Brookhaven National Laboratory

Dichroic Filters using Atomic Layer Deposition (ALD)

Update to the work presented in
DUNE Far detector 3-4 miniworkshop, Stony Brook University
https://indico.fnal.gov/event/59908

Thanks to

RAYTUM Photonics

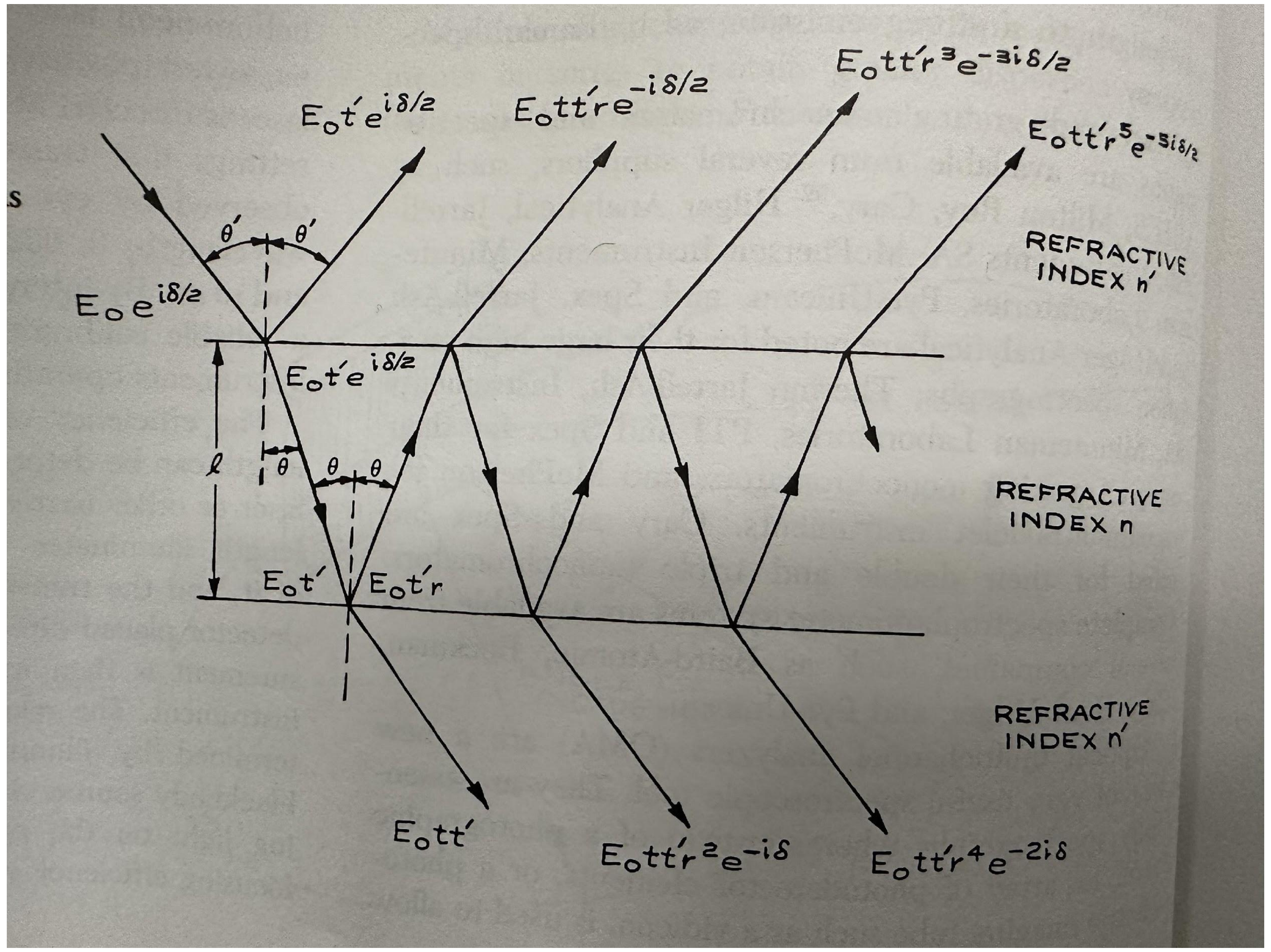
Milind Diwan Jul 11 , 2024

Outline/summary

- Background introduction
- Introduction to ALD. Why ALD ?
- Specifications from DUNE for the current project.
- Progress
  - The SBIR project will complete in September 2024
  - The project has been successful at designing the producing prototype filters. Large (DUNE 1 size) Filters on substrates of Saffire and B33 glass have been delivered.
  - Performance of these has been measured
  - The process has been optimized for producing very large filters (upto 50 cm x 50 cm).
  - Coatings of wavelength shifters can be placed on one side of the filters. If requested this work can be done in the next phase.
  - BNL also has the capability for PTP and TPB coatings, but some investment will be needed.

Reminder of interference filters

Basics of an etalon or two parallel mirrors.



Moore, Coplan, Davis

- If phase shift and absorption is neglected on interfaces.
- $$\frac{I_T}{I_0} = \frac{1}{(1 + \frac{4R}{(1-R^2)} \sin^2 \delta/2)}$$ where R is the reflectivity and $\delta = 2kl \cos\theta$
- Transmission maxima happen when
- $$l = \frac{m\lambda}{2\cos\theta}$$
- A stack of etalons can be modeled by software to create a bandpass filter. Each etalon is made of a high quality dielectric layer with different index of refraction.

How does one deposit the layers ?

There are many techniques; but the state of the art is consider atomic layer deposition.

Unique Advantages of ALD vs Physical vapor deposition(PVD)

1. Precise and easy thickness control in a monolayer scale over established PVDs for high performance optical filter fabrication
2. Excellent uniformity (<0.1-1%) for fabricating large area optical components.(up to sub-meters)
3. Super conformalty on Non-planar optical surface and components.
4. Low temperature process on plastics by energetic ALD.
5. Continuous and pin hole free.
6. Diversity of materials for DF designs.
7. Low maintenance cost and high volume manufacture is established.

https://www.veeco.com/products/savannah-thermal-ald-for-rd/

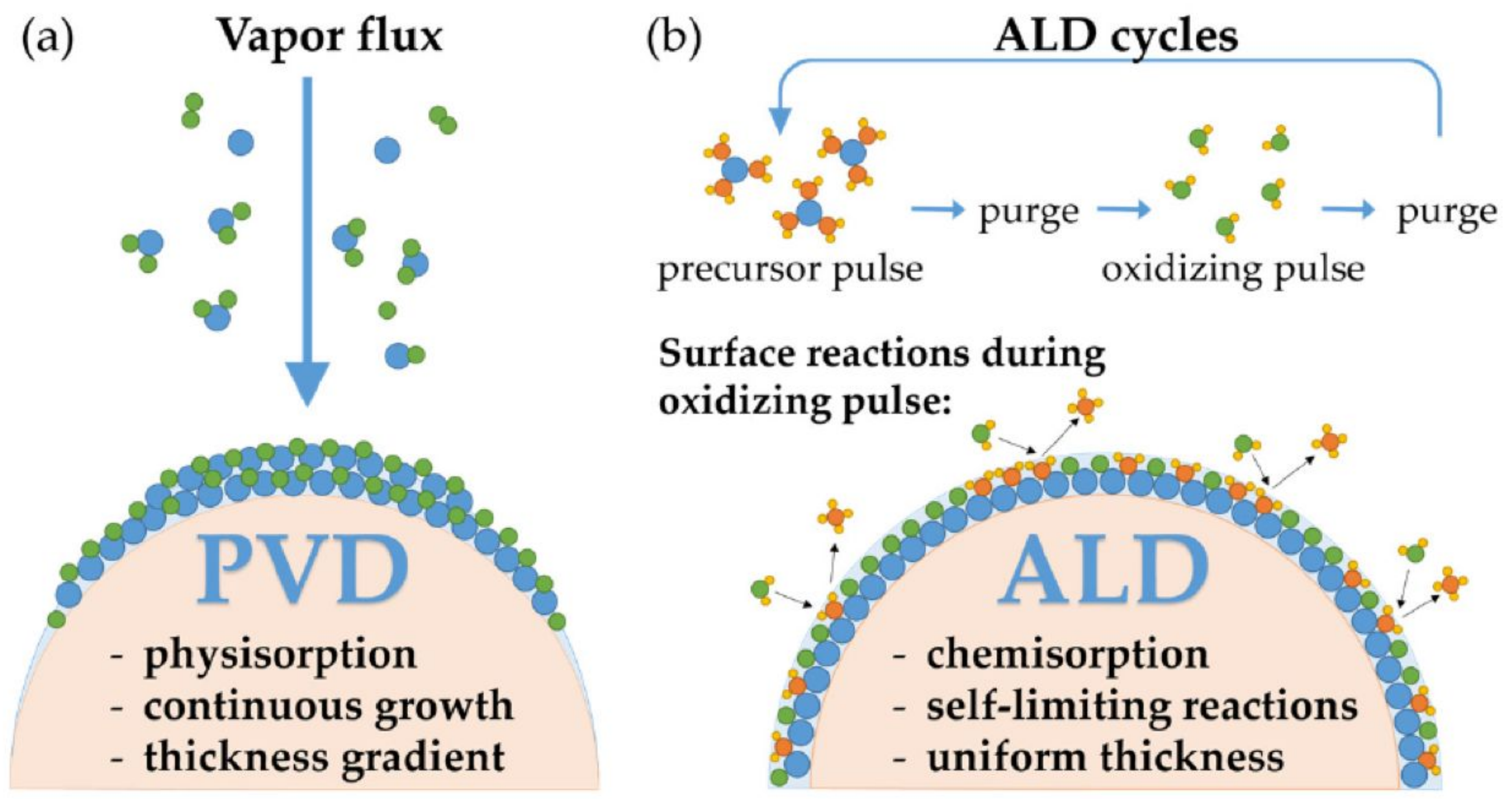


Figure 1. Illustration of (**a**) physical vapor deposition (PVD) deposition and (**b**) atomic layer deposition (ALD) on a hemispherical lens.

