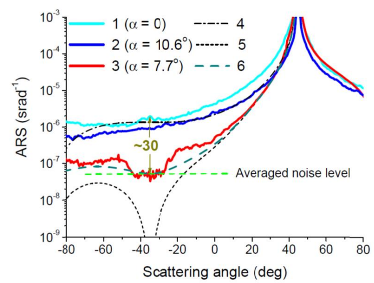
Conclusion

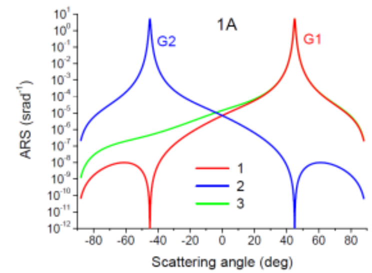
- **Scattering reduction of HR coatings by destructive interference of scattered waves on fully correlated interfaces**



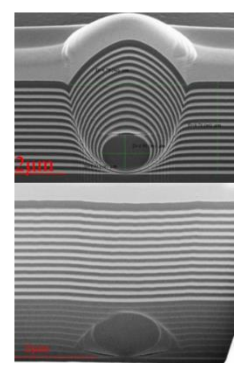


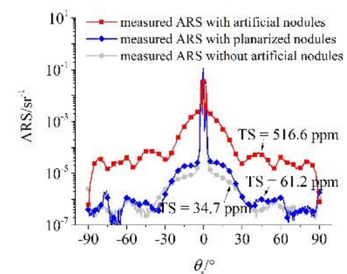
- **Interference suppression of light back scattering through oblique deposition**





- **Quantitative assessment of defect-induced scattering in HR coatings, suppression of nodules with planarization**





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Thank you!

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Thin Films Technical Group

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