CHROMA TECHNOLOGY CORP®

An employee-owned company producing the world's finest optical filters

Executing highly optimized sputtered interference-coating designs for colorimetry and light balance filters using broadband monitoring

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Principal Product Engineer
Chroma Technology Corp.

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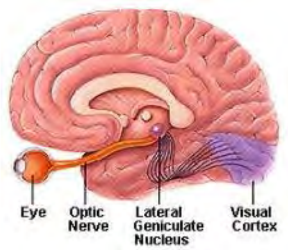
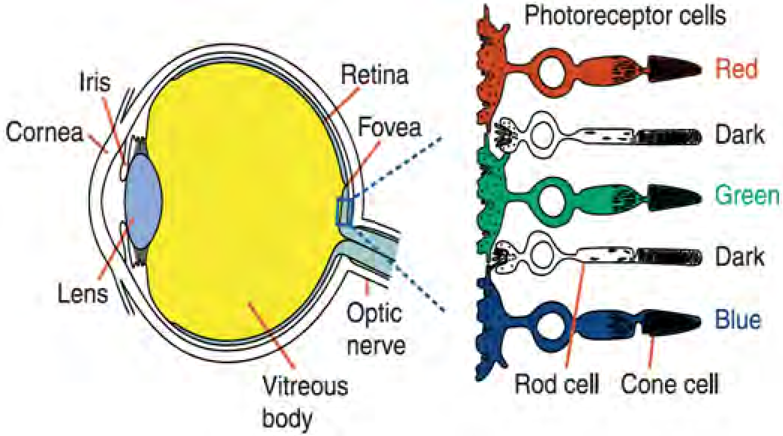
Color – Human Visual Perception

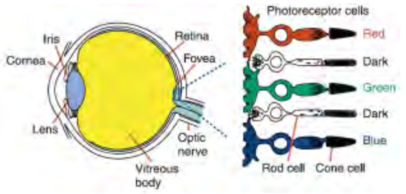

Photo by Amanda Dalbjörn on Unsplash





https://specialized-cells.weebly.com/uploads/4/7/9/0/47901671/3818983_orig.gif

Color – Human Visual Perception

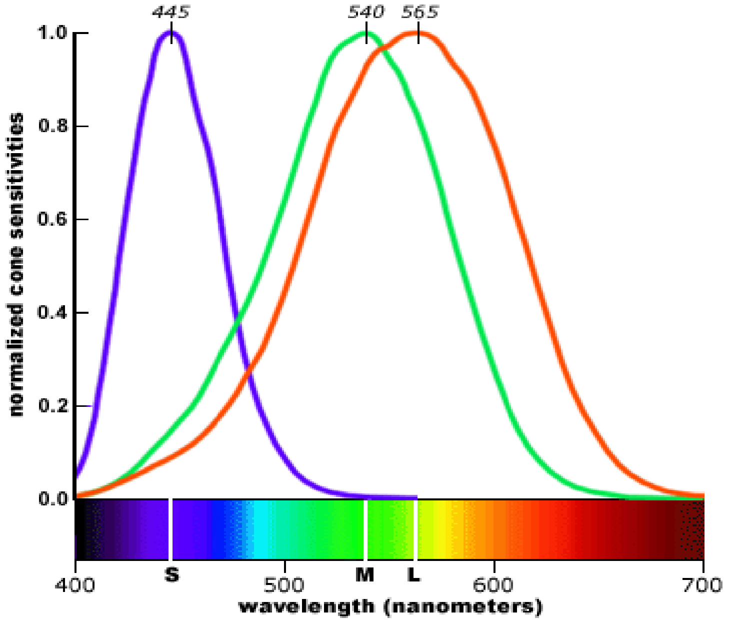


https://specialized-cells.weebly.com/uploads/4/7/9/0/47901671/3818983_orig.gif

The plot of normalized cone sensitivity shows three distinct peaks ...

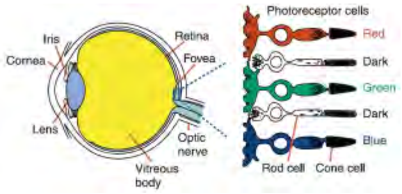
... but taking the log shows there is significant overlap, and in fact the L and M cones each cover almost the entire visible spectrum.

Normalized (log) cone sensitivity



http://www.handprint.com/

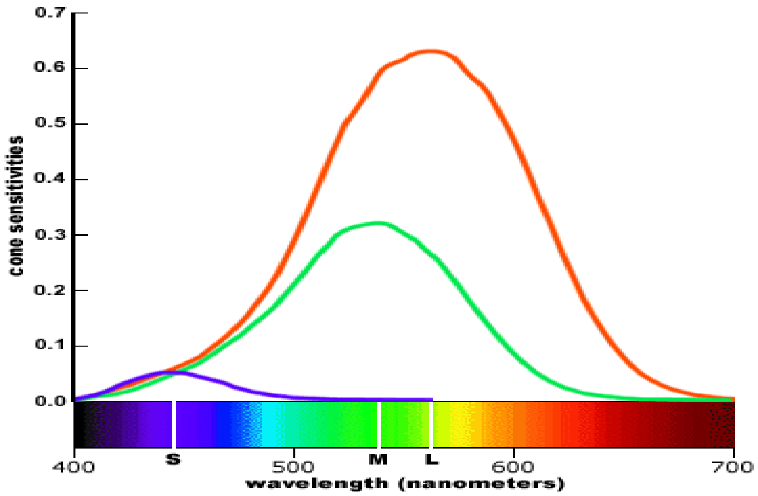
Color – Human Visual Perception



https://specialized-cells.weebly.com/uploads/4/7/9/0/47901671/3818983_orig.gif

The weighted response given the relative number of L, M, S cones in the retina gives a more accurate view of how our color vision is influenced by cone sensitivity.

Relative cone sensitivity



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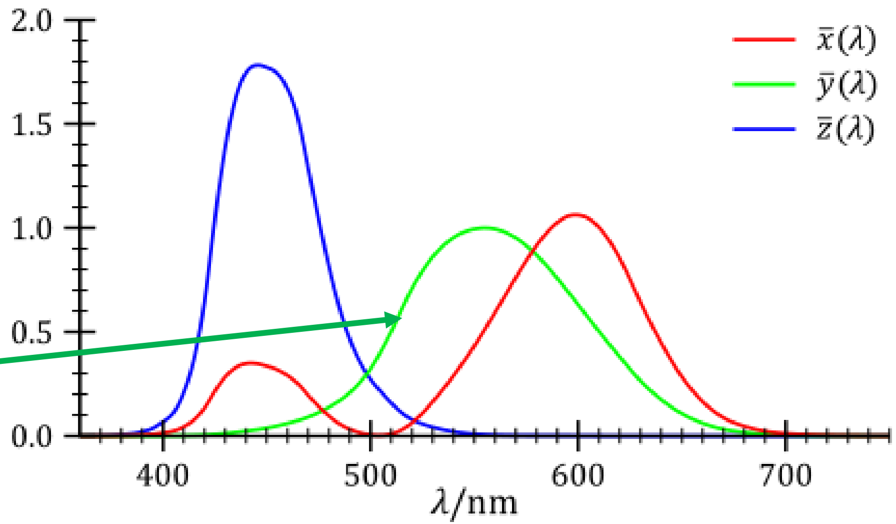
L & M cones dominate, so our eyes are overall more sensitive to green light!

Color – Human Visual Perception

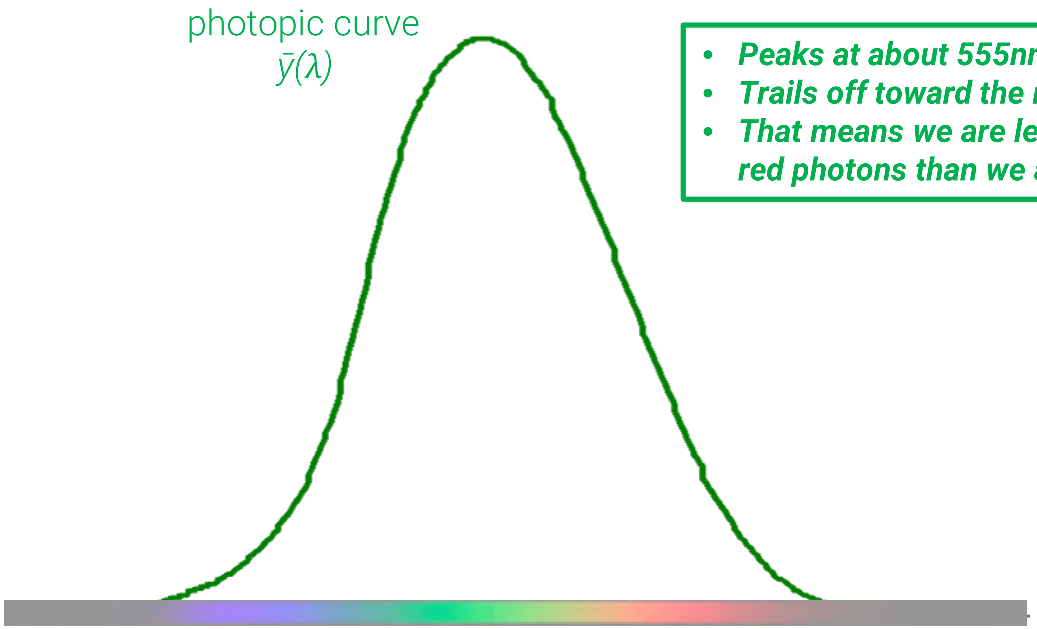
In 1931 the Commission Internationale de l´Eclairage (or CIE) gave us a construct to model color perception called the CIE 1931 Color Space. Essential to that theory are the Tristimulus curves or Color Matching Functions.

