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Effect of Heat of Treatment on the Optical Absorption of Dielectric Coatings: effect of temperature and Oxygen pressure

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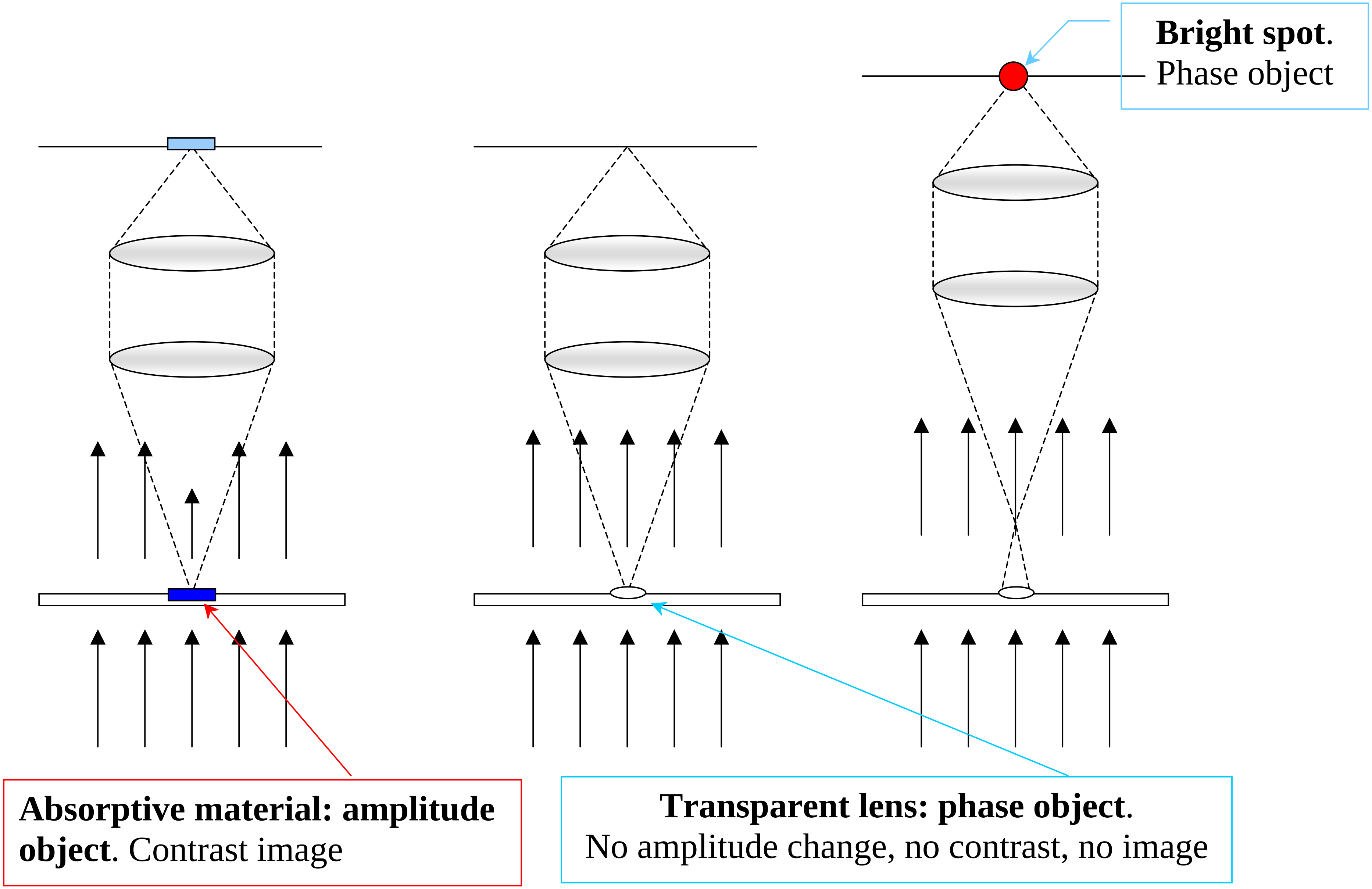
INTRODUCTION

The specifications for optical absorption losses of Advanced LIGO optics, of 0.5 ppm level, can now be reached using different techniques[1,2], among which ion-beam sputtering is anticipated as the most suitable for high-damage threshold and low loss dielectric optical coatings. The current challenge for AdLIGO optics is the optimization of the other parameters, like mechanical/elastic noises, spurious charge build-up, etc.

