Coating designs for Advanced Detectors

(Nazario MORGADO – LMA Lyon)

Preliminary :

- Mechanical losses from dielectric mirror coatings are a significant source of thermal noise in the more crucial frequency range (~ 100 Hz)

- Ta_2O_5 is the dominant source of dissipation in current SiO_2 / Ta_2O_5 coatings

  ↳ Ratio ~ 5 between silica and tantala

  Φ_{SiO2} ~ 0.4 10^{-4}

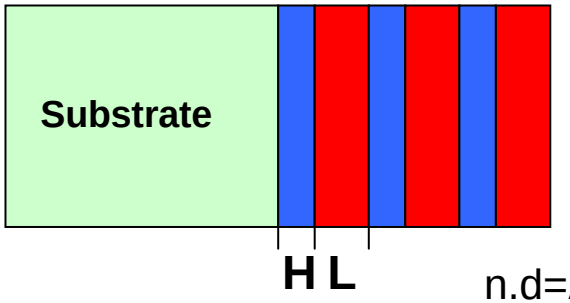
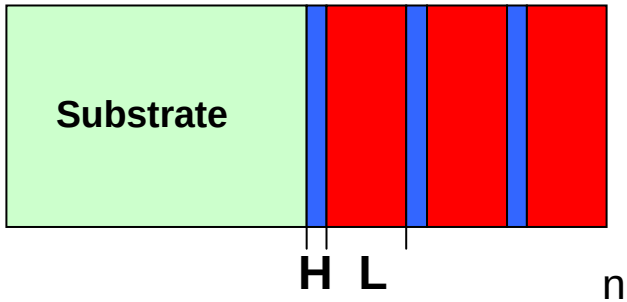
  $\Phi_{Ti:Ta2O5}$ ~ 2.3 10^{-4}

Goal : Reduce the weight of the mechanical losses of the high index material

Optimized coatings : Gain for the Thermal Noise

Innocenzo PINTO (University of SANNIO) [Optimized Coating (LSC 12-17 August 2005, LIGO Hanford Observatory LIGO G-050363-00-R]

Goal : Modify the physical stack without changing the optical response

Coatings for the TNI	Mirror transmission : 278 ppm H:$Ta_2 0_5$ (n : 2.035-i.3.10^{-8}, Φ : 3.10^{-4}) L:SiO_2 (n:1.465-i.4.10^{-8}, Φ : 5.10^{-5})
QWL mirror	Lowest noise end tweaked stacked doublet (PINTO-University of Sannio)
	
$(HL)_{13}$ HLL	0.56H(1.38 L0.62H)$_{16}$ 0.16L
Ta_2O_5 thickness : 1830 nm SiO_2 thickness : 2722 nm	Ta_2O_5 thickness : 1347 nm SiO_2 thickness : 4032 nm
Relative PSD (Power Spectral Density) : **1**	Relative PSD : **0.83**

Optimized coatings : Gain for the Thermal Noise

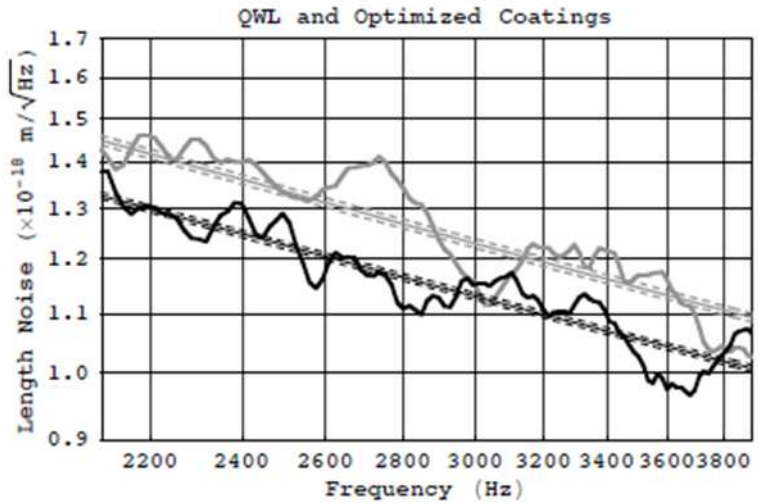


FIG. 14: This is the plot in figure 12 after the Savitzky-Golay smoothing filter was applied to each spectrum. The separation between the spectra of the two coatings can be seen more clearly.

Akira E. Villar and al (**Measurement of thermal noise in multilayer coatings with optimized layer thickness, Phys. Rev. D 81, 122001 (2010)**

The ratio between a QWL and an optimized coating of the coating loss angles observed is r = 0.82, which agrees with the predicted ratio 0.83

For a 26-layer coating 0.8167H (1.0736L 0.8828H)12 0.085L @ 1064nm (Transmission : 320 ppm)

-> LMA mesurement : $\Phi_{Ti:Ta2O5}$=4,2x10^{-4} +/- 0,2x10^{-4} (Φ coating = 2.52x10^{-4})(on silica membranes at LMA)

-> TNI mesurement : $\Phi_{Ti:Ta2O5}$=3,8x10^{-4} +/- 0,4x10^{-4} (Φ coating = 2.30x10^{-4}) (on 100 mm diameter silica substrate)

(Assuming Φ_{SiO2} = 0.5x10^{-4})

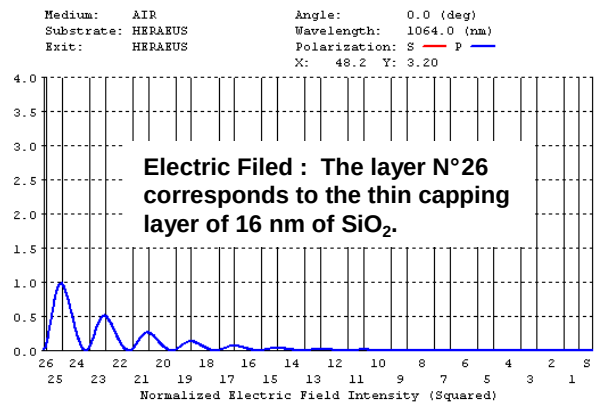
May 2010 (J. Franc, GWADW Kyoto)