- **$\bar{y}(\lambda)$ or "y-bar" is identical to the spectral luminous efficiency function V(λ) for photopic vision**
- **determines the overall sensitivity to brightness or luminance.**

CIE 1931 XYZ Color Matching or Tristimulus Functions

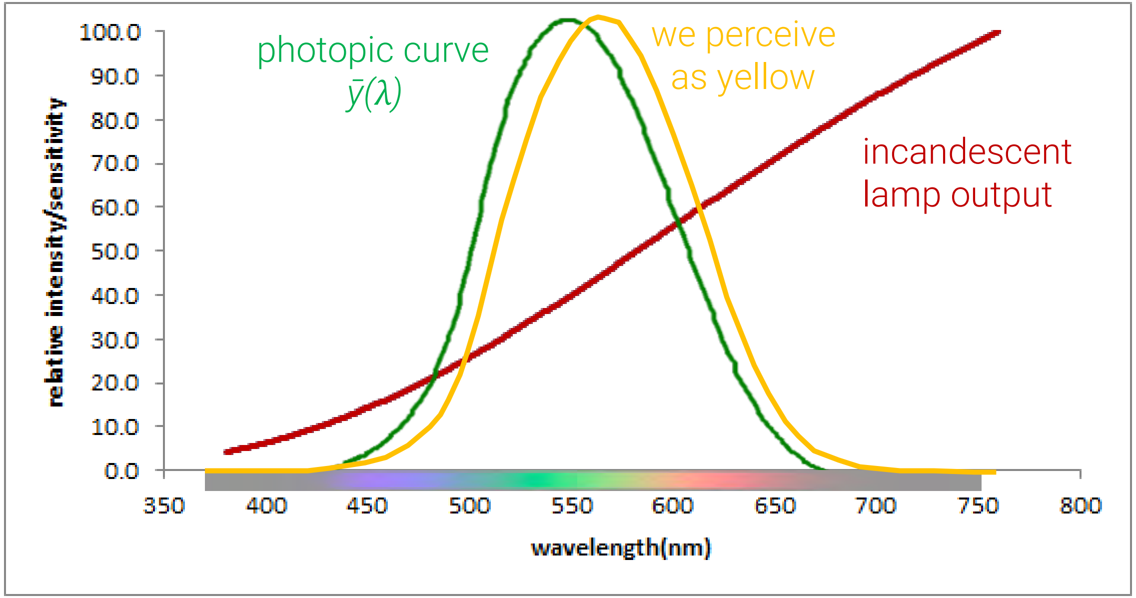


Human Spectral Sensitivity

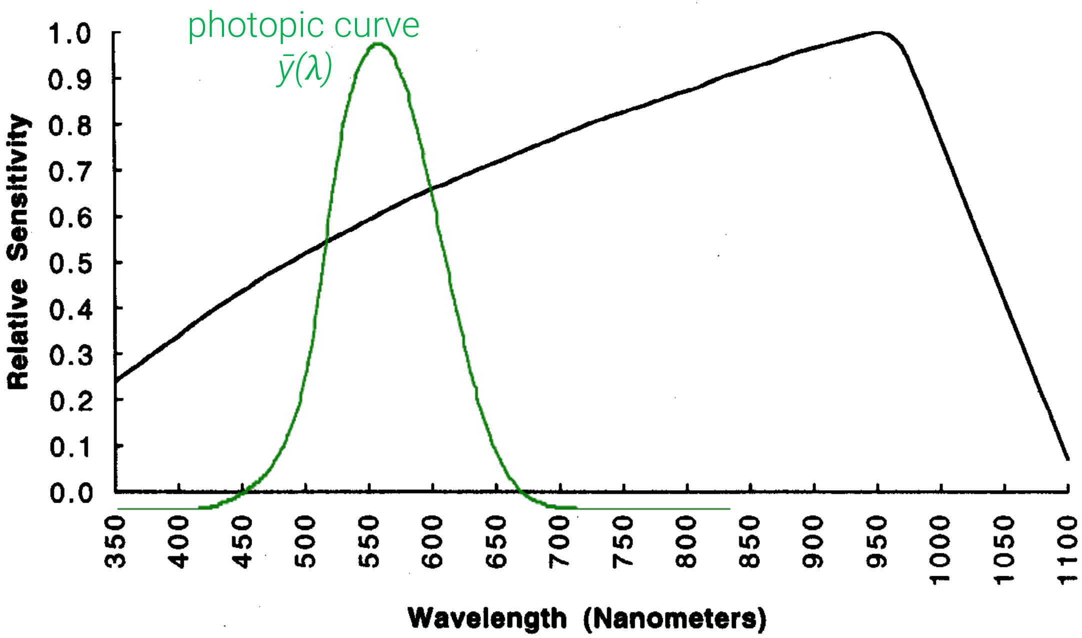


- ***Peaks at about 555nm***
- ***Trails off toward the red and blue***
- ***That means we are less sensitive to blue or red photons than we are green!***

Human Spectral Sensitivity & Incandescent Lamp Spectrum

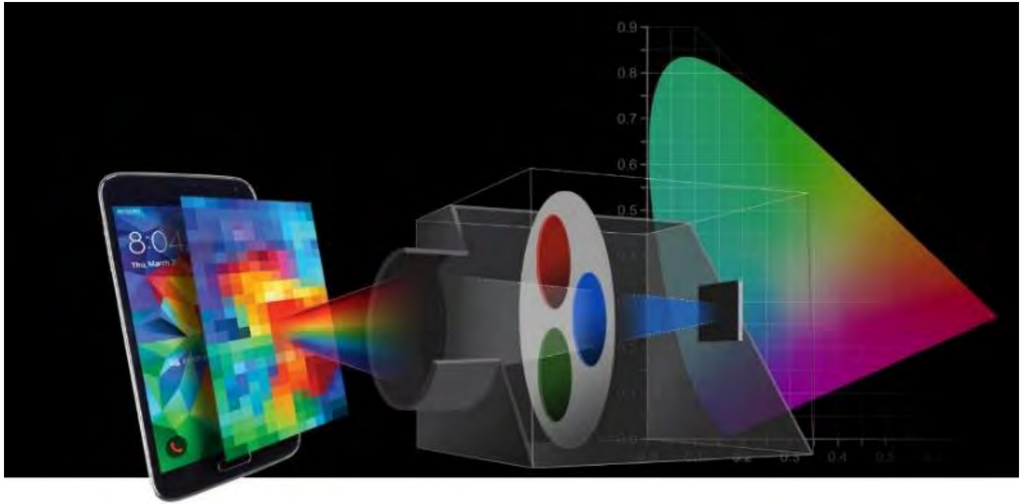


Human Spectral Sensitivity & Spectral Response of Silicon Photodiodes



Colorimetry & Photometry

- A colorimeter measures the color of an object, light source, or display as it would be perceived by the human eye.
- A photometer measures the luminance, or intensity, again as it would be perceived with the human visual system.

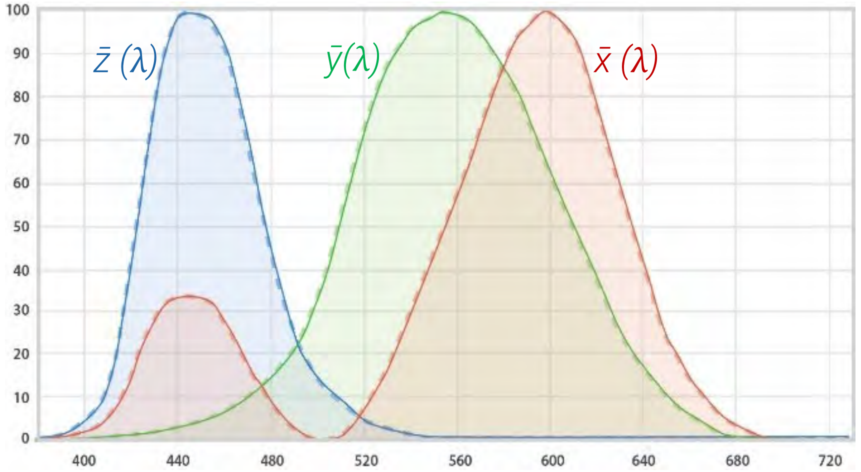


Colorimetry & Photometry

- **Colorimetry** by spectrophotometer is often the most accurate, but these devices are generally slower and more expensive than colorimeters that employ the tristimulus method (described by German Industrial Standard DIN 5033, part 6).