With this aim, the Stanford and Caltech teams in collaboration with CSIRO have been investigating the optical and mechanical properties of various coatings, both single- and multilayer, related to the LIGO AR and HR coating “recipes”.

This poster summarizes the results on the optical absorption study of coatings deposited at different conditions as well as the effect of post-annealing.

The PCI Method **(idea of thermal lensing)**



Physical Principles

The probe phase is distorted due to heating: $$\Delta\varphi = \left(\frac{2\pi}{\lambda}\right) \times L \times \frac{\partial n}{\partial T} \times \Delta T$$

$\Delta\varphi$ transforms into an intensity distortion

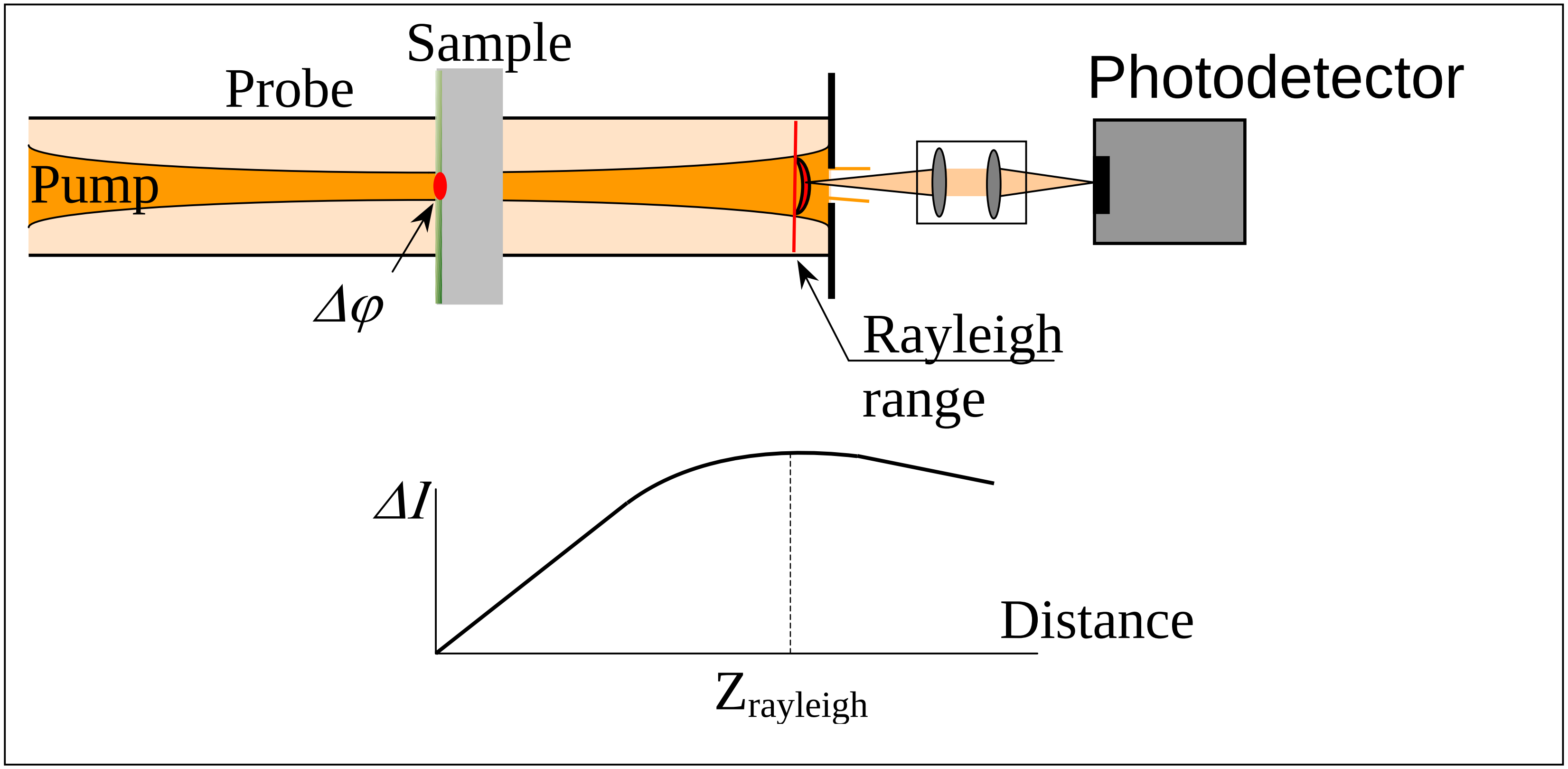
(maximum at the Rayleigh length): $$\Delta I/I \propto \Delta\varphi << \pi$$

