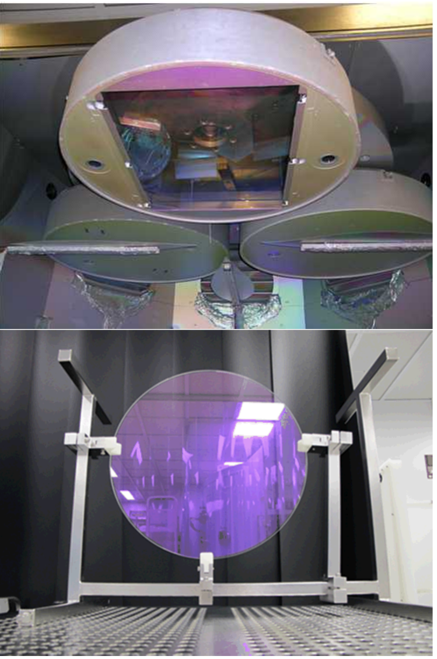
SAND2014-18710C

Design and Development of Laser Damage Resistant, Low Group Delay Dispersion Optical Coatings for High Reflection at 45° Incidence, P Polarization and Wavelengths from 800 to 1000 nm



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The 3rd Frontiers of Optical Coatings (FOC) Conference
October 23, 2014, Shanghai, China

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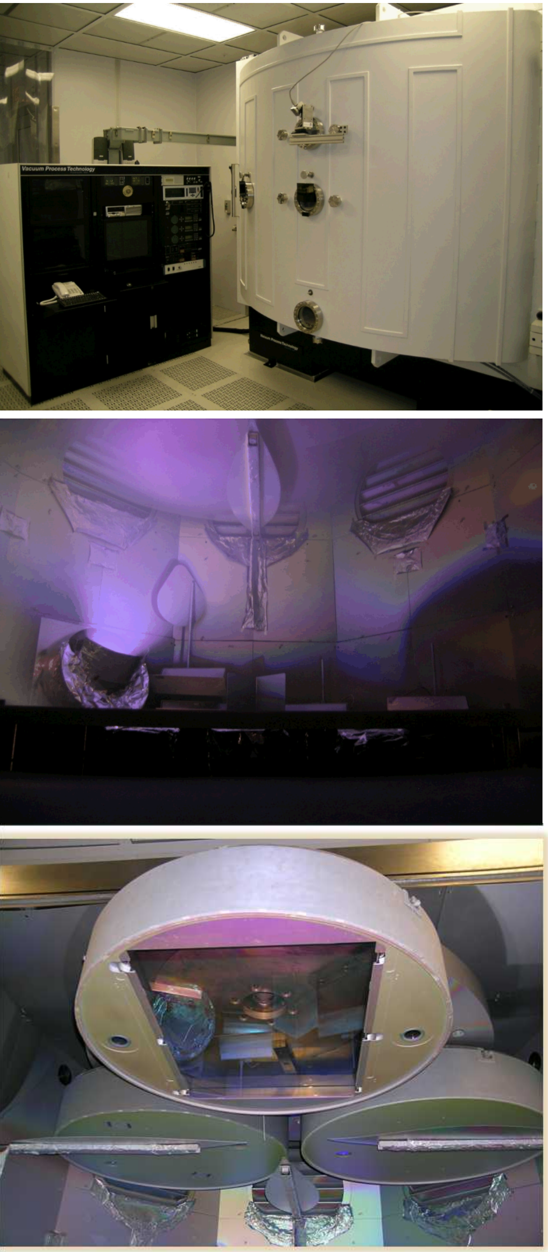
Sandia's Large Optics Coating Operation



- Mission: Provide high laser-induced damage threshold (LIDT) optical coatings for large optics of the Z-Backlighter TW and PW lasers

Z-Backlighter Lasers: Kilojoule class pulsed laser systems coupled to the most powerful and energetic x-ray source in the world, the Z-Accelerator

Z-Beamlet	Z-Petawatt
λ = 527 nm	λ = 1054 nm
τ = 0.3 – 8 ns	τ = 500 fs
I = 10^{17} W/cm^2	I = 10^{19} W/cm^2

- 2.3 m X 2.3 m X 1.8 m coating chamber in a Class 100 clean room
- E-beam deposited coatings (mostly hafnia/silica layer pairs) with or without ion-assisted deposition (IAD)
- 3 planet option accommodates up to 94 cm optic per planet
- Counter-rotation 2-planet option holds up to 1.2 m optic per planet
- 3 e-beam sources for thin film materials
- Process control based on crystal sensor monitoring of evaporated material

Aspirations: Advance the field of high LIDT coatings for large optics and cooperate within the international optical coating community

Introduction

Key technologies of PW class high intensity lasers:

1. Generation of low energy, broad bandwidth (BB), sub-ps laser pulses
2. Frequency chirped “stretching” of these low energy sub-ps pulses into ns pulses
3. Amplification of the low energy ns laser pulses to high energies
4. Compression of the high energy ns laser pulses into high intensity sub-ps pulses

Pulse Duration (τ) versus Frequency Range ($\Delta\nu$) and Bandwidth ($\Delta\lambda$)

$\tau = 1/\Delta\nu$ and $\Delta\lambda = -(\lambda^2/c)\Delta\nu$ where c = speed of light

Example for λ = 900 nm:

τ	$\Delta\nu$ (10^9Hz)	$\Delta\lambda$ (nm)
1 ns	1	0.0027 nm
100 ps	10	0.027 nm
10 ps	100	0.27 nm
1 ps	1000	2.7 nm
100 fs	10000	27 nm
10 fs	100000	270 nm

Range of pulse durations for high intensity PW lasers

Our interest:
200 nm bandwidth centered at 900 nm

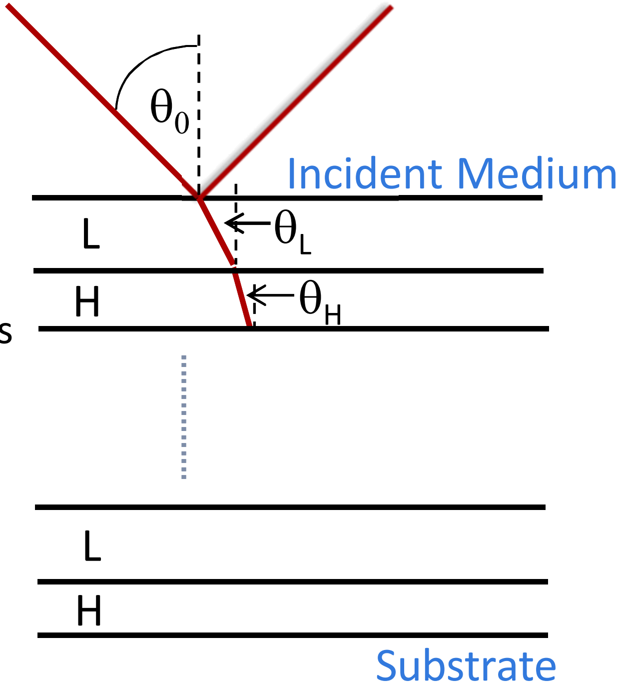
High reflection (HR) optical coating requirements for fs class pulses of high intensity lasers

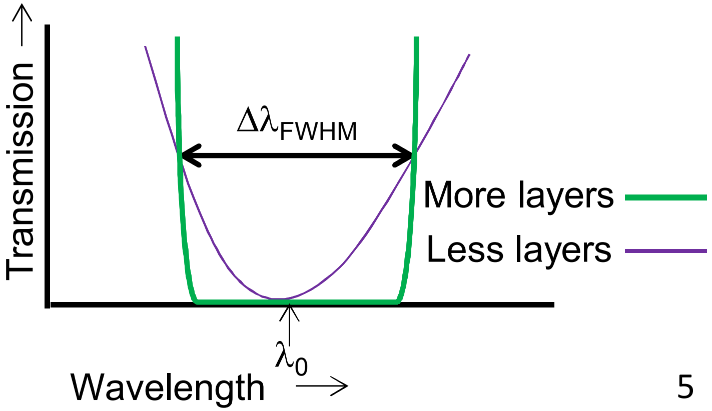
- Broad bandwidth high reflection (BBHR)
- High laser-induced damage threshold (LIDT)
- Reflection that does not temporally distort or lengthen the fs pulses
- Reflection at non-normal angle of incidence (AOI), usually 45°, in P and S polarization for laser beam steering