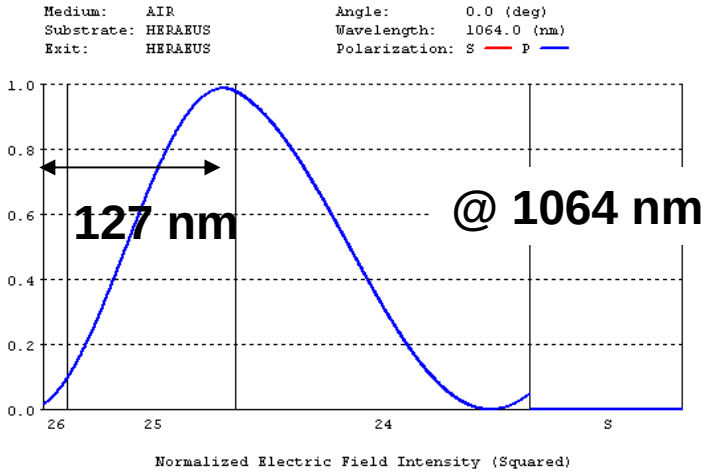
"Mechanical losses of different multilayer coatings with no defects have been measured and confirm larger losses than expected"

Interface lossy mixed materials ➪ on going work

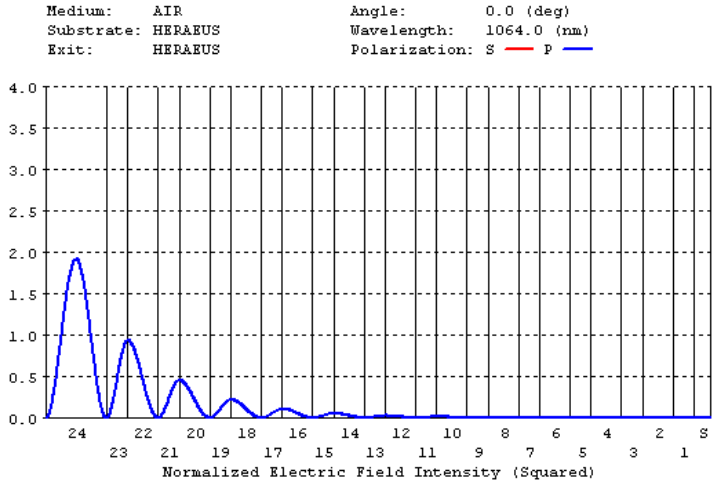
Optimized coatings : Gain for the Optical Absorption

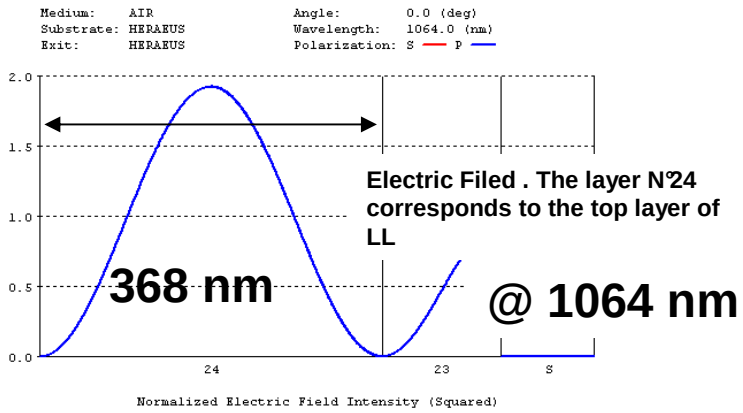
Substrate : 102.7 nm Ta_2O_5 - [12 doublets (dH=111 nm – dL = 193.6 nm)] – 15.65 nm SiO_2





Quarter wavelength design (transmission of 482 ppm @ 1064 nm: (HL)^11 HLL





The electric field is twice lower in the case of an optimized coating (PINTO style) than in a classical quarter wavelength design for a same transmission.

Minimize of the effect of the electric field on the absorption of the coating

Goal of the optimizations

✓ **Obtain the required transmittance @ 1064 nm and 532 nm**
-Use of a commercial software TFCalc from Sofware Spectra

✓ **minimize the electric field at the surface of the coating**

$$\|E_i\|(1-\sqrt{1-T}) < \|E_t\| < \|E_i\|(1+\sqrt{1-T})$$

With T = transmittance and Ei = 27.46 V/m (incident Electric Field)

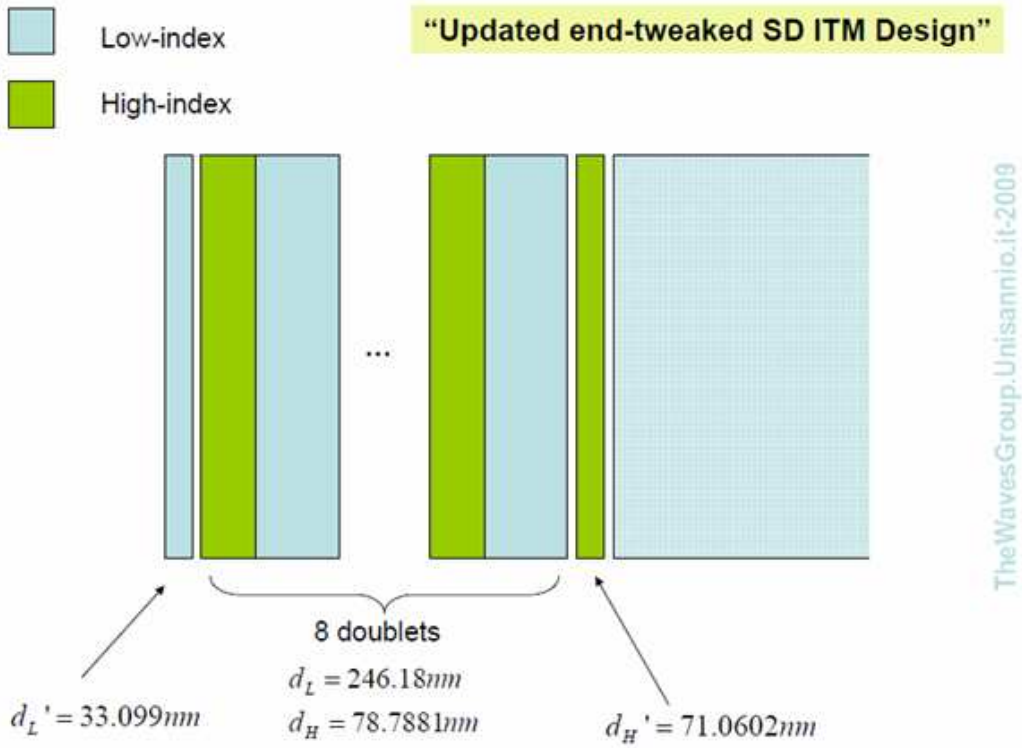
for the ITM, T = 0.014 and Ei = 27.46 V/m ; $P_{incident}$ = 1 W/m²

$$0.193V/m < \|E_t\| < 54.73V/m$$

✓ **Minimize the coating thermal noise (**Coating Thermal Noise Formulas (G.HARRY - LIGO-T 0900161)

$$\underset{\wedge\wedge\wedge}{S} := ZL + ZH\cdot\gamma \quad \textbf{with} \begin{cases} ZL := Dl\cdot\dfrac{nL}{\lambda 0} \\ ZH := Dh\cdot\dfrac{nH}{\lambda 0} \end{cases} \quad \textbf{and} \quad \underset{\wedge\wedge}{\gamma} := \frac{\Phi H}{\Phi L}\cdot\frac{nL}{nH}\cdot\frac{\left(\frac{YH}{Ysub}+\frac{Ysub}{YH}\right)}{\left(\frac{YL}{Ysub}+\frac{Ysub}{YL}\right)}$$