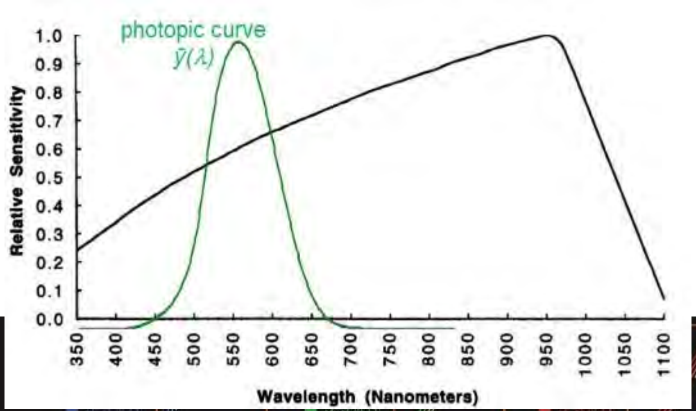
- **Tristimulus-based colorimetry** makes use of the CIE color-matching functions, or tristimulus curves.

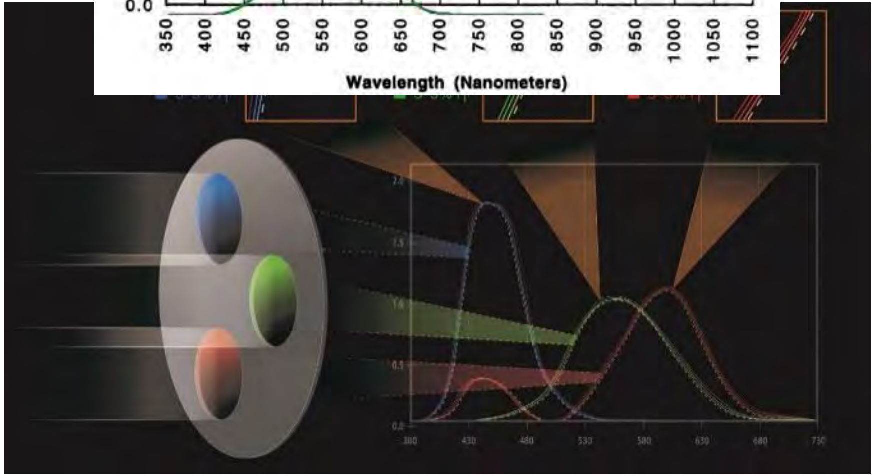
- In a tristimulus colorimeter, **optical filters called tristimulus filters** are used to *color* the detector, modifying the overall device response to mimic the CIE color-matching functions (taking the detector's QE into account).



Colorimetry & Photometry

A low number for f1' means a





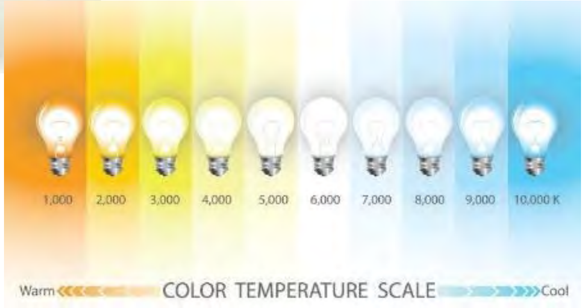
- In **photometry**, a V(λ), or photopic filter likewise *spectrally modifies* the detector for conducting luminance measurements.

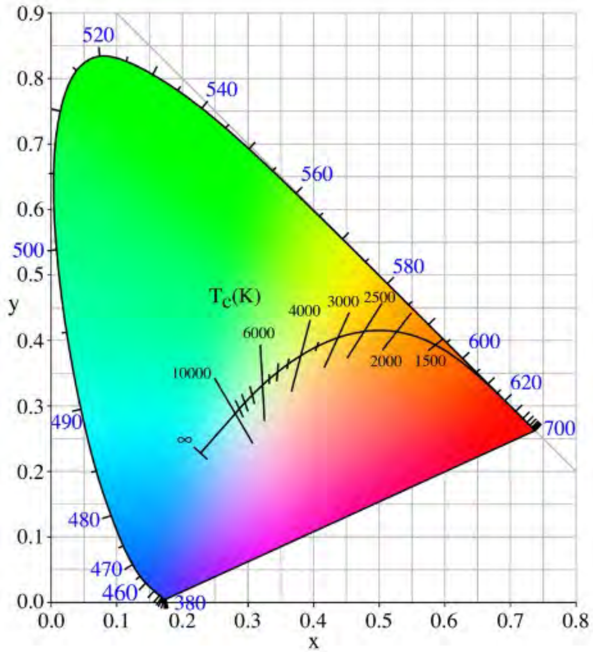
- In both tristimulus colorimeters and photometers, the accuracy of the instruments depends on how well the filters (combined w/detector QE) match the CIE tristimulus curves.

- From ISO/CIE 19476:2014 comes the integral term f1', which is a measure of **the quality of the spectral match**, and therefore determines the inherent accuracy of the instrument.

Chromaticity

- Color Quality Regardless of Brightness



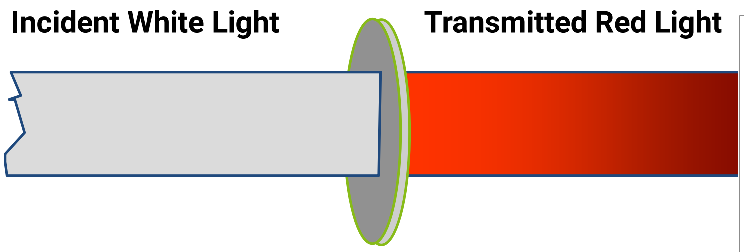


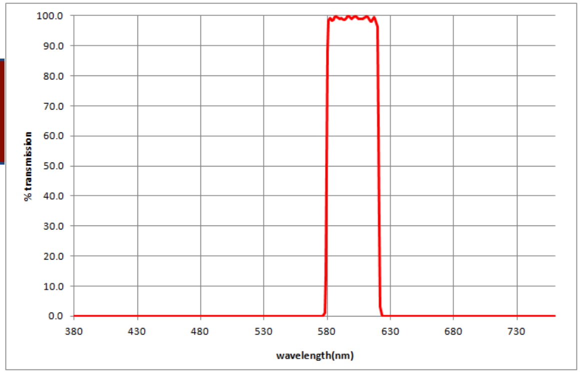
CIE 1931 Chromaticity diagram, x y color coordinates
2D representation of the CIE XYZ Color Space

Optical Filters

Optical filters are devices that transmit light of particular wavelengths while reflecting or absorbing light of other wavelengths, thus selecting what wavelengths get passed on in the optical system.

Example: 'red' filter





This spectral plot shows % transmission as a function of wavelength and represents the percentage of energy that gets through the filter -- what is not allowed to transmit is either absorbed or reflected. **T + A + R = 100%**

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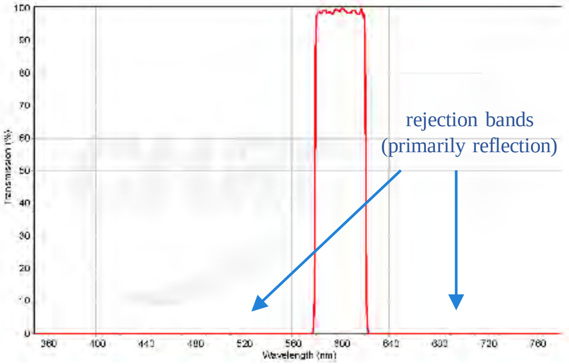
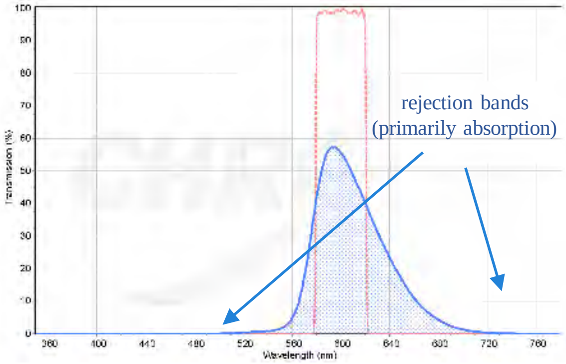
Optical Filters

Dielectric interference coating on glass



- A multi-layer stack of very thin coatings is deposited onto one or both sides of a glass substrate such that particular wavelengths of light interfere upon reflection at the multiple interfaces.
- Stacks are typically alternating layers of two non-absorbing materials, one with a 'high' index of refraction, and one with a 'low' index of refraction.

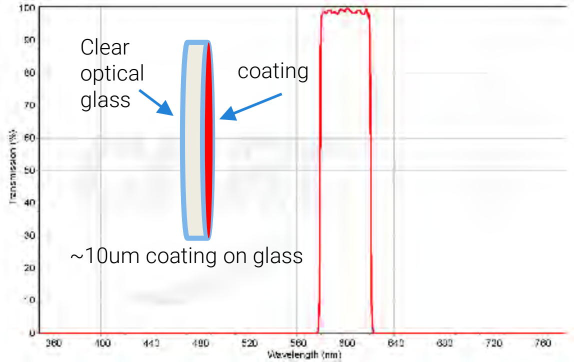
Absorption glass 'color' filters



- Metals and other inorganic and organic compounds are melted in with the glass upon manufacturing.
- These materials absorb some wavelengths of light (convert light energy to heat), while transmitting others.
- Many of these 'dyes' contain non-ROHS compliant substances, e.g. lead, cadmium.