These requirements also accommodate coating spectral drift and provide AOI flexibility for PW class lasers

Bandwidths of quarter-wave HR coatings for non-normal AOI – review

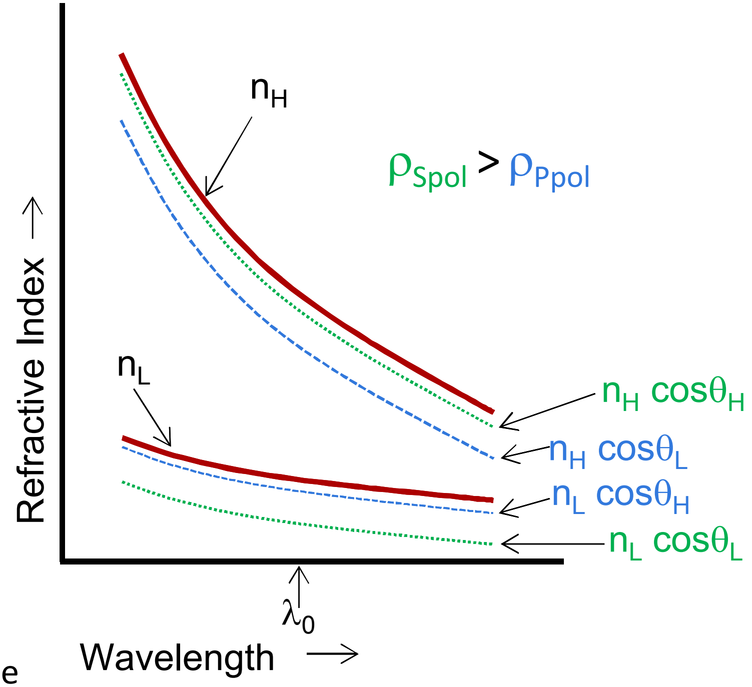
- Snell's Law: $n_0 \sin\theta_0 = n_L \sin\theta_L = n_H \sin\theta_H$
  - Propagation directions in coating layers governed by
    - AOI (θ_0) and incident medium index n_0
    - Low (L) and high (H) index layer indices, n_L and n_H
- HR Bandwidth increases with L and H index contrast ratios
  - Spol index contrast: $\rho_{Spol} = n_H \cos\theta_H / n_L \cos\theta_L > n_H / n_L$
  - Ppol index contrast: $\rho_{Ppol} = n_H \cos\theta_L / n_L \cos\theta_H < n_H / n_L$
  - $\rho_{Spol} > \rho_{Ppol}$ because $R_S > R_P$ at each layer boundary
  - Broad Ppol HR bands are more difficult to achieve
- Full width at half maximum (FWHM) for HR band
  - $\Delta\lambda_{FWHM} / \lambda_0 = (2\Delta g)/[1 - (\Delta g)^2]$
    - λ_0 is the HR band center wavelength
    - $\Delta g_{Ppol,\,Spol} = (2/\pi)\sin^{-1}[(\rho_{Ppol,Spol} - 1)/(\rho_{Ppol,Spol} + 1)]$
  - Valid for no dispersion of indices across HR band
    - Provides guideline only for broad HR bandwidths
  - HR band increases as number of layers increases

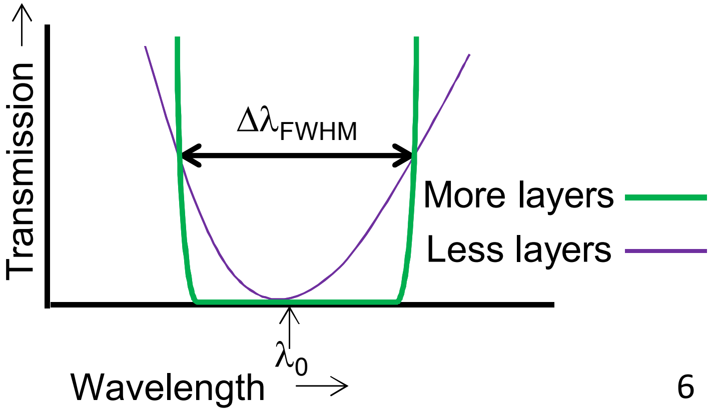




fs pulses and dispersion in coatings for BBHR at non-normal AOI

- The group of fs pulse frequency components must propagate into and back out of coating layers with low intensity loss (< 0.5% for R > 99.5%)
- Quarter-wave layer thicknesses exhibit large variation over the BBHR band for a given AOI due to index variations
- Each coating layer plays a different role for each wavelength across the broad spectra of fs-class optical pulses
- H and L index contrast ratios differ across the BBHR band due to index differences and related propagation direction differences
- Optical propagation velocity in coating layers changes non-linearly as a function of frequency for the group of fs pulse frequency components
- Non-linear group delay (GD) for fs pulses results from non-linear change of optical propagation velocity with frequency across the BBHR band
- Non-linear GD leads to deviation of group delay dispersion (GDD) from being constant across the BBHR band
- Non-constant GDD disrupts relative phases between fs pulse frequency components, resulting in temporal broadening of the pulse.
- Preserving fs pulse properties in reflection requires BBHR coating designs for which propagation of fs pulses into and back out of the coating layers results in GDD that is constant or near 0





BBHR Coating Design Goals

Reflectivity	R > 99.5% for 45^{o} AOI, Ppol
Operational Bandwidth	800 nm - 1000 nm
LIDT	> 800 mJ/cm^2 for fs class pulses
GDD	< 20 fs^2 over the operational bandwidth

Strategy for Design and Production of the BBHR Coating

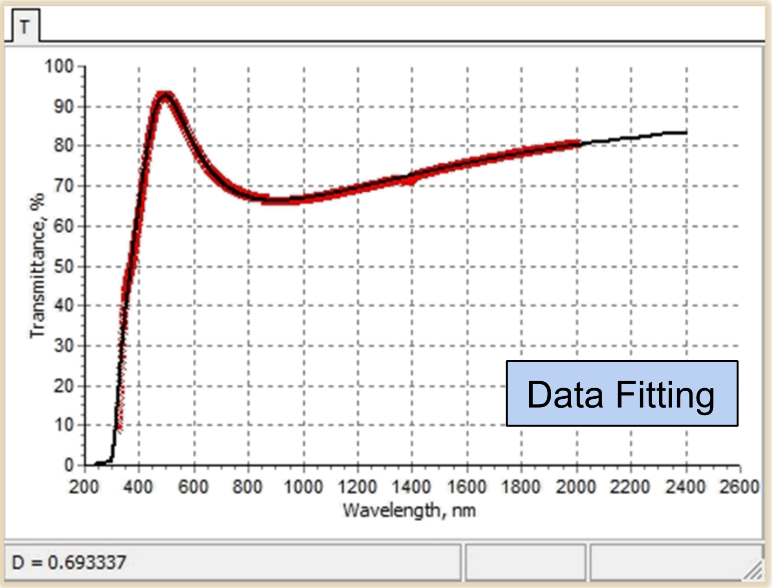
For an optimal coating design, the differing layer roles for each wavelength must combine to provide the broadest HR bandwidth while minimizing non-constant behavior of GDD over the broad bandwidth

- Choose the H index layer material and optimize its deposition
  - Seek the best compromise between high index of refraction, low absorption, high LIDT (high band gap), and ease of deposition
- Explore quarter-wave type HR coating designs based on the optimized H index layers and silica L index layers to maximize HR bandwidth while minimizing non-constant GDD behavior
  - Use coating design software such as OptiLayer to facilitate design study
  - Apply the basics of quarter-wave HR coatings in the context of dispersion and fs pulse properties to guide the design exploration
  - Seek the best compromise between the wide range of effective quarter-wave layer thicknesses and of optical wave propagation velocities across the operational bandwidth

