GRASS 2022

Light scattered by high performance optical components: Numerical prediction and accurate metrology

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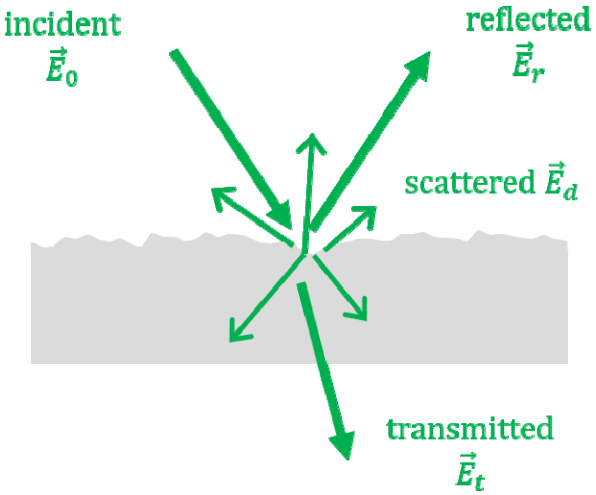
Light Scattering Group (CONCEPT)

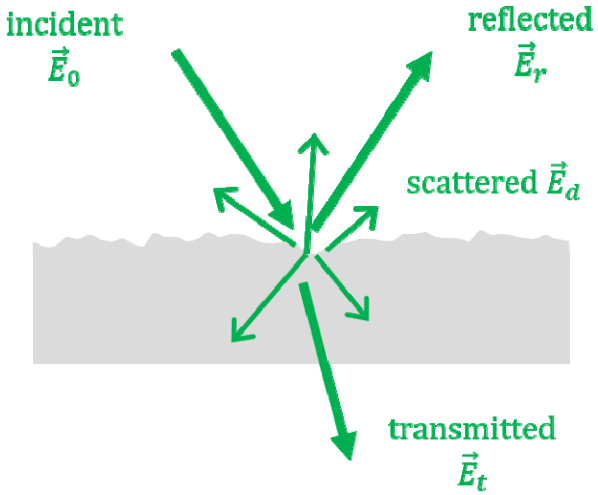
Theoretical considerations

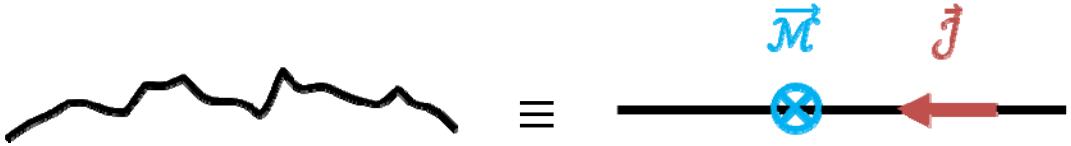
- **Light scattered by an optical surface**
  - ***Any optical surface is characterized by a certain roughness, possibly very low***
  - ***Any rough interface generates a scattered field***



Theoretical considerations

- **Light scattered by an optical surface**
  - ***Any optical surface is characterized by a certain roughness, possibly very low***
  - ***Any rough interface generates a scattered field***
  - ***A rough surface is equivalent to a plane surface supporting fictitious currents***





Theoretical considerations

- **Light scattered by an thin film stack**
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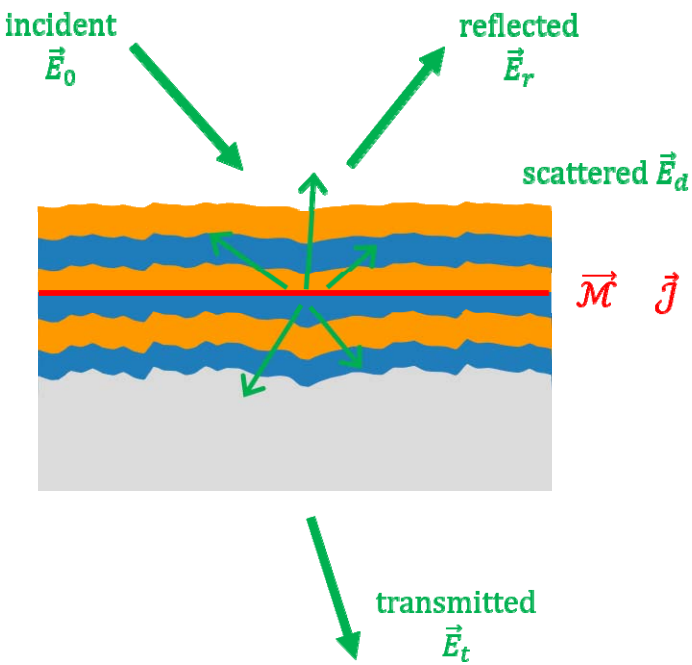

Theoretical considerations

- **Light scattered by an thin film stack**
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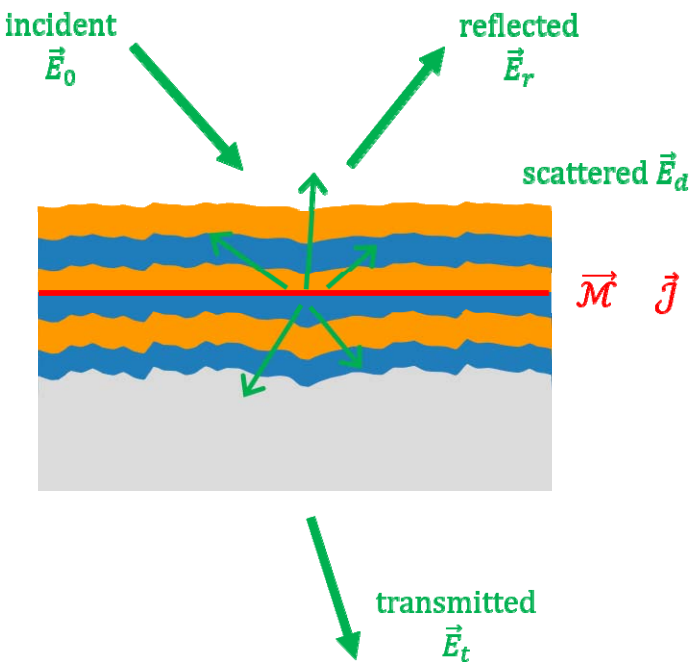
  - ***Thin-film energetic deposition processes replicate substrate roughness***



Theoretical considerations

- **Light scattered by an thin film stack**
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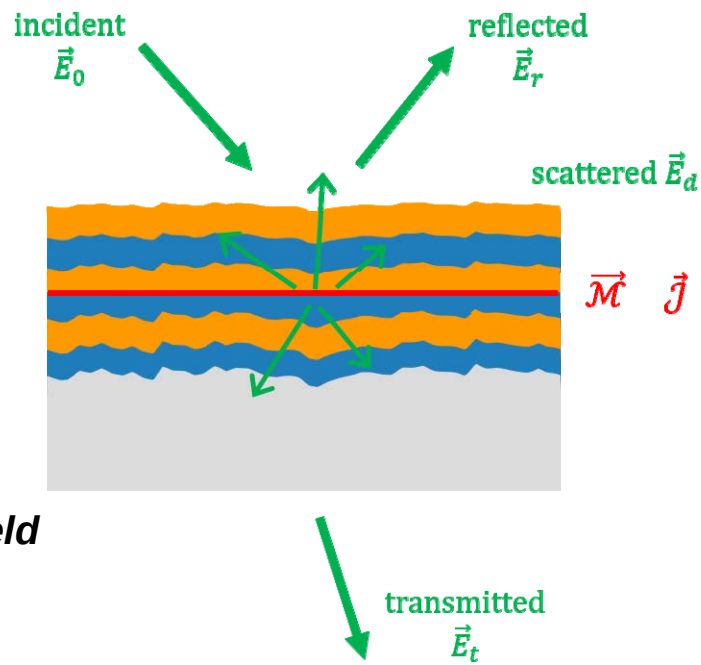