The PCI signal $\Delta I/I$, for a pump beam of power W_P and waist w_0 "chopped" at a frequency f, can be written as:

$$\boxed{\frac{\Delta I}{I} \propto B = \left(\frac{L}{2\lambda}\right) \times \left(\frac{\alpha}{\kappa}\right) \times \left(\frac{\partial n}{\partial T}\right) \times \left(\frac{W_P}{w_0^2}\right) \times f^{-1}}$$

where L is the interaction length, α is the thermalized absorption loss, and κ stands for the thermal conductivity.

PCI method (how it works)



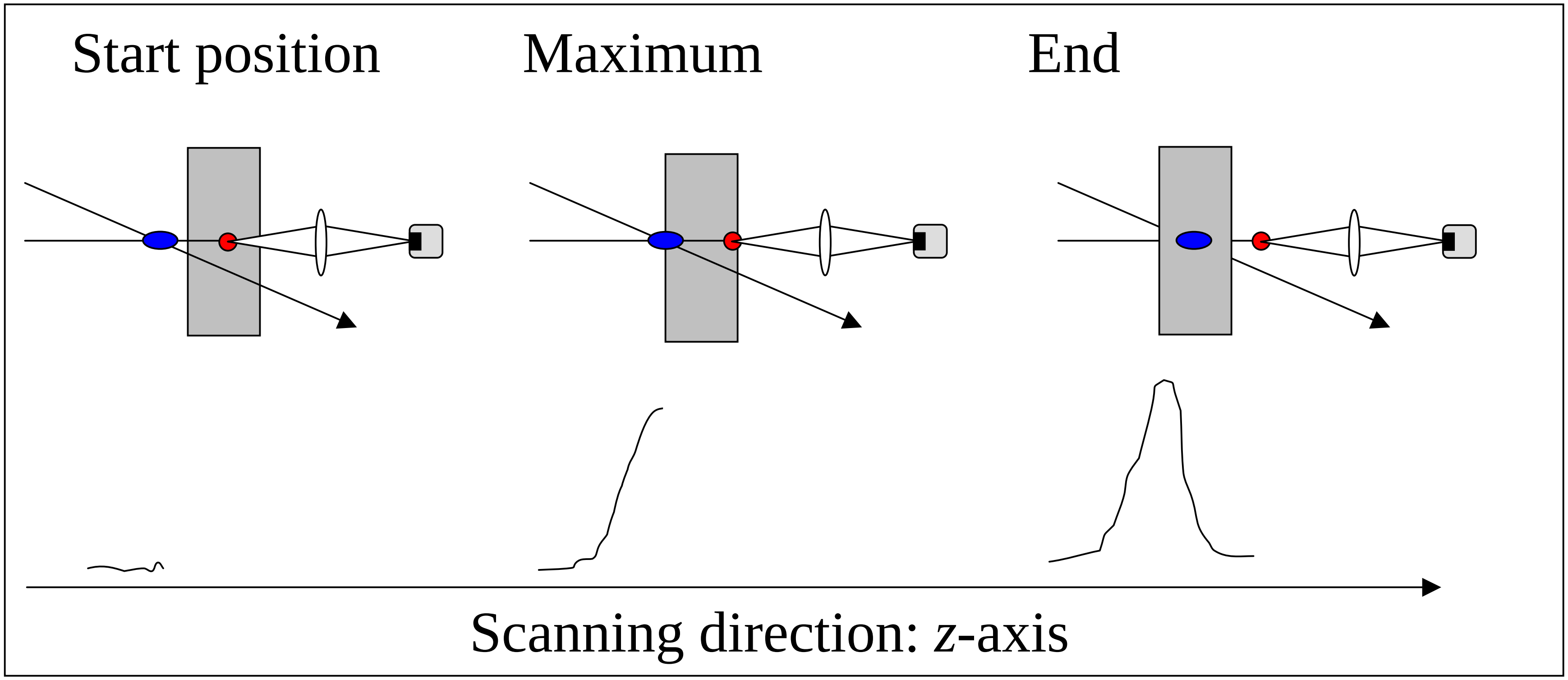
$w_{pump} < w_{probe}$. When the pump is on, the probe experiences phase distortion ($\Delta\varphi$) in the heated area. At some distance, $\Delta\varphi$ transform into ΔI and an effective interference occurs between the central spot (distorted) and outer ring area (undistorted) of the probe