Key technical issues

Coating materials (high and low index), Substrate and stresses.

Materials	*Coefficient of line expansion(×10-6/°C at RT)*	*Refractive index at 500nm*
TiO2	*9.19(//C); 7.14(^C)*	*2,54*
Al2O3(sapphire)	*6.7((//C); 5.0(^C)*	*1,77*
SiO2(fuse silica)	*0,55*	*1,46*
Si	*4,2*	
N-BK7	*7,1*	*1,52*
Borofloat (borosilicate from SCHOTT)	*3,25*	*1,52*
Soda lime glass	*8,1*	*1,528*

- ***There are other optical materials also, but practical list is limited.***
- ***Substrate has to be chosen so that the CTE is reasonably matched to both coatings.***
- ***The problem with fused silica is the mismatch of CTE. But this is getting resolved.***

R&D project timeline and scope

BNL and Raytum collaboration

- R&D project was proposed in 2021 and first phase was successfully executed with DOE funding. The Raytum laboratory is in Virginia.
- A second phase with 2 year timeline was started in FY23
- The total scope includes
    - Understanding the scientific requirements.
        - A miniworkshop was organzied with both liquid argon and water based liquid scintillator experts Oct 17, 2022
    - Development of test samples from Raytum adapting ALD technology.
    - Testing of samples in real conditions for
        - Material compatibility, Handling issues, Detector performance
    - Understanding requirements for large scale production.
    - Preliminary development of production techniques.

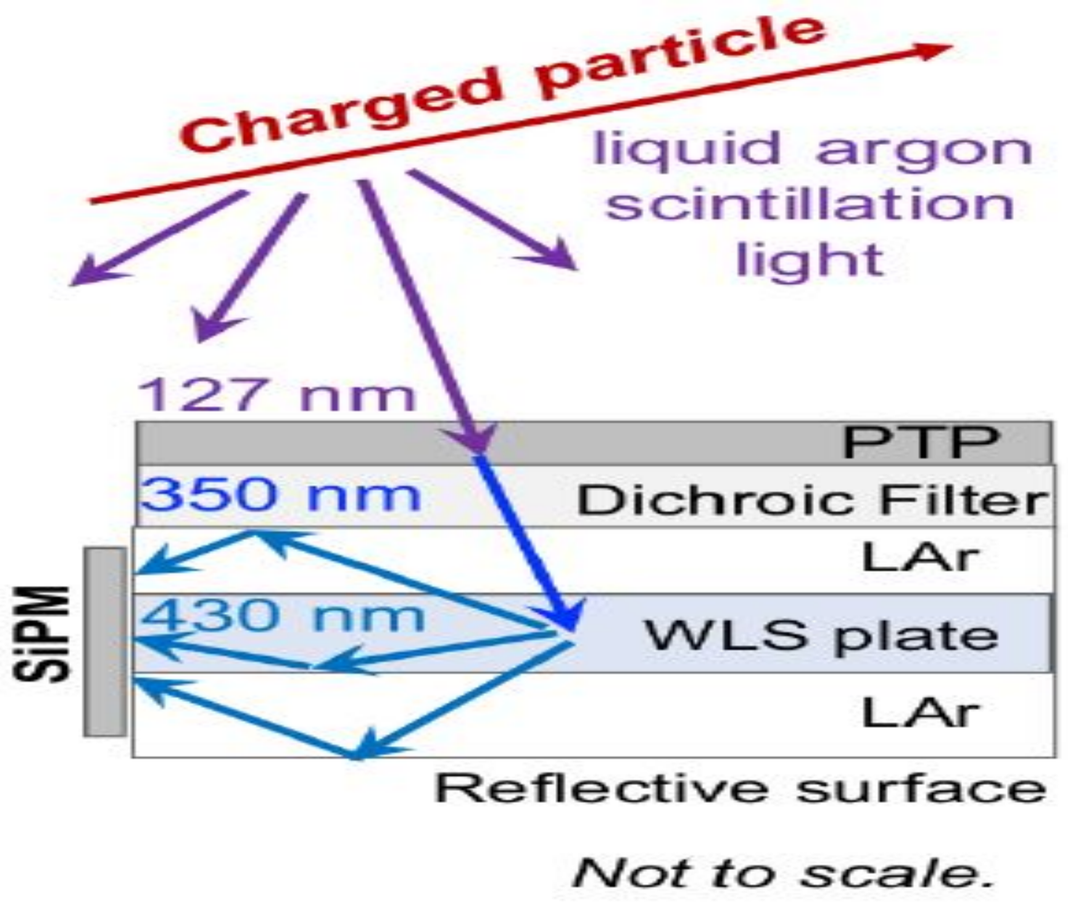
The entire scope has been accomplished. However, it would be best to use the produced filters in a real detector setup.

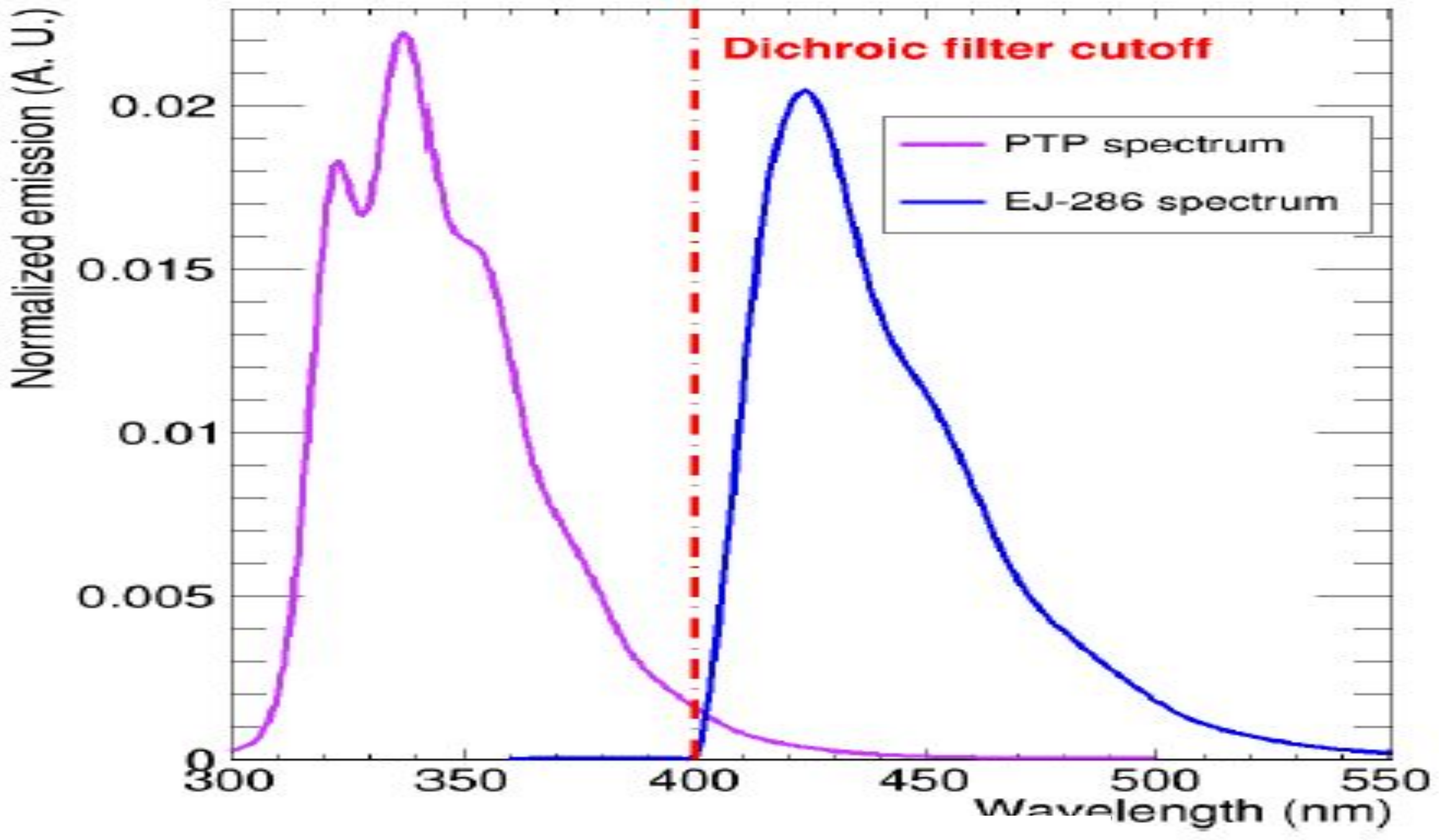
Updated Specifications for variety of projects for next phase (if funded)