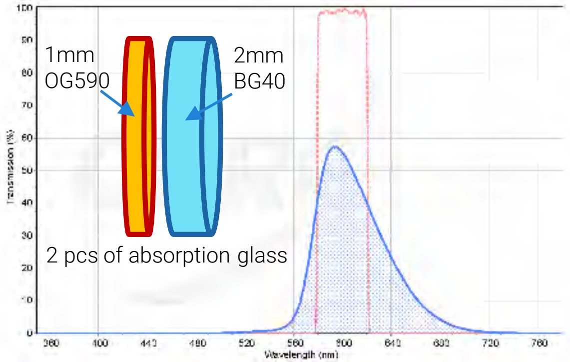
Optical Filters

Dielectric interference coating on glass



- Can theoretically reach 100% transmission in passband.
- The number of layers and their individual thicknesses determine the spectral characteristics.
- The thicknesses of the layers are controlled to a very high precision, and in this way the band-shape can be engineered.
- Overall coating thickness is typically < 20μm, and can be deposited onto clear glass substrates as thin as 0.5mm

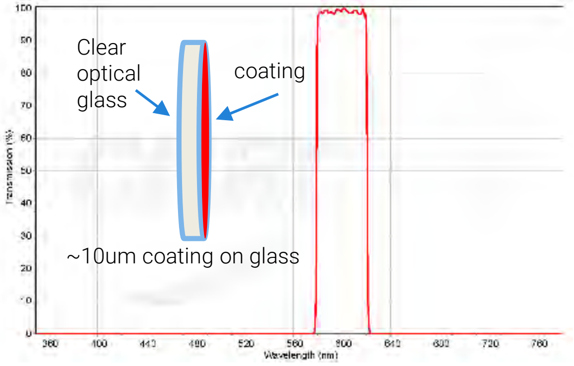
Absorption glass 'color' filters



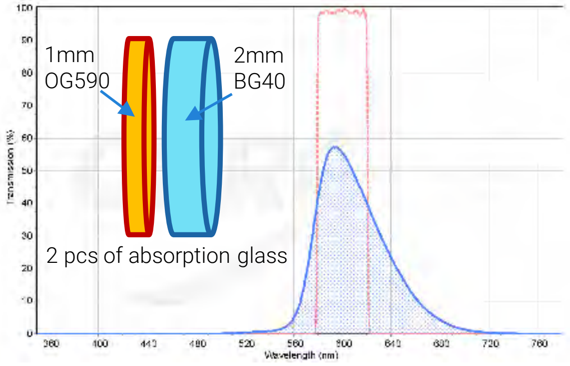
- The peak transmission is determined by how much the material absorbs and the thickness of the glass.
- The pass-band is generally broad, and not easily controlled because there are only so many materials with unique absorption characteristics that can be used.
- To effectively "block" unwanted wavelengths, an absorption filter must be thick (2-3mm); if two pieces are needed to define the edges of the pass-band then the overall thickness of the filter can be several mm thick.

Optical Filters

Dielectric interference coating on glass

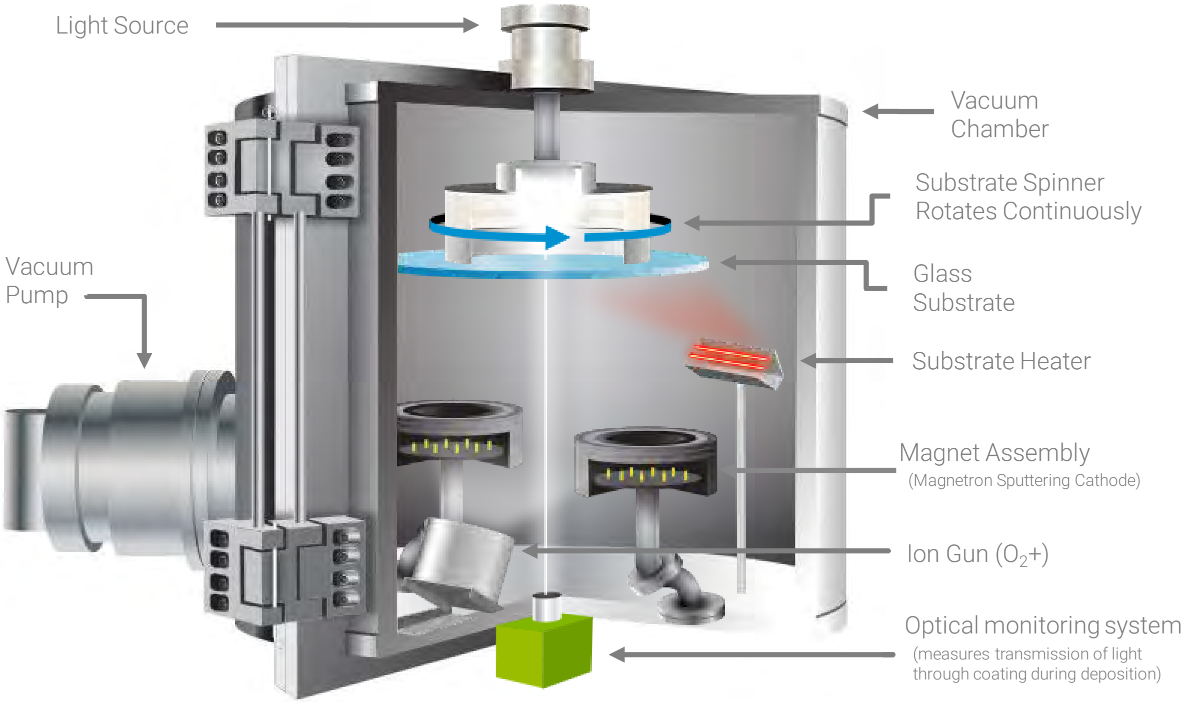


Absorption glass 'color' filters

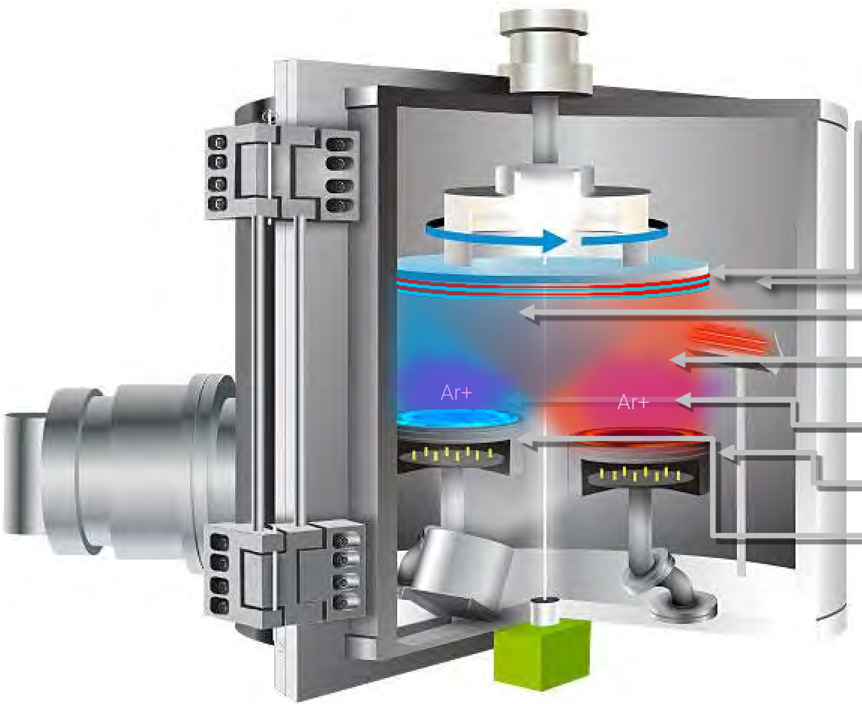


With high energy, high precision **sputter deposited coatings**, it is possible to get a durable "all-in-one" filter coating on a single side of relatively thin glass.

Sputter Coating Process – Main Components



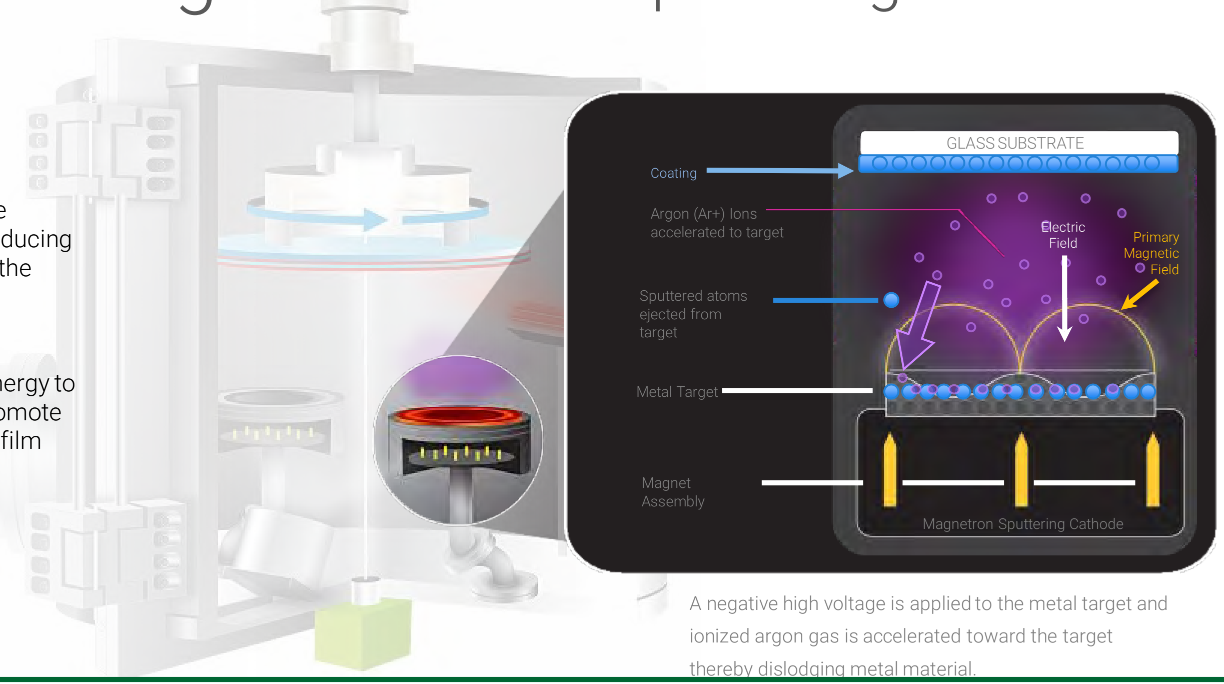
Sputter Coating Process – Deposition Primary Components