A small angle, ≤ 7°, between the probe and pump beams allows localization of the heated area and isolation of the probe output in space.

Sensitivity: better than 0.1 ppm (surface absorption)

better than 0.2 ppm / cm (bulk absorption)

Optical loss measurement scheme for surface absorption

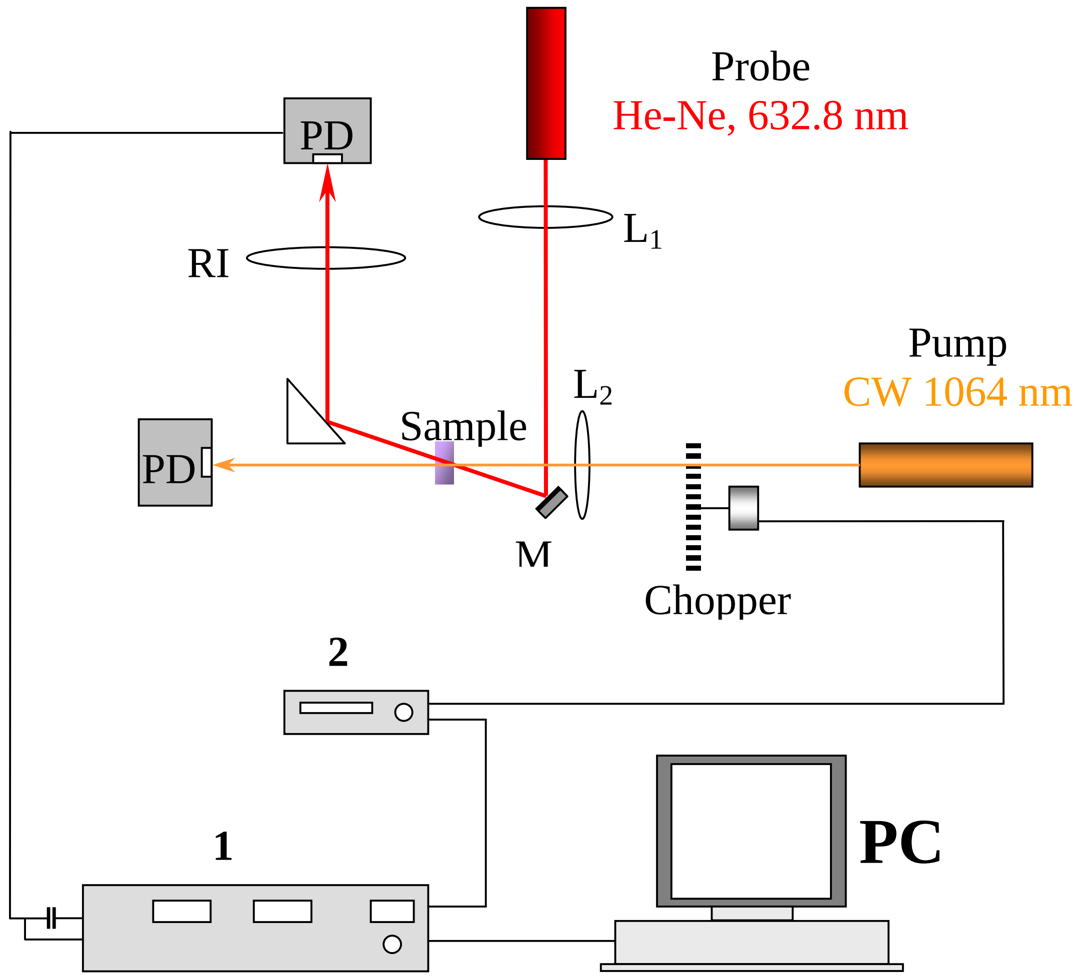


Blue: the position where the pump and probe beam cross:

Red: the position where the imaging system collects the signal from.