$$\vec{E}_d = \sum_j \vec{E}_{d,j}$$

Theoretical considerations

- **Light scattered by an thin film stack**

$$\mathrm{ARS} = \frac{1}{P_i}\frac{dP_s}{d\Omega_s}$$

$$\mathrm{ARS}^{\pm} = \frac{1}{S}\sum_{j=0}^{p}\left|D_j^{\pm}\hat{h}_{e,j}\right|^2 + \frac{1}{S}\left\{\sum_{j=0}^{p}\sum_{k\neq j} D_j^{\pm}\left[D_k^{\pm}\right]^{*}\hat{h}_{e,j}\hat{h}_{e,k}^{*}\right\}$$

$$\hat{h}_{e,j} = \mathrm{FT}\left[h_j s_e\right] \;;\; s_e(x,y) = e^{ik_0 x \sin\theta_0^i} e^{-\frac{(x\cos\theta_0^i)^2+y^2}{w_0^2}}$$

Coating & illumination

$D_j^{\pm}$

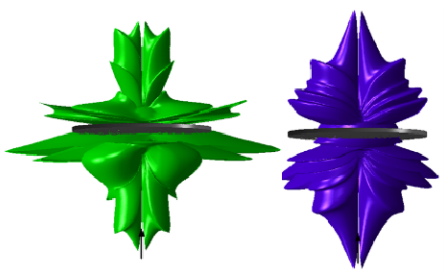
$\hat{h}_{e,j}$

Topography

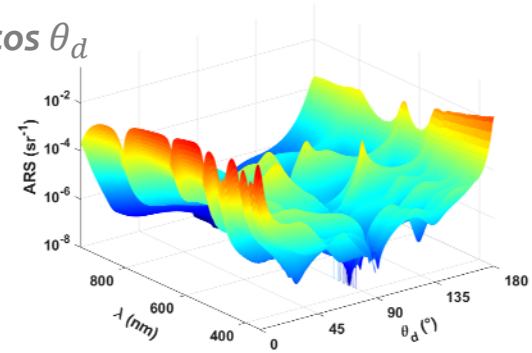
C. Amra, M. Lequime, and M. Zerrad, *Electromagnetic Optics of Thin-Film Coatings: Light Scattering, Giant Field Enhancement, and Planar Microcavities* (Cambridge University Press, 2021).

Theoretical considerations

- **Numerical implementation**
  - ***Inputs***
    - ✓ *Opto-mechanical characteristics of the stack (thicknesses d_j ; refractive indices n_j)*
    - ✓ *Illumination conditions (angle of incidence θ_0^i ; wavelength λ ; state of polarization)*
    - ✓ *Interfaces roughness (substrate roughness spectrum γ_s ; correlation coefficients $\alpha_{e,jk}$)*
  - ***Output***
    - ✓ *Angle Resolved Scattering* $\mathrm{ARS}(\lambda, \theta_d)$ *or BSDF* (λ, θ_d) *cos* θ_d



(θ_d, ϕ)

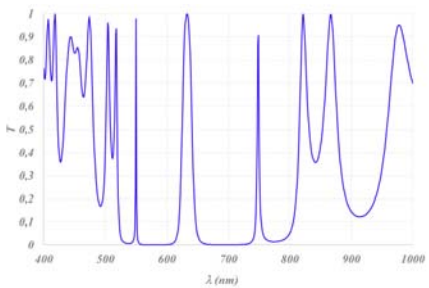


(λ, θ_d)

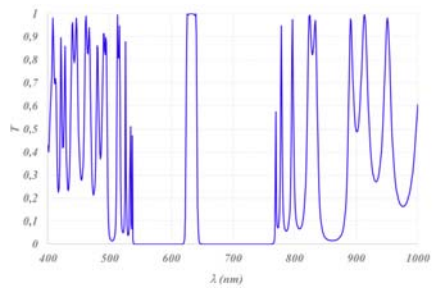
C. Amra, M. Lequime, and M. Zerrad, *Electromagnetic Optics of Thin-Film Coatings: Light Scattering, Giant Field Enhancement, and Planar Microcavities* (Cambridge University Press, 2021).

Numerical application on complex optical coatings

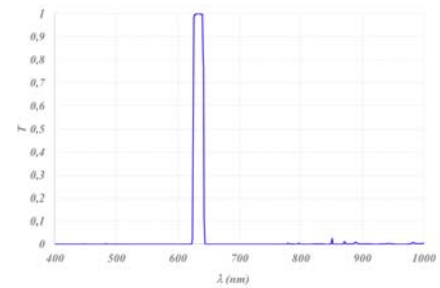
T (λ)



40 layers

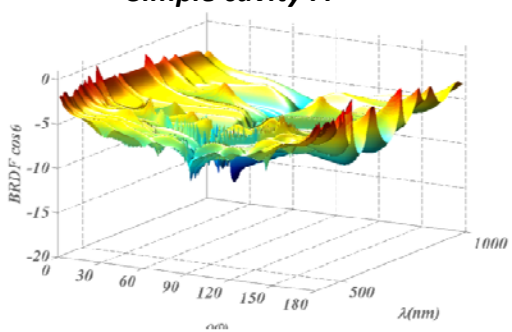


60 layers

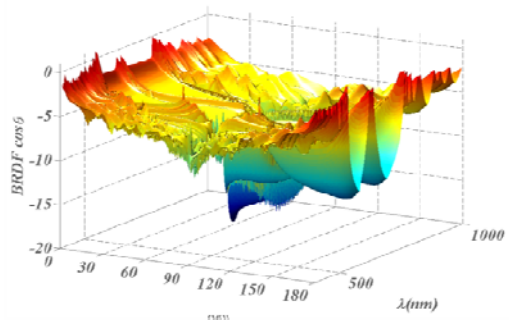


110 layers

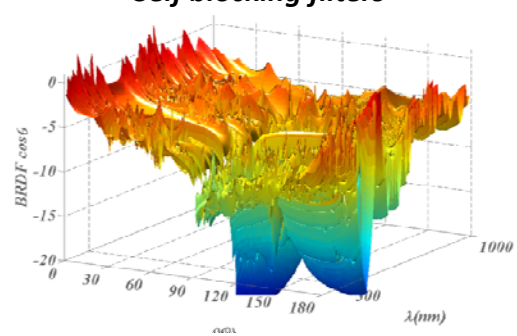
Simple cavity FP



Multiple cavities FP



Multiple cavities FP
+ Self blocking filters

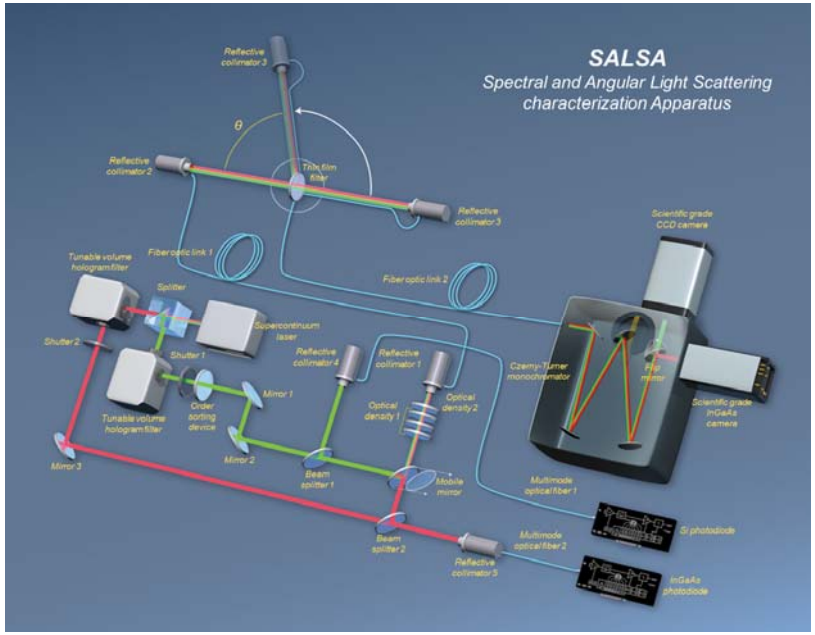


BSDF cos θ

Spectral and Angular Light Scattering characterization Apparatus - SALSA

- Performances 6 decades higher than State of the art spectrophotometers
- Performances of the best laser (monochromatic) scatterometers