Sputter Coating Process – Sputtering Basics

With **reactive sputtering**, oxide coatings can be made by introducing oxygen gas which reacts with the metal/semiconductor during deposition.

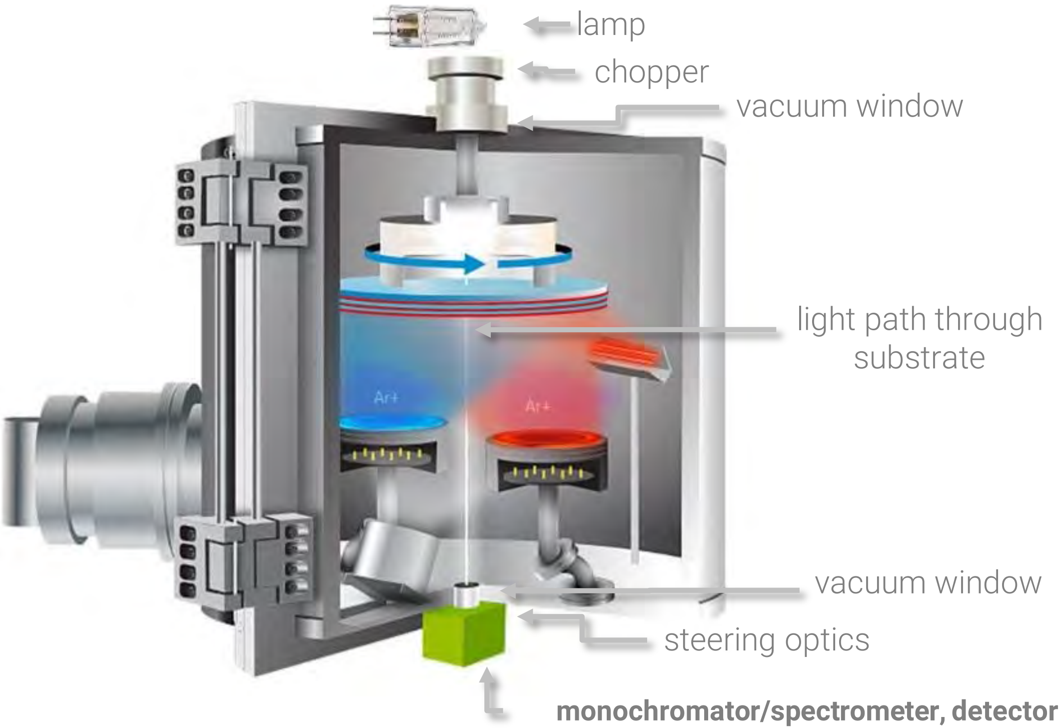
Ion-assist is used to deliver energy to the growing film in order to promote void-free growth and enhance film durability.



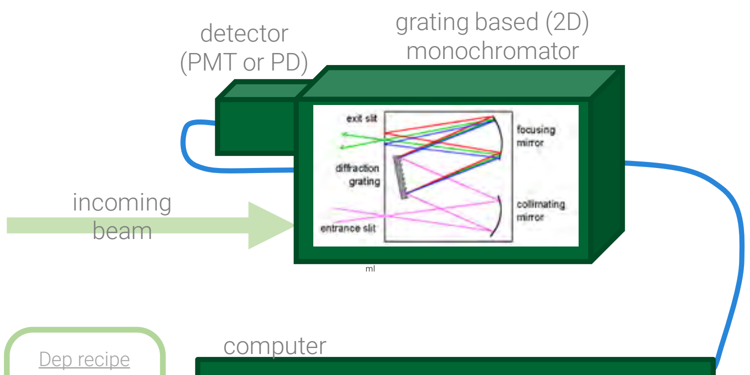
A negative high voltage is applied to the metal target and ionized argon gas is accelerated toward the target thereby dislodging metal material.

Vacuum chamber pressure/pumping performance, gas flows, temperature, temperature, cathode currents and voltages, ion-gun operation are all critical parameters for repeatable coating execution, stable refractive index, and consistent film structure.

Optical Monitoring Systems

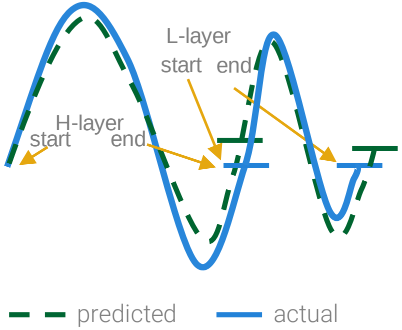


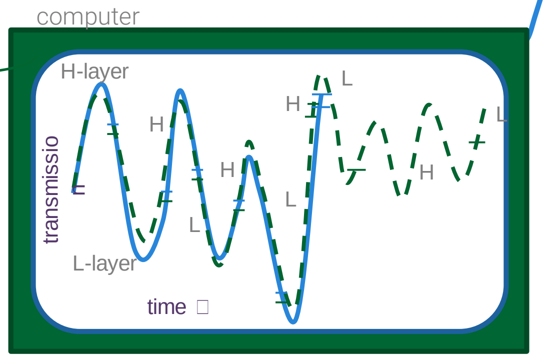
Optical Monitoring Systems - Traditional Single λ Monitoring



The monitor wavelength, mλ, is set to optimize precision layer termination for accurate layer

The dep recipe contains predicted trace info and layer cut points.





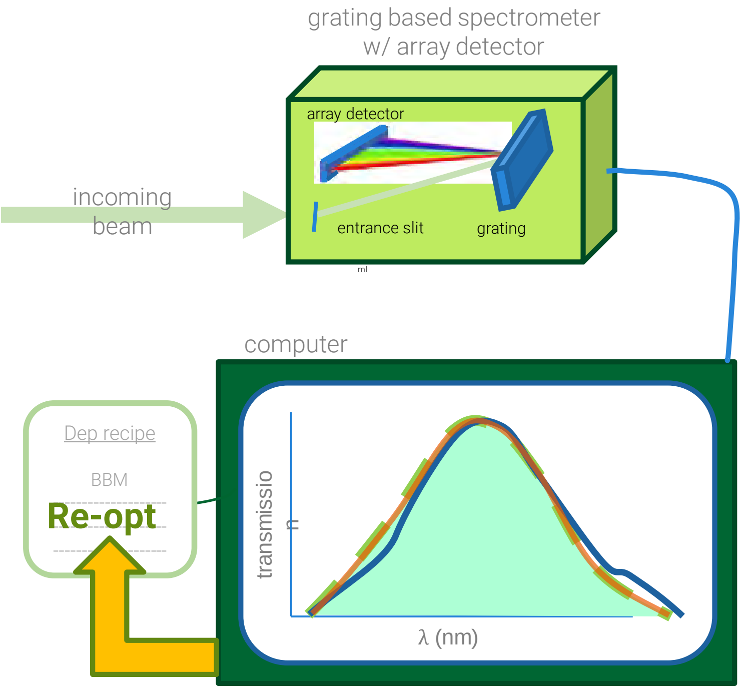
Deviations represent thickness errors!

But what's happening to the full spectrum?

How well the actual trace follows the predicted is largely dependent on signal noise and optical material constants, which in turn depend on deposition process control and stability.