Optimized ITM mirror



Goals :

- **@ 1064 nm : Transmittance = 1.3 % - 1.5 %**
- **@ 532 nm : 0.5 % < Transmittance < 2 %**
- **Minimize the Electric Field**

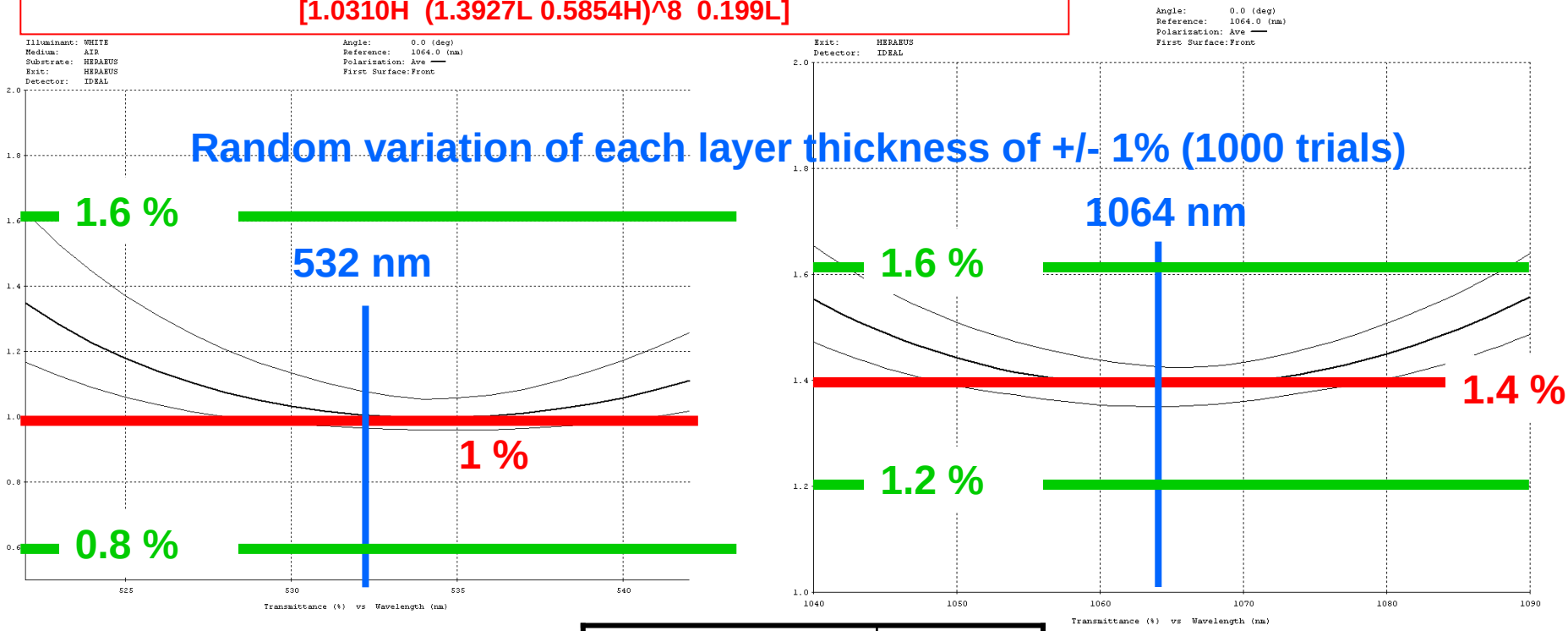
Always have in mind : ROBUST design (the less sensitive to manufacturing errors)

Optimized ITM mirror

ITM mirror with LMA Materials and optimized with TFCalc

Stack : 132.5 nm Ta2O5 - [8 doublets (dL=257 nm – dH = 75 nm)] – 37 nm SiO2

[1.0310H (1.3927L 0.5854H)^8 0.199L]



	N Ta2O5	N SiO2
@ 532 nm	2.14	1.45
@ 1064 nm	2.07	1.44

ϕc(opt)	4.20 10^{-9}
S	9.83
T @ 1064 nm	1.39 %
T @ 532 nm	1.005 %
Electric field (V/m)	0.192