Choice of H Index Layer Material: TiO_2

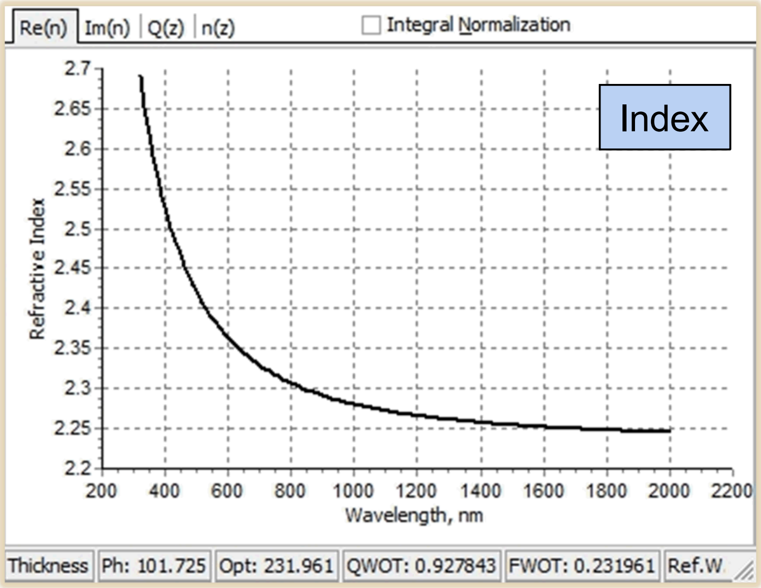
- TiO_2 affords one of the highest refractive indices among high index oxides
- The band gap of TiO_2 is not the highest, but is moderately high
- TiO_2 is easy to deposit by reactive evaporation of Ti (pellets) in O_2 back pressure using IAD to optimize index of refraction
- Varying chamber temperature, O_2 back pressure, deposition rate and IAD settings led to optimal TiO_2 layer deposition
- Lambda 950 spectrophotometer (Perkin Elmer) provided spectra of TiO_2 single layers
- OptiChar software provided analysis of the single layer spectra in terms of index of refraction (n) and extinction coefficient (k)
  - Normal dispersion model (Cauchy) and UV/Vis model (exponential) adequately described the refractive index and absorption, respectively

Example of TiO_2 Single-Layer Characterization in OptiChar



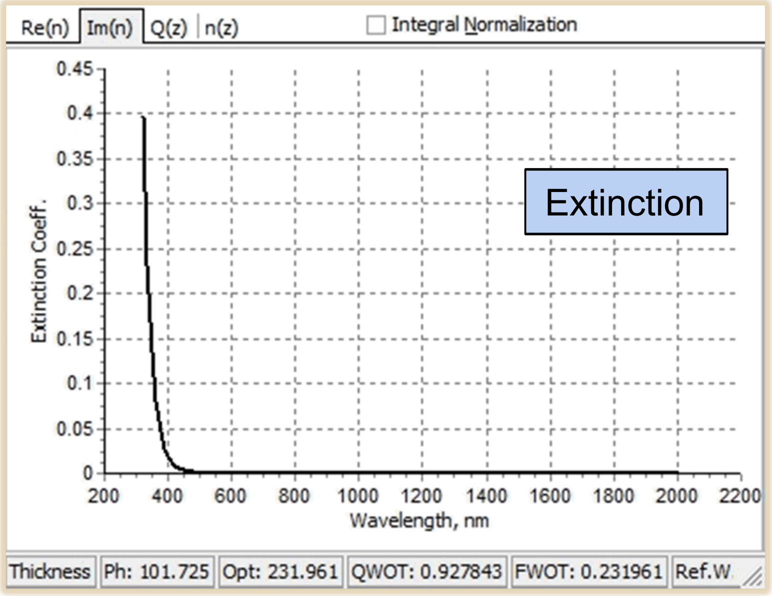
Data Fitting

D = 0.693337



Index

Thickness | Ph: 101.725 | Opt: 231.961 | QWOT: 0.927843 | FWOT: 0.231961 | Ref.W.



Extinction

Thickness | Ph: 101.725 | Opt: 231.961 | QWOT: 0.927843 | FWOT: 0.231961 | Ref.W.

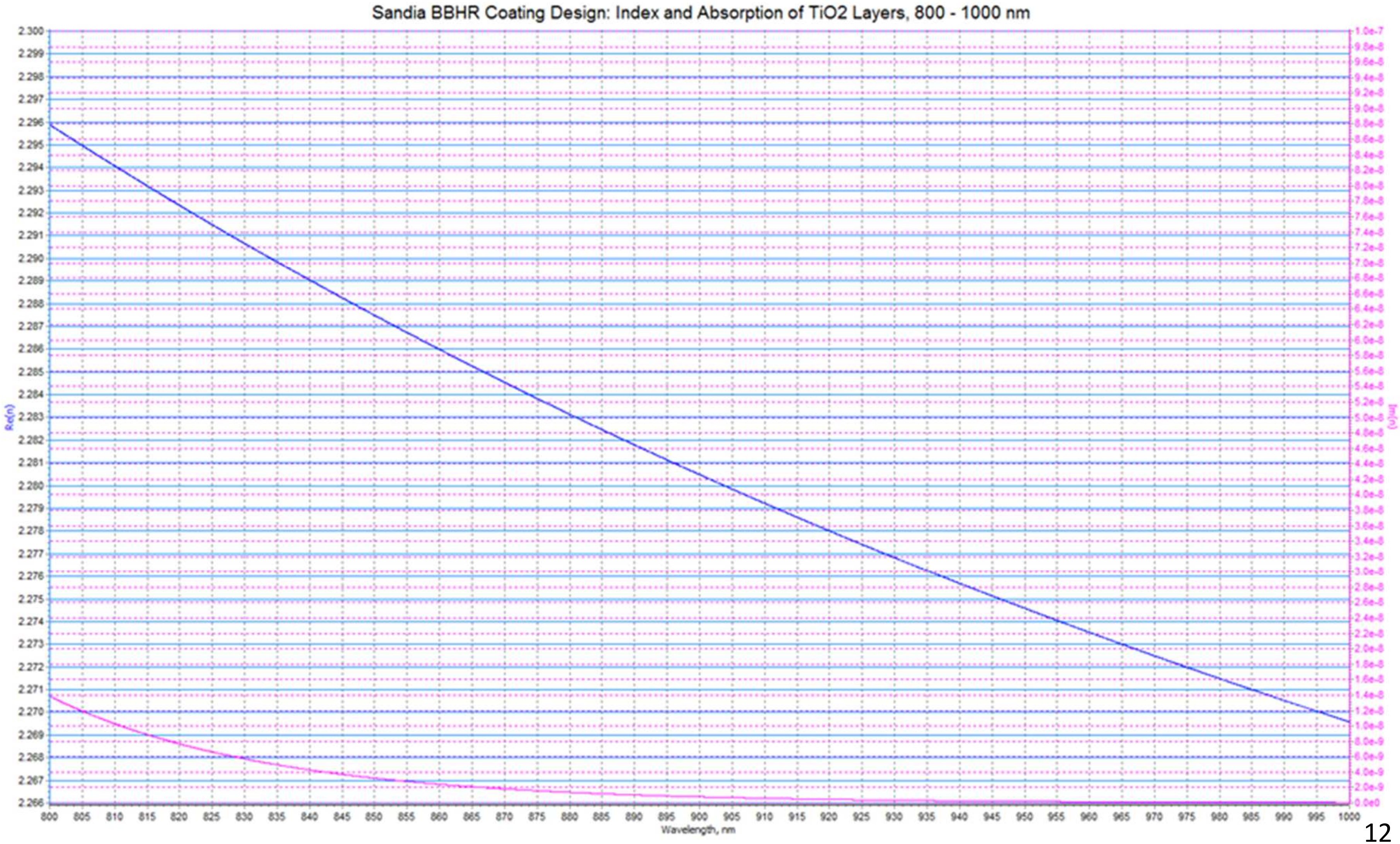
Formulas:

Cauchy: $n(\lambda)=A_0+A_1/\lambda^2+A_2/\lambda^4$
- $A_0=2.233316$
- $A_1=0.046818$
- $A_2=0$