On the whole Visible and NIR spectra



Spectral resolution<1 nm
Accuracy < 1%

Detection limits :
- Specular (T & R) : 10^{-13}
- Scattering : 10^{-8} sr^{-1}
(Rayleight Air diffraction)

Performances maintained from 400 to 1650 nm

PLATEFORME TECHNOLOGIQUE AIX-MARSEILLE

Liukaityte et al. Opt. Lett. 40, 3225-3228 (2015)
Lequime et al. Opt. Express 26, 34236-34249 (2018)
Fouchier et al. Opt. Lett. 45, 2506-2509 (2020)

cnes CENTRE NATIONAL D'ÉTUDES SPATIALES
AGENCE INNOVATION DÉFENSE
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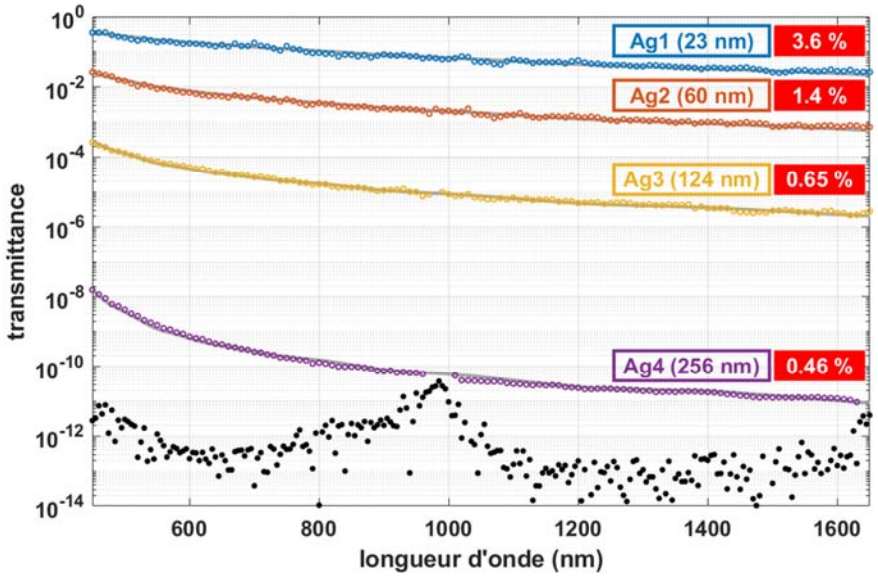
RÉGION SUD PROVENCE ALPES CÔTE D'AZUR

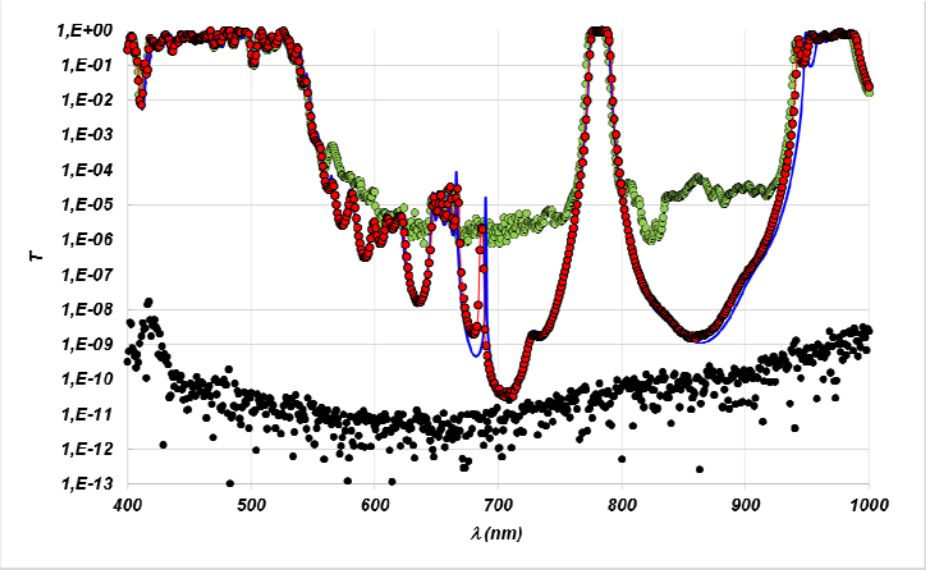
INSTITUT FRESNEL MARSEILLE

SALSA : Accuracy & detectivity



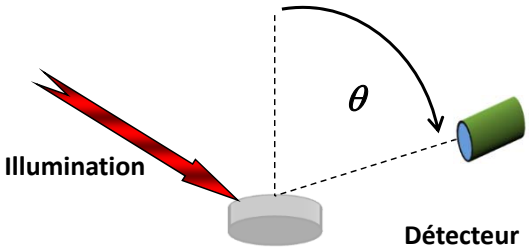
Lequime et al. Opt. Express 26, 34236-34249 (2018)

SALSA Design State of the art spectrophotometer



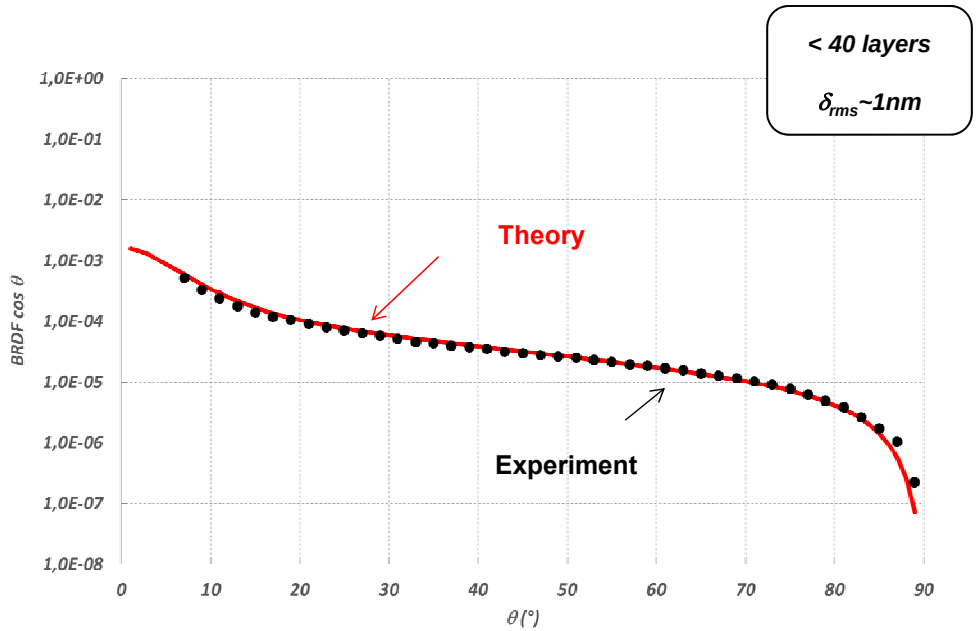
Liukaityte et al. Opt. Lett. 40, 3225-3228 (2015)