	DUNE Module 1	DUNE Module 2	DUNE Module 3 or 4	THEIA
Status	Technical Design Ready (ready for construction)	Technical Design Ready	Pre-concpetual	Pre-conceptual
Size	10000 tons	10000 tons	10000 tons	25000 to 100000 tons
Technique	Liquid Argon Scintillation	Liquid Argon Scintillation	Liquid Argon Scintillation	Water Cherenkov and Water Based Liquid Scintillator
Type of filter needed	Low pass	Low pass	Low pass	Both low and high pass
cut wavelength of interest	400 nm (modified to 380 nm)	400 nm (modify to 380 nm)	380 nm	450-475 nm
Transparent	320-400 nm	320-400 nm	320-400 nm	320-450 (low pass) > 450 (high pass)
Reflective	400-500 nm	400-500 nm	400-500 nm	> 450 (low pass) 320-450 (high pass)
Max tranmission efficiency	> 90 % (dependent on substrate)	> 90 %	> 90 %	> 90 %
Max reflection efficiency	> 95 %	> 95 %	> 95 %	>95 %
width of edge region	<10 nm	< 10 nm	< 10 nm	< 10 nm
angle of incidence optimize	20 deg - 70 deg	20 deg to 70 deg	20 deg to 70 deg	TBD
Optimize for	45 deg	45 deg	45 deg	TBD
movement of edge within angle	< 10 nm	< 10 nm	< 10 nm	< 10 nm
Preferred Substrate	BK270 glass (Fused silica possible ?)	BK270	Still open selection	Open
	~~Try fused silica, BK270 glass, UVT acrylic, B33 glass~~	~~Try fused silica, BK270 glass, UVT acrylic, B33~~	~~Try fused silica, BK270 glass, UVT acrylic, B33~~	~~Try fused silica, BK270 glass, UVT acrylic, B33~~
Shifter	PTP on the uncoated side	PTP on uncoated side	PTP on uncoated side	No shifter is needed on any filter.

DUNE

Liquid Argon ARAPUCA detector concept and roles of DFs



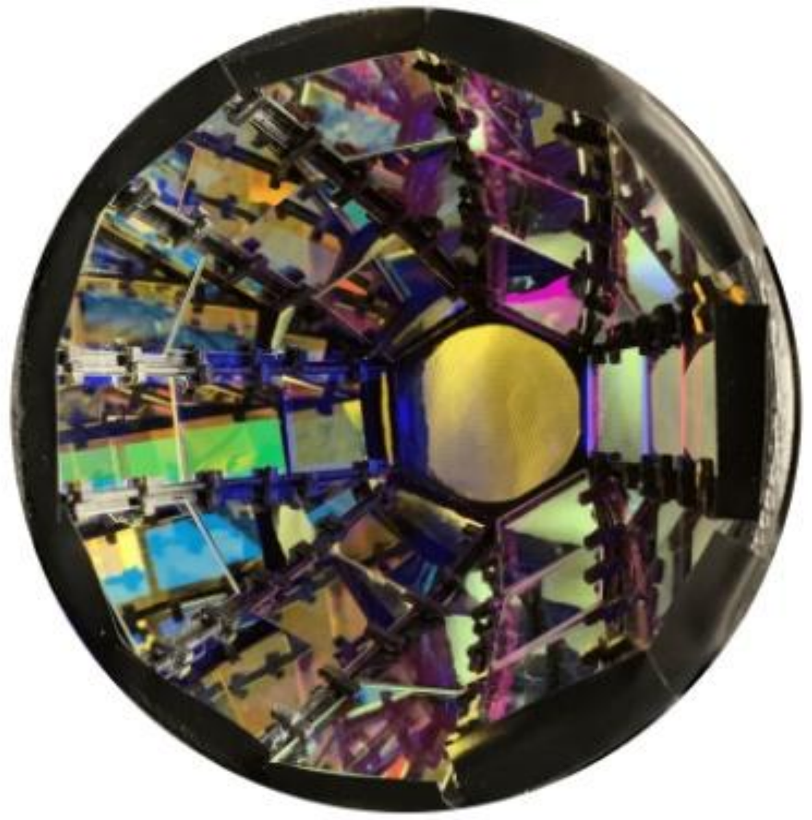


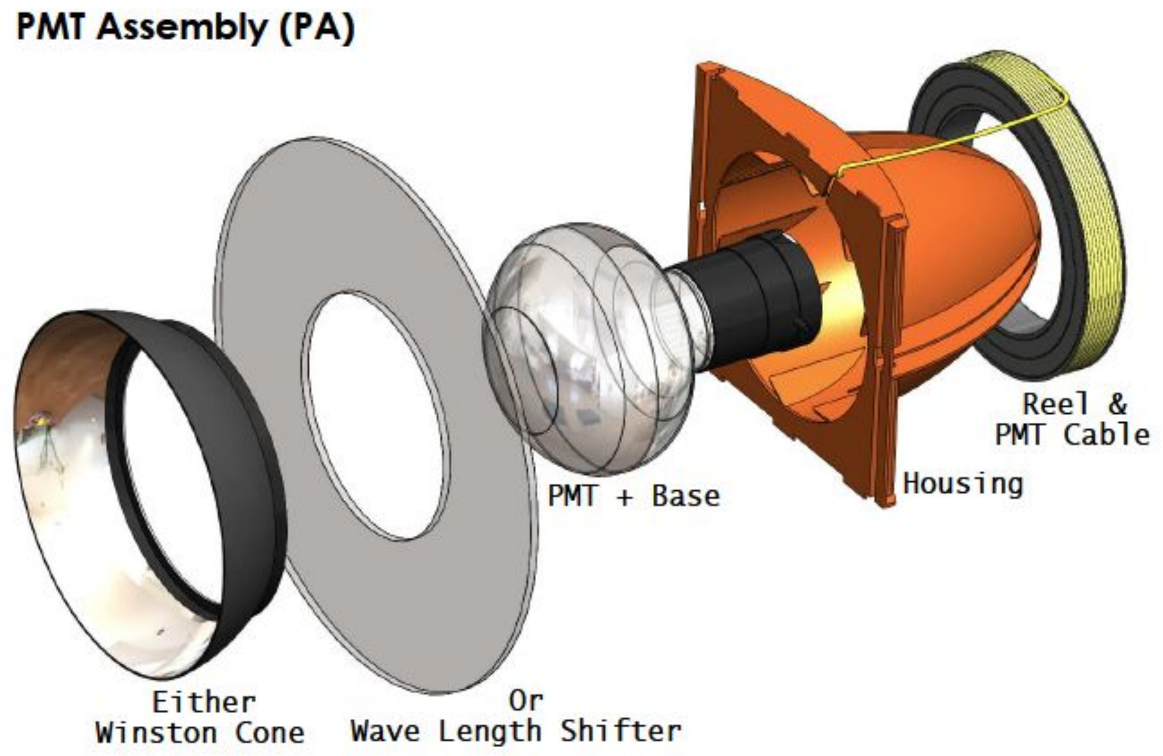
(Polymer EJ-286 WLSP)