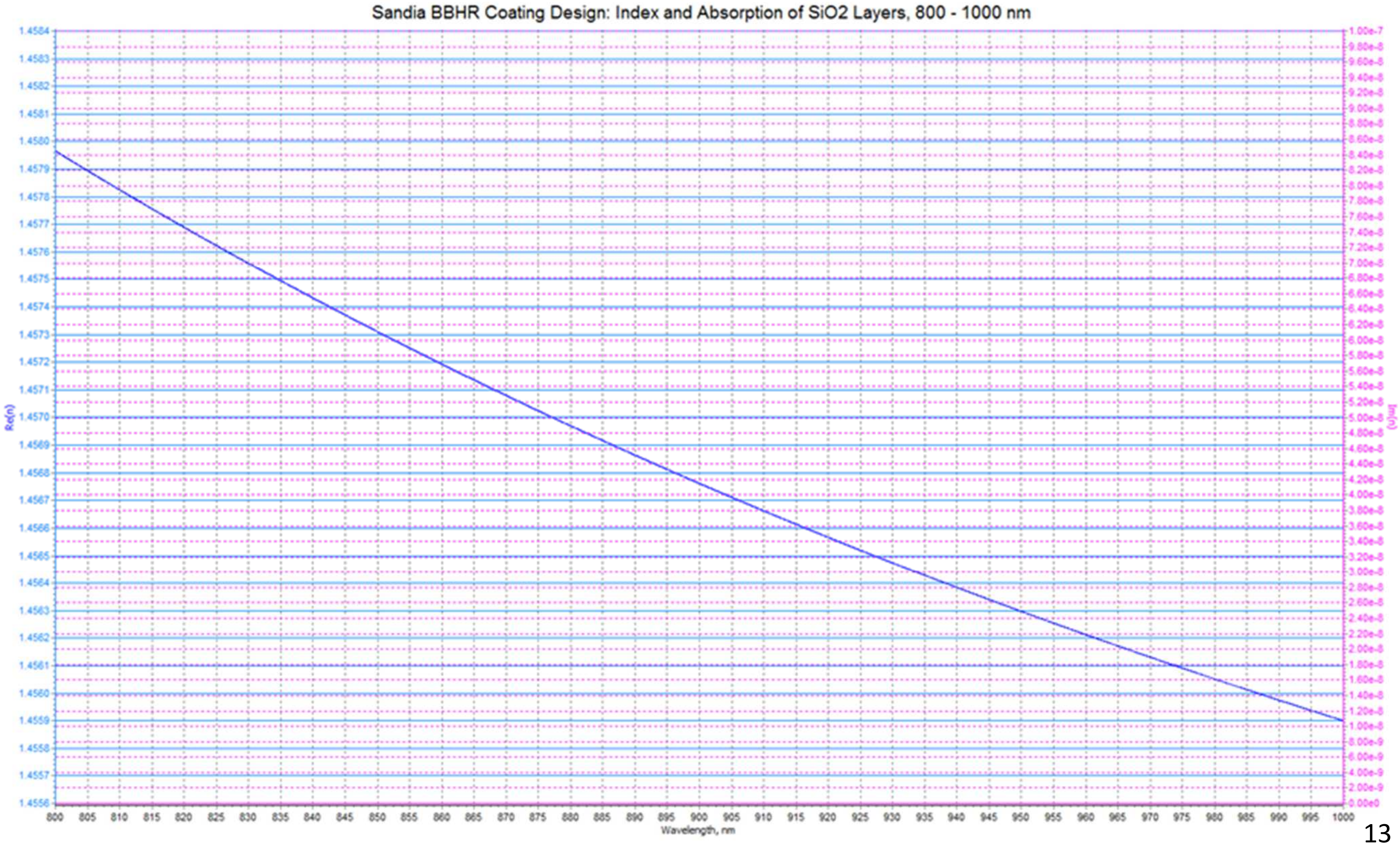
Exponential: $k(\lambda)=B_1\exp(B_2\lambda^{-1}+B_3\lambda)$
- $B_1=72946.15213$
- $B_2=0$
- $B_3=-37.880308$

Refractive index and absorption for TiO_2 layers

Refractive Index and Absorption for Optimal TiO_2 Layers



Refractive Index and Absorption for SiO_2 Layers



Laser Damage Considerations

- TiO_2 and SiO_2 exhibit some of the highest LIDTs

- Our TiO_2/SiO_2 coatings for broad bandwidth HR at 45^o AOI, P pol with 1054 nm central wavelength exhibit high LIDTs at 1064 nm for ns pulses

  19 J/cm^2 according to the NIF-MEL protocol (3.5 ns pulses)

  12.7 J/cm^2 according to the ISO 11254-1 protocol (7 ns pulses)

- LIDTs with fs pulses will be much lower and more dependent on intrinsic, band-gap related material properties

- Consequently, TiO_2 will be more vulnerable than SiO_2 to fs pulse laser damage since its band gap is considerably less than that of SiO_2

- Therefore, an optimal coating design with respect to LIDT for fs pulses will be one for which the strongest electric field intensity peaks in the coating occur within SiO_2 layers

- We take this into account in our BBHR coating design

Specific Aspects of the BBHR Coating Design Process

- We used the OptiLayer thin film design software
  - optimized designs were based on targeted HR and GDD performance properties

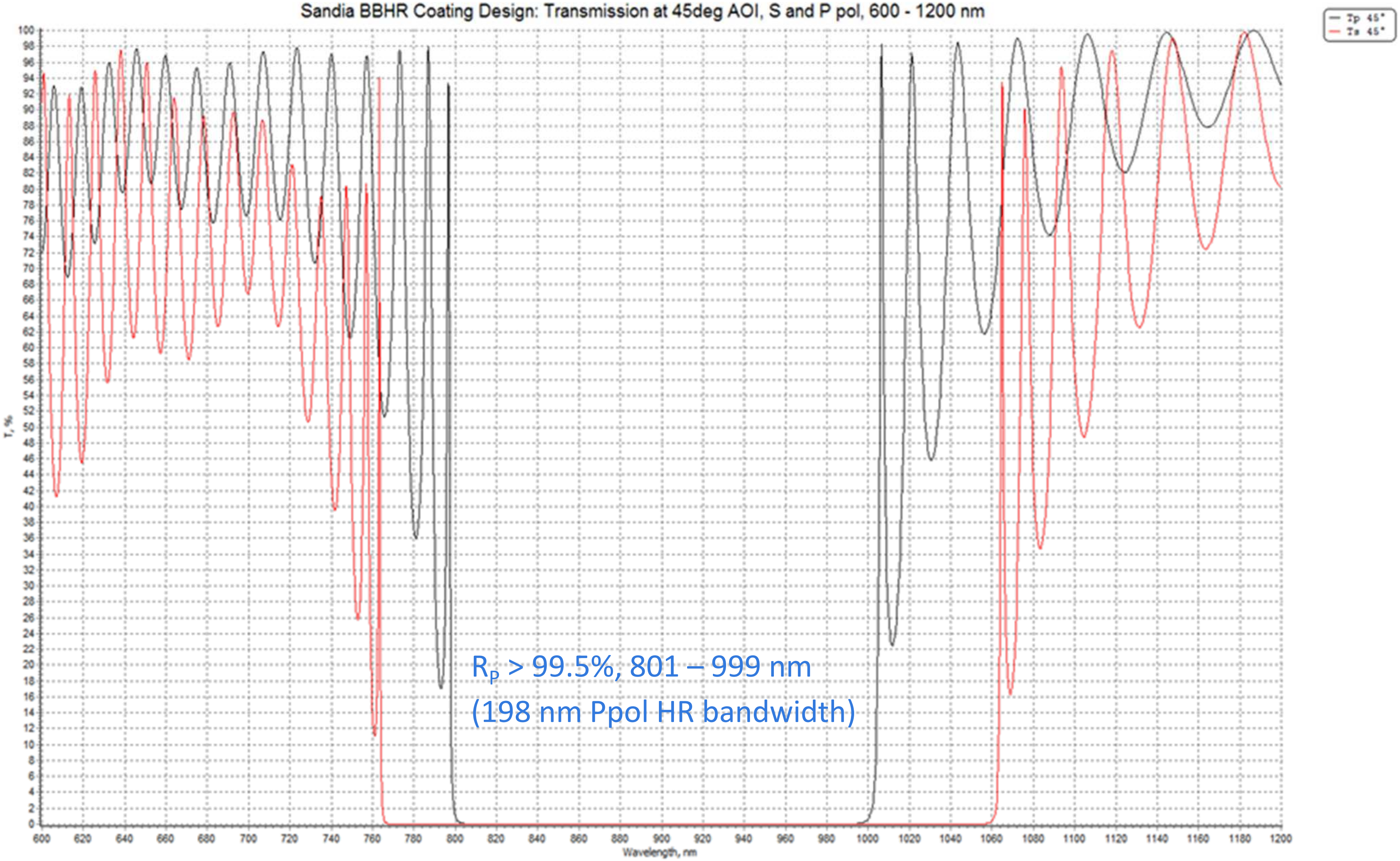
- Algorithms lead to different optimal designs depending on the starting design and performance targets