Angular Scattering : Metrology vs direct calculation



Measurement @ 1 wavelength

BRDF / BTDF / BSDF



"Light scattering from multilayer optics. I. Tools of investigation," C. Amra , J. Opt. Soc. Am. A **11**, 197- (1994).
"Light scattering from multilayer optics. II. Application to experiment,« , C. Amra , J. Opt. Soc. Am. A **11**, 211- (1994).
"First-order vector theory of bulk scattering in optical multilayers" C. Amra , J. Opt. Soc. Am. A **10**, 365- (1993)

Spectral & Angular Scattering : Metrology vs direct calculation

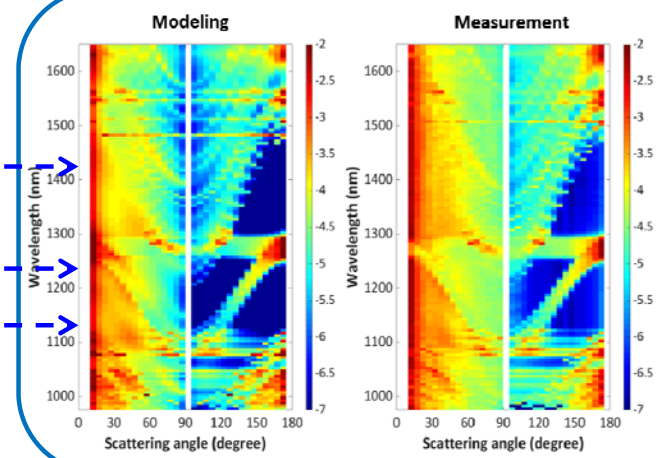
> 100 layers

δ_{rms}~1nm

λ_0

λ_1

λ_2



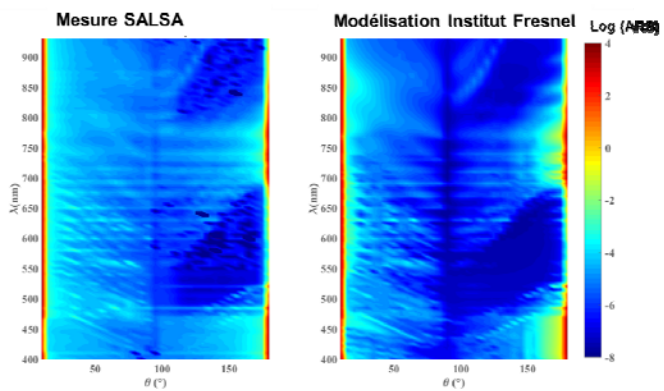
Near Infra-read (950 – 1650 nm)

- ✓ Highlight Photoniques (2020)
- ✓ Highlight NKT Photonics (2020)

Opt. Lett. 45, 2506-2509 (2020)

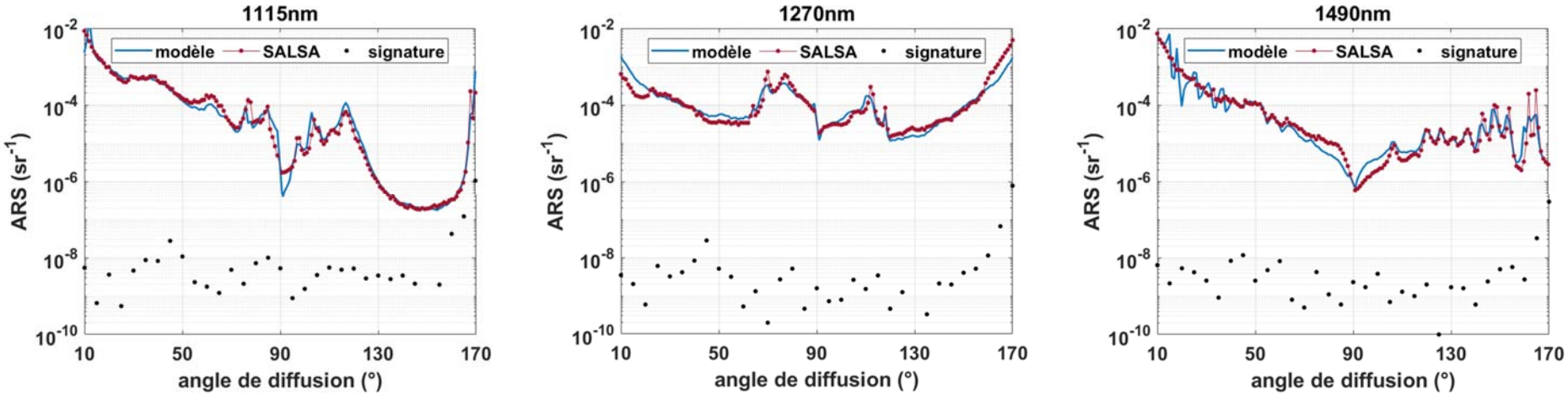
Visible (400 -1000 nm)

- ✓ Highlight CNRS (2018)
- ✓ Highlight NKT Photonics (2017)
- ✓ 2 PhD awards (2017)



Opt. Lett. 40, 3225-3228 (2015);
Opt. Express 23(20) 26863-26878 (2015)
CEAS, Space Journal, 9(4), 473-484 (2017)
Opt. Express 26(26) 34236-34249 (2018)

Spectral & Angular Scattering : Metrology vs direct calculation

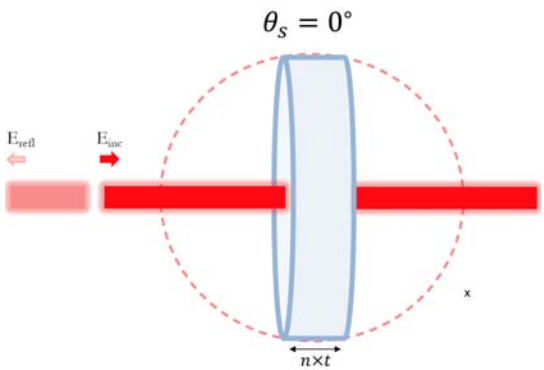


M. Fouchier, M. Zerrad, M. Lequime, C. Amra, "Wide-range wavelength and angle resolved light scattering measurement apparatus," Opt. Letters **45**, 2506-2509 (2020)

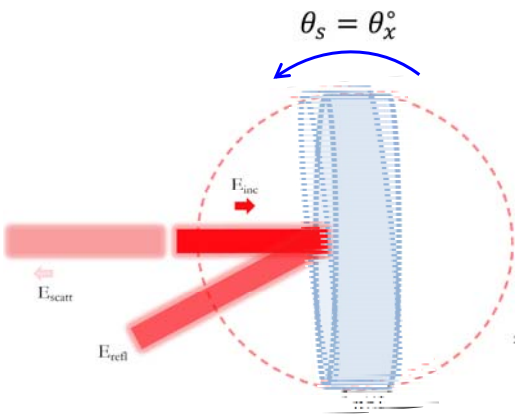
Back-reflection & Back-scattering

Retro-reflection and back-scattering

Retro-reflection



Back-scattering



Both can be problematic for GW detection due to the reinjection of light in the interferometers

Back-reflection and back-scattering metrology

- **OLCBS (*O*ptical *L*ow *C*oherence *B*ack *S*cattering)**

  - ***Balanced low coherence interferometry***
    - ✓ ***Central wavelength: 1060 nm***
    - ✓ ***Spectral range: 1040 – 1080 nm***

