MAKING A MATERIAL DIFFERENCE

Comparison of monochromatic and broadband optical monitoring for deposition of non-quarter wave filter designs

Symposium OCLA 2021

March 30 – 31, 2021

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Single Wavelength And Broadband Monitoring Hardware

OMS Type	Wavelength Selectivity	Spectral range, nm	Spectral resolution, nm	Signal-to-noise ratio *
Monochromatic	Grating Monochromator+ UV-Vis, IR detectors	Vis: 300 - 1100 NIR: 900 – 2000	Variable <0.5	Typical 1:1,000
Monochromatic	Tunable laser	NIR: 1260-1640	Fixed <0.1	Up to 1:10,000
Broadband	Grating+ CCD/photodiode array	Vis: 300-1100 NIR: 900-1700	Fixed 1.5-3	Typical 1:300

* Affected by substrate rotation, vibration etc

Optical Monitoring Strategies

- Level/spectrum matching
  - Layers terminated at pre-calculated transmittance/reflectance values
- Curve fitting
  - Fit simple functional form, e.g. parabola
  - OR calculate time interval between extrema
  - Model predicts termination point
- Thin film physics model based fitting
  - Fit thin film model parameters (thickness, dispersion) in real time
  - Model predicts layer termination point when given condition is met

Theoretical Analysis of Noise Sensitivity

Effect of random errors in transmittance data on optical monitoring

Standard deviation of thickness errors caused by inaccuracies in the monitoring of the *j*th layer

Summation over wavelength range

Broadband

$$\sigma(\beta_j) = \sigma_{\text{meas}} \Big/ \left[\sum_{\{\lambda_k\}} \left(\frac{\partial T^j}{\partial d_j} \right)^2 \right]^{1/2}.$$

Monochromatic

$$\sigma(\beta_j) = \sigma_{\text{meas}} \Big/ \left| \frac{\partial T^j}{\partial d_j} \right|$$

Standard deviation of transmittance measurements

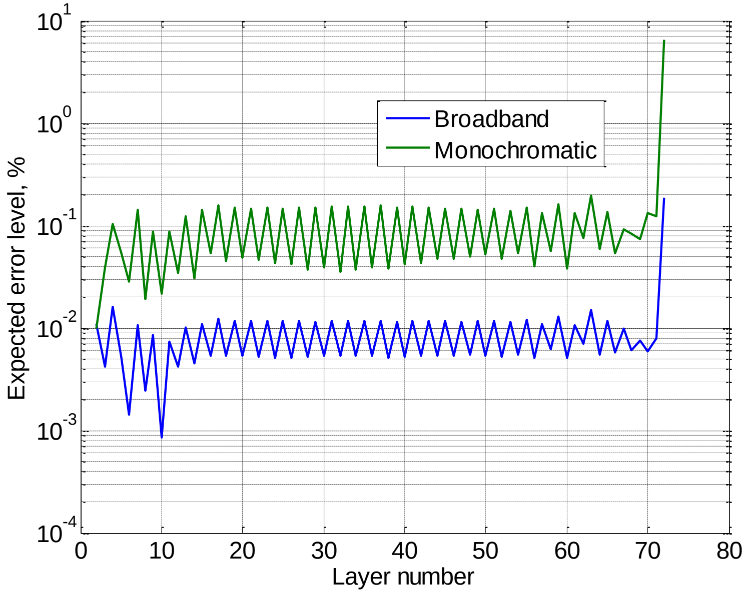
Sensitivity of transmittance value to layer thickness variation

Denominator is many times more for broadband – lower layer errors expected

A.Tikhonravov, M.Trubetskov, and T. Amotchkina, "Investigation of the effect of accumulation of thickness errors in optical coating production by broadband optical monitoring," Appl. Opt. 45, 7026-7034 (2006)

Theoretical Analysis of Noise Sensitivity

- Calculated error levels for 72-layer Short Wave Pass filter
  - Broadband: 400-1000 nm
  - Monochromatic: 400 nm
  - Measurement noise level: 0.1% RMS