- Starting designs were H/L index layer pairs with quarter-wave type thicknesses in an opposite (reversed) H versus L chirped sequence

- A limited OptiLayer optimization process led to the final design

- The thickness of the outermost SiO_2 layer was doubled
  - ensures that the highest peak electric field intensities over the HR bandwidth occur in the outermost, near half-wave, SiO_2 layer
  - favors enhanced laser damage resistance of the coating since SiO_2, with its higher band gap, is more resistant to laser damage by fs-class laser pulses than TiO_2.

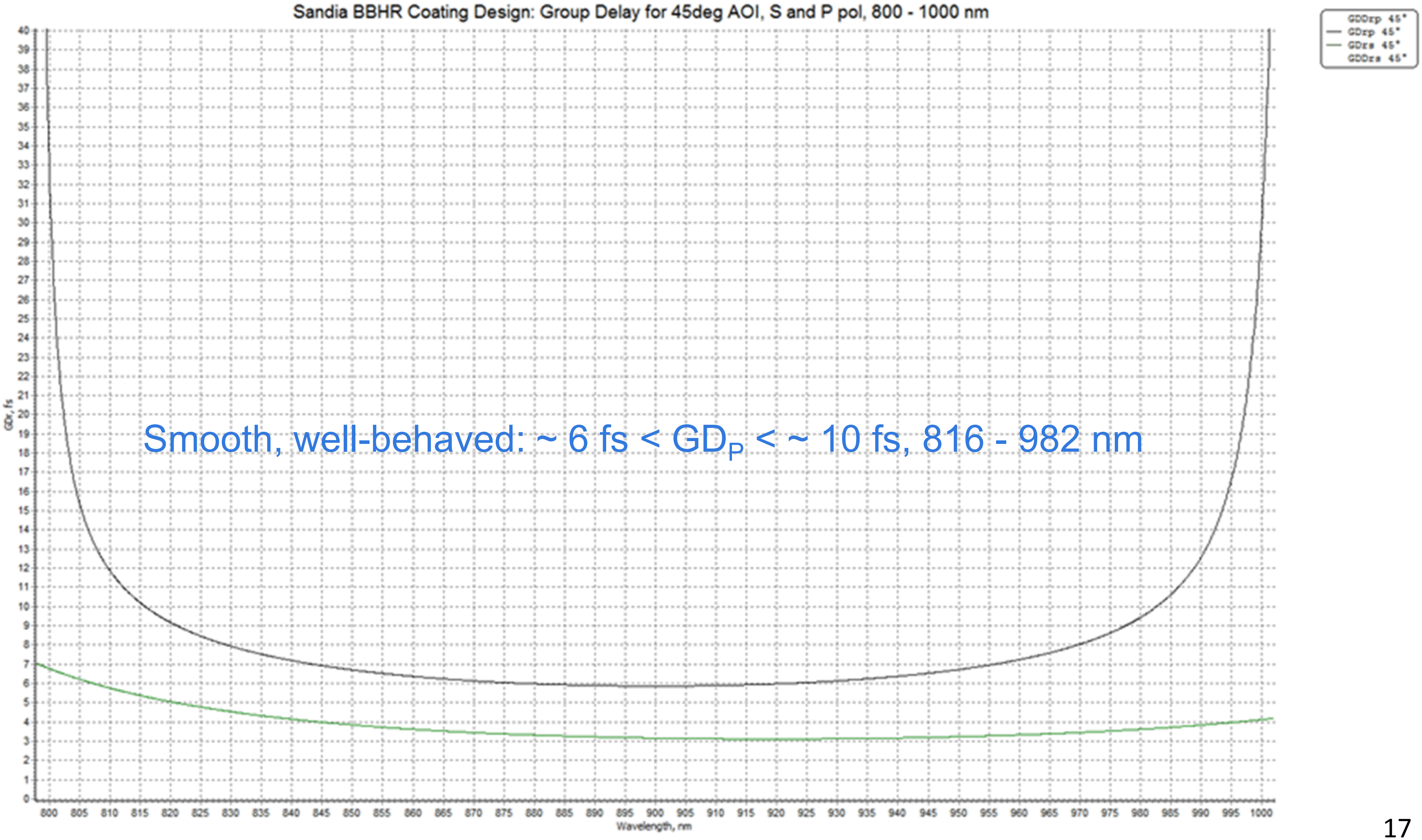
Transmission at 45° AOI, P and S pol, from 600 nm to 1200 nm for the BBHR coating design



R_P > 99.5%, 801 – 999 nm
(198 nm Ppol HR bandwidth)

R_P > 99.5%, 801 – 999 nm (198 nm bandwidth)

GD on reflection for 45^{o} AOI, S and P pol, from 800 nm to 1000 nm for the BBHR coating design