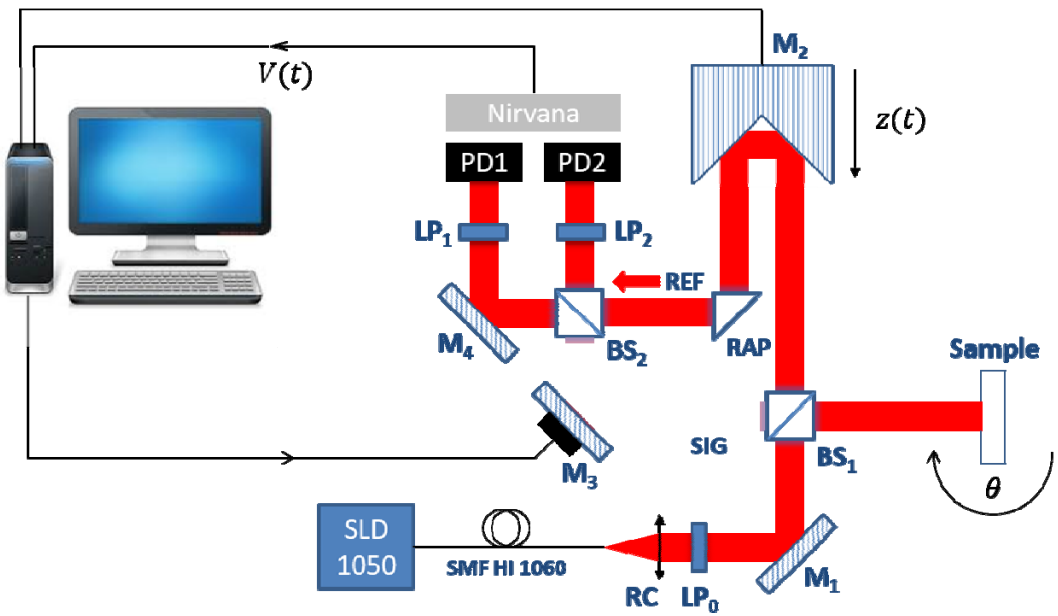
  - ***Detection limits***
    - ✓ ***Back-reflection 10^{-10}***
    - ✓ ***Back-scattering 10^{-6} sr^{-1}***

  - ***Ability to separate the contributions of each face of the component***

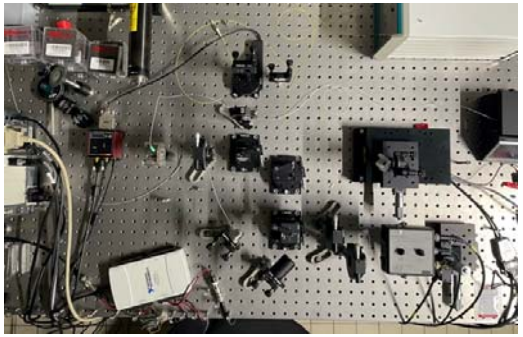
  - ***Ability to measure the spectral dependence of the complex amplitude of the field back-reflected or back-scattered by the front face of a sample***

I. Khan, M. Lequime, M. Zerrad, and C. Amra, Phys. Rev. Applied **16**, 044055 (2021)
M. Lequime, I. Khan, M. Zerrad, and C. Amra, Optica (to be published, 2022)

OLCBS (Optical Low Coherence Back Scattering)



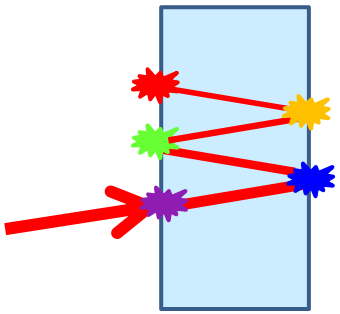
Low coherence interferometry & scattering metrology



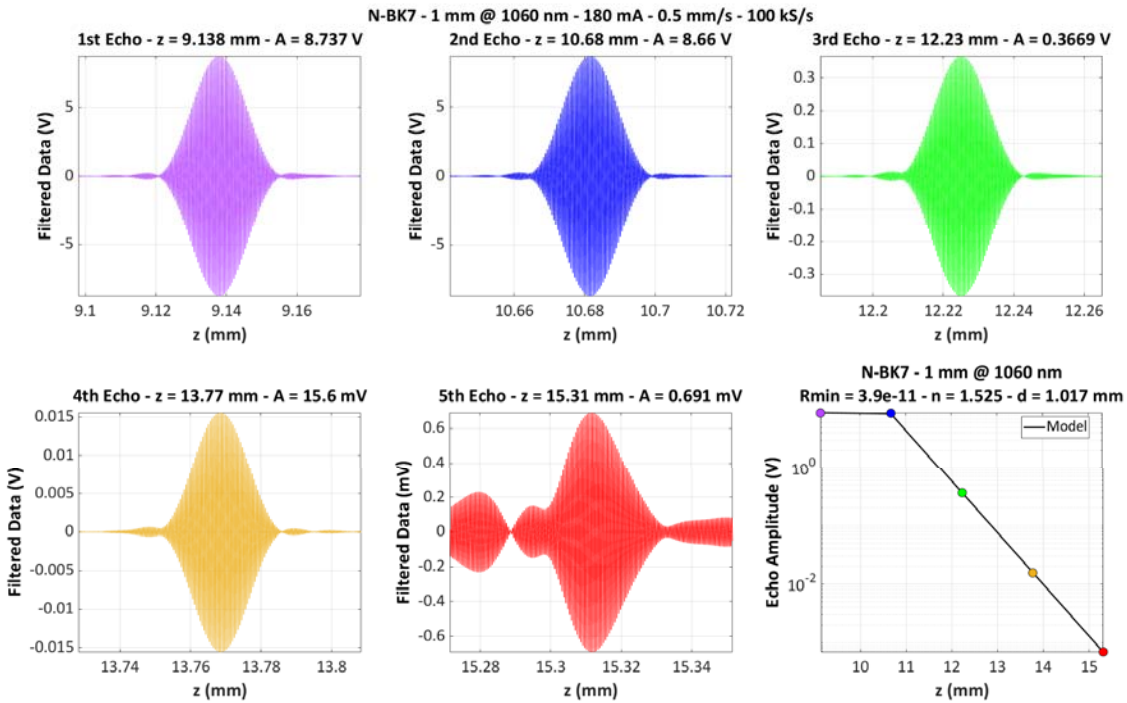
Talk I. Khan for detailed description

I. Khan, M. Lequime, M. Zerrad, and C. Amra, "Detection of Ultra-Low Light Power Back-reflected or Back-scattered by Optical Components using Balanced Low Coherence Interferometry," Phys. Rev. Applied **16**, 044055 (2021)

Back-reflection and back-scattering metrology
OLCBS (*O*ptical *L*ow *C*oherence *B*ack *S*cattering)



Order	R_{th}	R_{exp}
1	4.1×10^{-2}	3.4×10^{-2}
2	3.7×10^{-2}	3.3×10^{-2}
3	6.2×10^{-5}	6.0×10^{-5}
4	1.0×10^{-7}	1.1×10^{-7}
5	2.3×10^{-10}	1.7×10^{-10}



I. Khan, M. Lequime, M. Zerrad, and C. Amra, "Detection of Ultra-Low Light Power Back-reflected or Back-scattered by Optical Components using Balanced Low Coherence Interferometry," Phys. Rev. Applied **16**, 044055 (2021)

