Optical Monitoring Systems for Deposition of Optical Coatings

Presented by:

OSA Thin Films Technical Group

WELCOME TO JOIN OUR WEBINAR

OPTICAL MONITORING SYSTEMS FOR DEPOSITION OF OPTICAL COATINGS

12 February 2019 • 8:30 EST

OSA Thin Films Technical Group

OSA Thin Films Technical Group

At a Glance

- Focus

– Our group focuses on the design, preparation, and characterization of optical thin films and interference coatings from fundamentals to applications.
– Our group serves over thousand global members like YOU.

- Mission

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

Find us here

- Technical Group Website: www.osa.org/ThinFilmsTG
- LinkedIn: www.linkedin.com/groups/4783616

Interested in presenting your research?
Have ideas for our group activities/events?
Please contact your committee members on the next slide. Thank you!

Thin Films
Technical Group

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Executive Committee Roles and Responsibilities

- **Chair –** Primary responsibilities are to guarantee the technical group is active and engaging to our community.
- **Vice Chair –** Assists the chair and works with executive committee to guide new development of activities and events.
- **Social Media Officer –** Manages the group's social media platforms, posting discussion topics and event notices on a regular basis.
- **Events Officer –** Leads technical events, poster sessions, networking events at relevant OSA Meetings. Identifies potential topics and speakers for events.
- **Webinar Officers –** Identify topics of interest to the community, solicit potential speakers and organize webinars.

WELCOME TO OUR WEBINAR PRESENTER

Dr. Binyamin Rubin

Binyamin (Benny) Rubin holds PhD in Aerospace Engineering from Technion - Israel Institute of Technology and MSc and BSc from Moscow Institute of Physics and Technology.

He has 7 years of experience developing vacuum deposition equipment for optical coatings. He was involved in development of multiple optical monitoring systems.

In addition to optical film deposition he has extensive experience with developing ion thrusters for space propulsion and plasma sources for space environment simulation.

Optical Monitoring Systems for Deposition of Optical Coatings

BINYAMIN RUBIN,

VEECO INSTRUMENTS

Overview

1. Introduction
2. OMS classification
3. Hardware and specifications
4. Software and algorithms
5. OMS performance
6. Application examples
7. Conclusions

Motivation

- Eliminate calibration runs
- Improve run-to-run repeatability
- Enable production of complex filter designs
  - Higher layer count
  - Tighter layer thickness control
  - Error self-compensation
- OMS controls optical thickness, not mass or physical thickness
- Direct measurement of spectral performance: what you see is what you get

OMS History

1940s

Visual control by color variation Banning, 1947

1950s

Photo-electric detectors, chip changers

1970s

Broadband OMS Vidal et al. , 1978

1990s

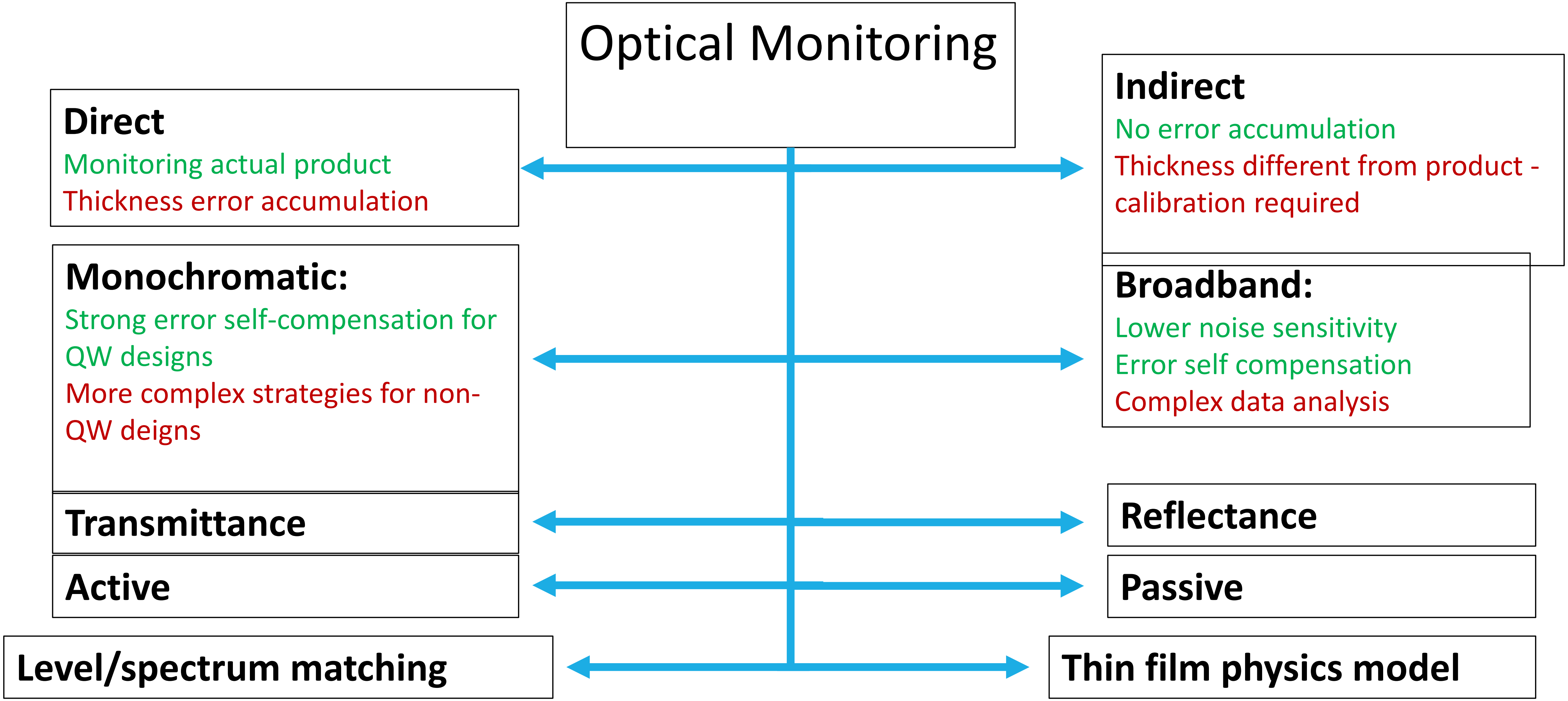
Fully automated OMS

Laser OMS for DWDM

Today

Multiple OMS commercially available from OEM and coating equipment vendors

OMS Classification



Optical Monitoring

Direct

Monitoring actual product

Thickness error accumulation

Indirect

No error accumulation

Thickness different from product - calibration required

Monochromatic:

Strong error self-compensation for QW designs

More complex strategies for non-QW deigns

Broadband:

Lower noise sensitivity

Error self compensation

Complex data analysis

Transmittance

Reflectance

Active

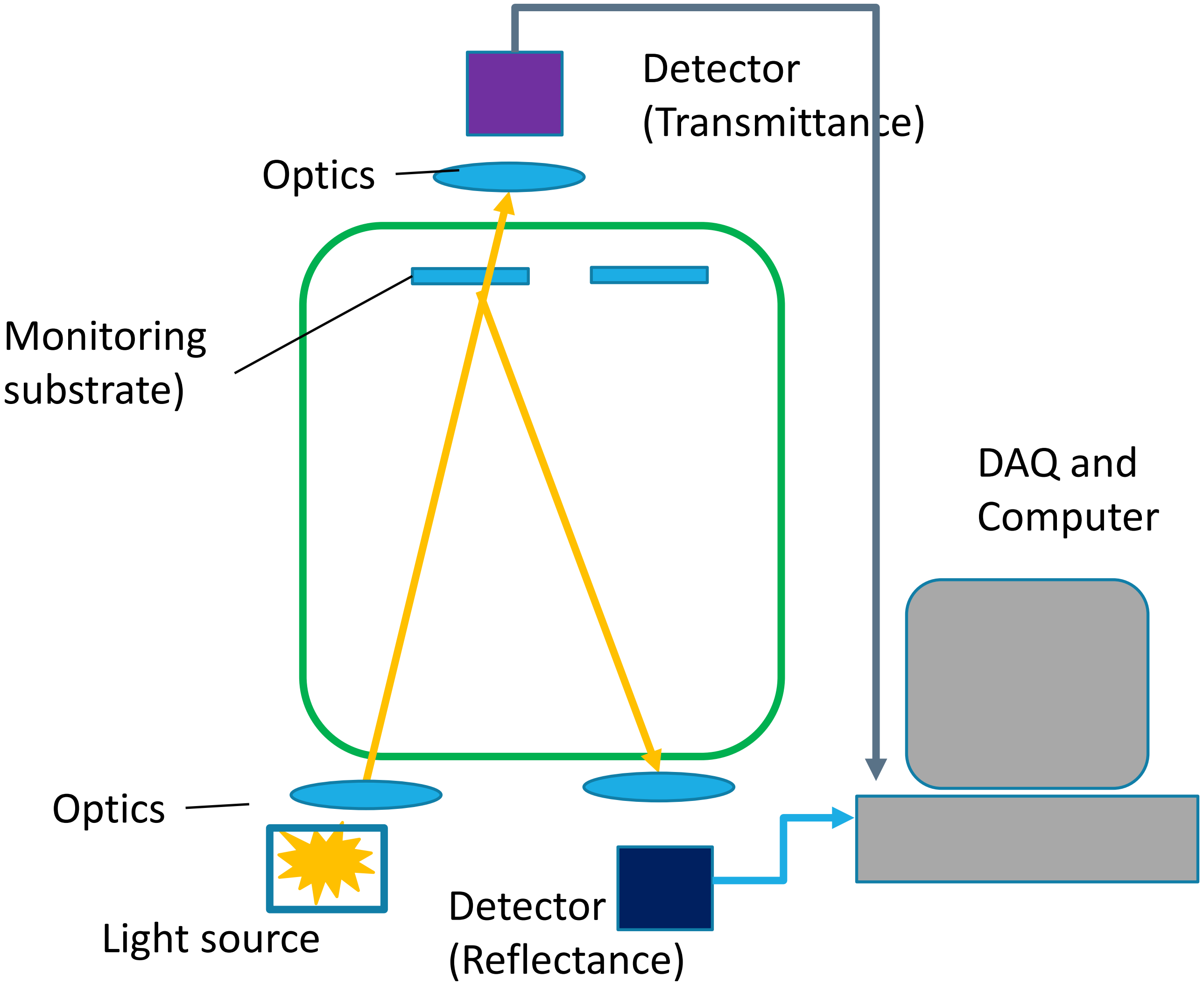
Passive

Level/spectrum matching

Thin film physics model

OMS Architecture

- Light source
  - Choppers
- Light delivery
  - Collimators
  - Mirrors
  - Fibers
- Detectors
  - Single detector
  - Spectrometer
- DAQ Electronics
- Computer



Light Sources

- Spectral range
  - Broadband
    - UV-Vis, e.g. deuterium* (~200-700 nm)
    - Vis-IR e.g. quartz, tungsten, halogen (~400-5000 nm)*
  - Monochromatic
    - Tunable laser: narrow spectral bandwidth
- Brightness, dynamic range
  - Gain flattening filters often used
- Stability and normalization
  - Modulation: reference and witness
  - Light fluctuations - re-normalization**

$$T = \frac{I_{witness} - I_{dark}}{I_{reference} - I_{dark}}$$

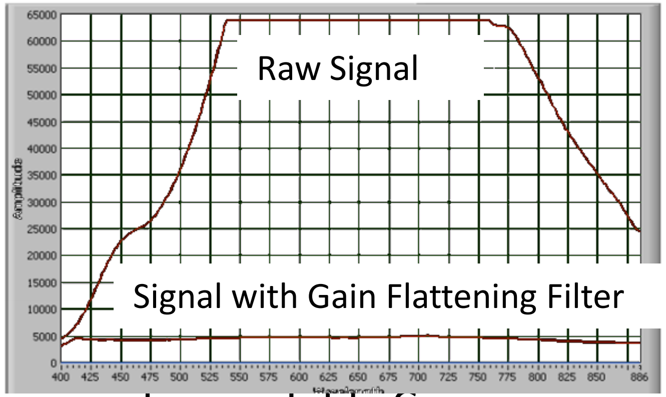


Image: Eddy Company

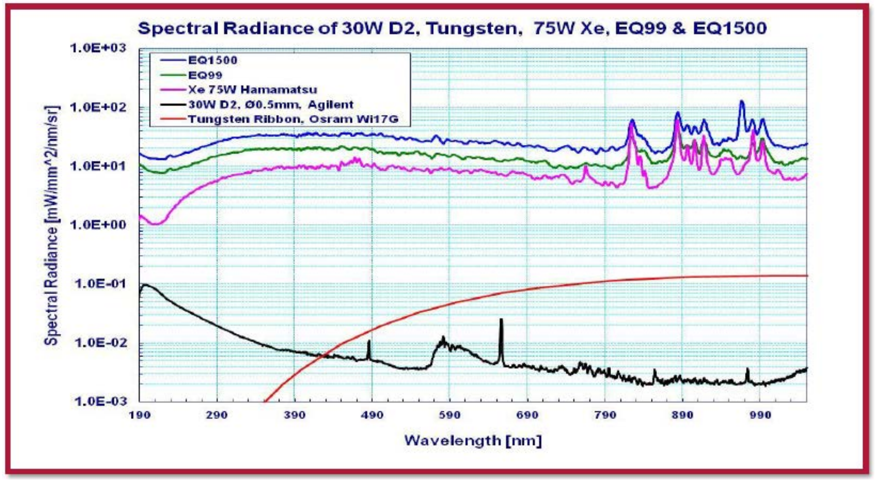


Image: Energetiq

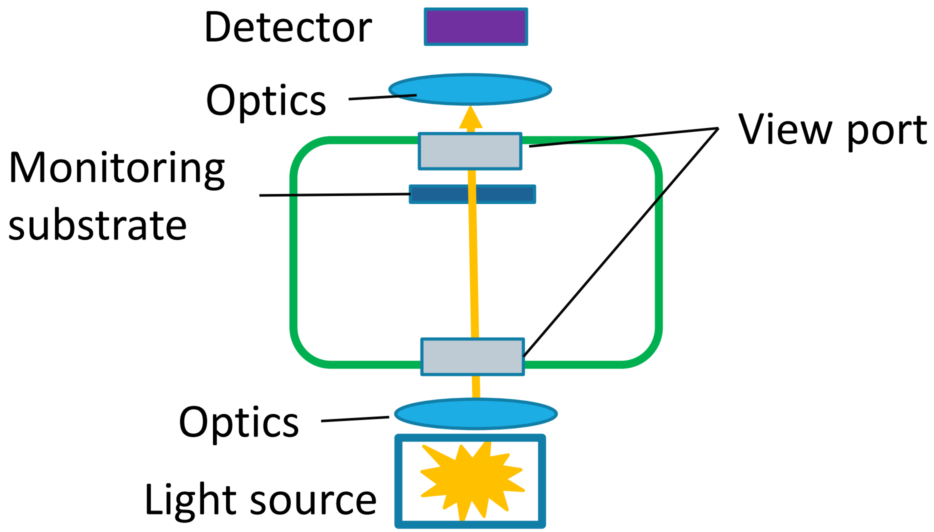
*D. Ristau, H. Ehlers, S. Schlichting, M. Lappschies, "*State of the art in deterministic production of optical thin films*", Proc. SPIE 7101, Advances in Optical Thin Films III, 71010C (2008)

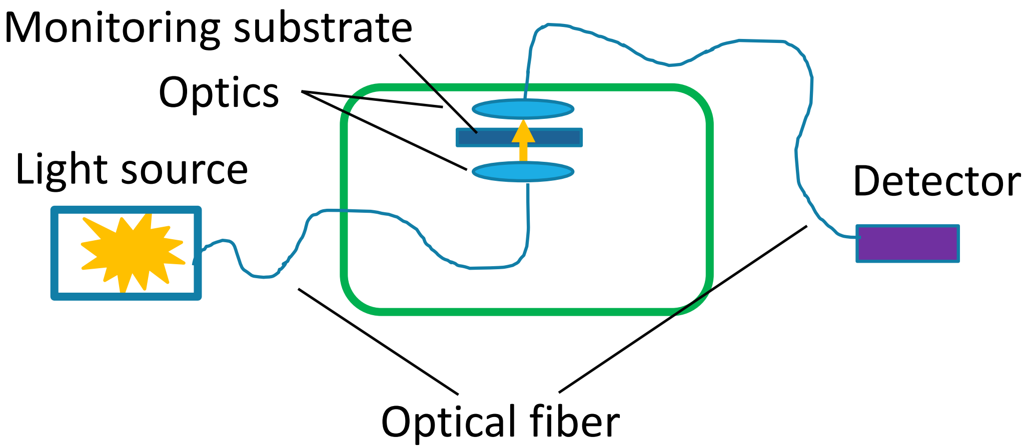
** K. Starke, T. Grosz, M. Lappschies, D. Ristau, "*Rapid prototyping of optical thin film filters*", Proc. SPIE 4094, Optical and Infrared Thin Films, (19 October 2000)

***M. Lequime, et al., "Determination of the optical constants of a dielectric layer by processing in situ spectral transmittance measurements along the time dimension", Applied Optics 56(4), C181-C187 (2017).]