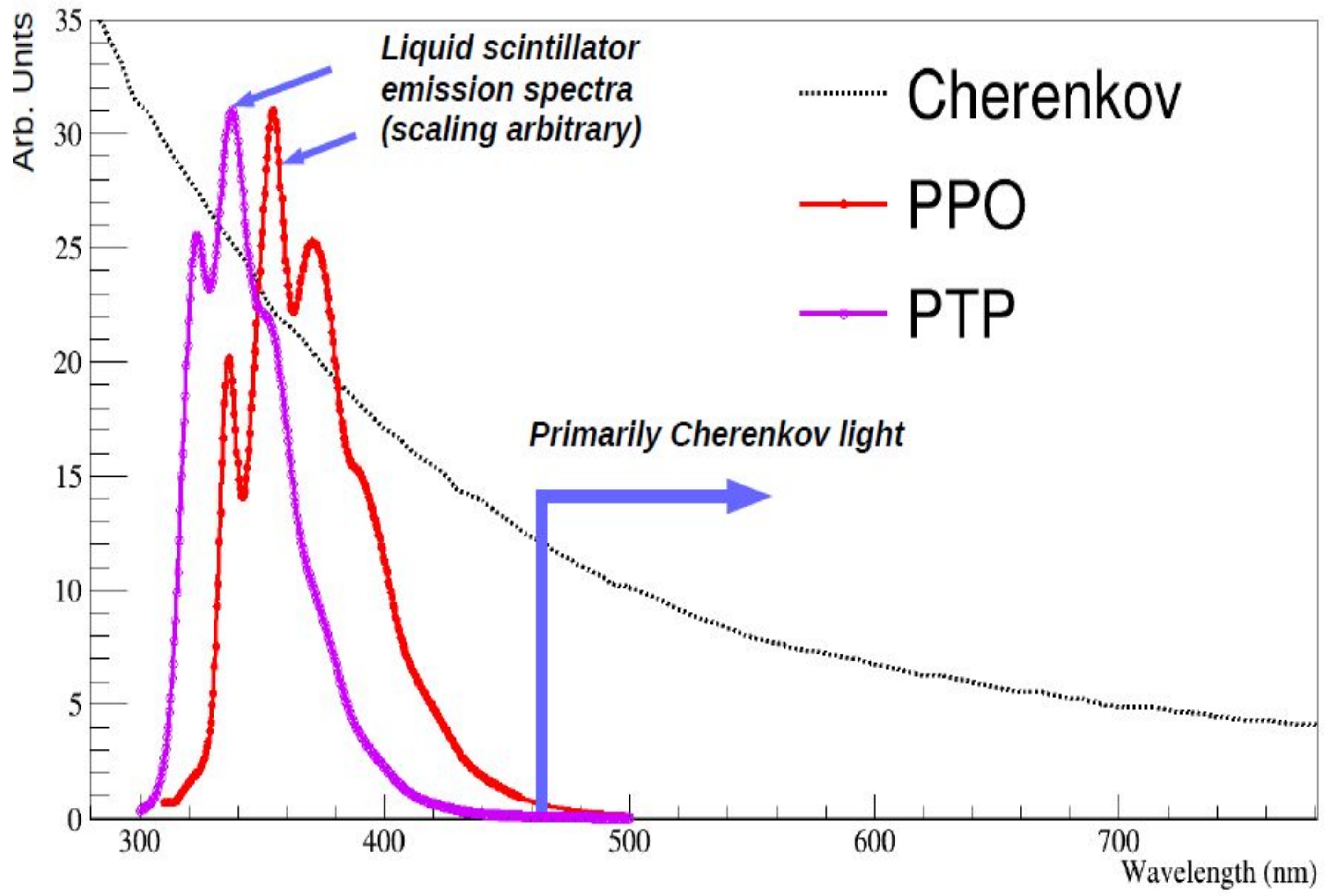
The dichroic cutoff (red dashed line), the PTP (purple) and the EJ-286 emission spectra. (b) X-ARAPUCA principle of work, with total internal reflection and the reflective cavity trapping photons.

THEIA

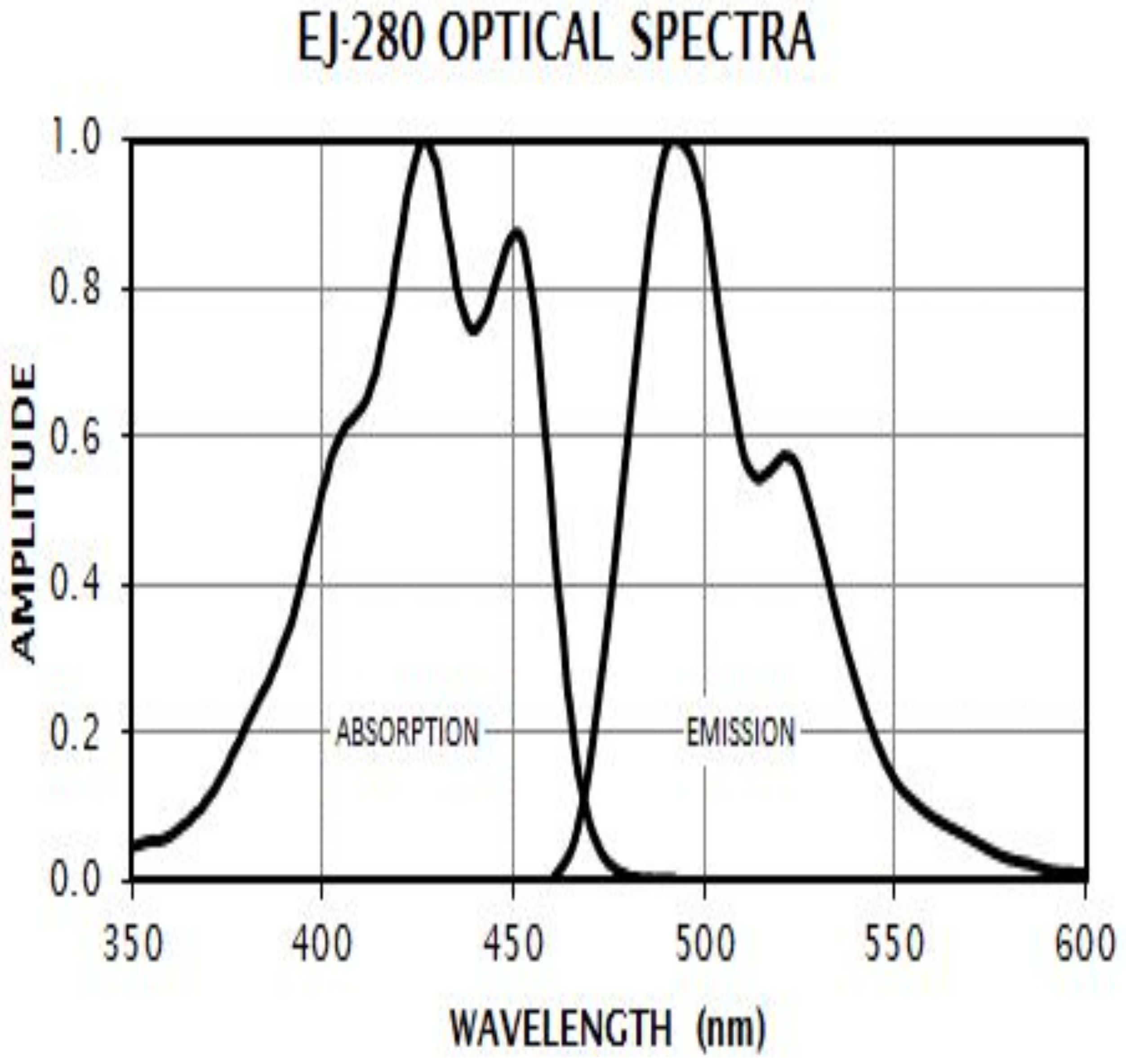
Winston cone(WC) /wavelength shifting plates(WLSP) type of detector concept and roles of DFS







Goal is to achieve Cherenkov and scintillation separation while losing as few total photons as possible.



The SP filters tile the barrel of the Winston cone and a central LP filter is placed at the aperture. A small amount of black electrical tape is used to block a small gap between the filters and the holder at the top of the dichroicon.

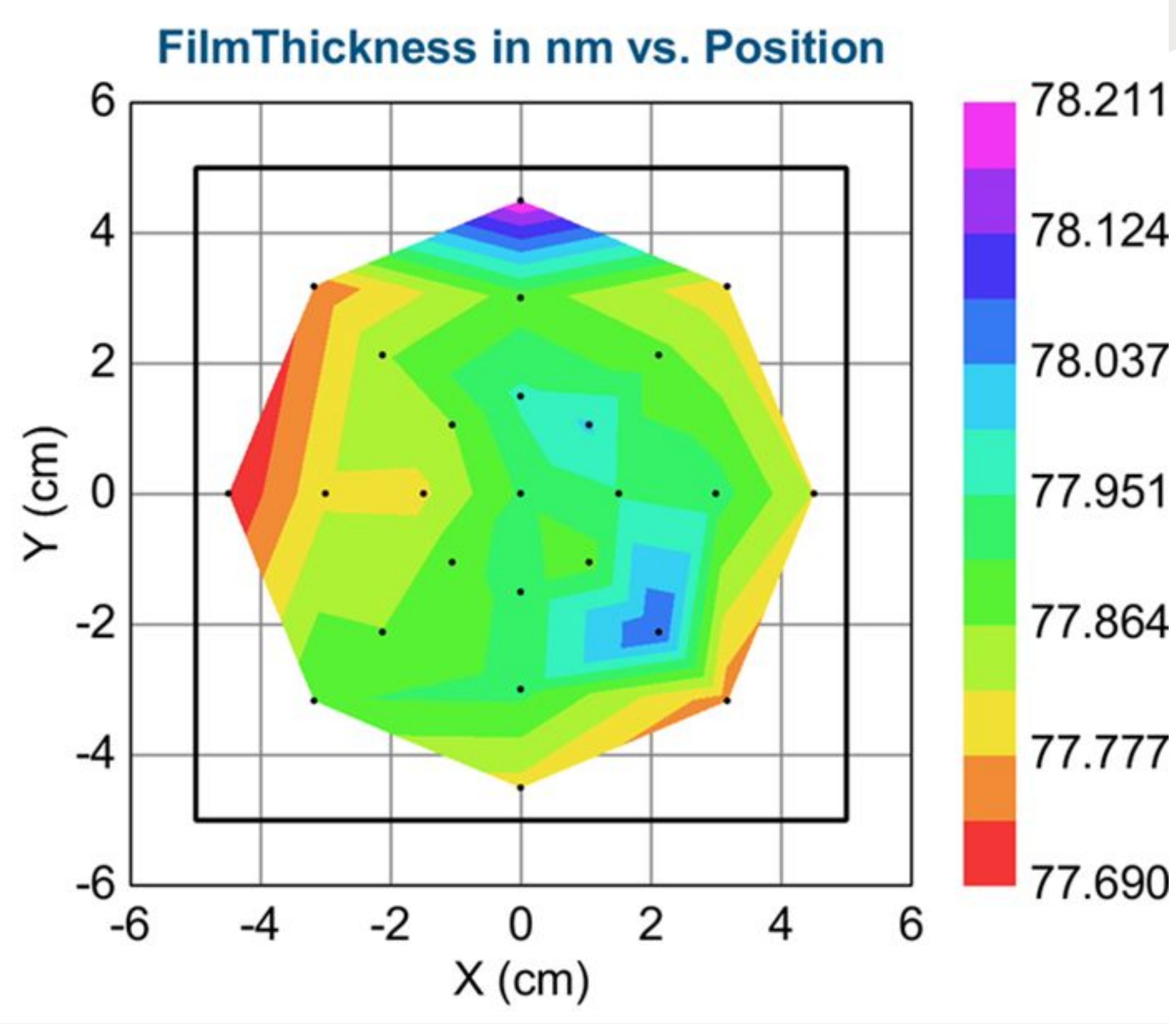
Significant Technology Breakthrough from Raytum Photonics