Total Thickness : 2825 nm

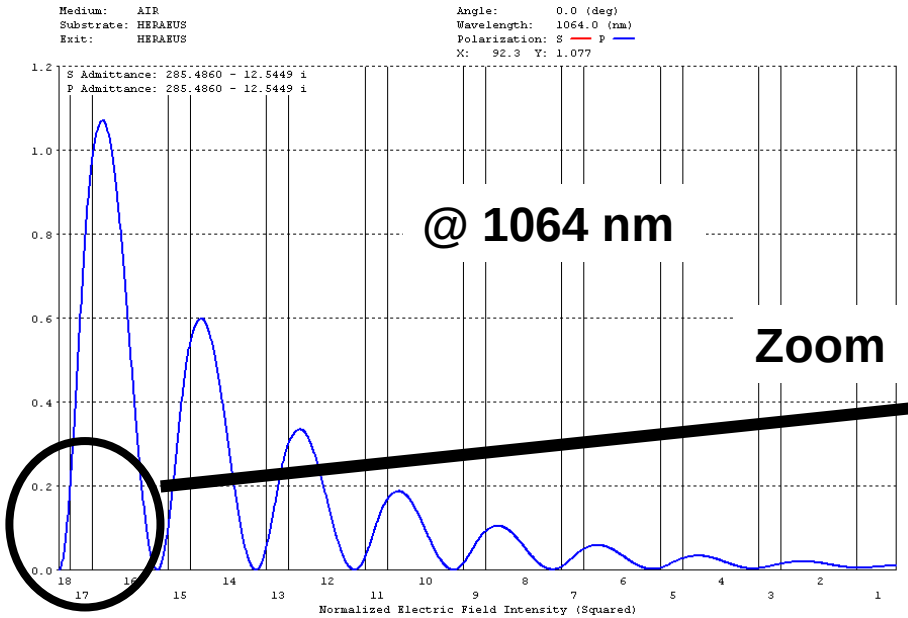
Total Ta_2O_5 : 732 nm

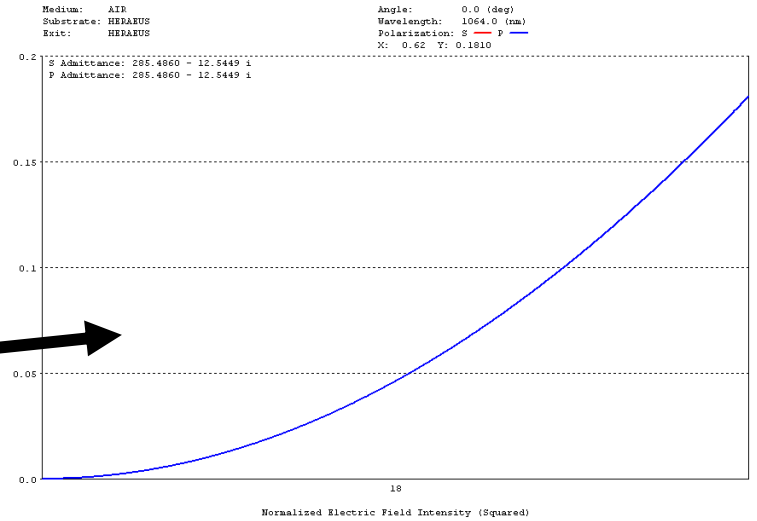
Total SiO_2 : 2093 nm

Optimized ITM mirror

Stack : [1.0310H (1.3927L 0.5854H)^8 0.199L]

$$E(V/m) = 27.46 * \left(\frac{T.P}{\mathrm{Re}(Y)} \right)^{1/2} = 27.46 * \left(\frac{0.0139 * 1}{285.486} \right)^{1/2} = 0.191 V/m$$



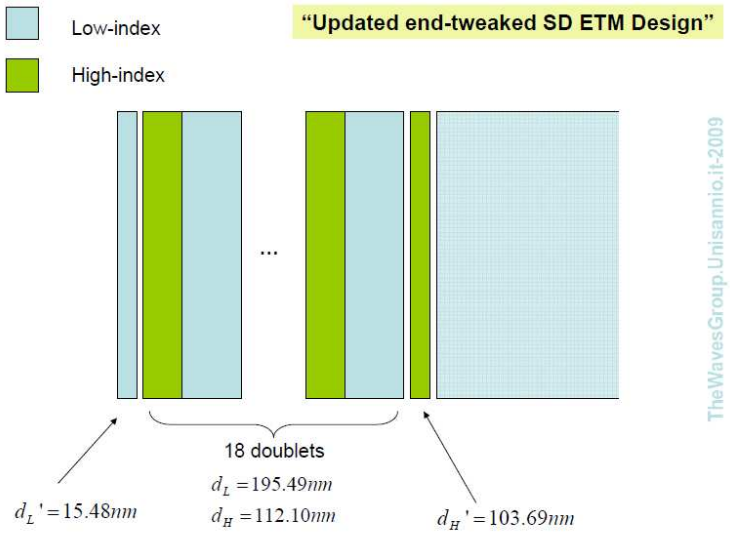


Electric Field Intensity in the whole stack

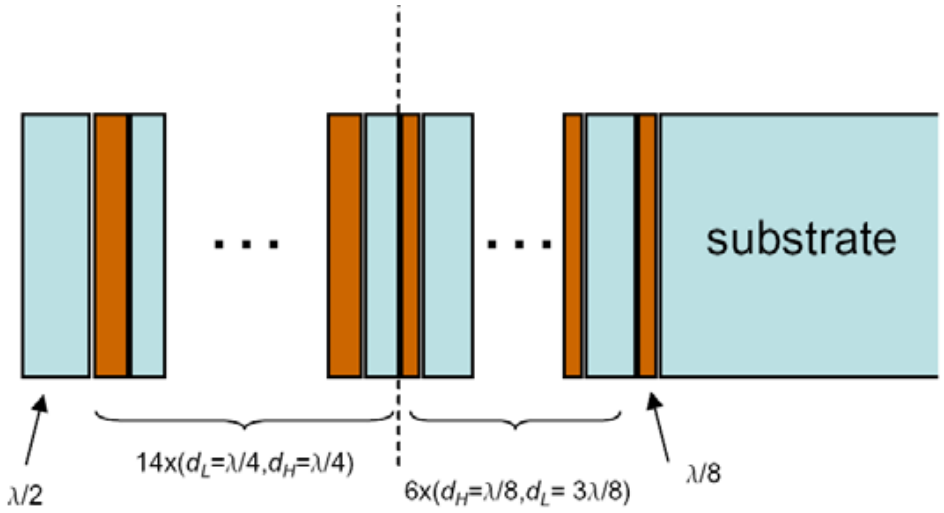
Electric Field Intensity in the Top layer

ETM mirror Designs

Optimized design



Reference dichroic design



Goals :

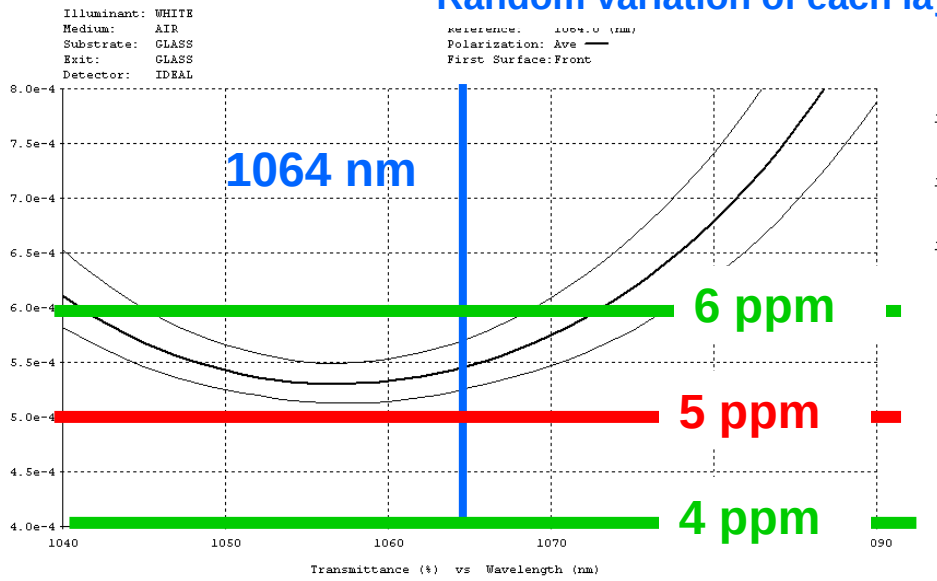
- **@ 1064 nm : Transmittance = 5 +/- 1 ppm**
- **@ 532 nm : 3 % < Transmittance < 15 % with goal 5% desired**
- **Minimize the Electric Field < 0.01 V/m**