Optical Path Considerations

- Free space coupling
  - Collimators
  - Viewports
- Fiber based
  - Vacuum fiber feedthrus
  - In-vacuum optics
- Losses in T, R
- Optical aberrations
- Alignment
- Protecting optics from coating





Detectors and Amplifiers

- Single detectors - Monochromatic OMS
- CCD array – Broadband OMS
- Spectral range
- Dynamic range
  - Saturation and noise floor
  - Analog-to-digital converter
- Linearity
- Time response, sampling rate
  - Typical 1-10 ms
- Noise
  - Typical 1:1000
  - Effects of rotation, vibration, averaging

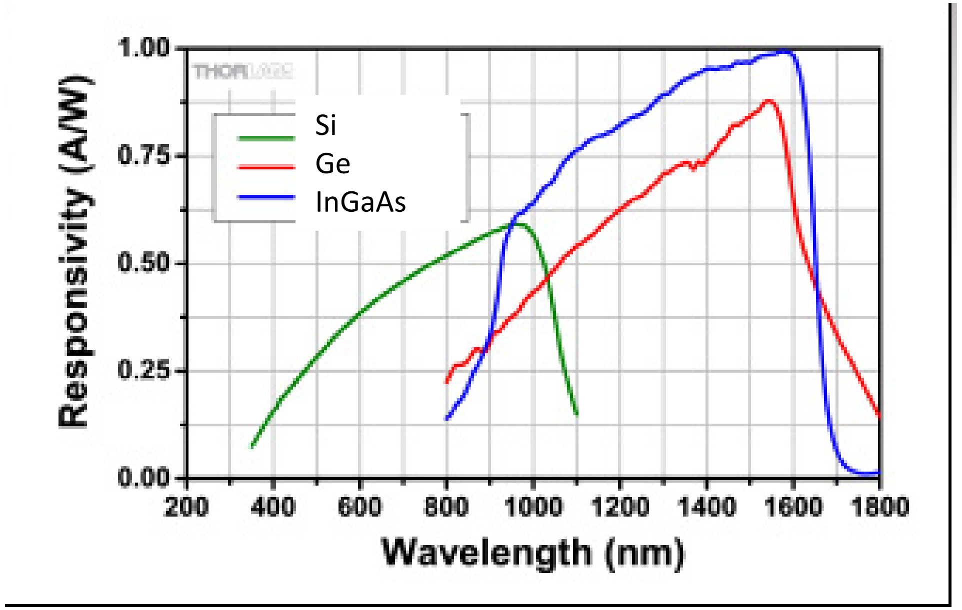


Image: Thorlabs.com

Spectral Selectivity and Resolution

Source side

- Bandpass filter at light source – several nm
- Tunable laser ~0.1 pm

Detector side

- Monochromator: Resolution <0.5 nm, wavelength precision~0.1nm
- CCD based spectrometer ≥1 nm, wavelength precision ~1nm

Effect of Spectral Resolution

- Spectral resolution of any spectrometer is finite
- Spectral resolution needs to be taken into account when monitoring sharp spectral features

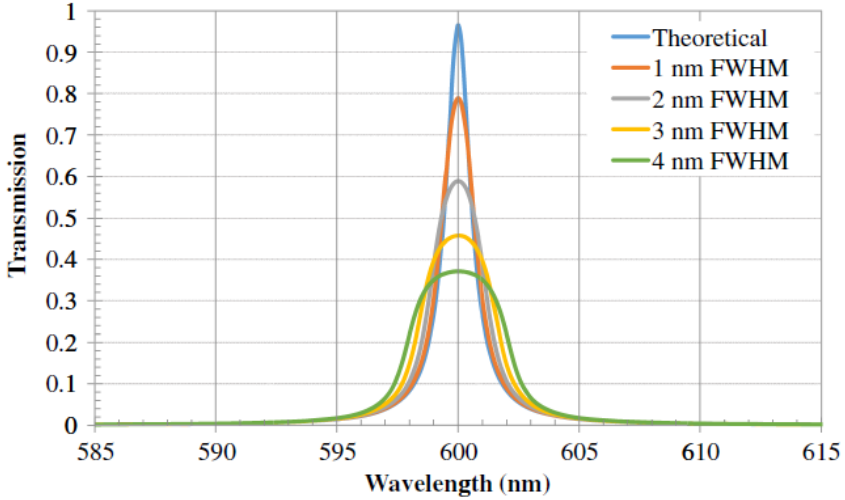
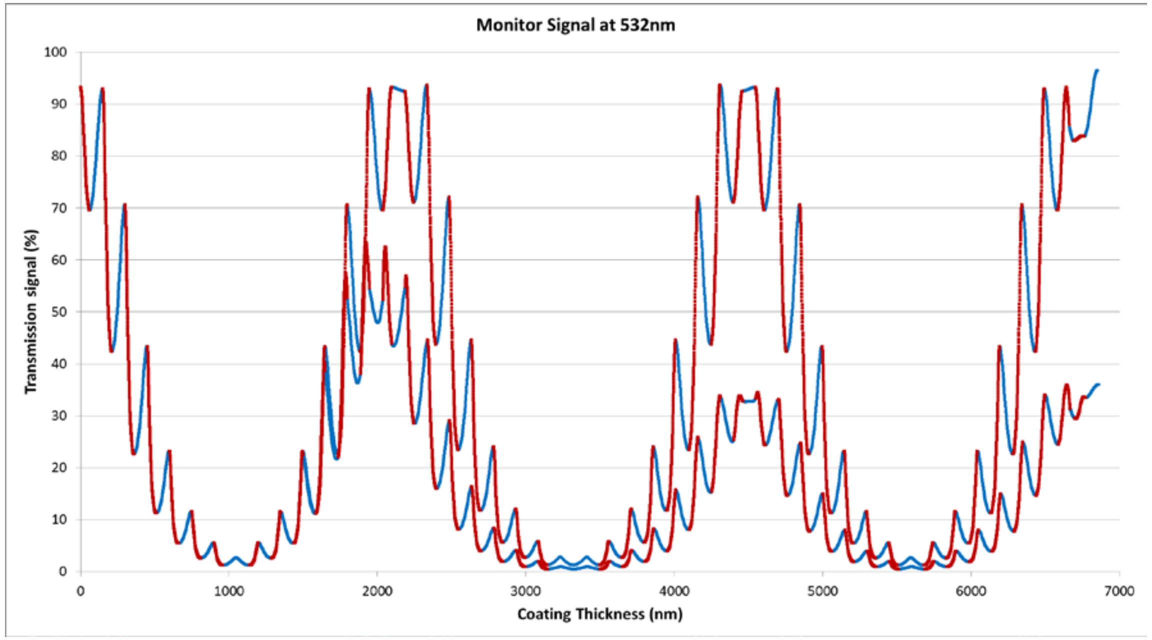


Fig. 3. Illustration of a Fabry–Perot filter measured with different resolutions from 1 nm to 4 nm.



M. Vignaux et al., "Trinary mappings: a tool for the determination of potential spectral paths for optical monitoring of optical interference filters," Appl. Opt. 57, 7012-7020 (2018)

O. Lyngnes, et al., "Optical monitoring of high throughput ion beam sputtering deposition", Proc. SPIE 9627, Optical Systems Design 2015: Advances in Optical Thin Films V, 962715

OMS Strategies: Matching vs. Fitting

- Level/spectrum matching
  - Use pre-calculated transmittance/reflectance values
- Thin film physics model based fitting
  - Fit thin film model parameters (thickness, dispersion) in real time

$$T_{sim}(\lambda, t) = \frac{4n_0 n_{sub}}{(n_0 B + C)(n_0 B + C)^*}$$

$$\begin{bmatrix} B \\ C \end{bmatrix} = \left\{ \prod_{j=1}^{q} \begin{bmatrix} \cos\delta_j & \frac{i\sin\delta_j}{y_j} \\ iy_j \sin\delta_j & \cos\delta_j \end{bmatrix} \right\} \begin{bmatrix} 1 \\ n_{sub} \end{bmatrix}$$

$$\delta_j(\lambda) = \frac{2\pi y_j \boldsymbol{d_j}}{\lambda}$$

$\boldsymbol{d_j} = physical\ thickness\ of\ layer\ j$

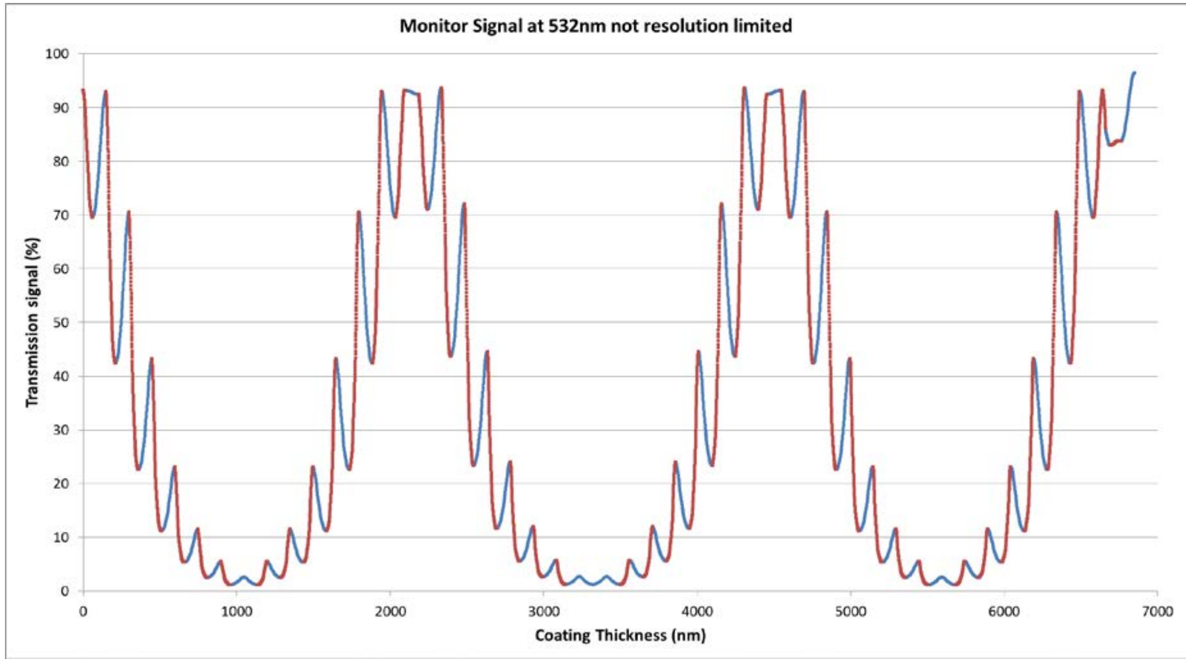
$y_j(\lambda) = n_j(\lambda) - ik_j(\lambda) = optical\ admittance\ of\ material\ for\ layer\ j$