Order of magnitude lower errors expected with broadband monitoring

Defining a Monochromatic Strategy

- Layer sensitivity – choose the wavelength where there is the greatest change during the layer
- "Trinary Mapping"*
  - High change of T% during the layer
  - Layer end: not near a turning point
  - Layer end: high derivative of T%
  - Layer end: T% above a minimum (avoids a high noise situation)
  - Low transmission variability within wavelength window (to account for linewidth errors)
  - Bonus criteria: visible max and min during the layer
- Manufacturing simulation of test strategy

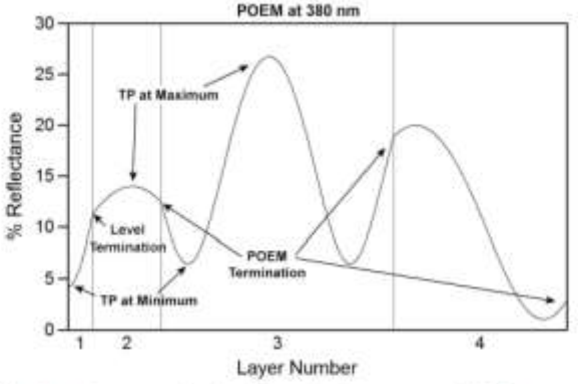


Fig. 1. Computer-simulated monitoring curve of %R versus physical thickness monitoring at 380 nm in reflectance for the four-layer AR.

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

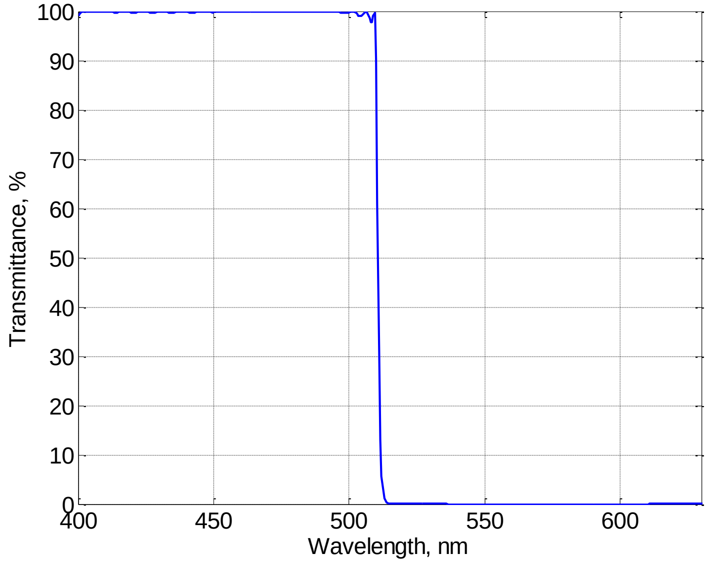
*Vignaux, Mael, et al. "Trinary Mappings: A Tool for the Determination of Potential Spectral Paths for Optical Monitoring of Optical Interference Filters." *Applied Optics* 57, no. 24, 2018

Experimental Work – Broadband and Monochromatic

- Several monochromatic filters have been demonstrated with excellent results using Trinary Mapping to define a strategy and POEM to monitor
- What are the limitations of the method? (a work in progress)
- We chose two challenge filters to fabricate