RAYTUM Photonics

- Large Area Coating using ALD Technology has been achieved. Long pass filters in UV band are successfully demonstrated over different substrates. The results match with the design very well.
- Extremely low absorption, only tens of ppm for 68 layers of coating , was confirmed by PCI technique.
- The uniformity as low as 0.12% has been achieved.
- By optimizing the coating process, the production rate could be greatly improved.
- The fabrication of short pass filter is on the way.

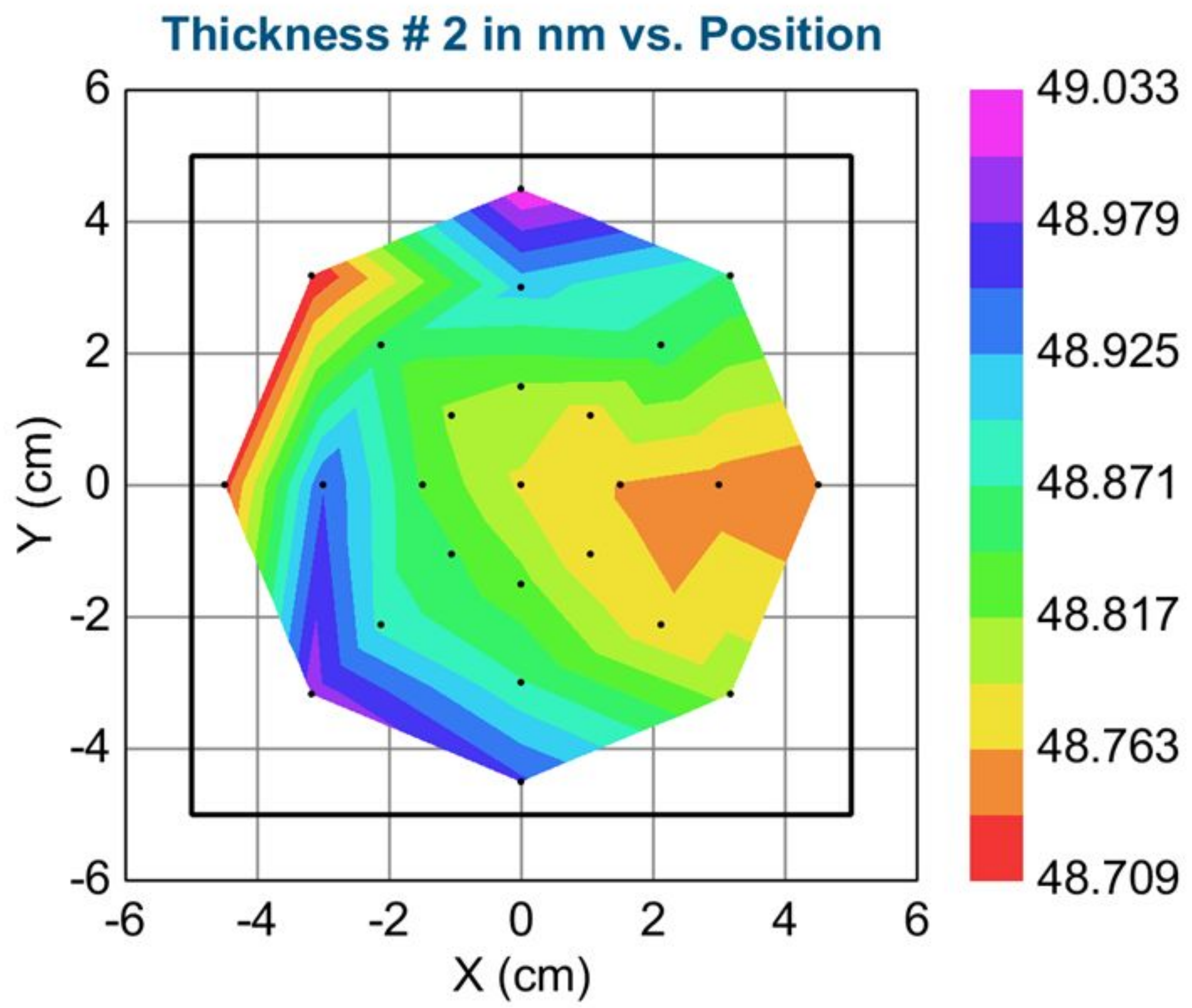
Coating Uniformity Measurement

RAYTUM Photonics



Parameter	Average	Std. Dev.	Slope	Min	Max	Range
Thickness in nm	77.88561	0.10829	0.12%	77.69048	78.21082	0.52035