Optical Monitoring System -

Broad Band Monitoring (BBM)



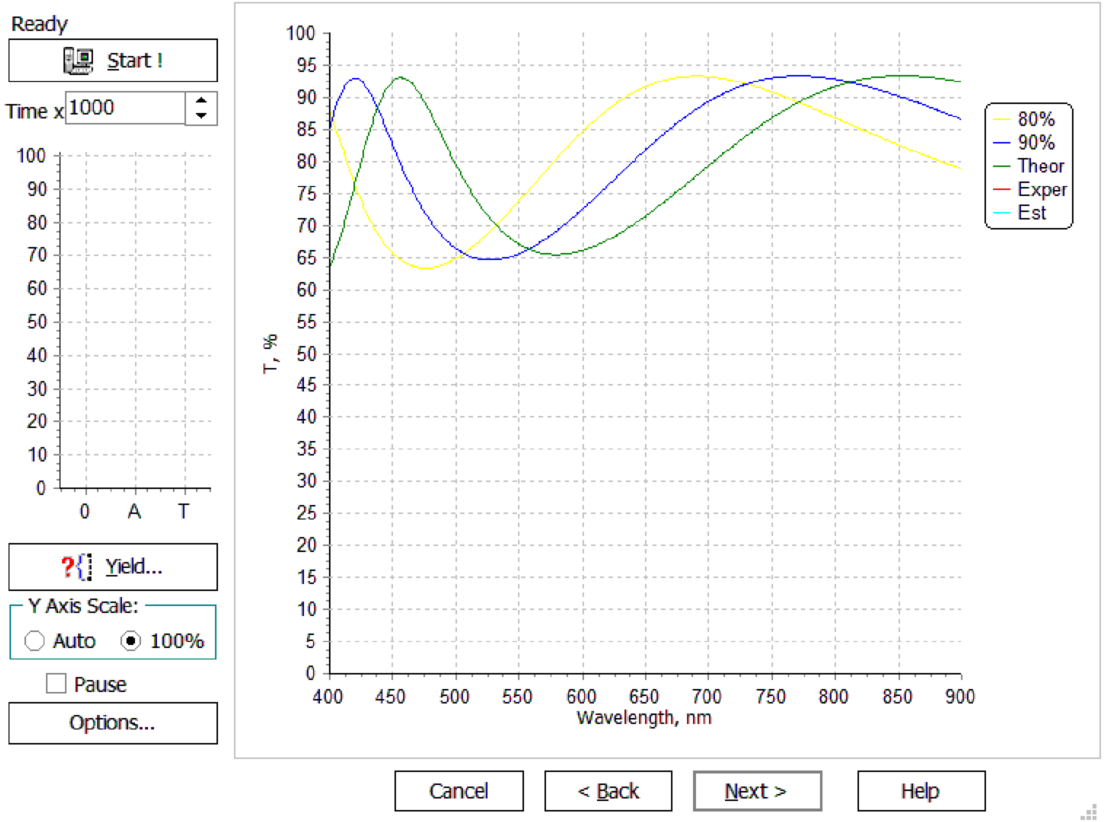
Advanced software control predicts the outcome, determines the best fit given the layers coated, and re-optimizes coating design in order to c the outcome and achie improved spectral match

With BBM a range of λ's is monitored.

This range could change dynamically during deposition as some narrower bandwidths are more important at the beginning of the run, while other broader bandwidths might become more important later in the process.

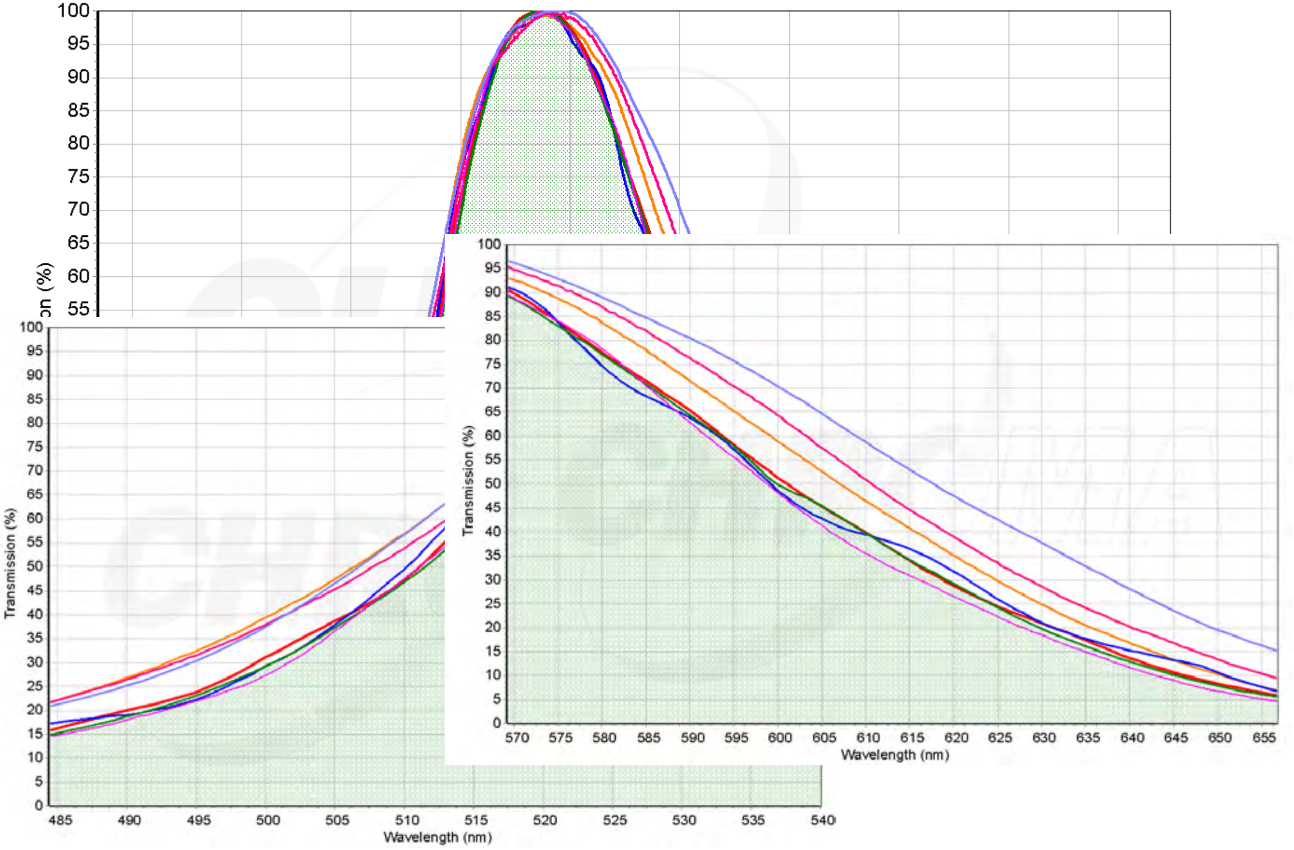
How well the actual trace follows the predicted is largely dependent on signal noise and optical material constants, which in turn depend on deposition process control and stability.

Re-optimizing



Tri-stimulus Filter Results

target (shaded)
f1' ~23% (303487), single λ
f1' ~16% (360425), single λ
f1' ~13% (353510), single λ
f1' ~5% BBM, non-optimized proces
f1' ~4% BBM w/ re-optimization
f1' ~3% BBM w/ re-optimization and optimized coating process