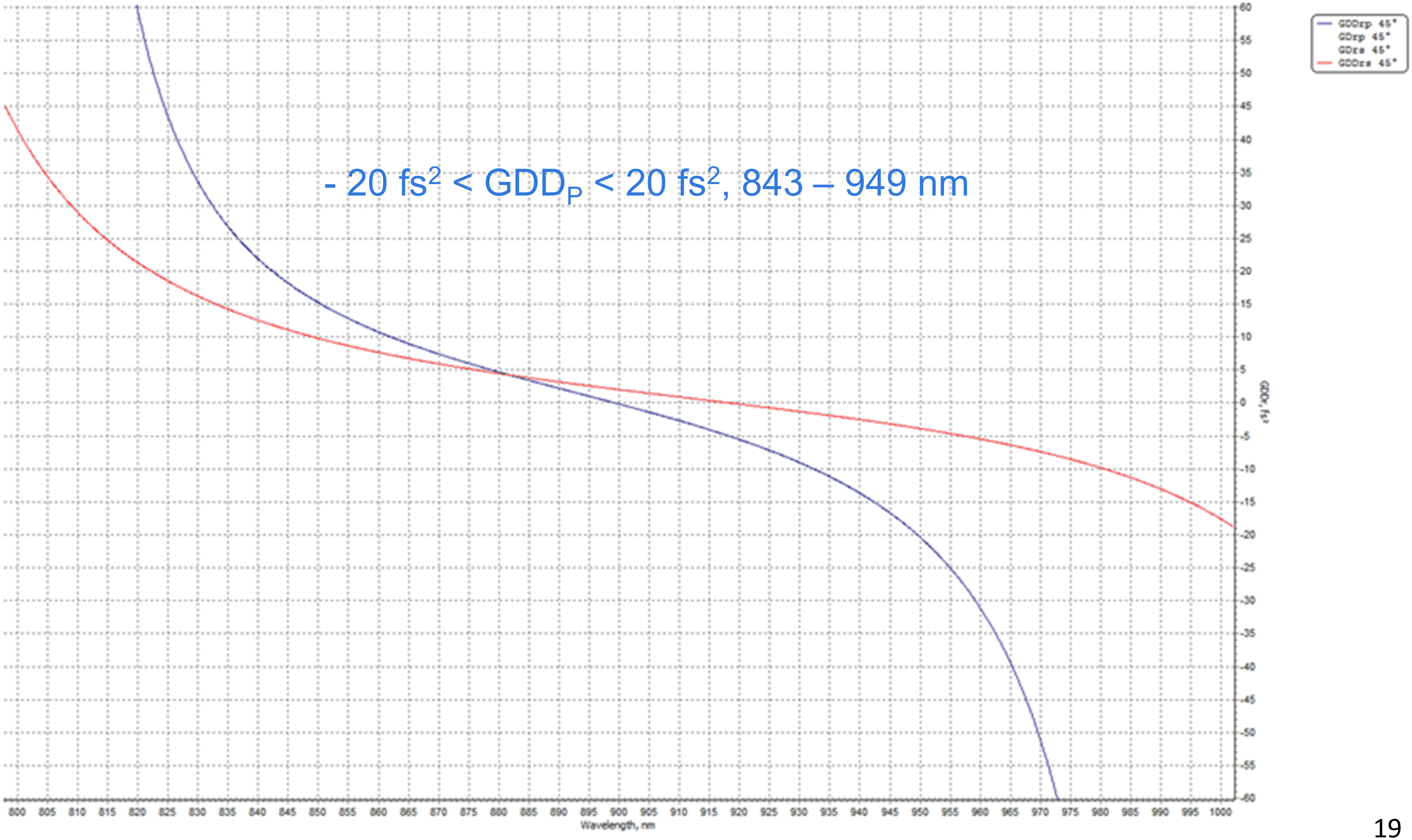


Smooth, well-behaved: ~ 6 fs < GD_P < ~ 10 fs, 816 - 982 nm

GDD on reflection for 45° AOI, S and P pol, from 800 nm to 1000 nm for the BBHR coating design

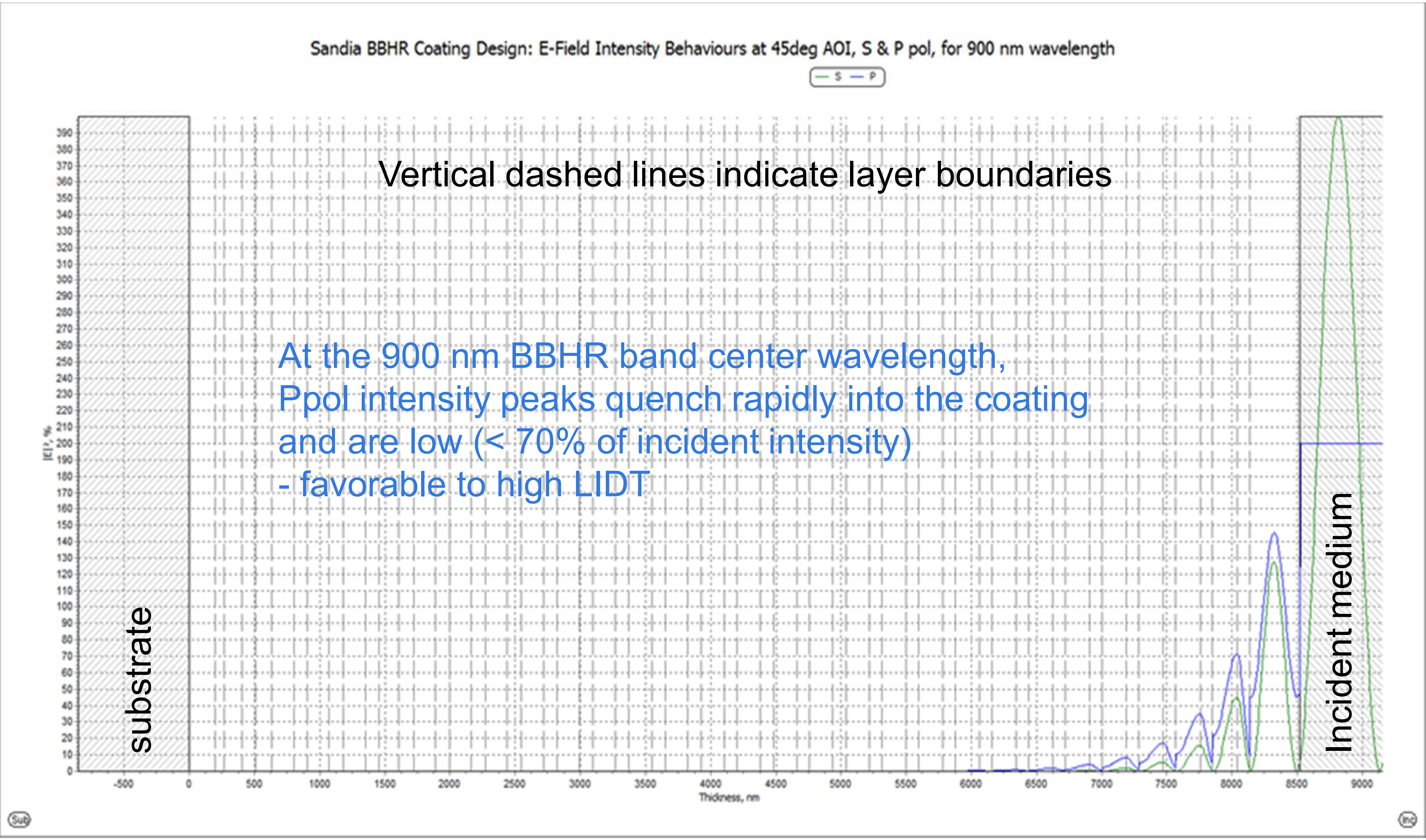
Smooth, well-behaved: - 20 fs^2 < GDD$_P$ < 20 fs^2, 843 – 949 nm

GDD on on reflection for 45° AOI, S and P pol, from 800 nm to 1000 nm and between + 60 fs^2 and - 60 fs^2 for the BBHR coating design



$- 20\ \text{fs}^2 < \text{GDD}_P < 20\ \text{fs}^2$, 843 – 949 nm

Optical E-field intensities (as % of incident intensity) within the coating for 900 nm wavelength light at 45^{o} AOI, S and P pol, for the BBHR coating design



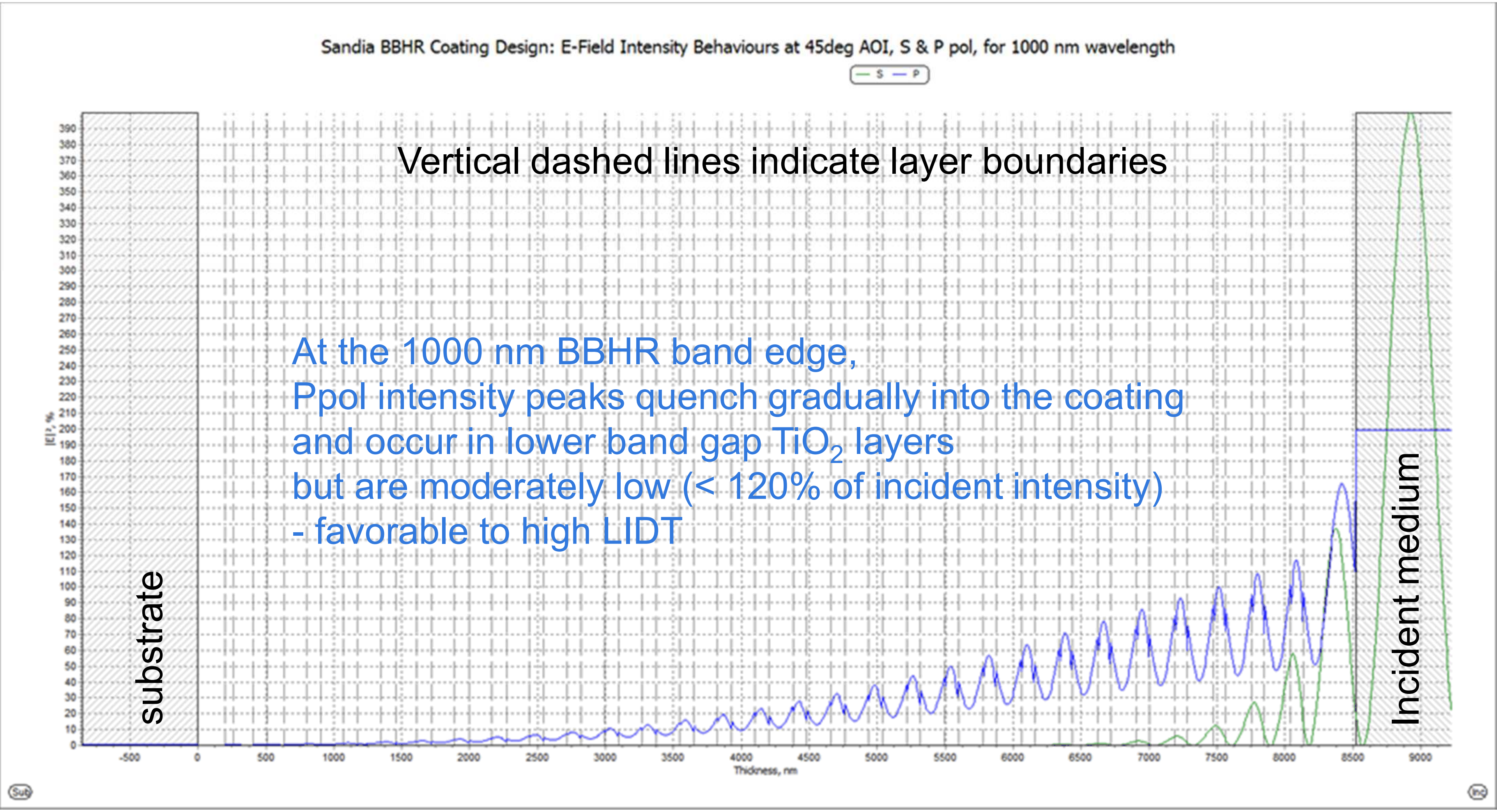
Vertical dashed lines indicate layer boundaries