Low Index Material

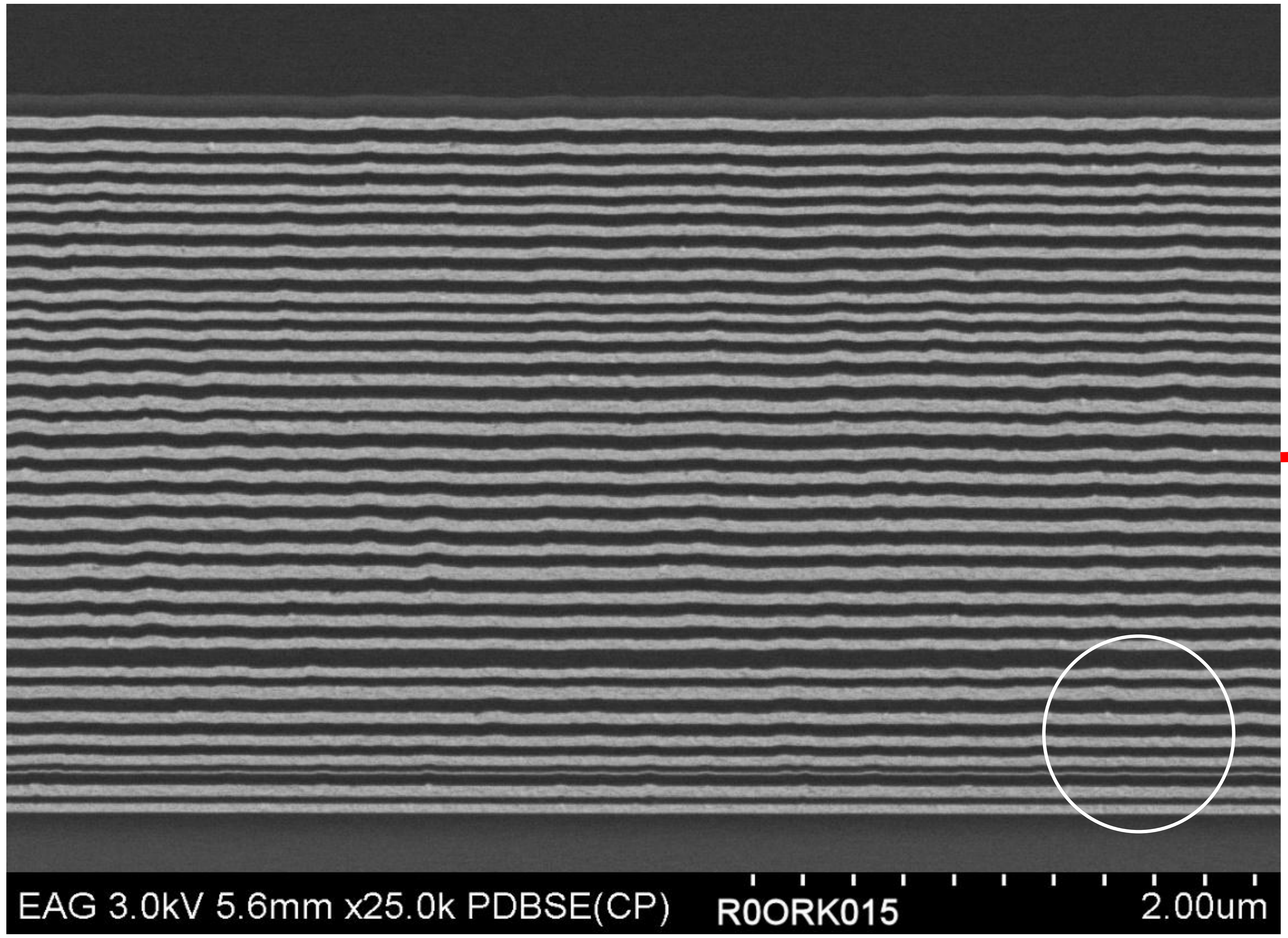


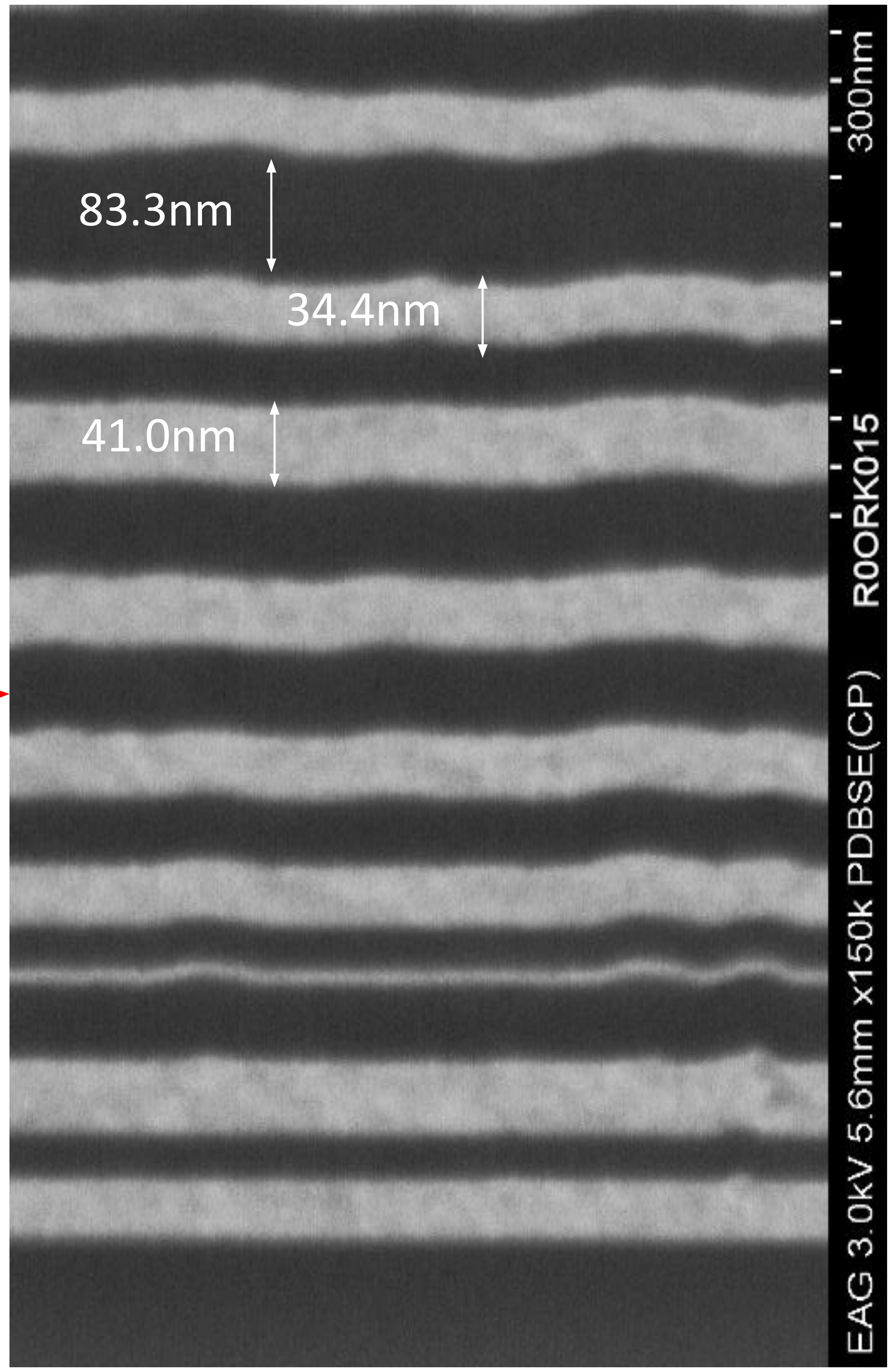
Parameter	Average	Std. Dev.	Slope	Min	Max	Range
Thickness in nm	48.83677	0.08485	0.17%	48.70925	49.03308	0.32383

High Index Material

Cross sectional SEM imaging of a full long pass Dichroic filter consisting of 64 total layers

RAYTUM Photonics





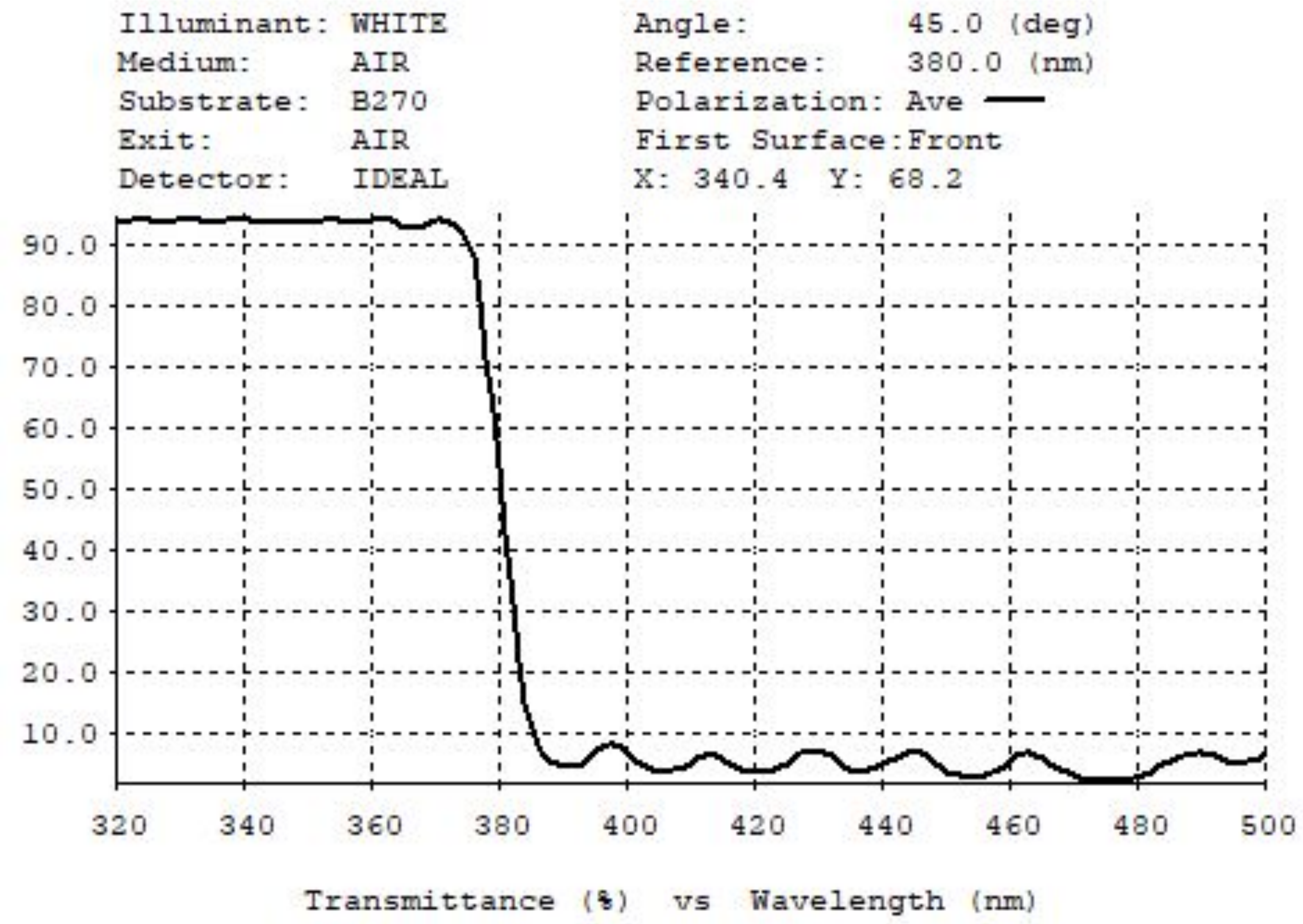
Dark band: dielectric material #1

Light band: dielectric material #2

Measurements are calibrated by a standard sample, estimated measurement error (±1nm).