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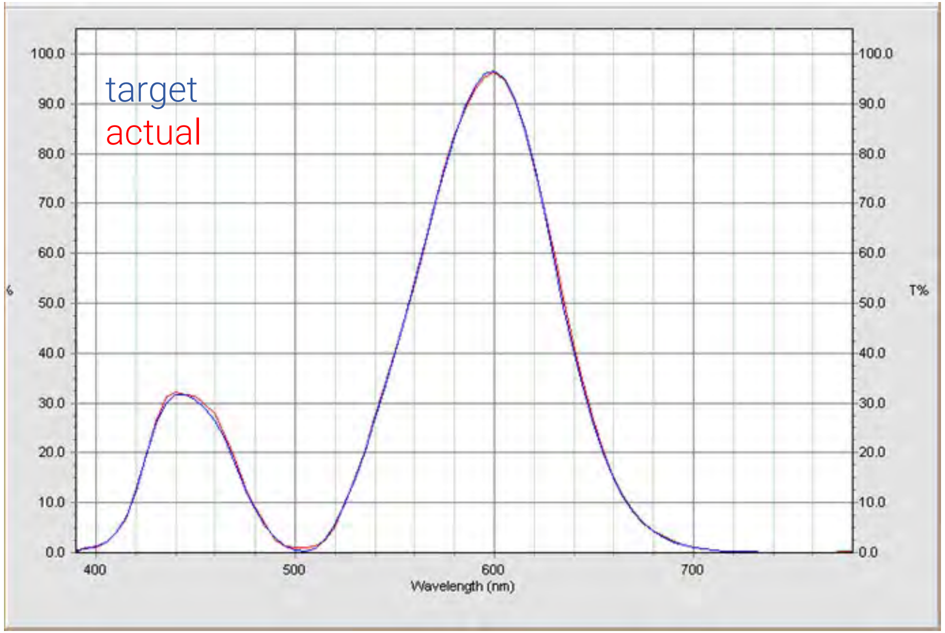
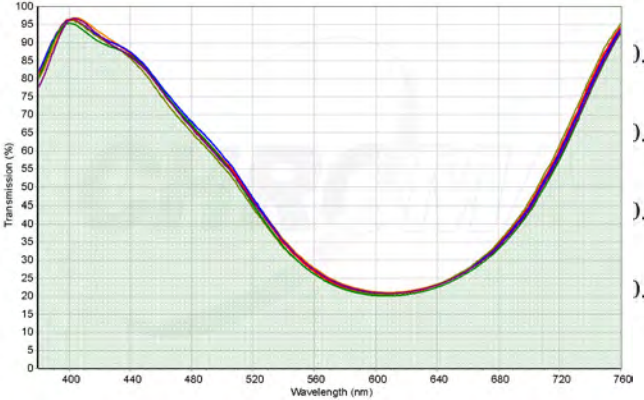
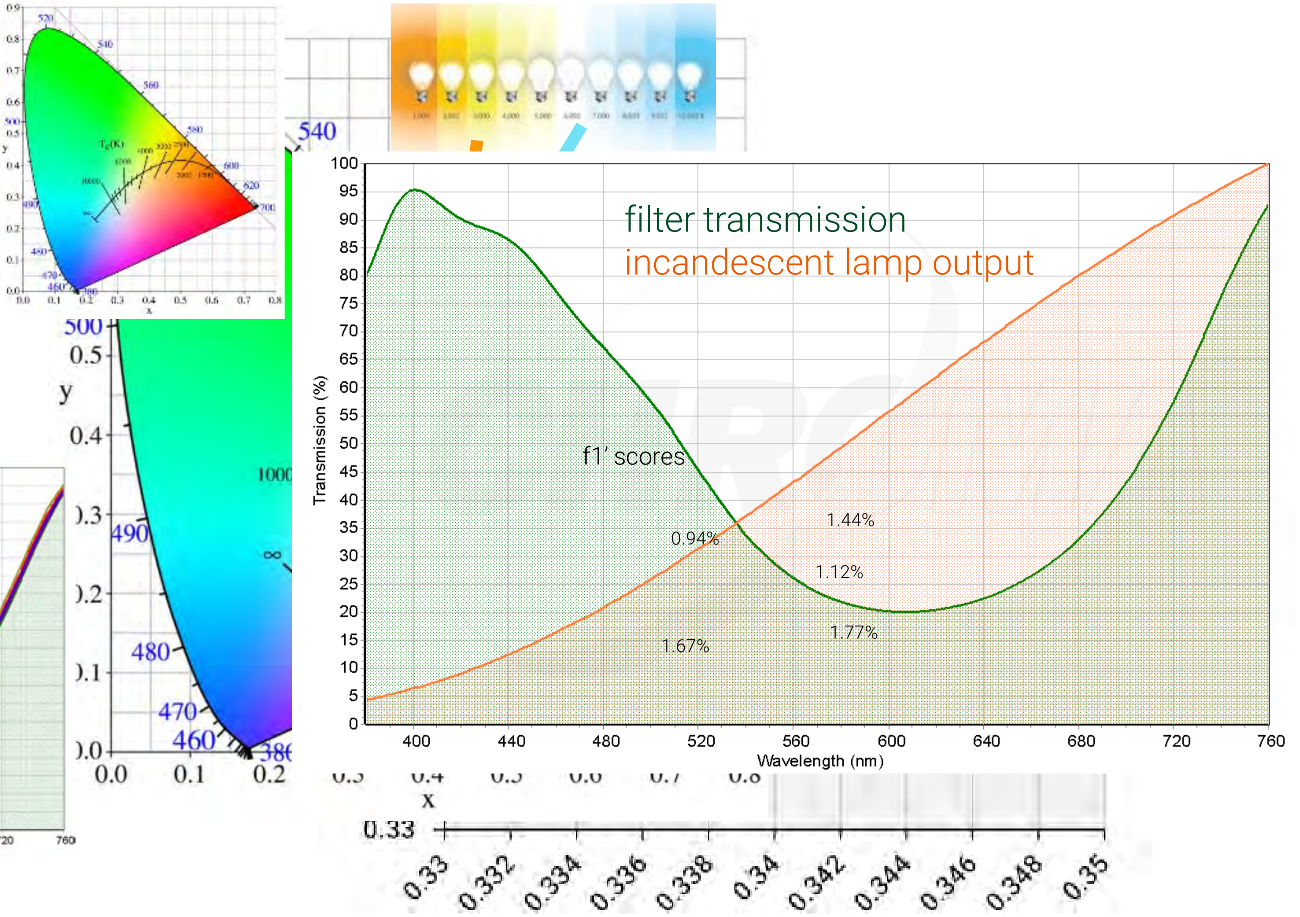
Tri-stimulus Filter Results

CIE X tristimulus filter, f1’ = 1.5%



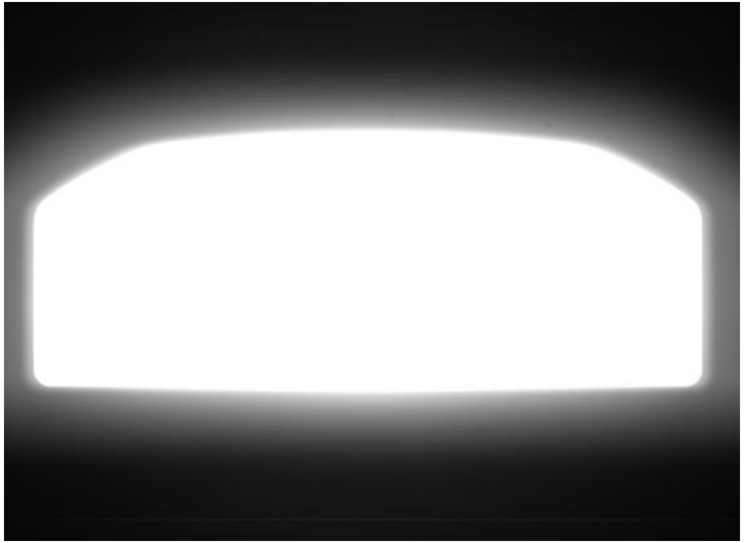
Light Balance Filters

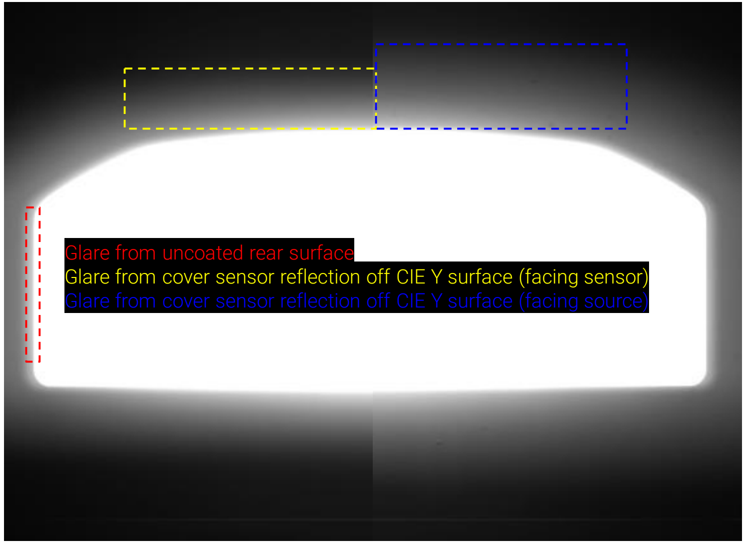




Optical modeling – Practical application

- Customer replaced absorption-glass based V(λ) filter with dielectric coating version
- Although the dielectric filter gave better spectral match = more accurate luminance measurement, the reflective coating caused glare when viewing bright LCD display





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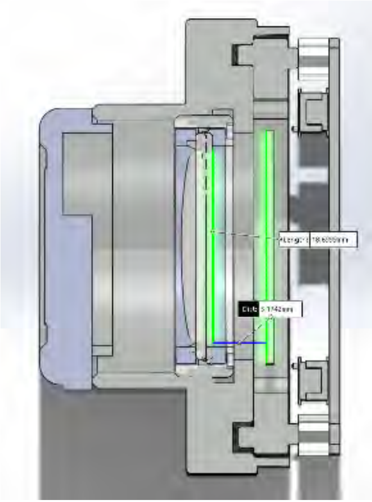
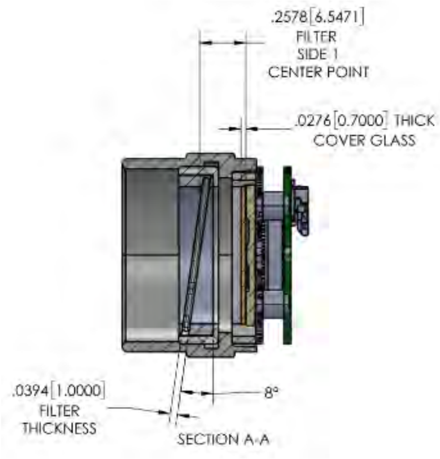
Optical Modeling – Practical Application

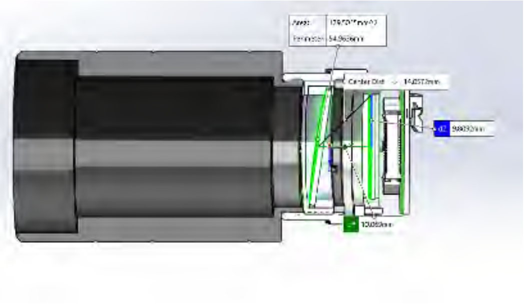
Different CIE Y filter configurations - CAD models