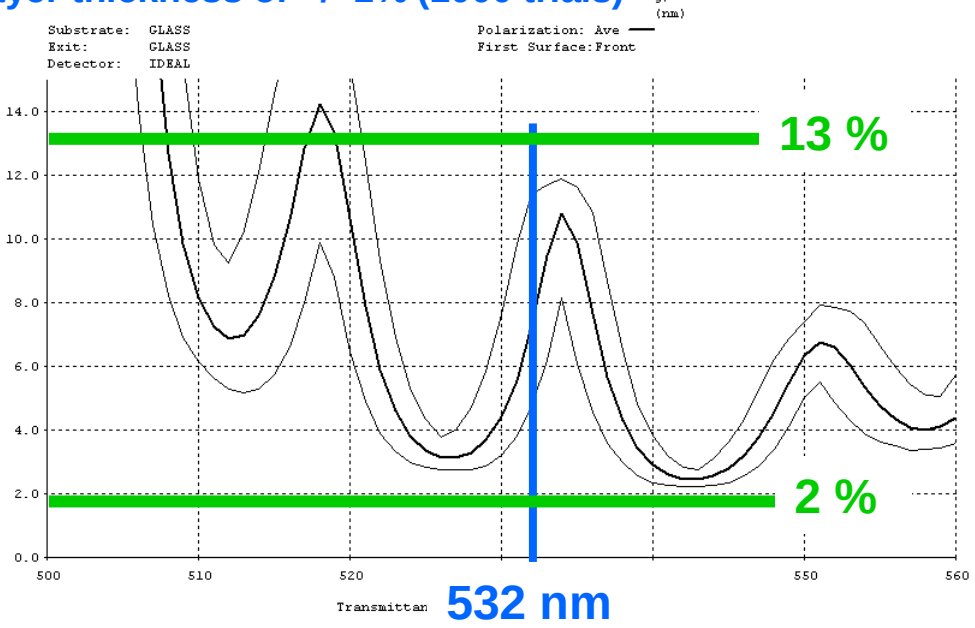
Always have in mind : ROBUST design (the less sensitive to manufacturing errors)

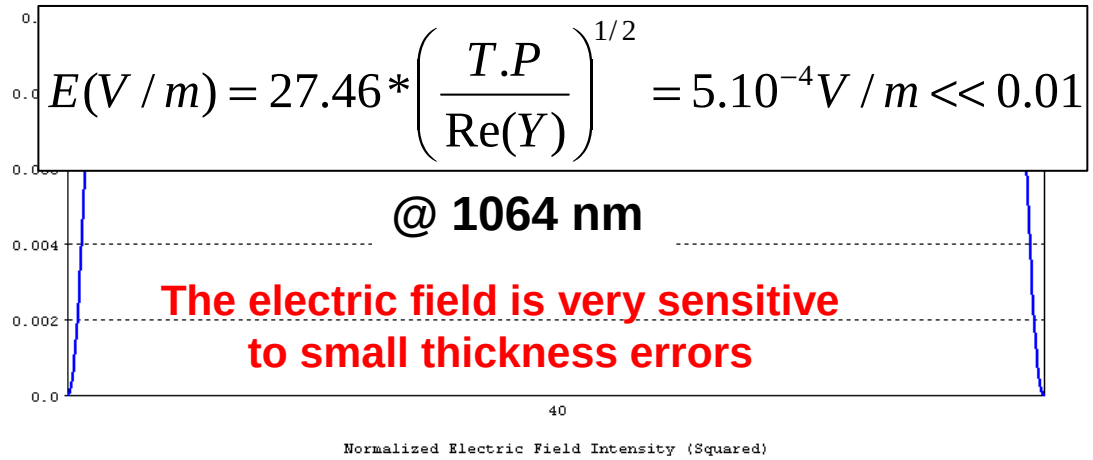
Reference Dichroic ETM mirror with LMA Materials and optimized with TFCalc

Stack : 64 nm Ta_2O_5 - [5 doublets (dL=277 nm – dH = 64 nm)]
- [14 doublets (dH=128 nm – dL = 184 nm)] – 368 nm SiO_2

Random variation of each layer thickness of +/- 1% (1000 trials)







$$E(V/m) = 27.46 * \left(\frac{T.P}{\mathrm{Re}(Y)} \right)^{1/2} = 5.10^{-4} V/m << 0.01$$

@ 1064 nm

The electric field is very sensitive to small thickness errors

T (@1064 nm) = 5.43 ppm

T (@532 nm) = 7.29 %

Thickness Tantala = 2184.54 nm
Thickness Silica = 4341 nm
Total Thickness = 6 525 nm