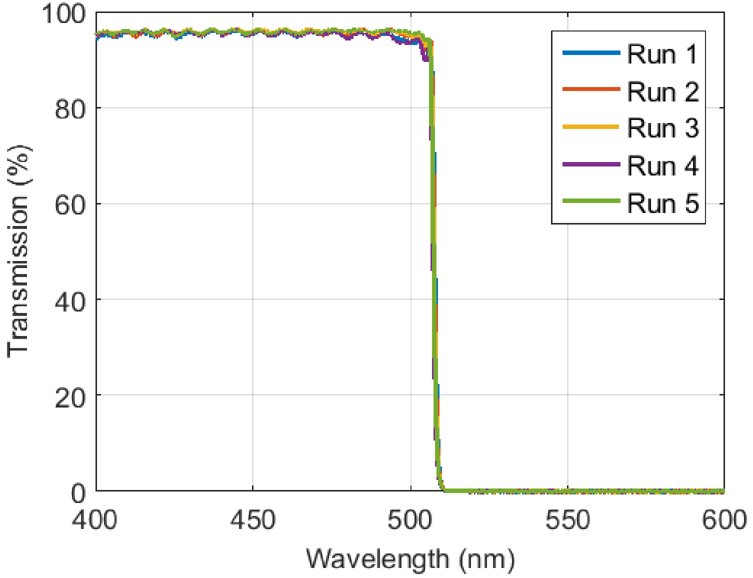
Experiment – Short Wave Pass

Theoretical Spectrum



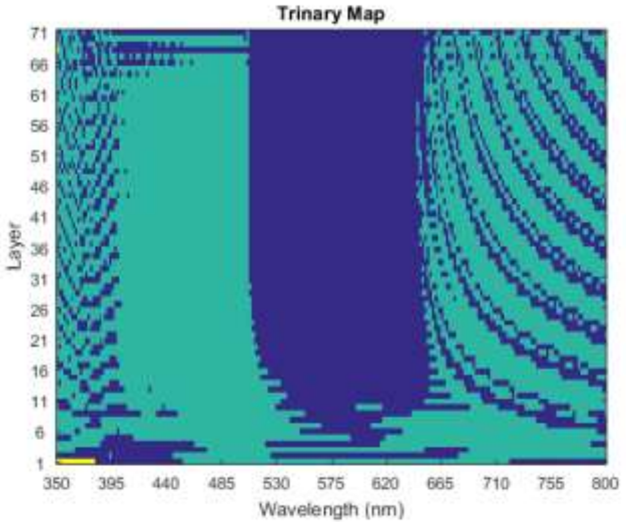
- 72 Layers
- All non-QWOT

Broadband Experiment



Simple strategy: monitor 400-1000 nm, fit to theoretical spectrum.

Short Wave Pass – Monochromatic Strategies



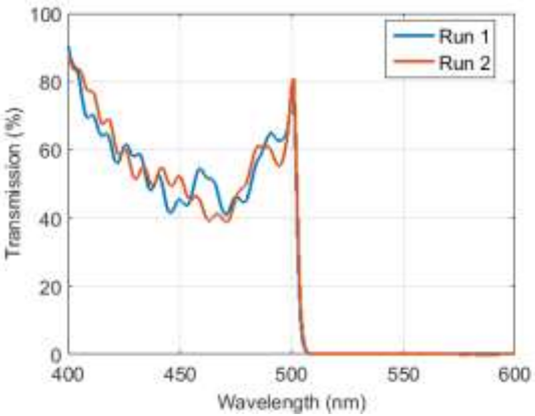
Strategy 1 Best Single WL	Strategy 2 Balance the number of WL while passing through some disallowed regions	Strategy 3 Minimum # of WL while strictly passing through "green" areas
500 nm	480 nm	468 nm
	495 nm @ layer 21	390 nm @ layer 14
	488 nm @ layer 41	388 nm @ layer 30
		392 nm @ layer 44
		388 nm @ layer 59

- Passes all 5 criteria
- Does not pass all 5 criteria
- Passes all criteria and there is a max and min within the layer

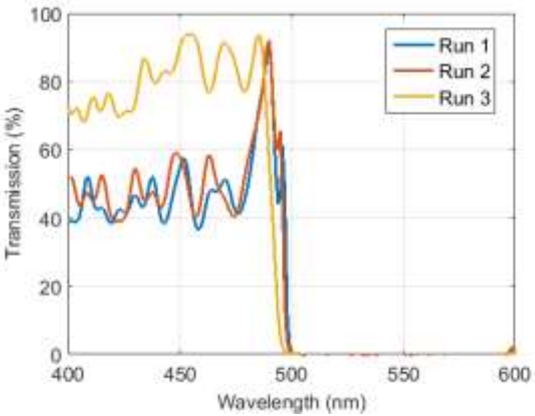
For monochromatic monitoring, the user must carefully design the monitoring strategy.