Back-reflection and back-scattering metrology
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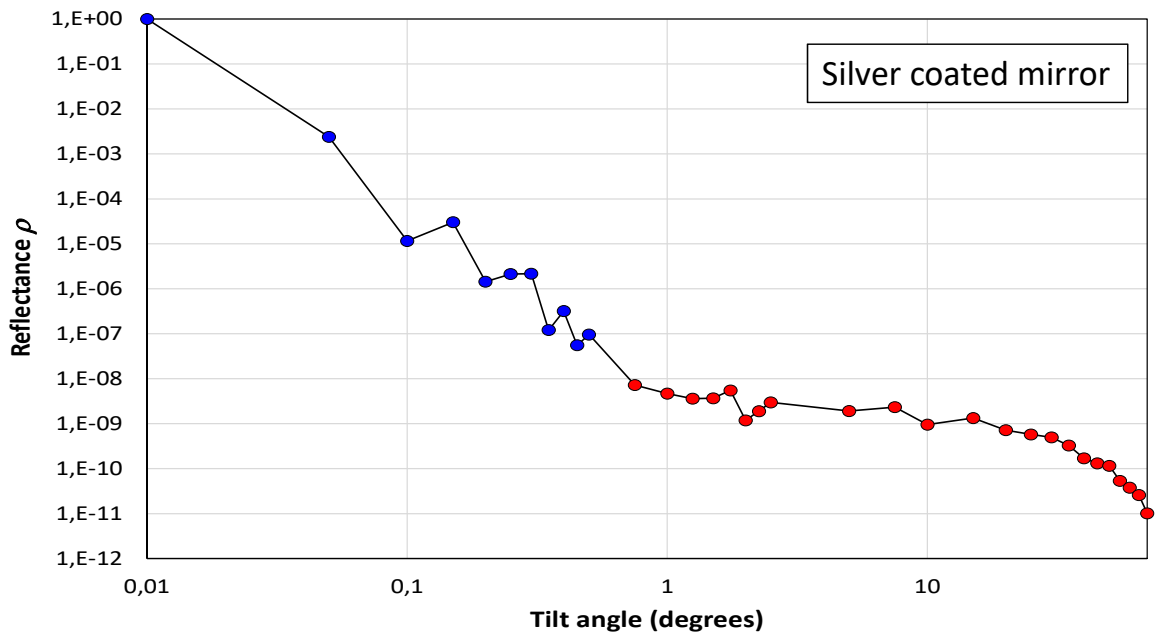


Retro-reflection

&

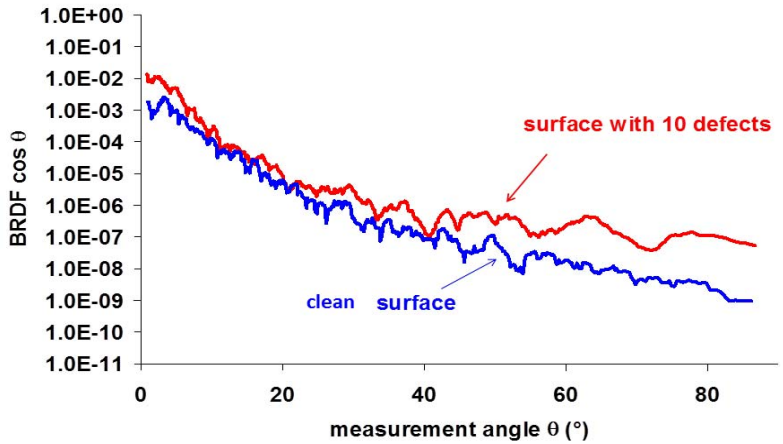
Back scattering

I. Khan, M. Lequime, M. Zerrad, and C. Amra, "Detection of Ultra-Low Light Power Back-reflected or Back-scattered by Optical Components using Balanced Low Coherence Interferometry," Phys. Rev. Applied **16**, 044055 (2021)

What about contamination & defects ?

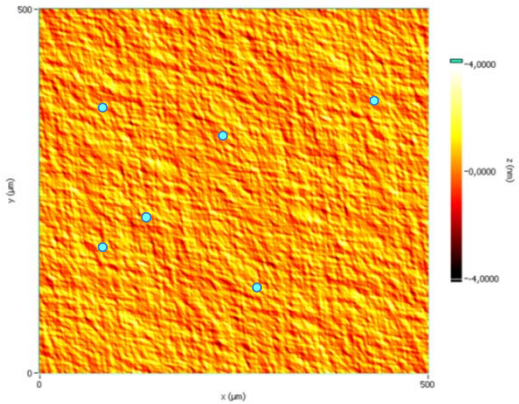
Defects and contamination….

- **The presence of defects can induce additional scattering losses**



$\delta_{rms,\,10}$ = 3.93 nm

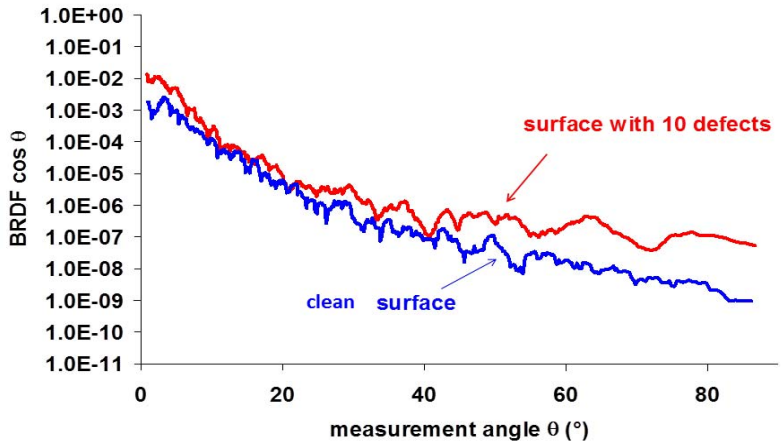
$\delta_{rms,\,0}$ = 0.87 nm



Challenge : quantify the weight of defects and contamination

Defects and contamination….

- **The presence of defects can induce additional scattering losses**



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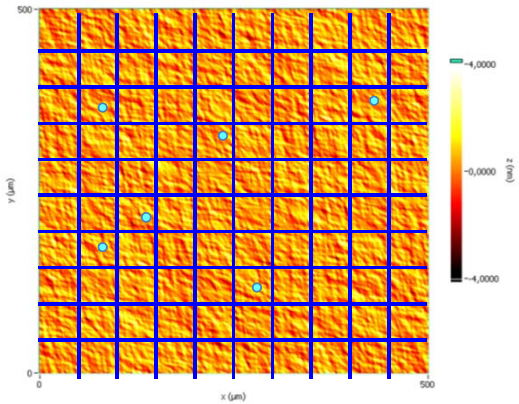
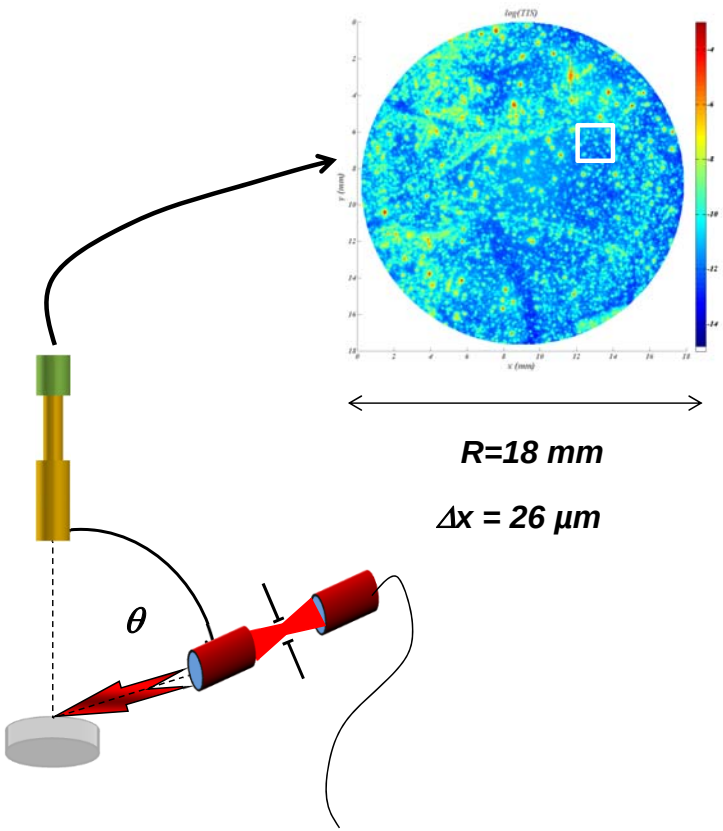