$\phi_{LMADichroic} = 1.13265*10^{-8}$

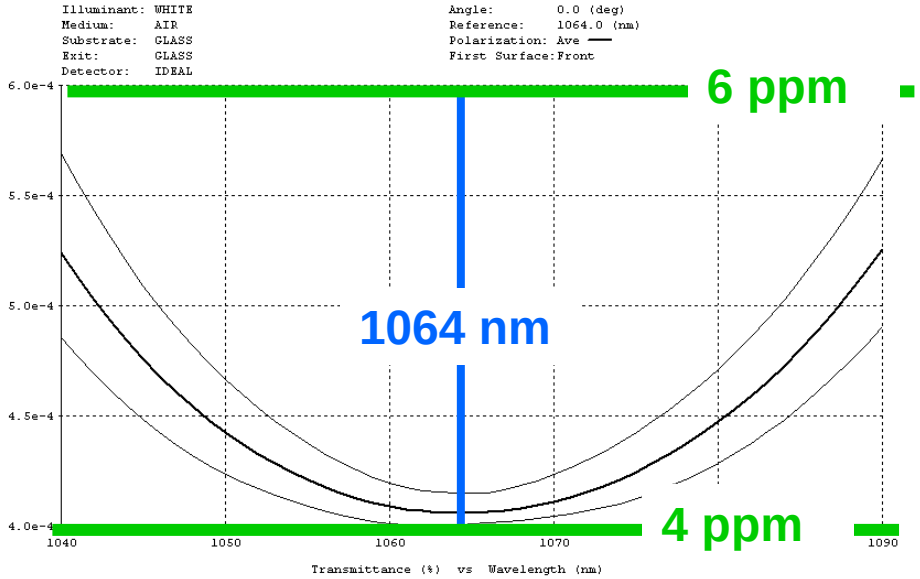
S = 26.69

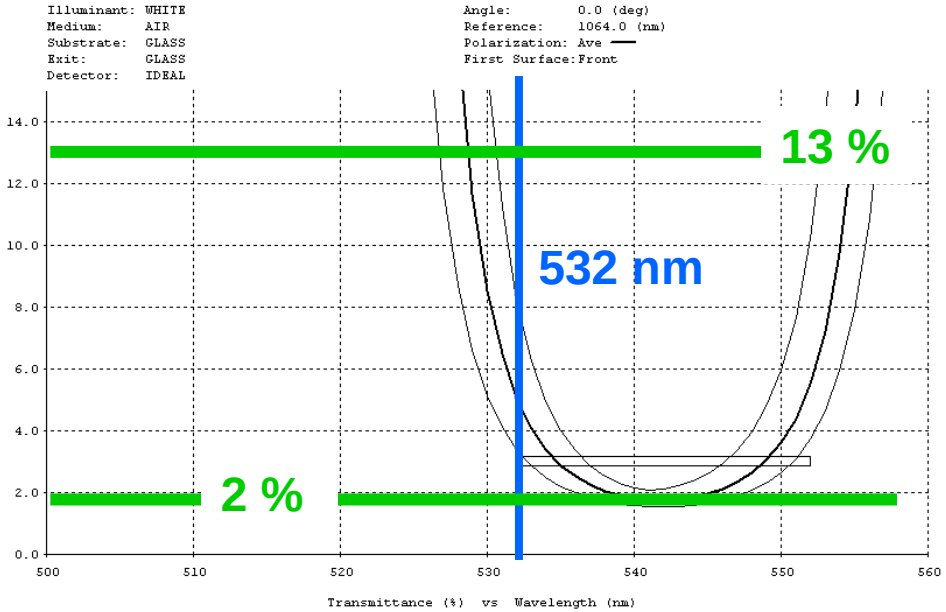
Optimized ETM mirror

Stack : 142 nm Ta_2O_5 - [18 doublets (dL= 210 nm – dH = 110 nm)] – 11 nm SiO_2

1.1068H [1.1371B 0.8591H]^18 0.0617L

Random variation of each layer thickness of +/- 1% (1000 trials)





	N Ta_2O_5	N SiO_2	T
@ 532 nm	2.14	1.45	5.09 %
@ 1064 nm	2.07	1.44	4.06 ppm

Thickness Tantala = 2129.27 nm
Thickness Silica = 3792.11 nm
Total Thickness = 5921 nm

$\phi_c^{(opt)} = 1.07598*10^{-8}$

$\phi c(opt) / \phi LMADichroic = 25.43/26.69 = 0.95$

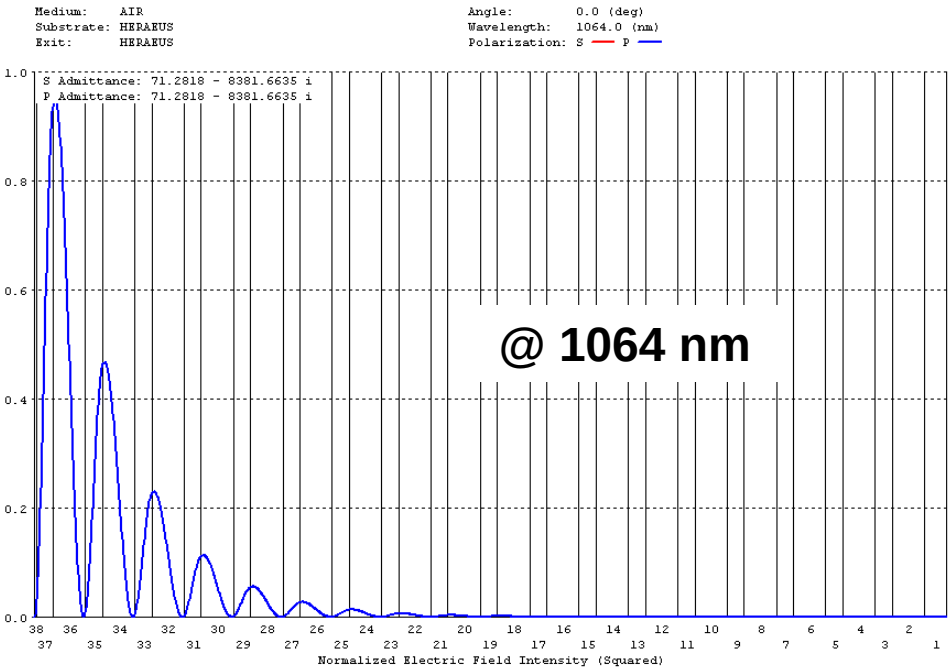
S = 25.43

Optimized ETM mirror

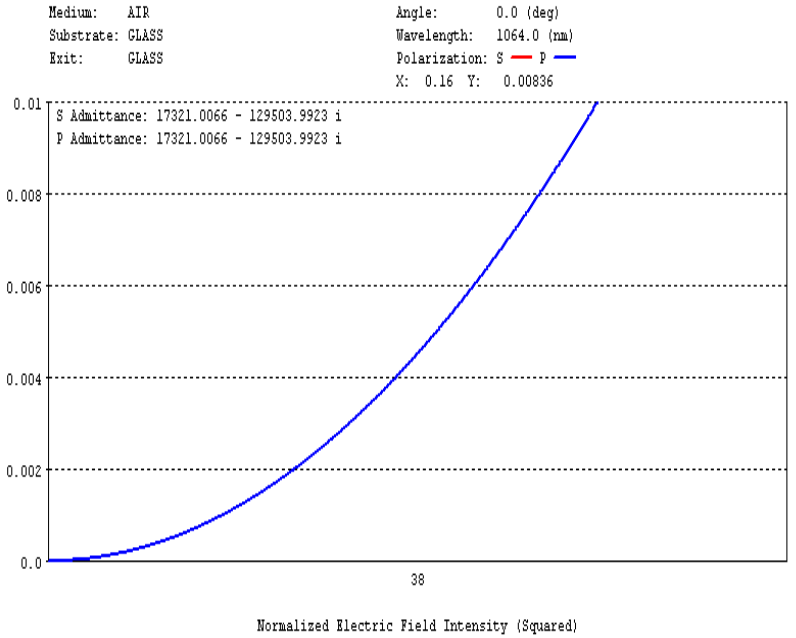
End-Tweaked SD ETM mirror with LMA Materials optimized with TFCalc