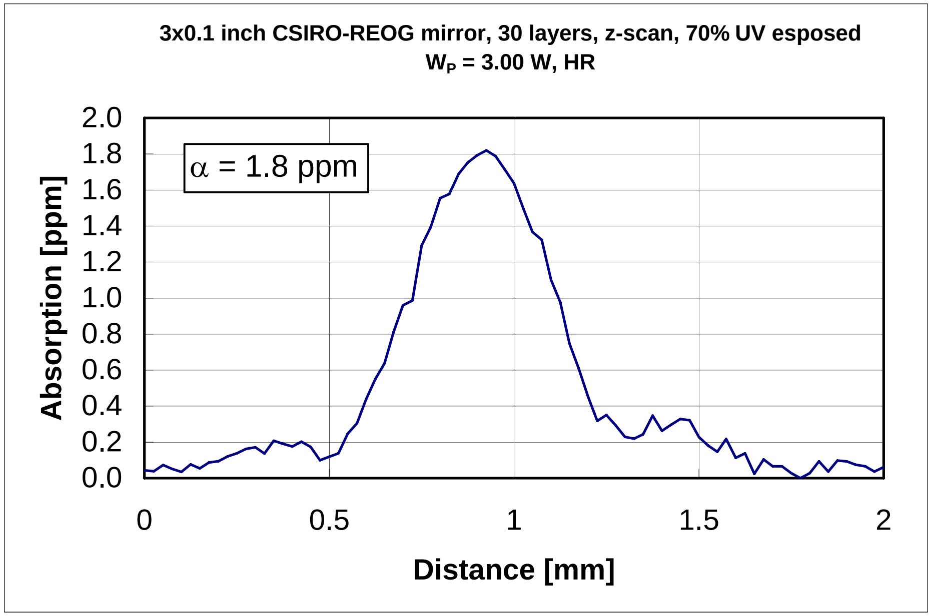
PCI setup

RI Re-imaging System
PD Photodetectors
L$_i$ Lenses
M Mirror
1 Lock-in Amplifier SR830 DSP
2 Chopper Controller SR340
PC with GPIB-connection (LabVIEW software)



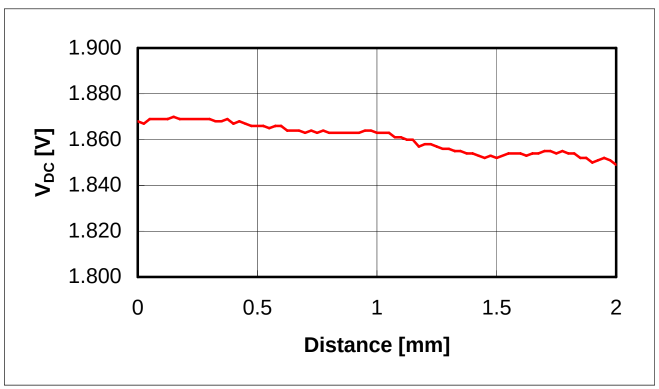
The probe wave (632 nm) with a larger waist (90 µm) senses the lensing effect of the pump (1064 nm) with a smaller waist (35 µm). Interference occurs between different parts of the probe wave due to phase mismatch.