Original - without AR coated rear surface



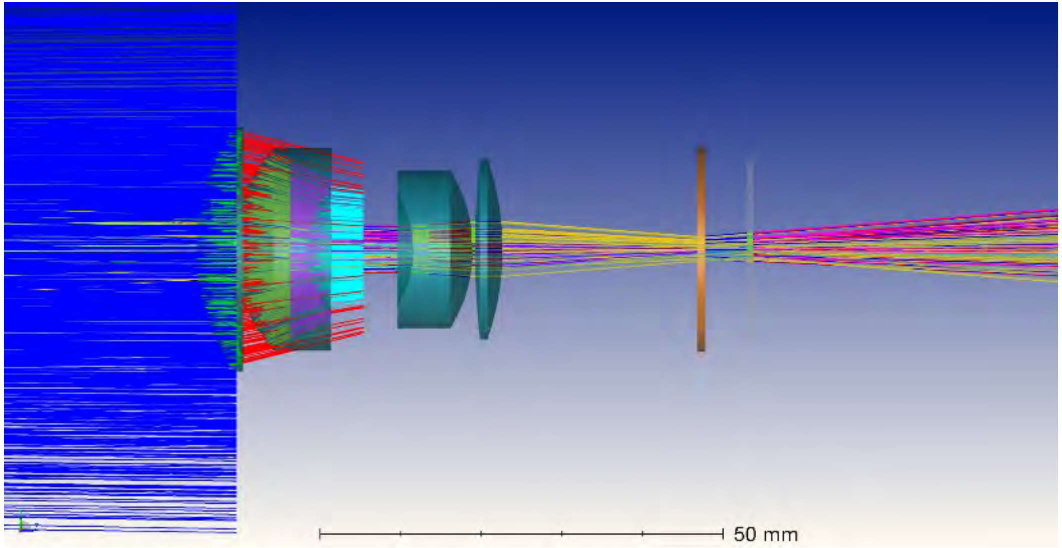
Tilted - relatively close to the cover glass, w/ AR coated rear surface



Tilted - as far from sensor as possible, practically against the lens, w/ AR coated rear surface

Optical Modeling – Practical Application

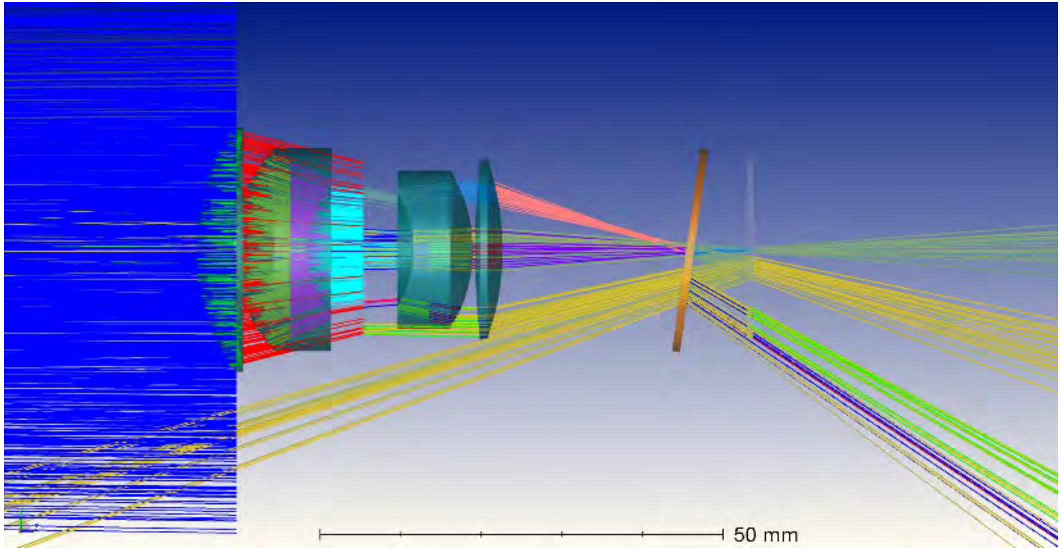
0° Tilt CIE Y Filter - No Rear AR coating



Ghost reflections overlap with main beam, resulting in a rotationally symmetric defocused blur around image.

Optical Modeling – Practical Application

8° Tilt CIE Y Filter - Rear AR coating - Closer to Sensor

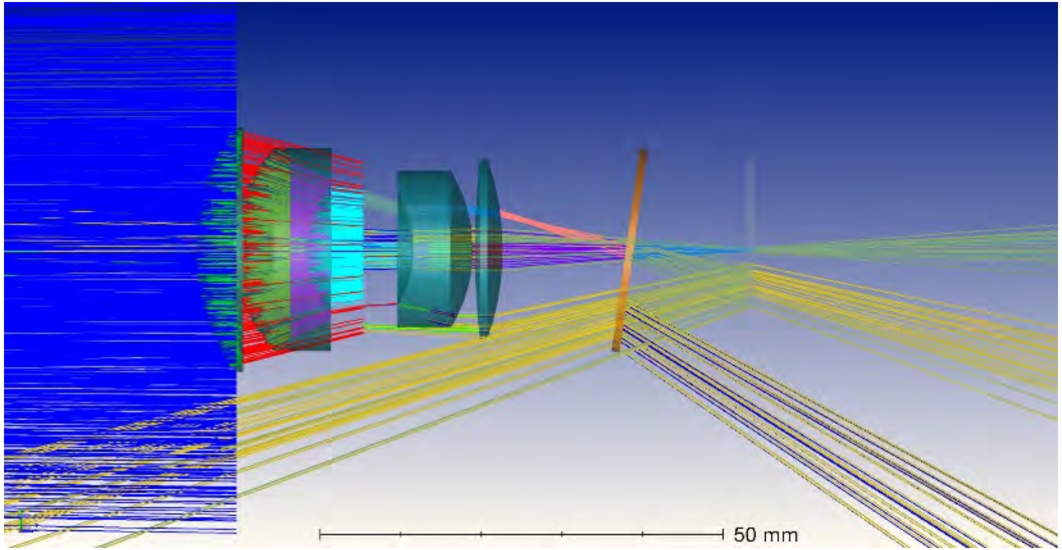


Ghost reflections off of cover glass reflect at an angle, with little overlap of main beam on image plane.

Ghost reflections off rear surface of CIE Y filter would still be on-axis of main image plane, but with AR coating they are assumed to be negligible.

Optical Modeling – Practical Application

8° Tilt CIE Y Filter - Rear AR coating - Further from Sensor

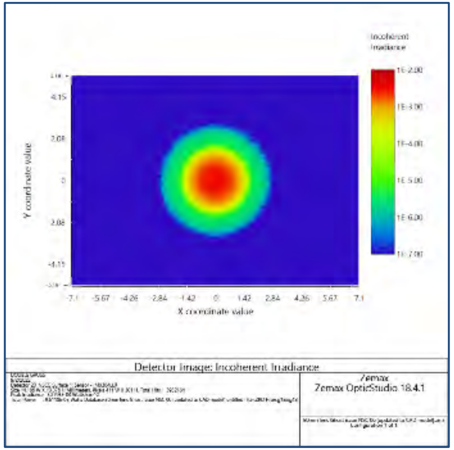


Ghost reflections off of cover glass reflect at an angle, with little overlap of main beam and some missing sensor altogether.

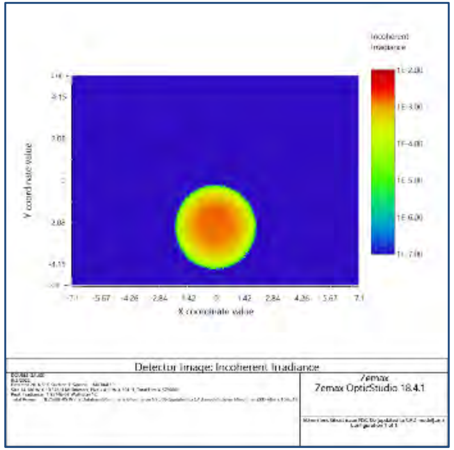
Ghost reflections off rear surface of CIE Y filter would still be on-axis of main image plane, but with AR coating they are assumed to be negligible.

Optical Modeling – Practical Application

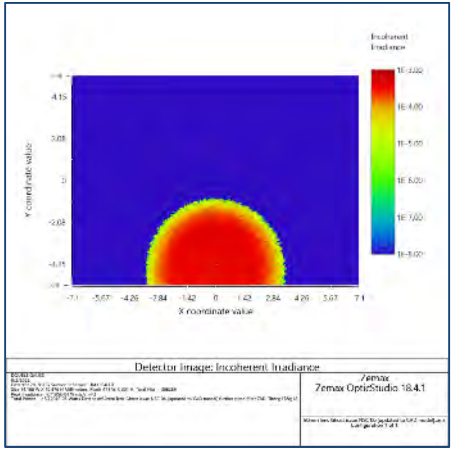
Ghost reflections - Comparison



No tilt, ~6.9mm from sensor



8° Tilt, ~8.3mm from sensor



8° Tilt, ~15.8mm from sensor

Results in the 0° tilted sample show how a second back reflection is occurring at around four orders of magnitude lower.

Thank you for Joining!

John Atkinson
Principal Product Engineer at Chroma Technology

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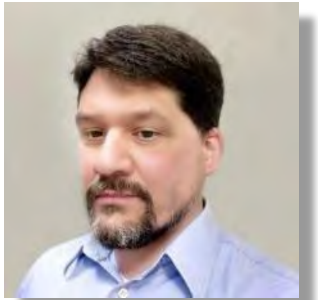
Chroma.com



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