Challenge : quantify the weight of defects and contamination

Spatially resolved BRDF measurement

Defects and contamination…. : Spatially resolved BRDF measurement



R=18 mm

Δx = 26 µm

Imaging system for pixellisation

(CCD array + telecentric objective)

Quantitative metrology requires angular information :

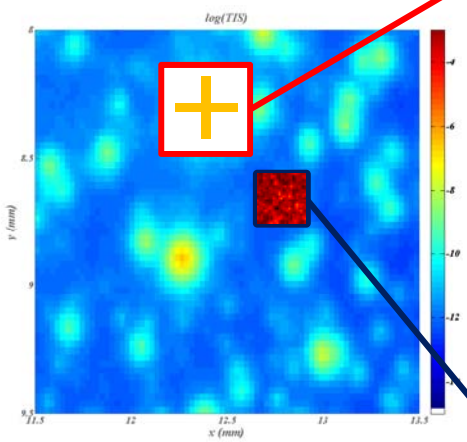
Rotating illumination

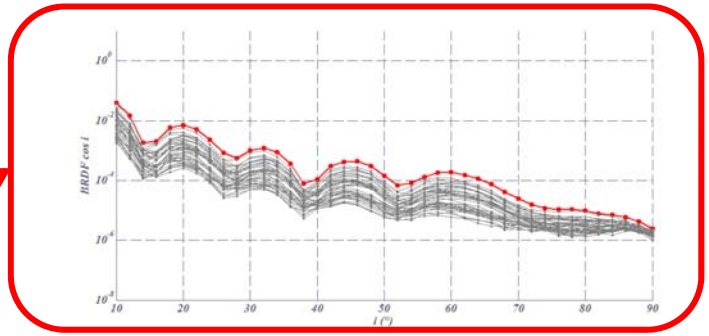
Constant illumination shape:

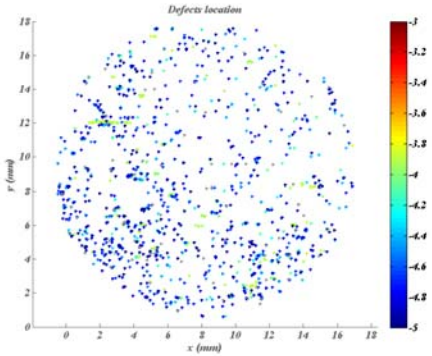
Intermediary tunable image for anamorphose

"A goniometric light scattering instrument with high-resolution imaging", M. Lequime, M. Zerrad, C. Deumié, C. Amra, Opt. Com. 282 (2009) 1265–1273

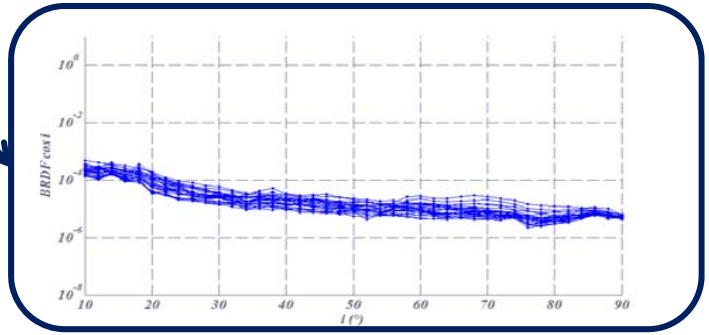
Defects and contamination…. : Spatially resolved BRDF measurement

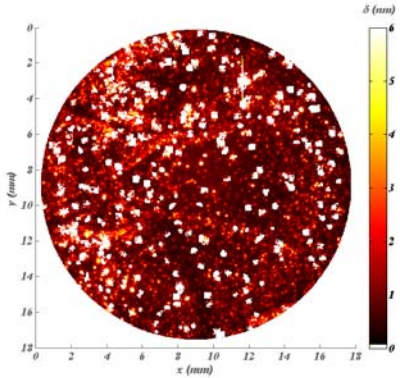






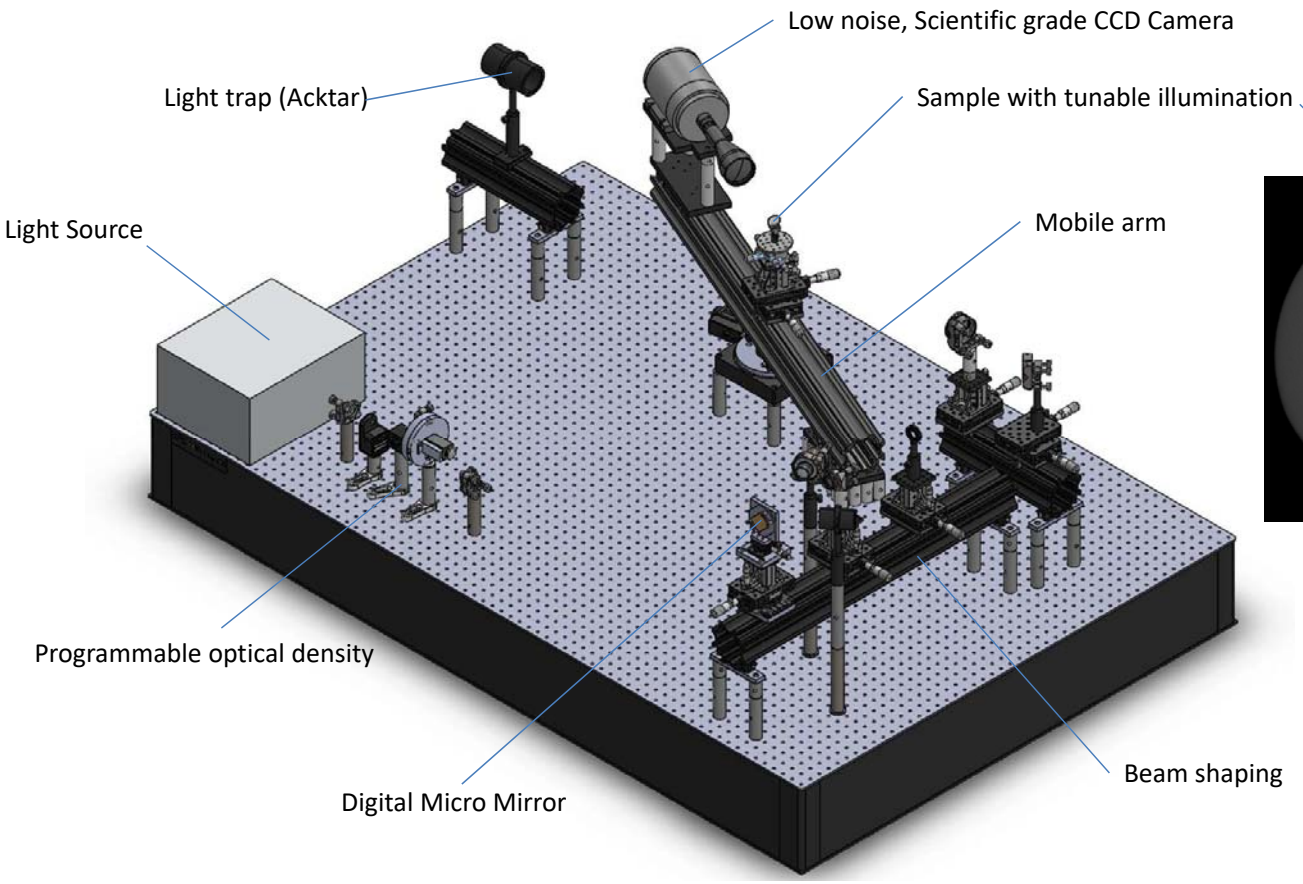
Each 26 µm² surface has its own BRDF pattern (~1 million)