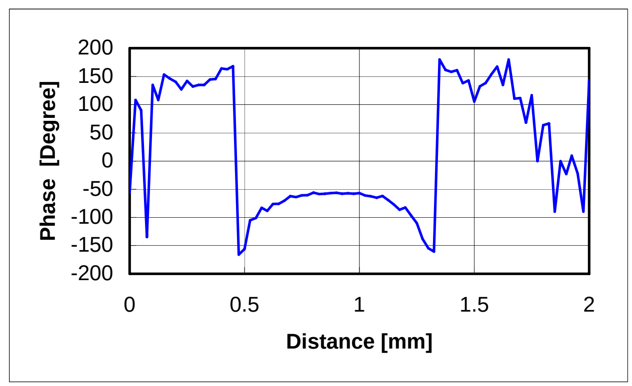
The PCI signal and additional monitored parameters



Intensity of the AC PCI signal,

AC signal ∝ to absorption





DC signal from probe ∝ W_{probe}

Phase delay of the AC signal (characterizes the substrate material)

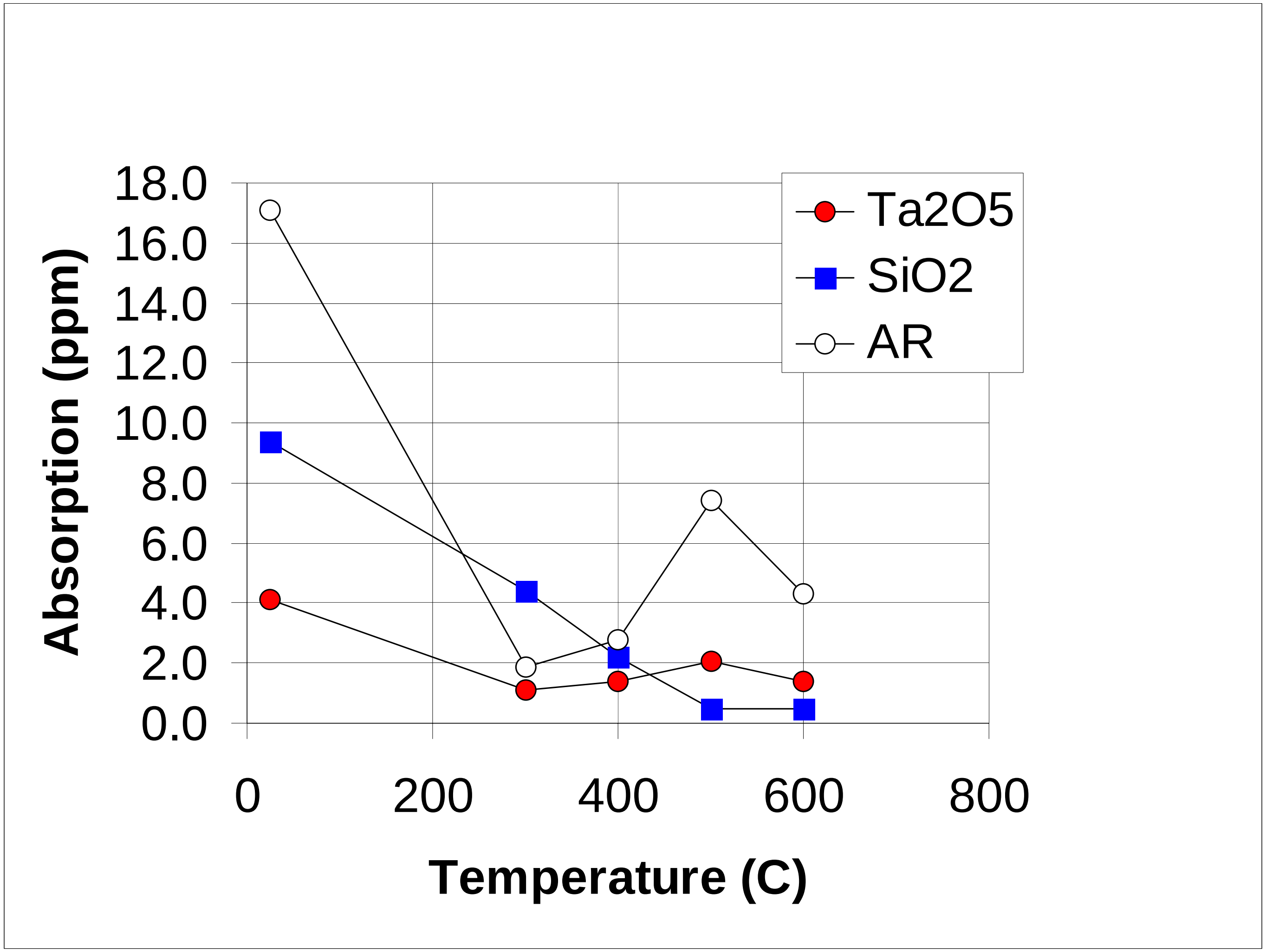
1) Monolayer coatings

Sample	Thickness (nm)	Absorption (ppm)
Ta2O5	500	1 to 4 ppm
SiO2	500	<0.5 to 9 ppm
Nb2O5	500	25 to 40 ppm
Ta2O5/SiO2	48/238	1.85 to 17 ppm

Annealing effect

Sample	Alpha before (ppm)	Alpha after (ppm)	Annealing regime
Ta2O5	4.1	1.15	350, 24 hrs
SiO2	9.4	3.1	350, 24 hrs
Ta2O5/SiO2	17.1	2.4	350, 24 hrs
Ta2O5	1.9	1.65	600, 19 hrs
Ta2O5/SiO2 (AR)	4.3	4.05	600, 19 hrs