Veeco

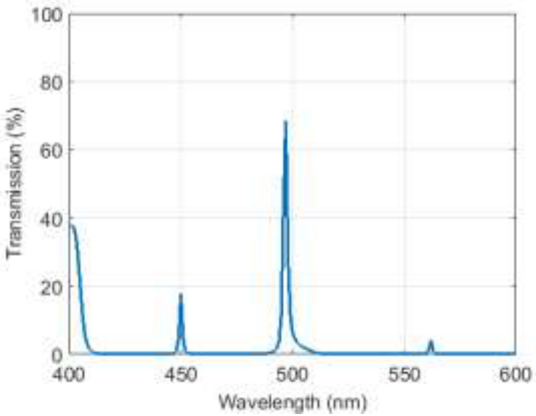
Short Wave Pass – Single Wavelength Experiment



Strategy 1:
Single Wavelength



Strategy 2:
3 Wavelengths

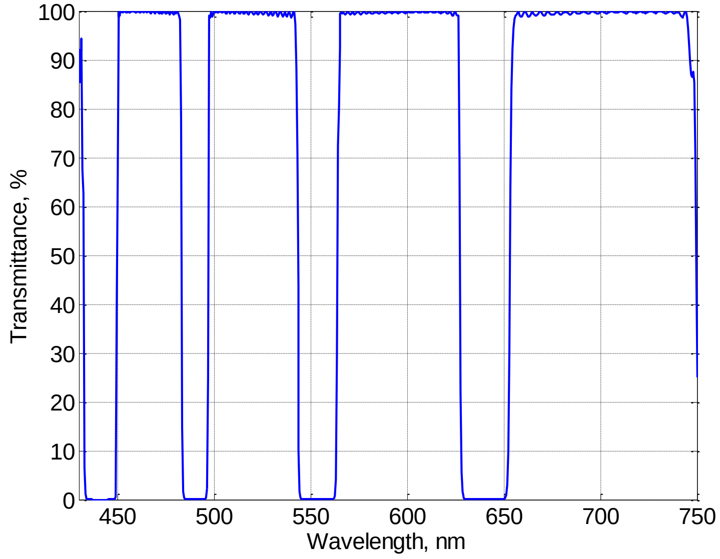


Strategy 3:
5 Wavelengths

- All monitored using Percent of Optical Extremum monitoring (POEM)
- No monochromatic strategy was able to produce the filter.
- The strategy with many wavelength changes underperformed.