Stack : 1.1068H [1.1371B 0.8591H]^18 0.0617L

$$E(V/m) = 27.46 * \left(\frac{T.P}{\mathrm{Re}(Y)} \right)^{1/2} = 27.46 * \left(\frac{4.35.10^{-6} * 1}{17321} \right)^{1/2} = 4.10^{-4} V/m << 0.01$$



Electric Field Intensity in the whole stack



Electric Field Intensity in the Top layer

The electric field is very sensitive to small thickness errors but less than with the Dichroic design

Quarter Wavelength ETM mirror : Phase sensitivity to manufacturing errors

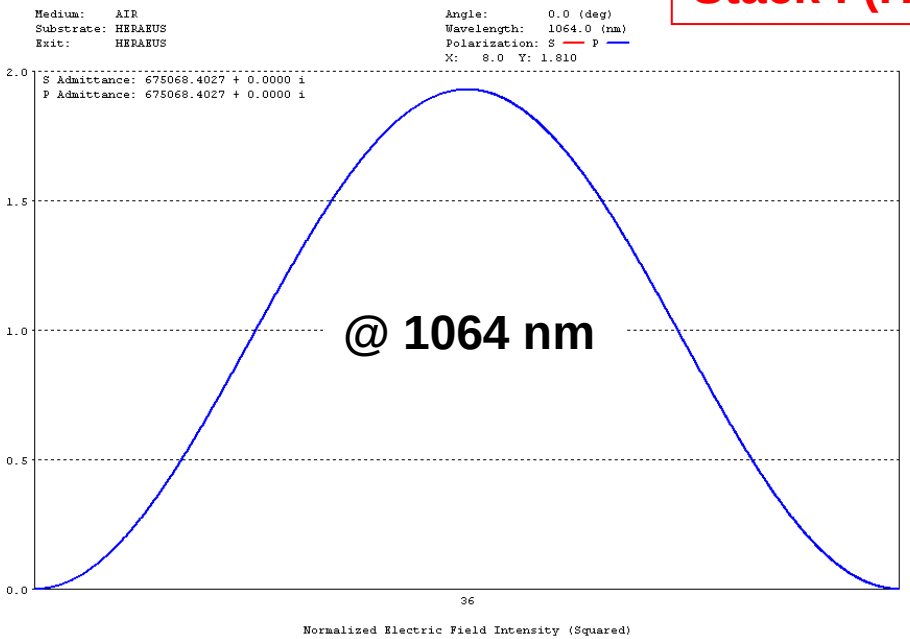
$$R = \frac{\eta_0 - Y}{\eta_0 + Y} = \frac{1 - Y}{1 + Y} = \|R\|.e^{i.\varphi_R}$$

With R : reflectivity

Y : admittance of the coating

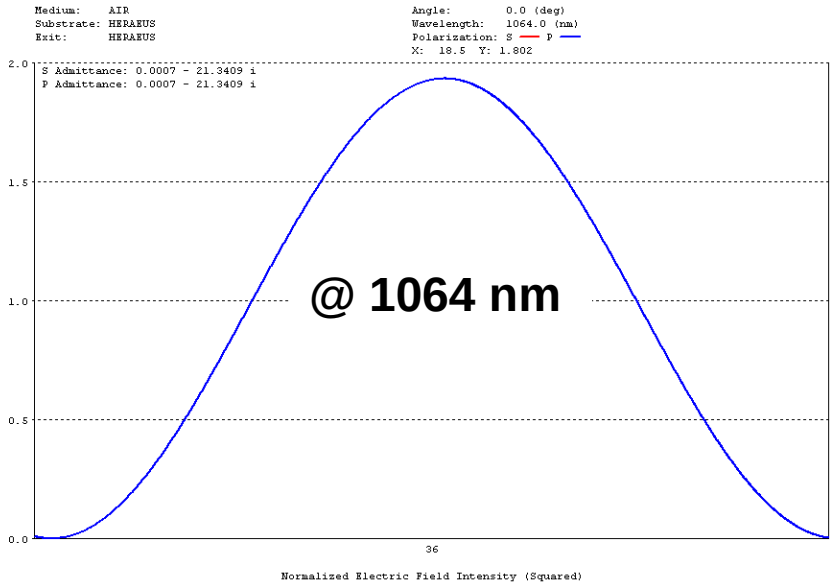
φ_R : Phasis of the reflected beam

Stack : (HL)^17 HLL



Phase of the reflected beam is = π

(T @ 1064 nm = 5.93 ppm)