At the 900 nm BBHR band center wavelength,
Ppol intensity peaks quench rapidly into the coating
and are low (< 70% of incident intensity)
- favorable to high LIDT

substrate

Incident medium

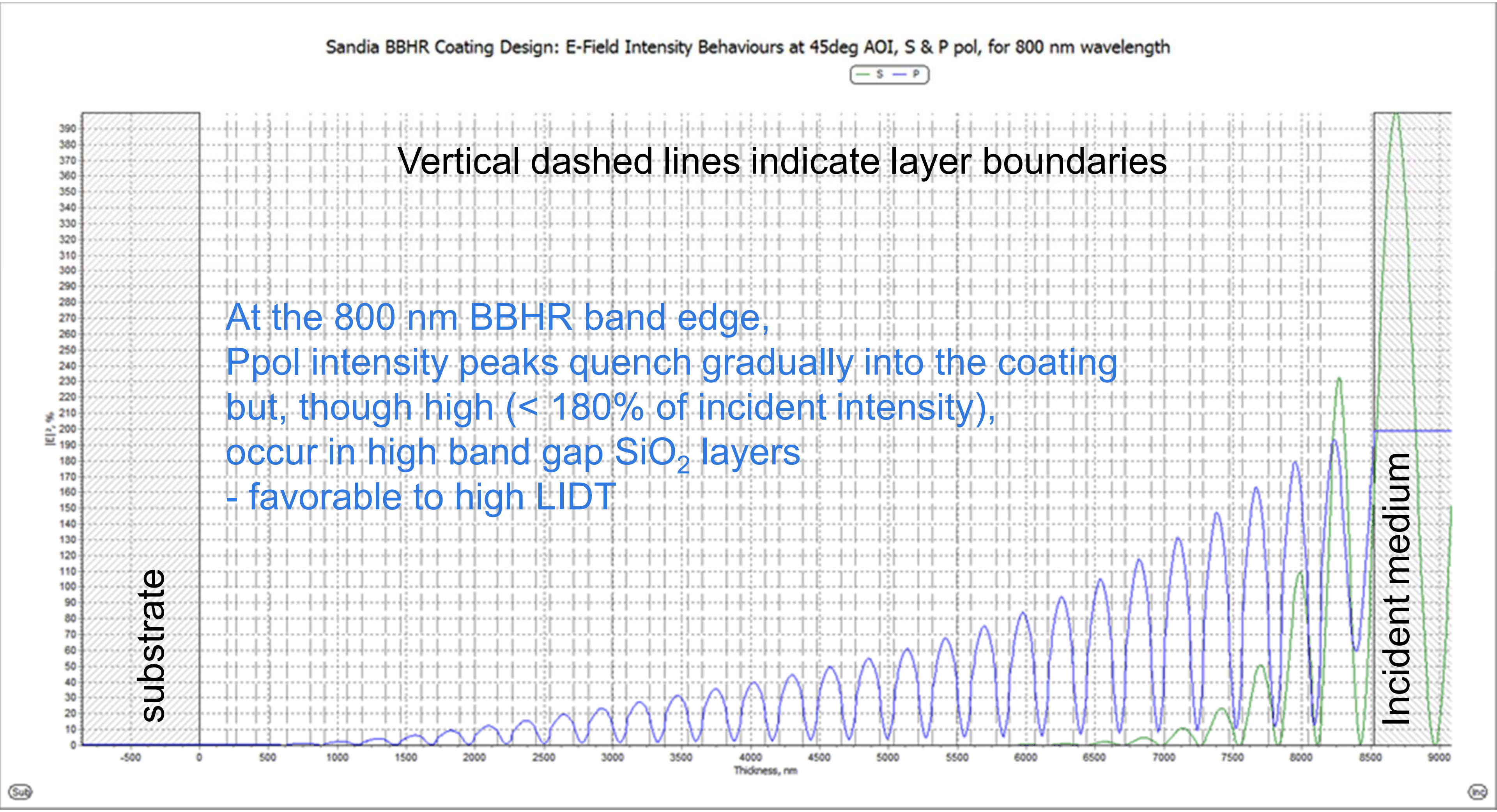
Optical E-field intensities (as % of incident intensity) within the coating for 1000 nm wavelength light at 45^o AOI, S and P pol, for the BBHR coating design



Vertical dashed lines indicate layer boundaries

At the 1000 nm BBHR band edge,
Ppol intensity peaks quench gradually into the coating
and occur in lower band gap TiO_2 layers
but are moderately low (< 120% of incident intensity)
- favorable to high LIDT

Optical E-field intensities (as % of incident intensity) within the coating for 800 nm wavelength light at 45° AOI, S and P pol, for the BBHR coating design



Vertical dashed lines indicate layer boundaries

At the 800 nm BBHR band edge,
Ppol intensity peaks quench gradually into the coating
but, though high (< 180% of incident intensity),
occur in high band gap SiO_2 layers
- favorable to high LIDT