The goal of this 1st phase annealing was the study of the stress removal effect.



As seen, low-temperature annealing, 300 to 350°C, is more efficient. The increase of the optical absorption at higher temperatures is possibly due to the growth of crystallites.

2) Double-layer AR coatings (oxygen effect)

Tantala/Silica double layers (~41 nm Ta_2O_5/241.4 nm SiO_2) were deposited at different oxygen excess in chamber, 25, 33, and 40 cm^3, and were annealed subsequently at temperatures varying from 350 to 550°C in vacuum or air.

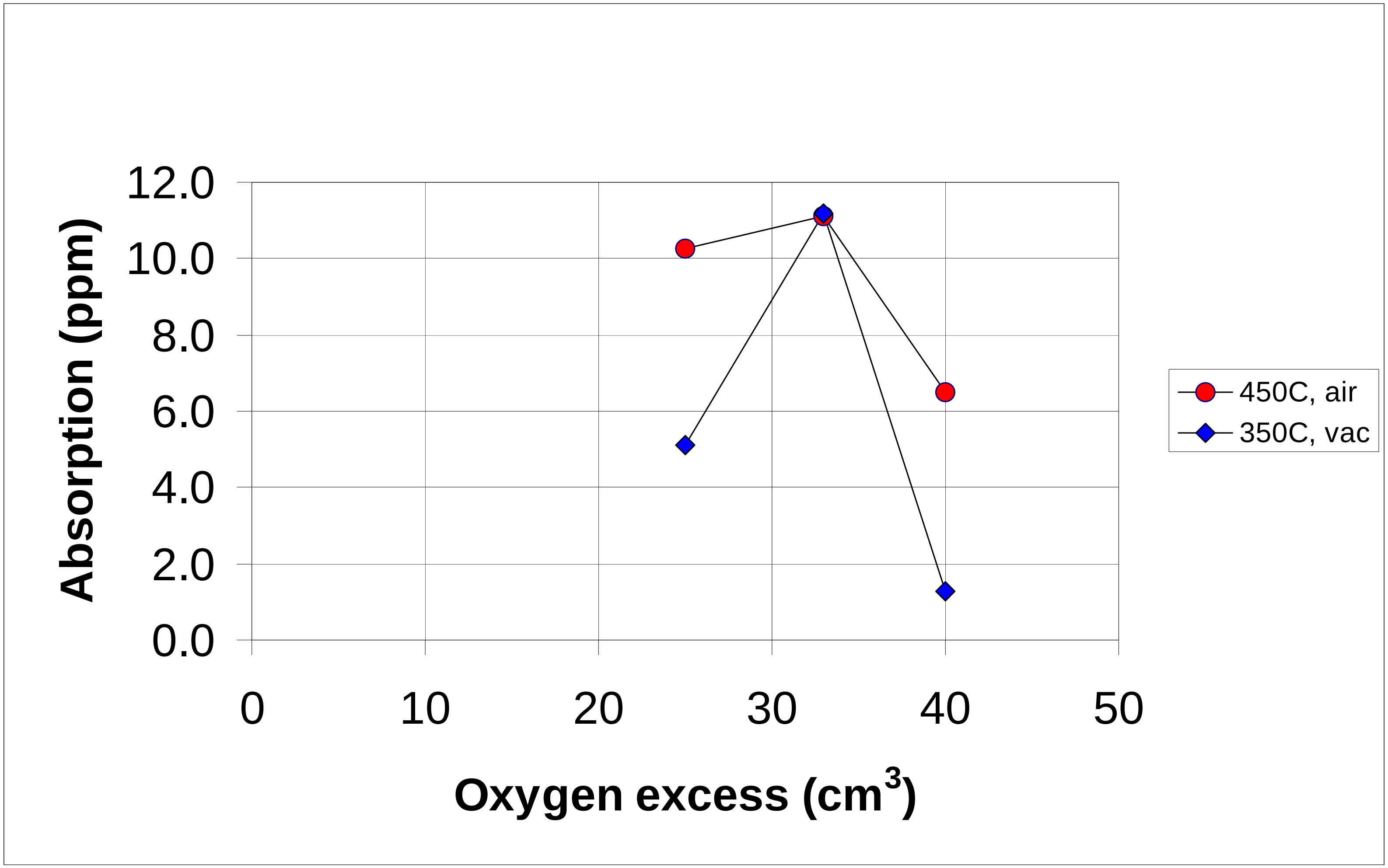
Oxygen 40 cc in chamber		
Sample #	**Annealing**	**Alpha (ppm)**
21	None	4.5
22	450 air	6.5
23	550 air	8.05
24	350 vac	1.28
25	450 vac	8.55
26	550 vac	15.65