New generation : SPARSE

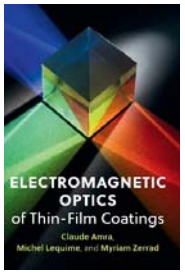
SPatially and Angularly Resolved Scatterometry Equipment



In progress…

DIFFUSIF platform

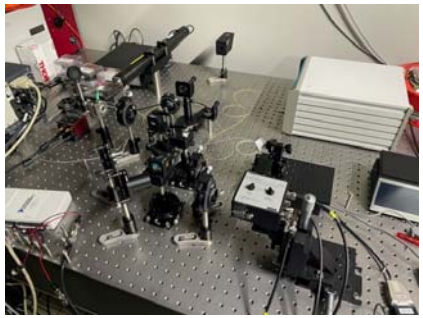
www.fresnel.fr/diffusif
myriam.zerrad@fresnel.fr



SALSA

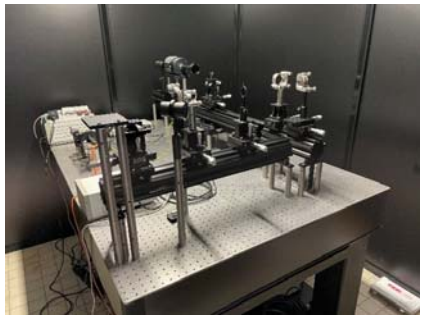
Spectral & Angular

OLCBS



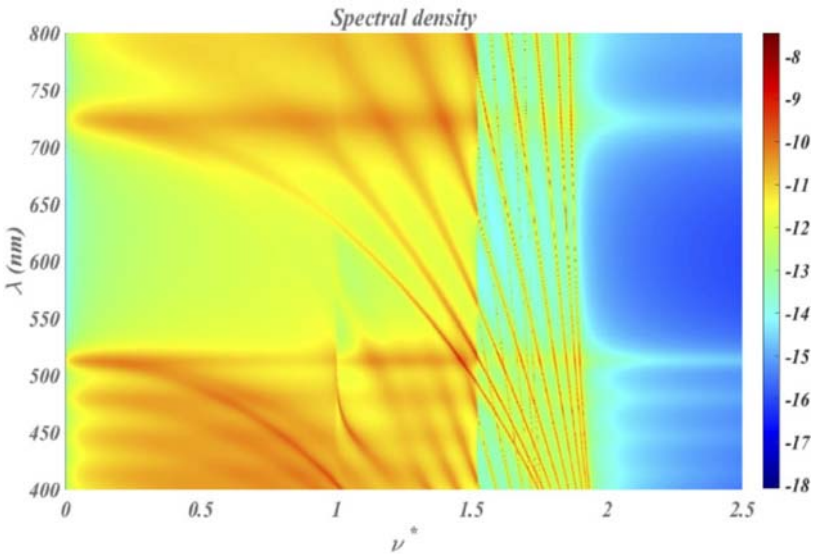
Back-reflection & Backscattering

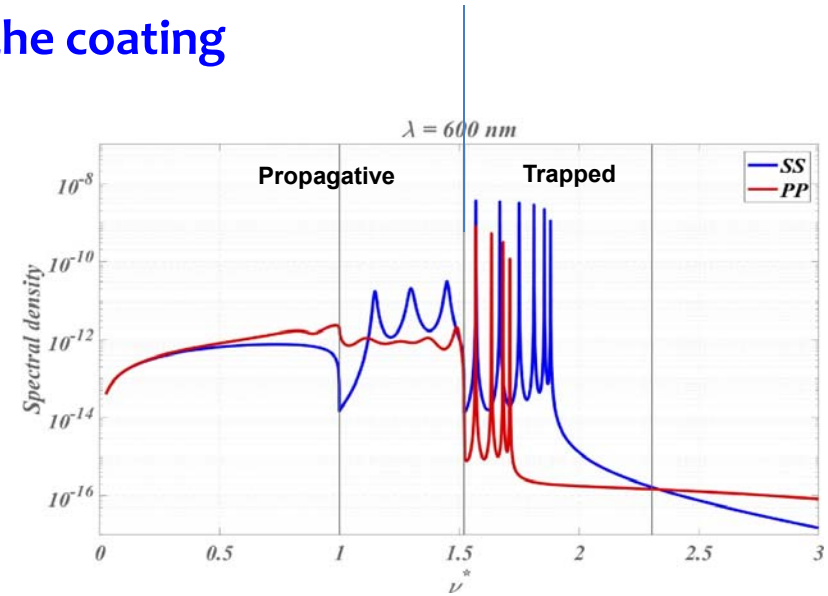
SPARSE

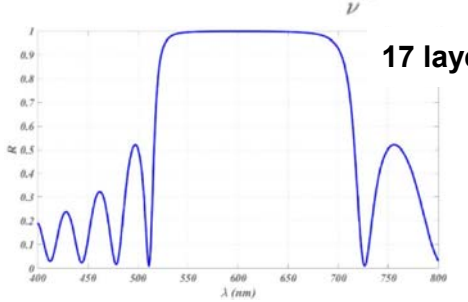


Defects & Contamination

To go further : Scattered light trapped in the coating

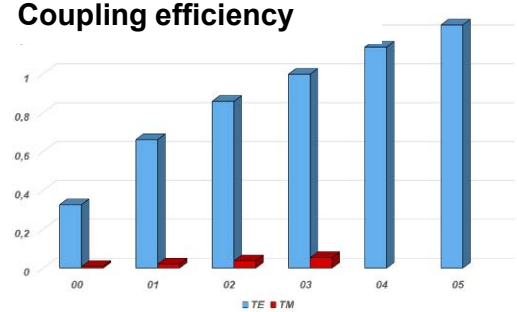






17 layers mirror

Coupling efficiency



C. Amra, M. Zerrad, and M. Lequime, "Trapped light scattering within optical coatings: a multilayer roughness-coupling process," Opt. Express **29**, 25570-25592 (2021)

Conclusion & perspectives

- ***Modeling of light scattered by :***
  - ✓ ***Surfaces***
  - ✓ ***Optical coatings***
  - ✓ ***Optical components***
  - ✓ ***Trapped light***
  - ✓ ***Perturbative bulks***
  - ✓ ***Thermal radiation emitted by coatings under illumination***

- ***Metrology***
  - ✓ ***Spectral***
  - ✓ ***Angular***
  - ✓ ***Backscattering & retro-reflection***
  - ✓ ***Defects & contamination vs roughness***
  - ✓ ***Polarization***

In progress

- ***Metrology of :***
  - ✓ ***Thermal radiation pattern***
  - ✓ ***Phase of scattered & backscattered light***

Thank you for your attention !!!

GRASS 2022

Light scattered by high performance optical components: Numerical prediction and accurate metrology

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Light Scattering Group (CONCEPT)