$n_0 = refractive\ index\ of\ medium$

$n_{sub} = refractive\ index\ of\ substrate$

Single Wavelength Algorithms: Turning Point

- Fabri-Perot filters that include quarter-wave layers
- Transmittance at center wavelength has extrema (turning points) at end of each layer
- Strong error self-compensation effect
  - Mechanism explained in:



A. V. Tikhonravov and M. K. Trubetskov, Automated Design and Sensitivity Analysis of Wavelength-Division Multiplexing Filters, Appl. Opt. **41**, 3176-3182 (2002)

Single Wavelength Monitoring: Non-QW layers

- Non Quarter-wave layers are not terminated at turning points of T/R at reference wavelength
- Level cut: layers terminated at pre-defined level
  - Sensitive to photometric errors
- Percent of optical extrema (swing): layers terminated at a specified %T (or %R) of the difference between the previous two extrema
  - Insensitive to photometric errors
  - Provides error self-compensation
- Single or multiple wavelength can be used
- Strategies to optimize monitoring wavelength exist
  - Reduce sensitivity to photometric noise
  - Provide error self-compensation

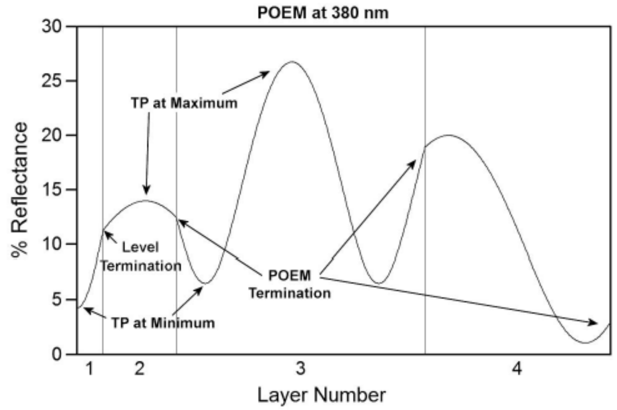


Fig. 1. Computer-simulated monitoring curve of %R versus physical thickness monitoring at 380 nm in reflectance for the four-layer AR.

R. R. Willey, "Simulation comparisons of monitoring strategies in narrow bandpass filters and antireflection coatings," Appl. Opt. 53, A27-A34 (2014).).

Single Wavelength Monitoring: Non-QW layers

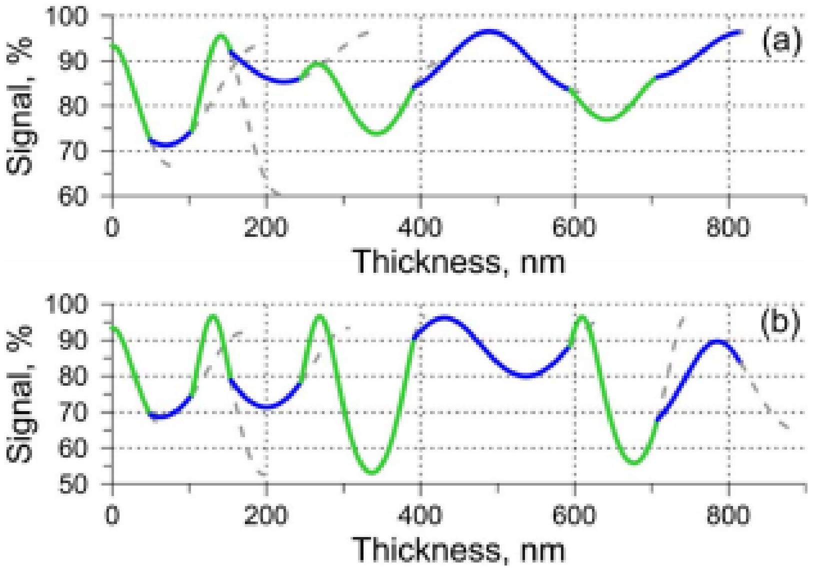


Fig. 2. AR design monitoring curves corresponding to (a) 700 and (b) 621 nm. The green and blue lines are related to the monitoring signal inside the high- and low-index layers, respectively. The gray dashed lines show the theoretical signal expected if the corresponding layer deposition continues without interruption until the next extremum.

M. Trubetskov, et al., "Automated construction of monochromatic monitoring strategies," Appl. Opt. **54,** 1900-1909 (2015).

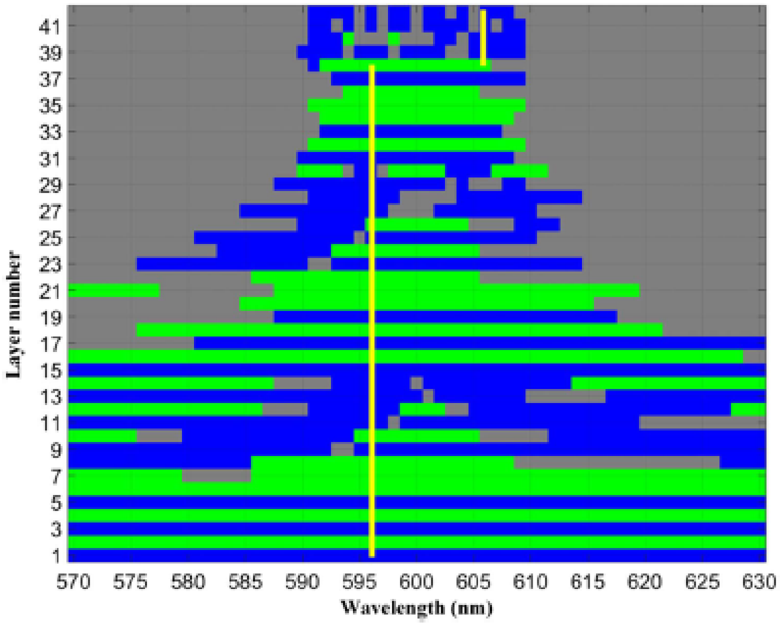
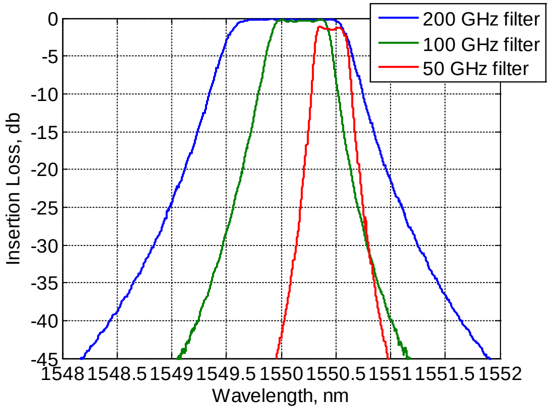


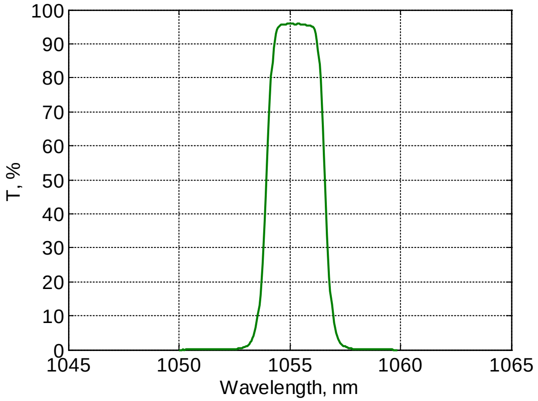
Fig. 7. Trinary mapping of a non-conventional Fabry–Perot filter [570–630] nm. Optimal path is highlighted with yellow lines.