substrate

Incident medium

Coating Uniformity

- Uniformity of reflection and GDD is essential for large optics of fs lasers

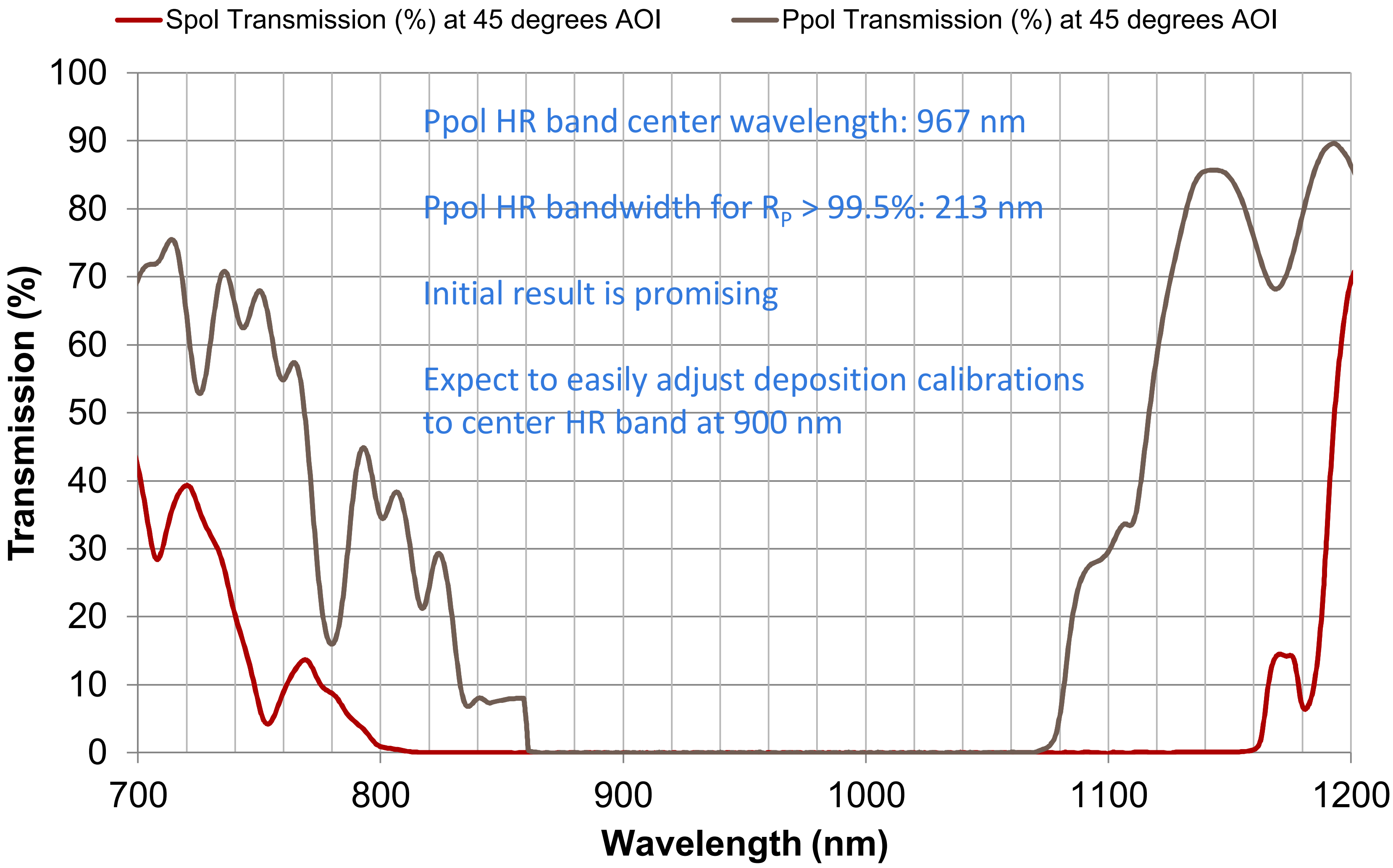
- Most attention has focused on uniformity of reflectivity, with little known about GDD uniformity

- Coating uniformity at Sandia
    - Large, 2.3 m x 2.3 m x 1.8 m, chamber makes uniformity easier to achieve
    - Planetary motion of the large optics during deposition favors uniform deposition
    - masking just below the coating plane is specially designed to ensure uniformity of spectral (reflection/transmission) properties of coatings
    - GDD uniformity has not yet been assessed

- The Sandia large optics coater consistently produces multi-layer coatings with +/- 0.5 % uniformity over 94 cm diameters of the planetary fixtures

Initial Test Coating Run for BBHR Design

Measured Transmission at 45^o AOI, P and S pol, from 700 nm to 1200 nm



Ppol HR band center wavelength: 967 nm

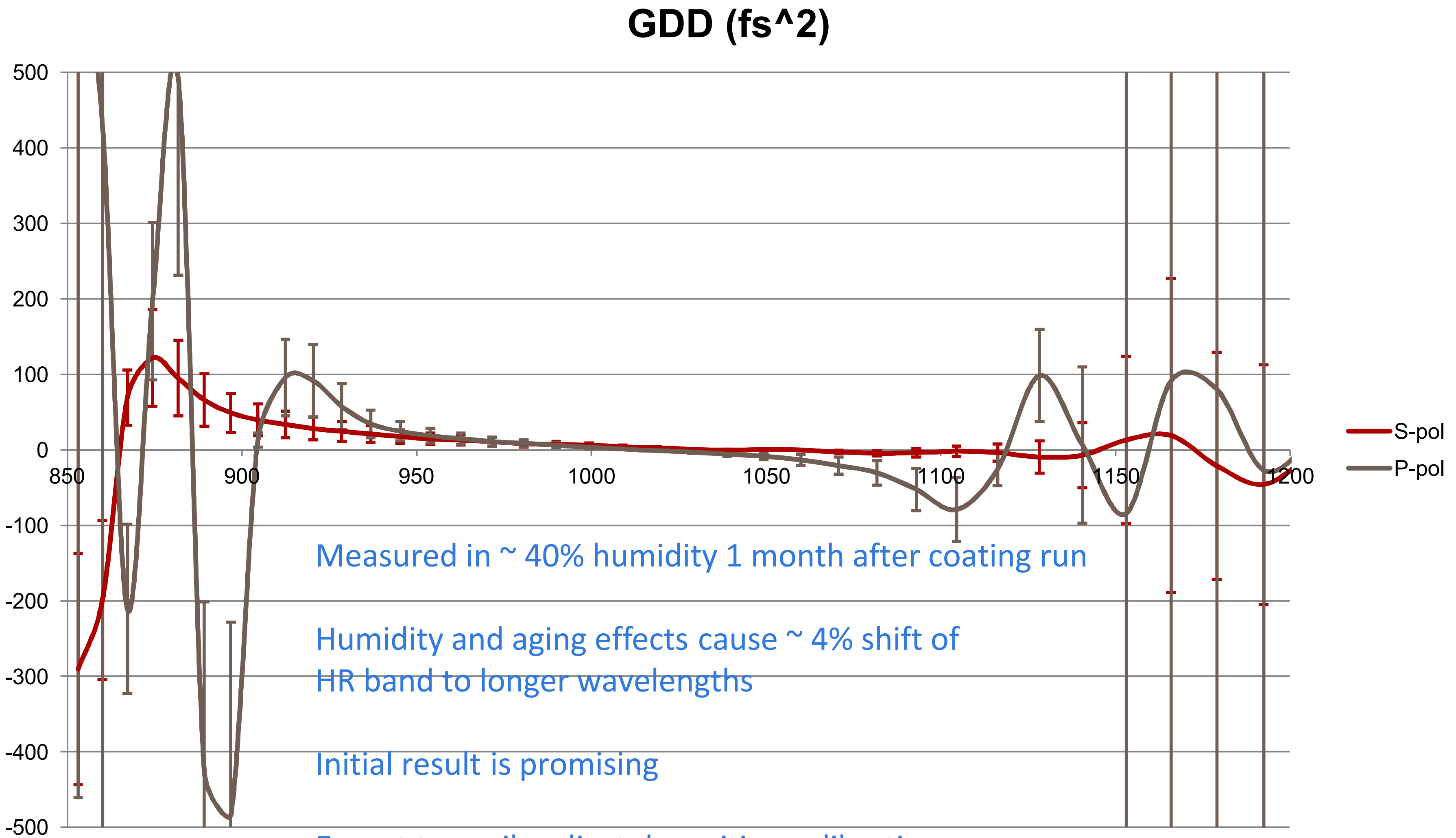
Ppol HR bandwidth for $R_P > 99.5\%$: 213 nm

Initial result is promising

Expect to easily adjust deposition calibrations to center HR band at 900 nm

Initial Test Coating Run for BBHR Design

Measured GDD for Reflection at 45° AOI, P and S pol, from 850 nm to 1200 nm



Measured in ~ 40% humidity 1 month after coating run

Humidity and aging effects cause ~ 4% shift of
HR band to longer wavelengths

Initial result is promising

Expect to easily adjust deposition calibrations
To center HR band at 900 nm and improve GDD

Summary

- We have developed a coating design for 45° AOI, Ppol BBHR centered at 900 nm
- The BBHR coating design is favorable to high LIDT and exhibits HR and GDD performances that behave smoothly and deviate only slightly from design goals
- Furthermore, because of their smooth behavior, the slight deviations from GDD design goals very likely can be compensated
- Measured HR and GDD results for the initial BBHR test coating run are promising
- Our experience in producing multi-layer dielectric optical coatings on meter-class optics supports the eventual goal of uniformly depositing this BBHR coating on a large dimension mirror substrate