Oxygen 33 cc in chamber		
Sample #	**Annealing**	**Alpha (ppm)**
28	None	12.3
29	None	10.6
31	450 air	11.1
32	550 air	3.05
33	350 vac	11.2
34	450 vac	14.2

Oxygen 25 cc in chamber		
Sample #	**Annealing**	**Alpha (ppm)**
35	None	16.75
36	450 air	10.25
37	550 air	9.95
38	350 vac	5.1
39	450 vac	12.7
40	550 vac	14.05

The trends are

1) **Annealing in air is better than in vacuum;**
2) **Annealing temperature must be below 450C.**
3) **Oxygen excess 40 cc in chamber is better in general**



Variation of the optical absorption of two AR Ta_2O_5/SiO_2 coatings versus oxygen excess content in the chamber for depositions in air and vacuum.

2) Double-layer AR coatings (effect of substrate temperature)

Tantala/Silica double layers (~41 nm Ta_2O_5/241.4 nm SiO_2) were deposited at different target temperature. Oxygen pressure was slightly different for SiO2 (35 cm^3) and Ta_2O_5 (49 and 45 cm^3). Samples were annealed subsequently at 450°C in 0.2 atm O_2 .

Sample #	Deposition Temp (C)	Absorption (ppm)	Notes
85	50	1.6	
93	100	11.8	uv-ozone cleaned substrate
67	100	9.55	
78	100	13.8	uv-ozone cleaned substrate
80	100	10.9	
68	125	9.75	
90	125	13.15	

Conclusion: lower the target temperature lower the optical absorption

Summary of the Results

The deposition and post deposition conditions are optimized for monolayer and AR (1064 nm) coating using the ultra-low optical absorption measurements PCI setup.

The trends favorable for lower optical absorption are:

1) **Lower deposition target temperature (50°C)**
2) **Slightly oxygen enriched atmosphere with respect to air (25 cm^3 in SCIRO IBS chamber)**
3) **Moderate stress releasing post-annealing temperature (300 to 350°C)**

References

[1] *Handbook of Deposition Technologies for Films and Coatings*, R.F. Bunshah (ed), William Andrew Publishing (1994).

[2] *Thin Solid Films* **260** (1995) 86, N. Kaiser, H. Uhlig, et al.

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