M. Vignaux et al., Trinary mappings: a tool for the determination of potential spectral paths for optical monitoring
of optical interference filters, Applied Optics, Vol. 57, No. 24

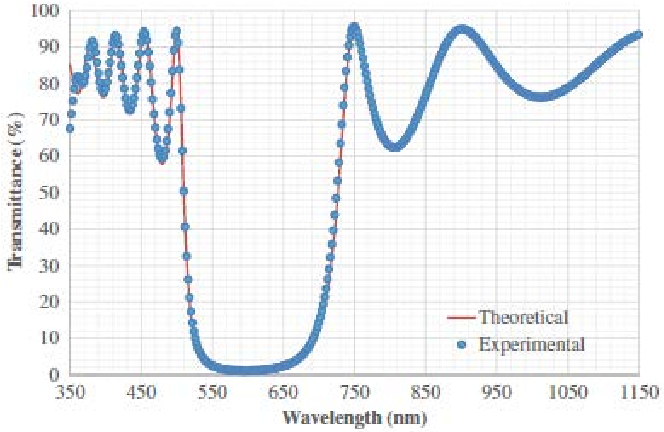
Application Examples: Monochromatic OMS

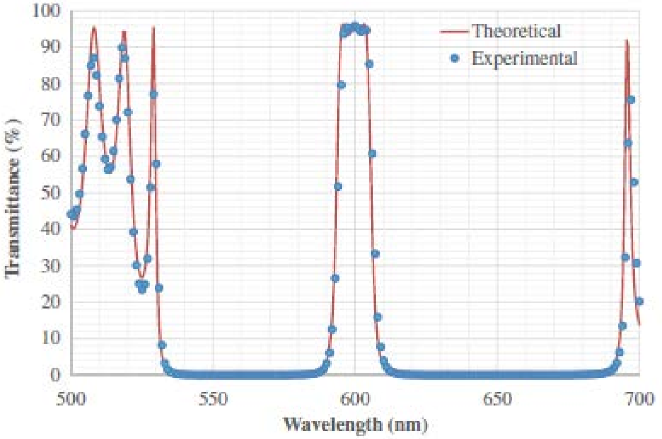
Turning Point





Non-Turning Point



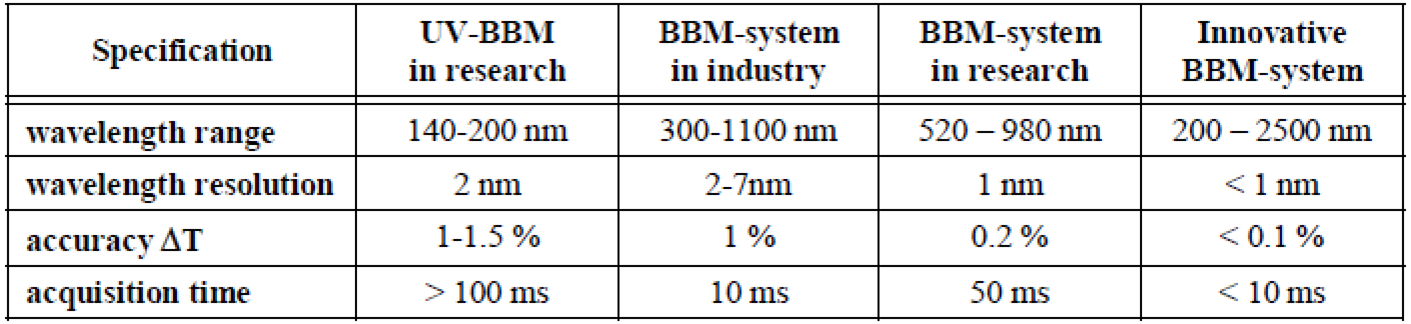


B. Rubin, et al. Monochromatic and broadband optical monitoring for deposition of band pass filters, Submitted to Optical Interference Coatings Conference, 2019

M. Vignaux, et al., "Trinary mappings: a tool for the determination of potential spectral paths for optical monitoring of optical interference filters," Appl. Opt. 57, 7012-7020 (2018)

Broadband OMS

- Lower sensitivity to errors in measurement data
- Lower effects of thickness error accumulation
- Error self-compensation
  - A. Tikhonravov, et al., "Investigation of the error self-compensation effect associated with broadband optical monitoring," Appl. Opt. 50, C111-C116 (2011).
- Direct broadband OMS allows direct estimation of filter performance



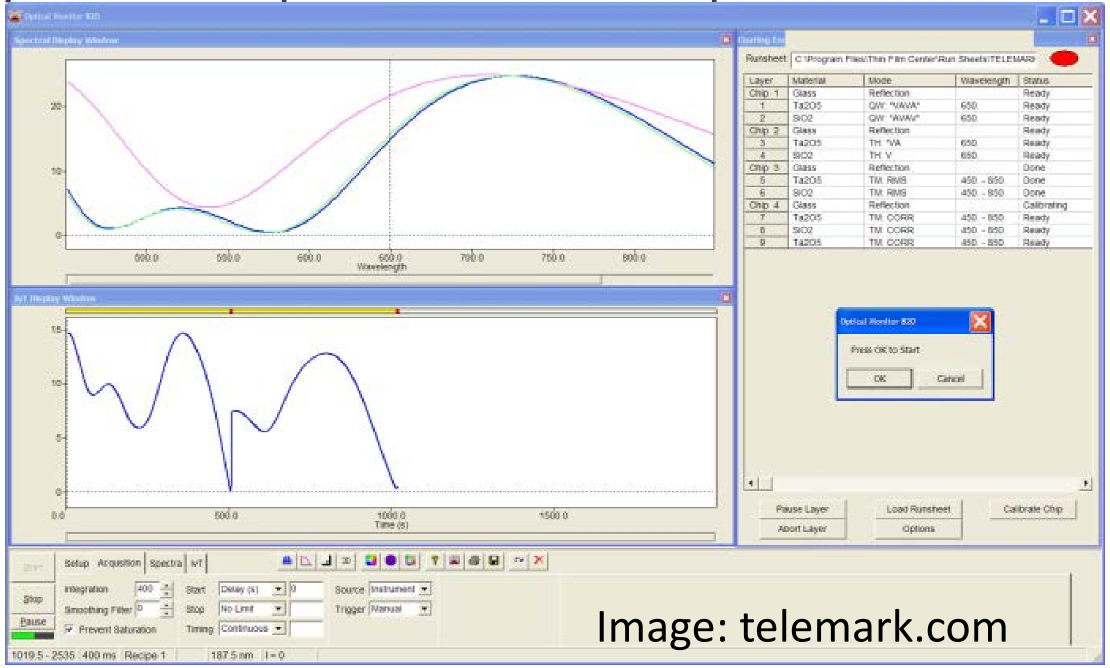
Specification	UV-BBM in research	BBM-system in industry	BBM-system in research	Innovative BBM-system
wavelength range	140-200 nm	300-1100 nm	520 – 980 nm	200 – 2500 nm
wavelength resolution	2 nm	2-7nm	1 nm	< 1 nm
accuracy ΔT	1-1.5 %	1 %	0.2 %	< 0.1 %
acquisition time	> 100 ms	10 ms	50 ms	< 10 ms

D. Ristau et al., State of the Art in Deterministic Production of Optical Thin FilmsProc. of SPIE Vol. 7101 71010C-5, 2008

(OMS has improved since then!)

Spectrum Matching

- Generate spectra using thin film software
- Terminate layers when spectrum matches pre-calculated shapes



Runsheet C:\Program Files\Thin Film Center\Run Sheets\TELEMAR

Layer	Material	Mode	Wavelength	Status
Chip 1	Glass	Reflection		Ready
1	Ta2O5	QW: "VAVA"	650.	Ready
2	SiO2	QW: "AVAV"	650.	Ready
Chip 2	Glass	Reflection		Ready
3	Ta2O5	TH: "VA	650.	Ready
4	SiO2	TH: V	650.	Ready
Chip 3	Glass	Reflection		Done
5	Ta2O5	TM: RMS	450. - 850.	Done
6	SiO2	TM: RMS	450. - 850.	Done
Chip 4	Glass	Reflection		Calibrating
7	Ta2O5	TM: CORR	450. - 850.	Ready
8	SiO2	TM: CORR	450. - 850.	Ready
9	Ta2O5	TM: CORR	450. - 850.	Ready

Press OK to Start

Integration 400
Smoothing Filter 0
☑ Prevent Saturation
Start Delay (s) 0
Stop No Limit
Timing Continuous
Source Instrument
Trigger Manual

1019.5 - 2535 400 ms Recipe 1 187.5 nm I = 0

Image: telemark.com

If spectrum deviates too far – no recovery

Model Based Fitting

- Real-time fit of layer thickness

o Sequential: fit only current layer thickness

$$F_S\left(d_j^S\right)=\left[\frac{1}{N}\sum_{i=1}^{N}\left(\frac{T_{\mathrm{meas}}^{S\ (j)}\left(\lambda_i\right)-T_{\mathrm{calc}}^{S\ (j)}\left(\lambda_i,d_1,\ldots,d_{j-1},d_j^S\right)}{\Delta T_S\left(\lambda_i\right)}\right)^2\right]^{\frac{1}{2}}$$

T- transmittance, *d* –thickness, *λ* – wavelength, *N*- number of wavelengths,
ΔT - transmittance measurement error

Error propagation can be a problem

o Full triangular algorithm: fit current and all previous layers

$$F_T^{(J)}\left(d_1,\ldots,d_j\right)=\left[\frac{1}{JN}\sum_{j=1}^{J}\sum_{i=1}^{N}\left(\frac{T_{\mathrm{meas}}^{T\ (j)}\left(\lambda_i\right)-T_{\mathrm{calc}}^{T\ (j)}\left(\lambda_i,d_1,\ldots,d_j\right)}{\Delta T_T\left(\lambda_i\right)}\right)^2\right]^{\frac{1}{2}}$$

- Potential to detect errors in previous layers
- More time- consuming, sometimes used between layers

T. Amotchkina, et al. "Comparison of algorithms used for optical characterization of multilayer optical coatings." Appl. Opt. **50**, 3389-3395 (2011).