With an + 1 % error on each layer

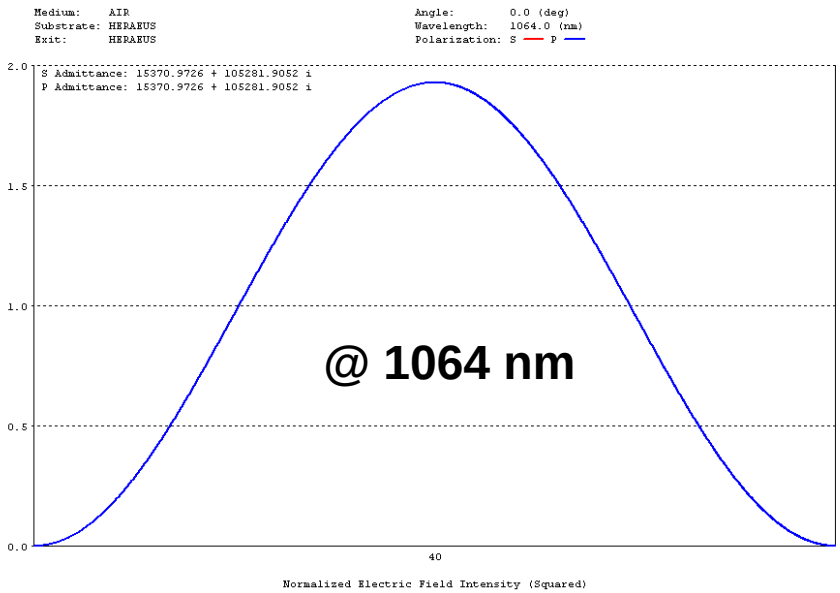
Phase of the reflected beam is = 175 °

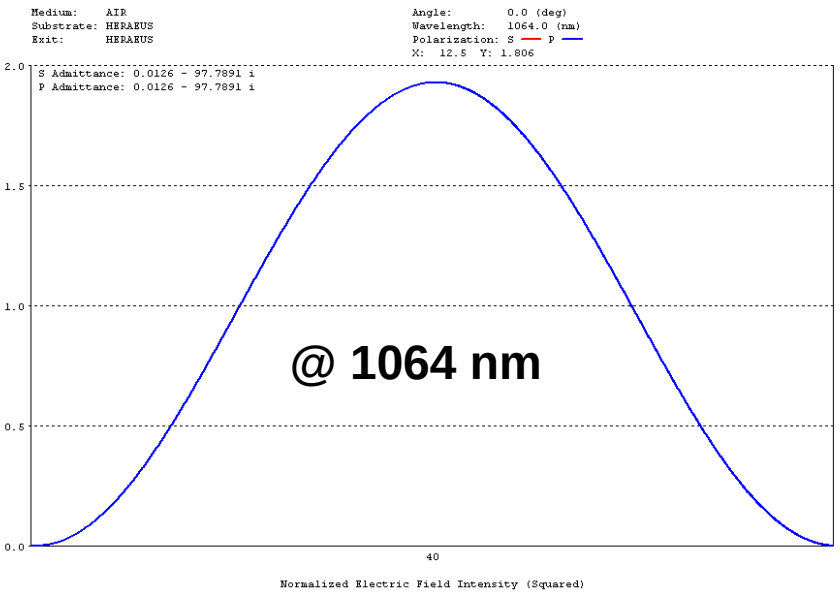
(T @ 1064 nm = 6.19 ppm)

Reference Dichroic ETM mirror : Phase sensitivity to manufacturing errors

Stack : 64 nm Ta_2O_5 - [5 doublets (dL=277 nm – dH = 64 nm)]

- [14 doublets (dH=128 nm – dL = 184 nm)] – 368 nm SiO_2





Phase of the reflected beam is = π

(T @ 1064 nm = 5.43 ppm)

With an + 1 % error on each layer

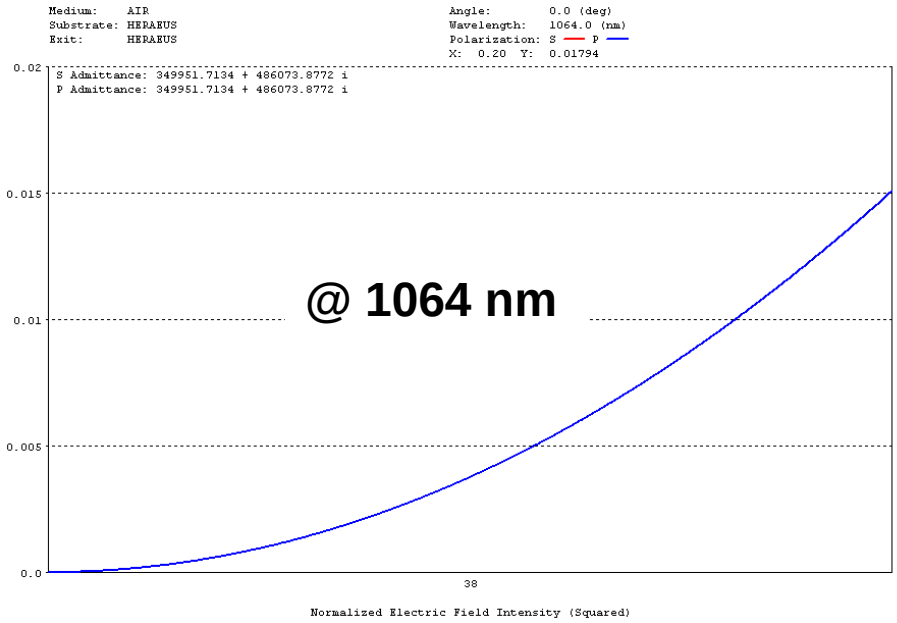
Phase of the reflected beam is = 178.8 °

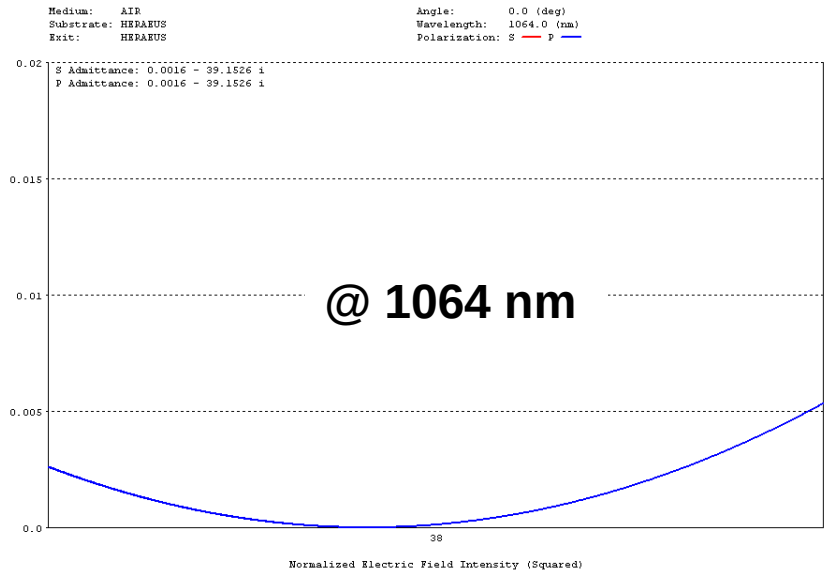
(T @ 1064 nm = 5.26 ppm)

Design 7 ETM mirror : Phase sensitivity to manufacturing errors

Stack : 142 nm Ta_2O_5 - [18 doublets (dL= 210 nm – dH = 110 nm)] – 11 nm SiO_2

1.1068H [1.1371B 0.8591H]^18 0.0617L





When the Electric Field is Minimized

Phase of the reflected beam is = π

(T @ 1064 nm = 4.11 ppm)

With an + 1 % error on each layer

Phase of the reflected beam is = 177 °

(T @ 1064 nm = 4.11 ppm)

Conclusions

- The optimized designs for the ITM and ETM mirrors match the LIGO requirements :
  - Transmittance @ 532 and 1064 nm
  - Minimize the Electric field of the coating
  - Gain of the coating thermal noise

- The optimized designs for the ITM and ETM mirrors bring :
  - Gain compared to the dichroic designs
  - IBS manufacturing compatibility
  - but the phase of the reflected beam is still sensitive to manufacturing errors ➪ non-uniformity ➪ losses