New SP filters coated by S200 at RP

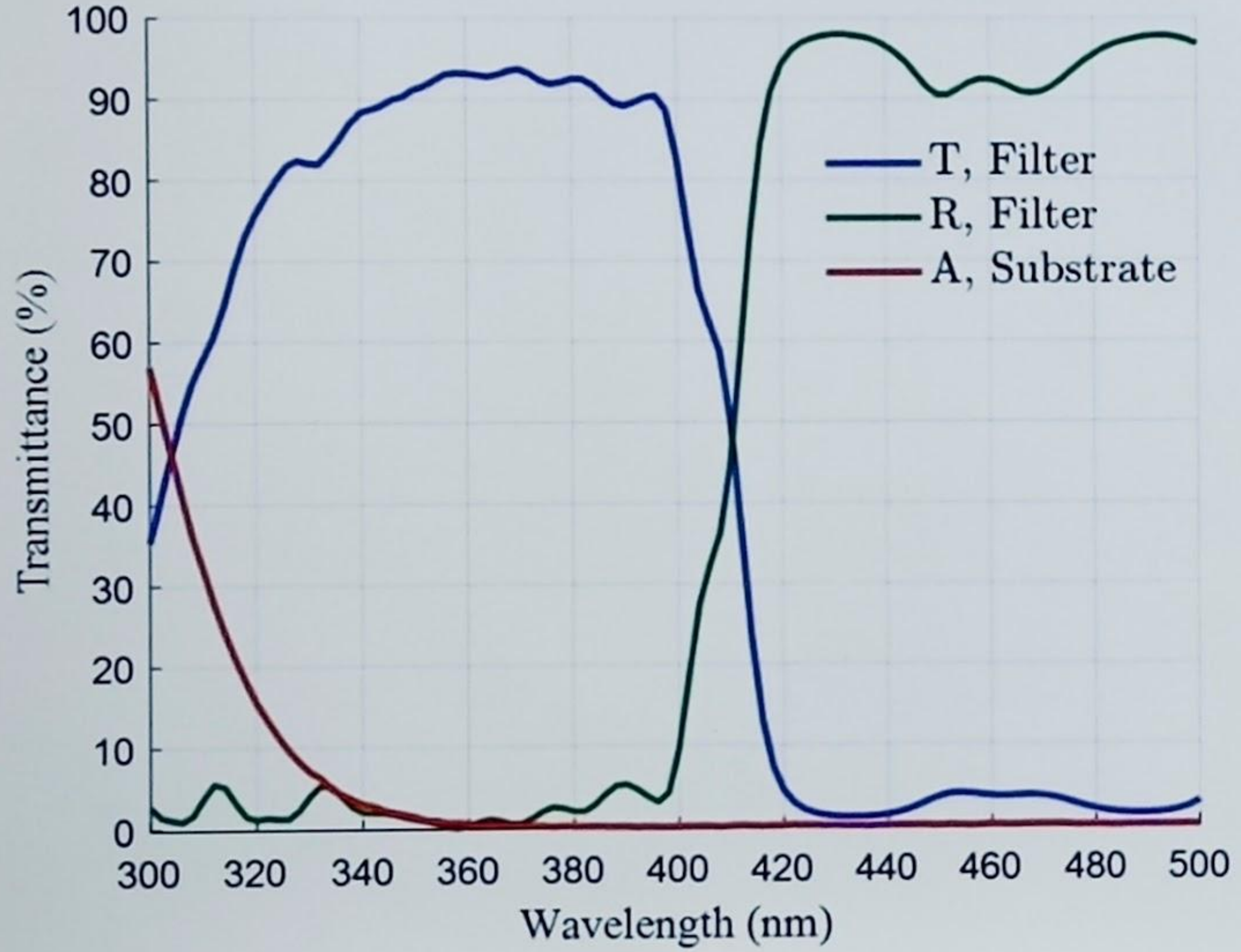
Serial Number	Substrate	Run	ALD method	deposition temperature(℃)	Material	Comment
A1	Sapphire, B33, B270(100mmx77 mm)	4	Thermal temporal	200	highly tensile HfO2 by nanolaminate /Al2O3 tensile	no cracks o sapphire, visible crack lines on B270, B33