Error Accumulation Effects

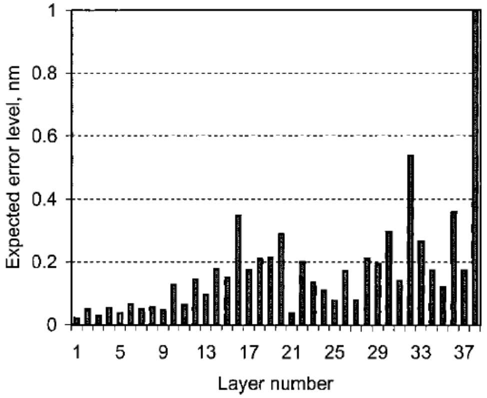
- Analytical equations can be used to estimate cumulative effect of errors in previous layers
- Effect of systematic measurement errors higher then effect of random errors
- Effect of direct thickness errors due to dep. rate fluctuations can be higher than errors related to OMS algorithm

$$\delta d_j = \sum_{i=1}^{j-1} \alpha_j^{\,i} \delta d_i + \beta_j,$$

where

$$\alpha_j^{\,i} = -\sum_{\{\lambda_k\}} \left(\frac{\partial T^j}{\partial d_j}\,\frac{\partial T^j}{\partial d_i}\right) \Bigg/ \sum_{\{\lambda_k\}} \left(\frac{\partial T^j}{\partial d_j}\right)^2.$$

$$\beta_j = -\sum_{\{\lambda_k\}} \frac{\partial T^j}{\partial d_j}\,\delta T_{\mathrm{meas}}(\lambda_k) \Bigg/ \sum_{\{\lambda_k\}} \left(\frac{\partial T^j}{\partial d_j}\right)^2.$$



A. Tikhonravov, et al., "Investigation of the effect of accumulation of thickness errors in optical coating production by broadband optical monitoring," Appl. Opt. **45**, 7026-7034 (2006)

Indirect Monitoring with Multiple Witness Substrates

- Chip changer can be used to avoid error accumulation
- Multiple witness substrates used to monitor several pre-defined layers

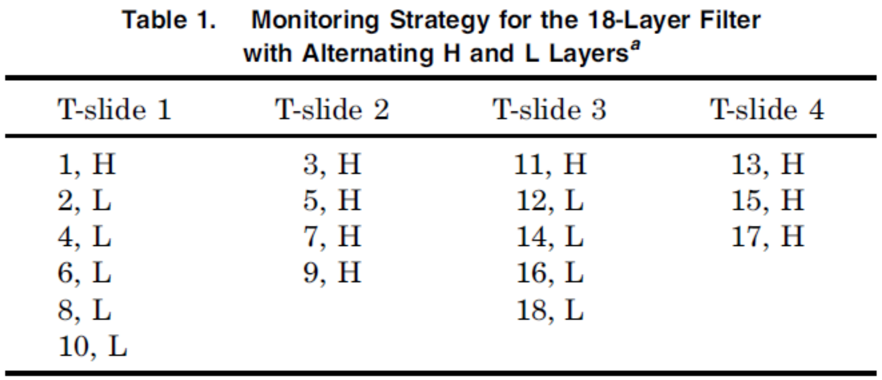


Table 1. Monitoring Strategy for the 18-Layer Filter with Alternating H and L Layers[a]

T-slide 1	T-slide 2	T-slide 3	T-slide 4
1, H	3, H	11, H	13, H
2, L	5, H	12, L	15, H
4, L	7, H	14, L	17, H
6, L	9, H	16, L	
8, L		18, L	
10, L			

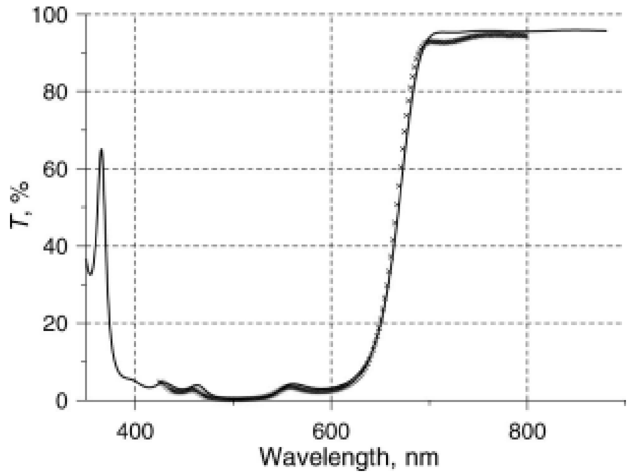


Fig. 4. Measured transmittance of the manufactured 18-layer filter (crosses) and theoretical transmittance of this filter calculated by taking into account the substrate backside reflectance (thin solid line).

V. Zhupanov, et al., "Indirect broadband optical monitoring with multiple witness substrates", Applied Optics **48**, 2315-2320 (2009).

OMS Performance Metrics

- Hardware related
  - Spectral range
  - Signal to noise ratio
  - Wavelength resolution
  - Photometric accuracy
  - Spectral accuracy
- Performance related
  - Equivalent layer errors
  - Repeatability
  - Maximum layer count

Sources of Errors

- OMS related
  - Detector noise (shot noise, CCD digitization)
  - Vibrations
  - Beam walk (angle of incidence, substrate parallelism, wobble)
  - Error accumulation (compensated by chip changer)
- Process related
  - Deposition rate fluctuations/drifts
  - Material properties fluctuations/drifts
  - Substrate rotation and averaging

Production Yield Estimation

Production yield affected by uniformity, filter design, monitoring strategy

Numerical simulations can be used to estimate yield, optimize design and strategy

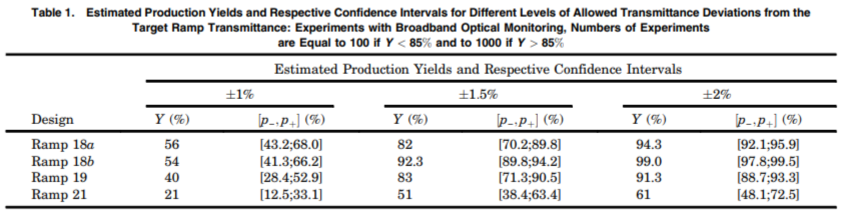


Table 1. Estimated Production Yields and Respective Confidence Intervals for Different Levels of Allowed Transmittance Deviations from the Target Ramp Transmittance: Experiments with Broadband Optical Monitoring, Numbers of Experiments are Equal to 100 if $Y < 85\%$ and to 1000 if $Y > 85\%$

	Estimated Production Yields and Respective Confidence Intervals					
	±1%		±1.5%		±2%	
Design	Y (%)	$[p_-, p_+]$ (%)	Y (%)	$[p_-, p_+]$ (%)	Y (%)	$[p_-, p_+]$ (%)
Ramp 18*a*	56	[43.2;68.0]	82	[70.2;89.8]	94.3	[92.1;95.9]
Ramp 18*b*	54	[41.3;66.2]	92.3	[89.8;94.2]	99.0	[97.8;99.5]
Ramp 19	40	[28.4;52.9]	83	[71.3;90.5]	91.3	[88.7;93.3]
Ramp 21	21	[12.5;33.1]	51	[38.4;63.4]	61	[48.1;72.5]

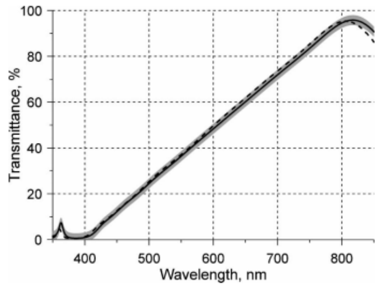
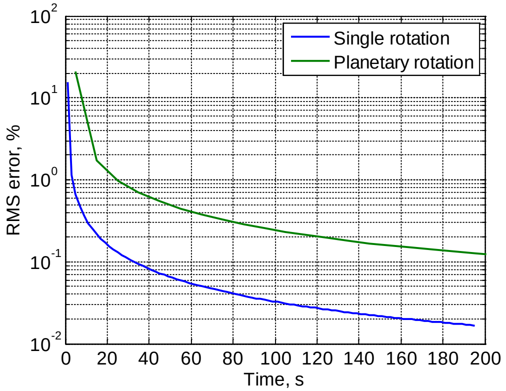
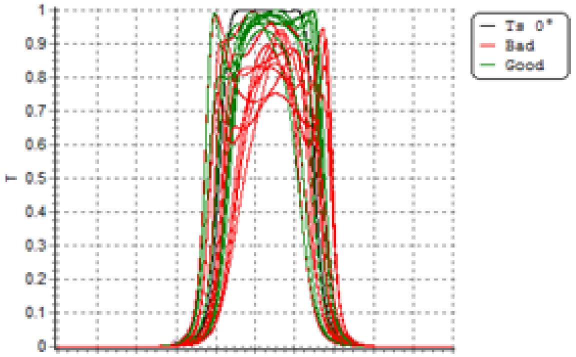


Fig. 4. Measured transmittance of the 21 layer coating (dashed curve), theoretical transmittance of the Ramp 21 design (solid curve), and the corridor of ±2% deviations from the theoretical transmittance (gray area).