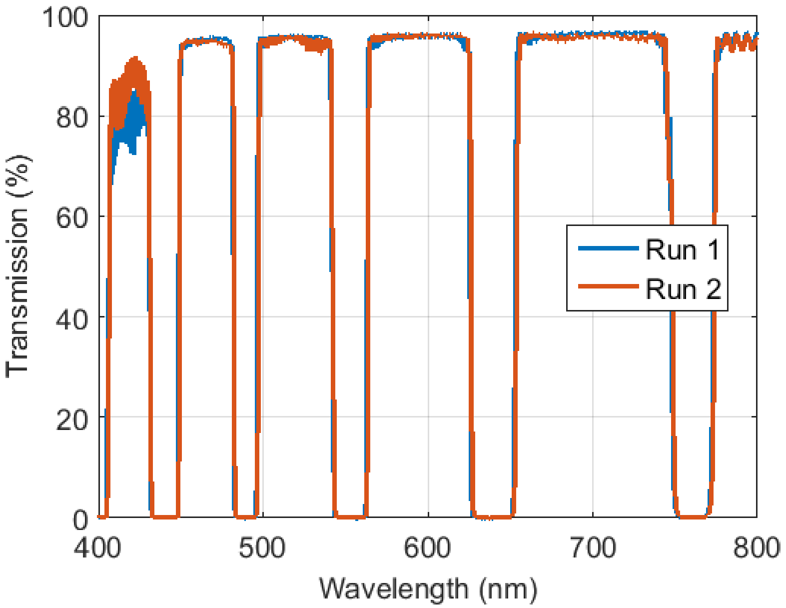
Multi-Notch: Experiment

Theoretical Spectrum



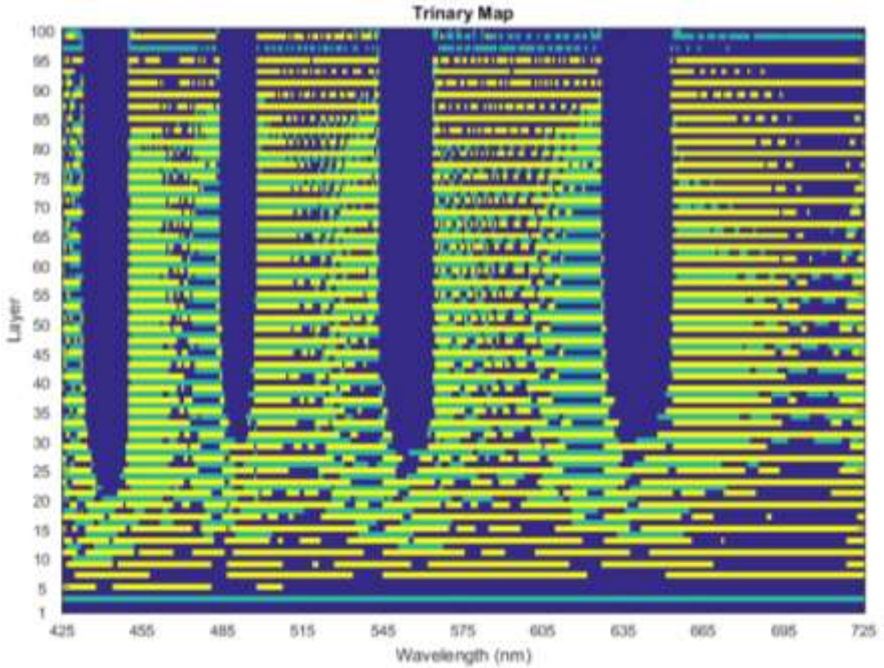
- 100 Layers
- All non-QWOT

Broadband Experiment



Complex control strategy: broadband for most layers and then switching to single wavelength (simple level cut)..

Multi-Notch: Broadband and Monochromatic

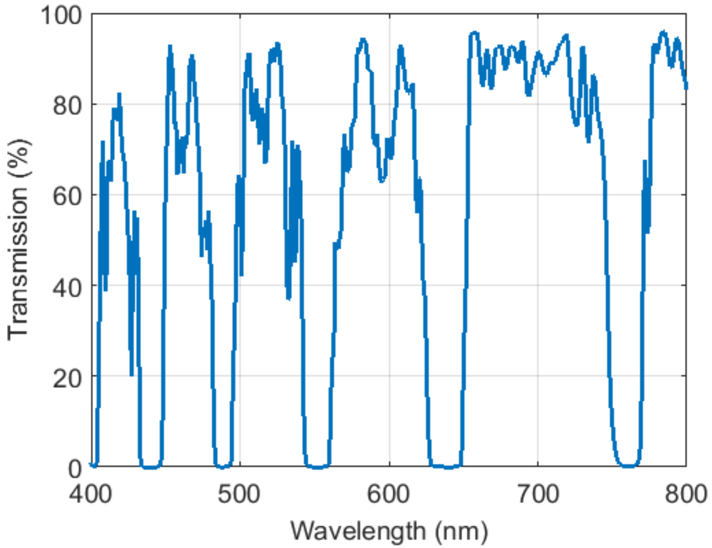


Passes all 5 criteria

Does not pass all 5 criteria

Passes all criteria and there is a max and min within the layer

Monochromatic Experiment



Wavelength	Layers
569	1-14
453	15-84
469	85-100

Conclusions

- Broadband monitoring has several advantages for monitoring filters with non-quarter-wave layers
  - Easier control strategy set-up
  - Stronger error self-compensation
  - "What you see is what you get"
- Monochromatic monitoring has some capability for monitoring non-quarter wave layers
  - More complex strategy is required compared to broadband
  - Main advantage is high spectral resolution – relevant for narrow band pass filters

MAKING A ***MATERIAL*** DIFFERENCE

Model Based Fitting

- Real-time fit of layer thickness

  - Sequential: fit only current layer thickness

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

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

Error propagation can be a problem

  - Full triangular algorithm: fit current and all previous layers

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

- 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).