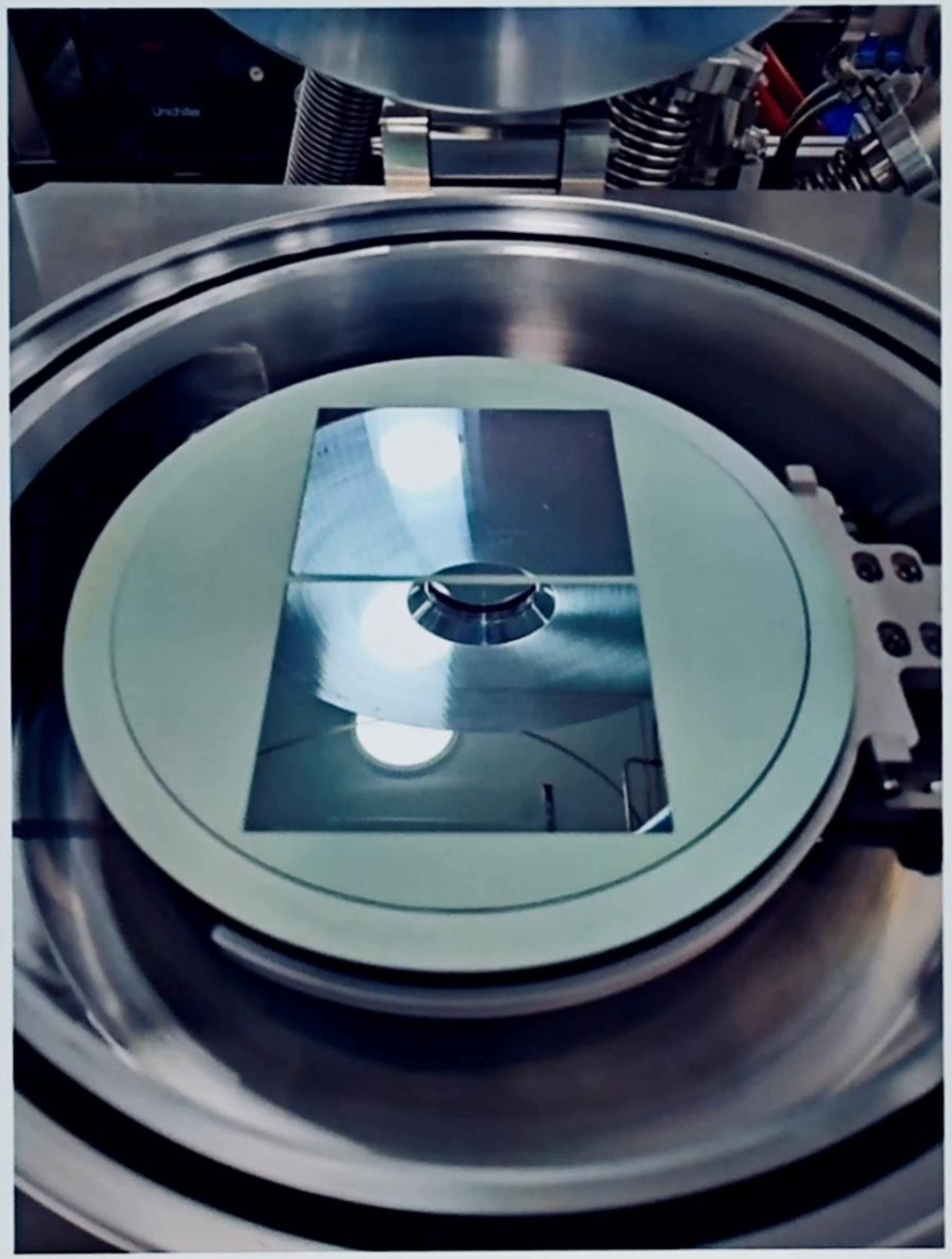


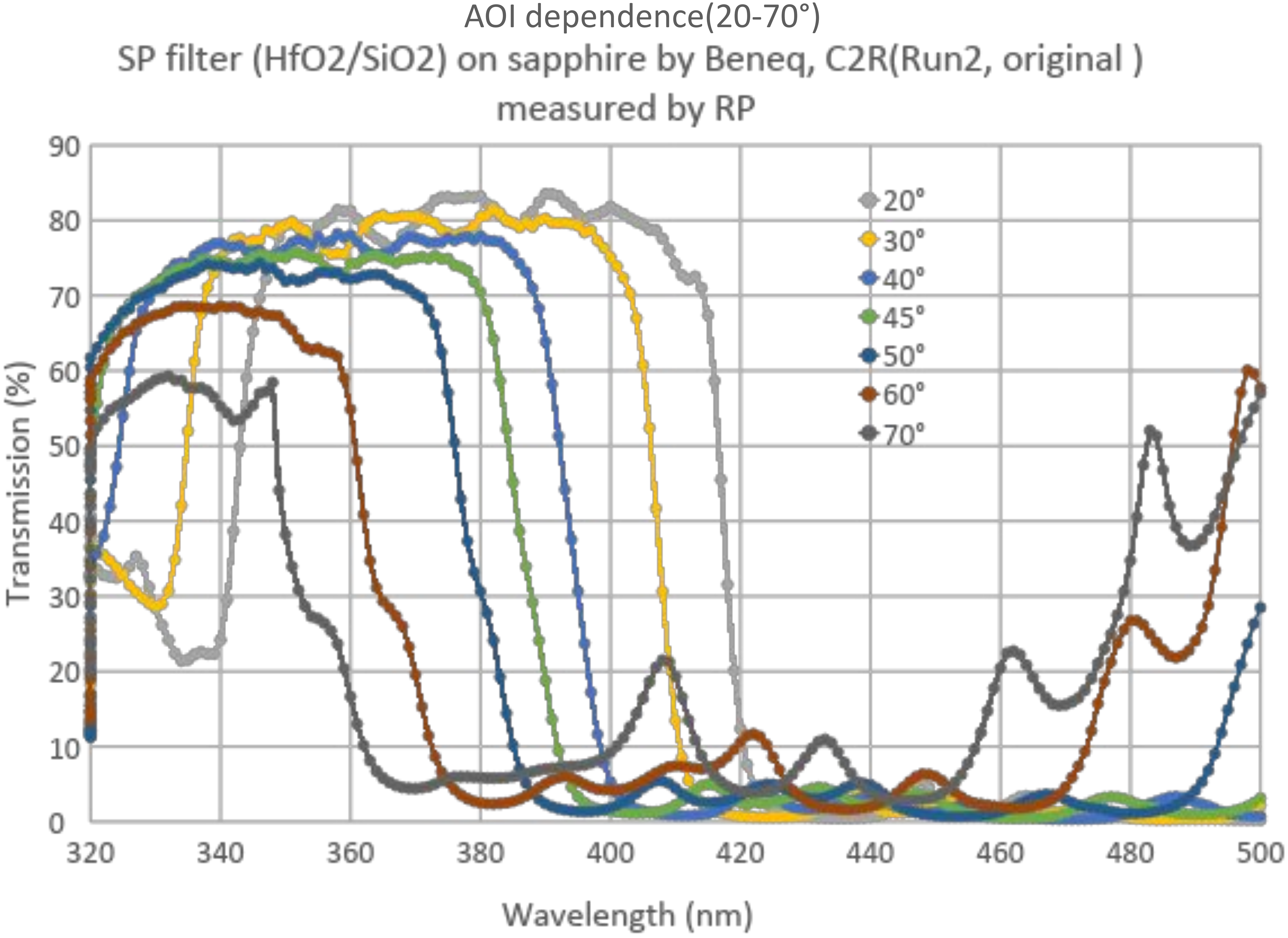
1. Use nanolaminate structure(NL) to prevent formation of crystals at 200°C and reduce Al2O3 internal compressive stress.
2. Cutting-off edge tuned to 380nm in order to prevent leak of back scattered WLS light at 430nm(peak) at AOI from 20-70°.
3. Use different substrates to verify UV transparency.(sapphire, B33, B270)
4. Optimized in air not in liquid AR or water.
5. AOI dependence(20-70°) is studied on cutting edge width(spec<10nm), and it seems that very limited improvement thus decided to go ahead with#1-4.

Preliminary Results

- SiO_2 and HfO_2 at 100°C
  - Both films amorphous, stress-controlled processes
  - Preliminary results on B270-substrates
  - Design is 37-layers, 2900 nm thick

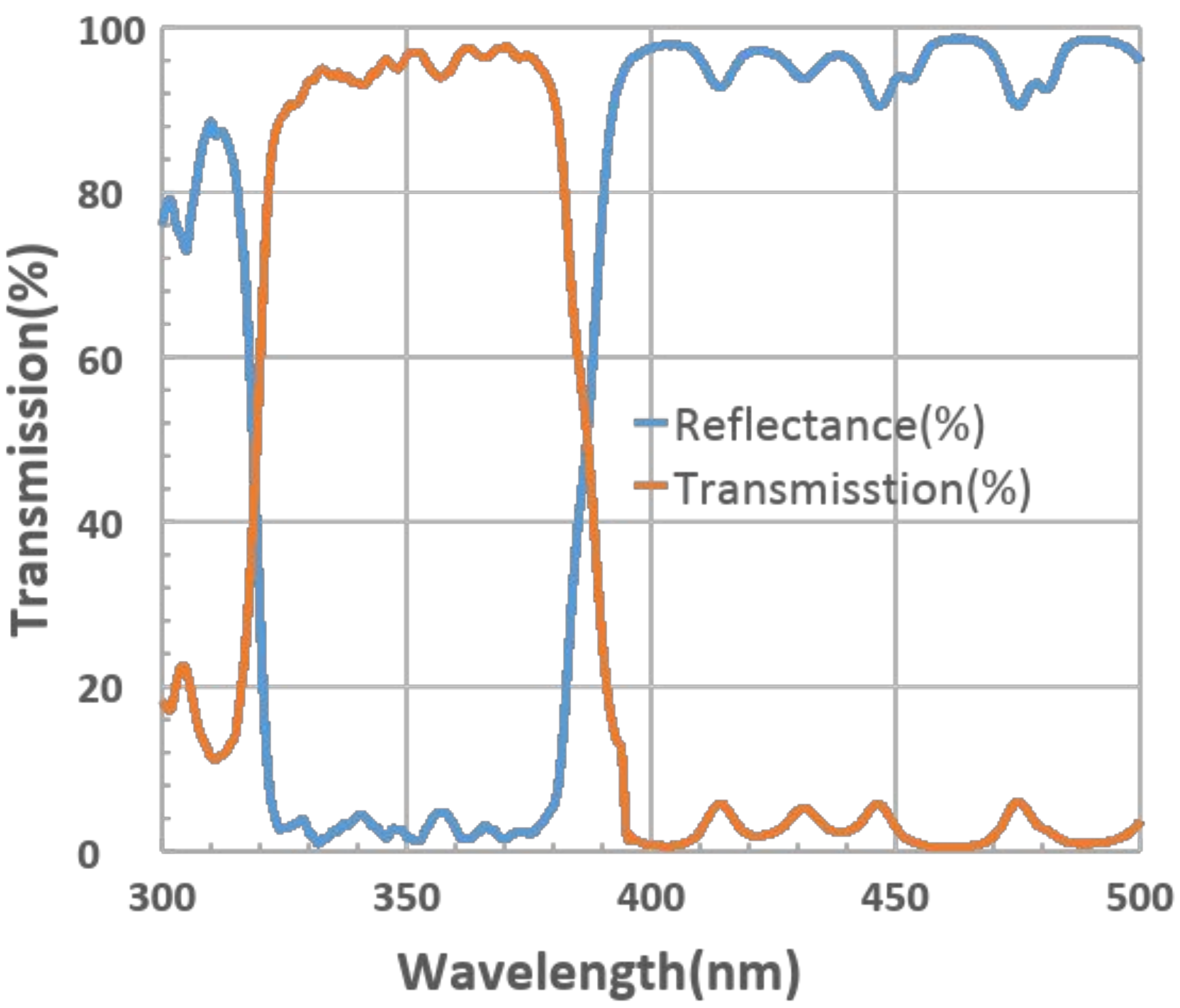






1. Edge width(15nm)
2. Edge movement at AOI 20-70°(70-80nm)

Run2



This is the most recent fabrication run of a SP filter on 100mmx77mm sapphire by the Beneq C2R coater.

1. Transmission is recalibrated for sapphire both side reflectance.(confirmed by PR)
2. Transmission in UV < 340nm is significantly improved by using a sapphire substrate. This proves that the it is the substrate not the SP filter itself, that limits transmission near UV region.
3. The cutting-off edge is tuned from 400nm to 380nm which can significantly reduce reflected light >410-420nm from the WLSP (EJ286) and improve the angular dependence.

BENEQ   C2R coater

ALD is now extremely important technology for silicon production.

The new gate structures for near future GPU's will be manufactured using ALD for part of the process.

The key leader in this is https://beneq.com/en/

The filters delivered from RAYTUM were made with BENEQ system C2R

"Beneq C2R provides an optimal solution for high performance ALD in industrial applications, such as optical coatings and barriers."

Questions that need to be answered in collaboration with DUNE

- What are the correct requirements for FD3 FD4 ?
- What measurements are needed in the medium in real conditions
- What is the requirement for the angle ? What is the movement of the cut wavelength with angle.
- Can we do angle-resolved measurements in the real fluid ?
- How do the layer stresses get annealed ? Does the annealing affect the cut wavelength. What are the thermal changes in LAR ?
- What is the best way to limit the movement of the cut wavelength with temperature.
- Measurements may be needed on stoichiometry of the high index material (ratio of oxygen to the metal). It may affect the index of refraction across the surface

This kind of full quality control program will require project support.

Conclusion

- A project using atomic layer deposition ALD for carefully tuned high quality dichroic filters will complete in September 2024.
- An important break-through in achieving high transmission from high index layers has been achieved.
- Design of filters needed for DUNE or THEIA has been demonstrated.
  - A lot of data can be made available for optimization.
- Preproduction prototypes have been delivered.
- Further collaboration on testing is very much needed.
- A next phase of SBIR is possible, but needs close collaboration at this stage. A lot of flexibility is possible in coatings and optimization.
- ***A caution: The optical performance is quite complicated and needs a proper physics simulation. Naive modeling of transmission and reflection will not work.***