A. Tikhonravov, et al. "Estimations of production yields for selection of a practical optimal optical coating design," Appl. Opt. 50, C141-C147 (2011).

RMS Error – 0.05%. Yield – 45%





B. Rubin et al., Effects of fixture rotation on coating uniformity for high-performance optical filter fabrication, Advanced Optical Technologies, Volume 7, Issue 1-2, P. 39 (2018)

Active Strategy: Re-Optimization

- Determine deposited layer thickness
- Re-optimize the remaining layer thicknesses

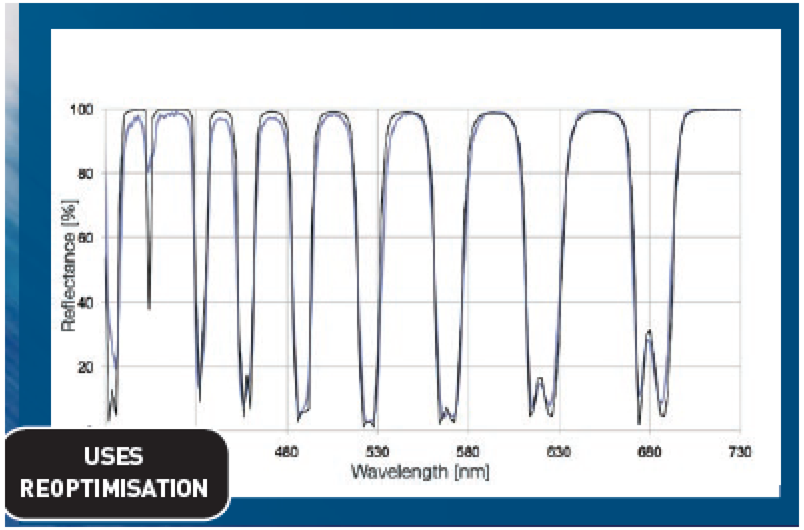
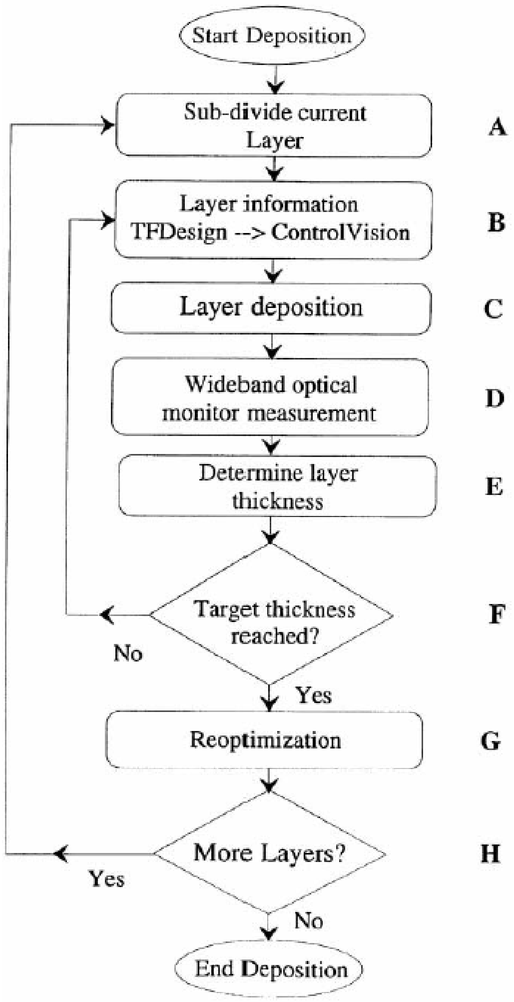


Image :Evatec

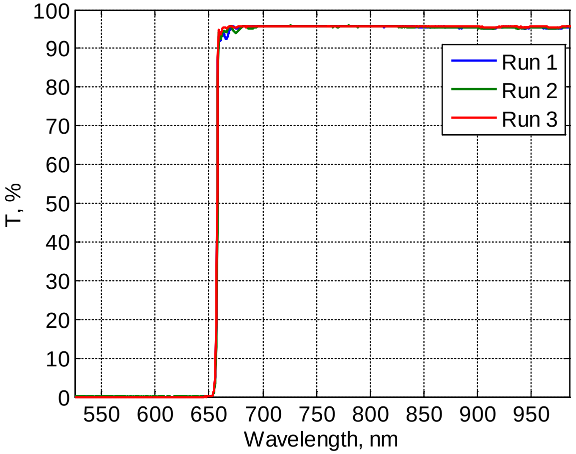


B. Sullivan et al., Manufacture of complex optical multilayer filters using an automated deposition system, Vacuum, Vol.51, 4, p. 647

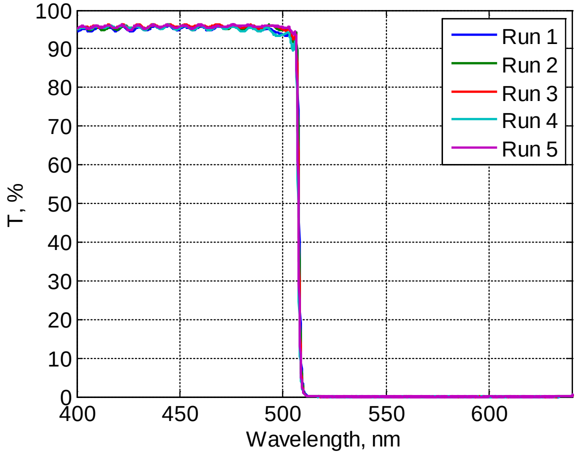
Examples of OMS Controlled Coatings

Coated without chip changer

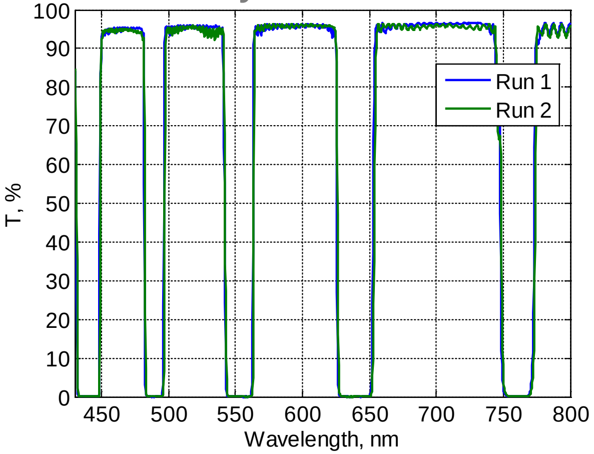
90-layer Long Wave Pass



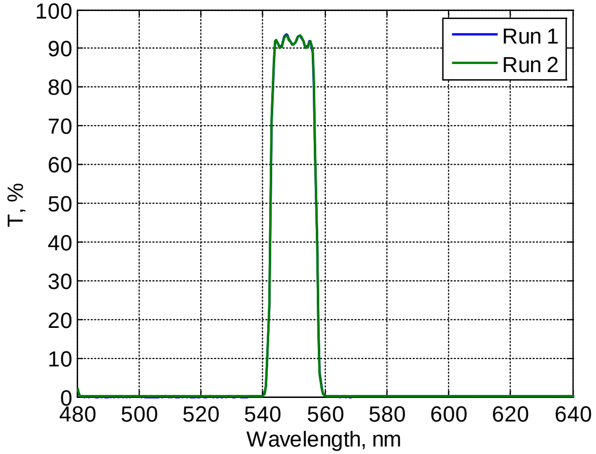
72-layer Short Wave Pass



100-layer Multi-Notch



79-layer Band Pass



B. Rubin, et al. Improving Contrast in Broadband Optical Monitoring, 2018 SVC Technical Conference Proceedings, Optical Coatings

Examples of OMS Controlled Coatings

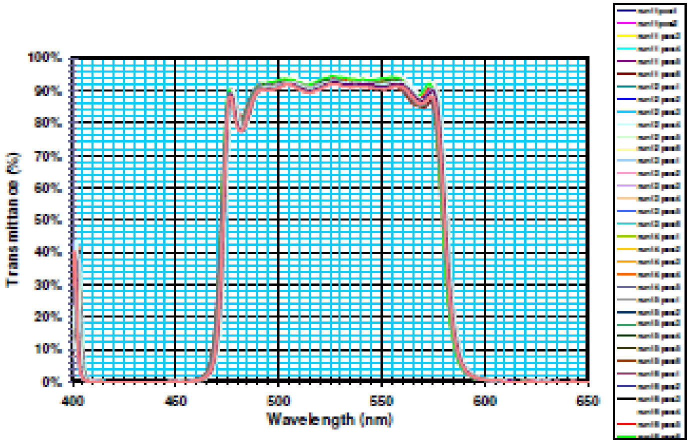


Fig. 4b: Performance of 6 substatrate positions over 9 consecutive runs (AOI=0°)

A. Zöller et al., Precision Filter Manufacture Using Direct Optical Monitoring, in Optical Interference Coatings, OSA Technical Digest (2010), paper TuC8.

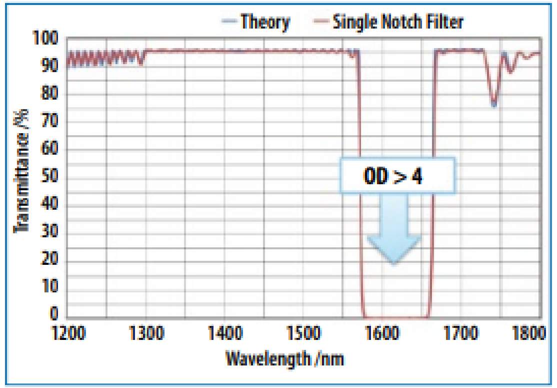
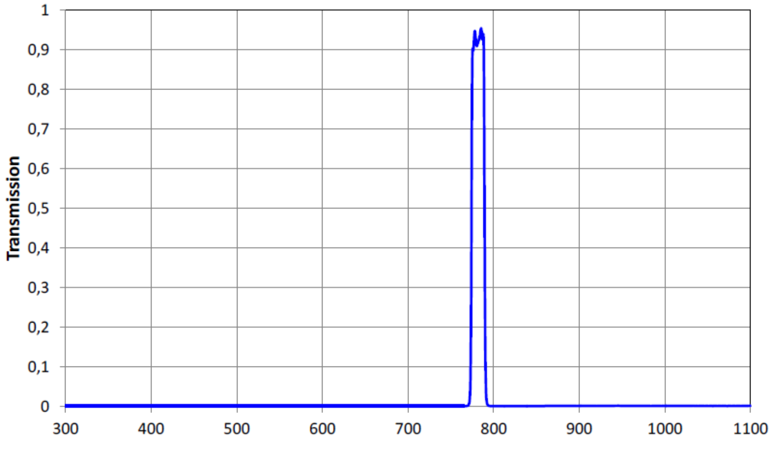


FIGURE 10: Spectral performance in transmittance of a IR Notch filter with a sharp transition at the band edge achieving a high light suppressing (OD 4) at 1615 nm.

Jens-Peter Biethan et al., High precision optical filter based on magnetron sputtering, Vacuum in Research and Practice 29 (4): 26-31



T. Begou et al., "Optical filters for UV to near IR space applications," Proc. SPIE 10563, International Conference on Space Optics — ICSO 2014, 1056306

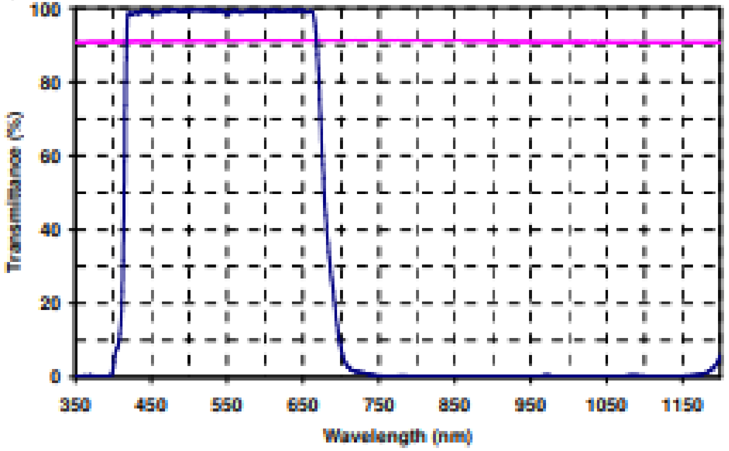


Fig. 3: UV-IR cut filter with backside AR

H. Hagedorn et al., High Performance Coatings with Large RF Plasma Source

Examples of OMS Special Applications

LZH: Optical Monitoring of Rugates

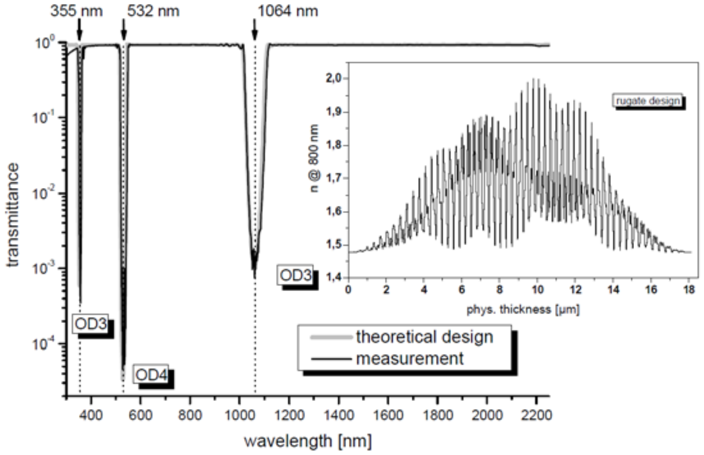


Fig. 7. Theoretical and realized spectrum of a rugate filter for an application in laser protection. The coating system was produced with an IBS-process based on a zone target of Ta_2O_5/SiO_2. The insert illustrates the refractive index step function which was controlled by a BBM-tracing algorithm during deposition.

D. Ristau et al., State of the Art in Deterministic Production of Optical Thin Films, Proc. of SPIE Vol. 7101, 71010C

LZH: In-Situ GDD Measurement

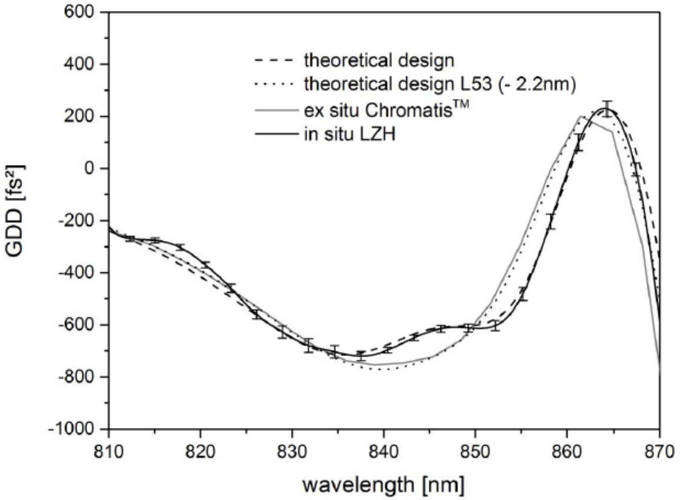


Figure 7: In situ GDD measurement in comparison to ex situ Chromatis™ measurement and theoretical design GDD

S. Schlichting et al., Direct in situ GDD measurement in optical coating process, Proc. of SPIE Vol. 9627, 96271S

Institut Fresnel: Monitoring absorbing films

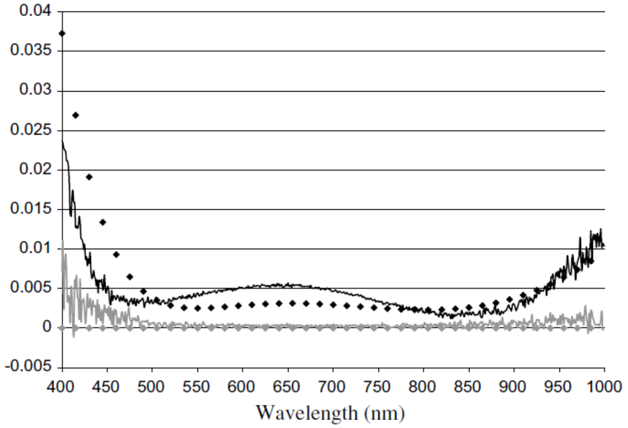


Fig. 8. Black and grey diamond pattern are, respectively, the theoretical reflectance and transmittance. Black and grey curves are, respectively, the reflectance and the transmittance measurements.

B.Badoil et al., Direct monitoring of broadband light absorbers. Optics Communications, Vol. 281, 9, 2008

OMS Research Groups and Vendors

Leading research groups

- Laser Center Hannover
- Moscow State University, OptiLayer
- Institut Fresnel
- National Research Center of Canada
- R.Wiley
- National Central University, Taiwan

- Coating equipment vendors that offer OMS
  - Buhler
  - Cutting Edge Coatings
  - Dynavac
  - Denton Vacuum
  - Evatec
  - Optorun
  - Shincron
  - Veeco
- OMS Vendors
  - Eddy Company
  - Essent optics
  - Intellemetrics
  - Telemark

…And many others

Conclusions

- Many types of OMS exist in academia and industry
- Selecting correct OMS for your application can be confusing
- No ‘silver bullet’ exists: different applications demand different OMS
- There is OMS for almost every application
- Areas of improvement:
  - Broader spectral range
  - Higher layer counts
  - Automated strategy generation